Comparison of Uniaxial Behavior of Fibre Reinforced Geopolymer and Conventional Concrete Columns

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***Abstract*— In this experimental investigation the structural behaviour of geopolymer concrete (GPC) columns and fibre reinforced geopolymer concrete (FRGPC) columns under monotonically increasing axial compressive loading were studied and compared with that of corresponding conventional concrete columns (RCC). A total of four GPC columns and four RCC columns were tested to evaluate the performance. Strength and behaviour of the tested columns were evaluated based on mode of failure, ultimate strength, stress-strain behaviour, energy absorption capacity and ductility. For better understanding of stress and strain distribution an analytical model for GPC column was developed by Finite Element Method. Analytical stress strain relationship obtained from FEM showed that the predictions were in close agreement with experimental curves. This indicated that the behaviour of confined geopolymer concrete columns under concentric compressive loading could be approximately predicted by the FEM approach.**

Keywords*— *Geopolymer concrete; alumino silicate; stress – strain behaviour; ductility

I.INTRODUCTION

Geopolymer concrete is an innovative construction material that does not contain cement. Constituent materials of geopolymer concrete include any source material which is rich in Silica (Si) and Alumina (Al), and an alkaline activator. Alkaline liquid would react with a source material containing Si and Al to produce aluminosilicate binders [2]. These inorganic binders along with fine aggregate and coarse aggregate produce geopolymer concrete. Fly ash which is an industrial by- product is found to be a good source material for geopolymer concrete. Geopolymer technology offer many environmental advantages by diverting material from waste stream, thus reducing the energy investment in processing virgin materials

Due to its eco friendliness and superior mechanical and durability properties geopolymer concrete has gained much interest among researchers. The properties of GPC include high early strength, low shrinkage, freeze-thaw resistance, sulphate resistance and corrosion resistance [8]. The stress-strain relations and Young's modulus of fly ash based geopolymer concrete for various compressive strengths have been reported by Hardjito et al [8]. Then empirical relationships between various mechanical properties of GPC were also established [6]. The process of geopolymerisation needs temperature

curing, at a temperature of $40^{O}C$-$70^{O}C$ for a period of 24 - 48 hours [8]. Since GPC requires temperature curing it is more suitable for prefabricated construction. Prefabricated industry has evolved to a stage that even multi-storeyed buildings can be constructed using assemblage of individual structural elements (beams, columns, slabs. wall panels). Once the behaviour of GPC structural elements is understood, it can be used for various construction purposes.

Even though a lot of studies have been reported on the mechanical properties of GPC, studies on GPC structural elements are limited [4, 12, 14, 15]. Studies on geopolymer concrete columns are only countable [12, 14, 15]. So more studies need to be conducted in this area to understand the behaviour of GPC columns.

In the present study an attempt has been made to understand the strength and behaviour of plain and fibre reinforced GPC columns and to compare the same with conventional concrete column. An analytical model for GPC column was also proposed using finite element method.

II EXPERIMENTAL INVESTIGATION

A. Constituent materials

Fly ash: Fly ash (ASTM Class F) was used as the base material for synthesizing the geopolymer binder. The physical and chemical tests results conform to ASTM C 618 F specifications.

Aggregates: Coarse aggregate of 20mm nominal size was used for making GPC and conventional concrete (PCC). Locally available river sand was used as fine aggregate. Laboratory tests were conducted on aggregates to determine the different physical properties as per IS: 2386 [10]. The results showed that the aggregates conformed to IS: 383 [9] specifications.

Alkaline solution: A combination of sodium silicate solution and sodium hydroxide (NaOH) solution was chosen as the alkaline liquid to activate the source material. Commercially available sodium silicate solution with SiO2–to-Na2O ratio by mass of 2 (Na_2O=14.7%, SiO_2=29.4%) and water=55.9% by mass was used for the study. Sodium hydroxide pellets with 97% purity were used for making NaOH solution.

Super plasticiser: The super plasticiser used in the study was Conplast SP 430 with specific gravity 1.25 (at 30^0C).

Reinforcing bars: HYSD bars of nominal diameter 12mm, 8mm and 6mm were used for the study. Tension test was conducted on reinforcing bars to obtain the yield stress and modulus of elasticity. Yield stress of the 12 mm bar, 8 mm bar and 6 mm bar were obtained as 450.6 N/mm^2, 423.5 N/mm^2 and 415.6 N/mm^2 respectively. The Young's modulus obtained is 2x10^5N/mm^2.

B. Mix Design

GPC mix was designed by trial and error procedure as per the guidelines available [13]. In order to compare the properties of GPC, PCC mix of same grade was also prepared as per the guidelines in IS10262(2009). Fibre reinforced GPC (FRGPC) and PCC(FRC) mixes were also developed by adding steel fibres of aspect ratio 60 and diameter 0.5mm. Mix proportion for all the developed mixes are given in Table 1.

TABLE 1 MIX PROPORTIONS

Mix	GPC	FRGPC	PCC	FRC
Fly ash (kg/m^3)	408	408	-	
Sodium silicate solution (kg/m^3)	103	103	-	
Sodium hydroxide solution (kg/m^3)	41	41	-	
Coarse aggregate (kg/m^3)	1237	1237	1266	1266
Fine aggregate (kg/m^3)	600	600	598	598
Water (kg/m^3)	14.5	16.5	192	192
SP (kg/m^3)	10	12.5	-	4
Fibre content (%)	0	0.5	0	0.5

C. Specimen details

Column specimens having 150 mm x 150mm square cross section with a tapering column head of 230 mm x 230 mm x 100 mm were used for the present investigation. Four numbers of 12 mm diameter bars were used as longitudinal bars and 6 mm diameter bars at 100 mm centre to centre spacing was provided as ties. Four bars of 8 mm nominal diameter were used in the stub region to avoid crushing failure of the stub. Special provision was made in the mould to insert plates for attaching LVDT to measure the axial deformation [1, 5]. This arrangement made it possible to determine the core strains. Table 2 shows the designation of column specimens used in the study.

TABLE 2: DESIGNATION OF SPECIMENS

Specimen designation	Type	Fibre Content (%)
GCA0	Geopolymer Concrete	0
GCA2	Geopolymer Concrete	0.5
RCA0	Conventional Concrete	0
RCA2	Conventional Concrete	0.5

D. Preparation of test specimens

The coarse aggregate and fine aggregate in the saturated surface dry condition were mixed in laboratory pan mixer with fly ash for three minutes. Then the alkaline solutions, superplasticiser and extra water were added to the dry materials and mixed for four minutes. Immediately after preparing concrete, the slump and compacting factor of fresh concrete were determined. In order to determine the hardened properties, standard cubes, cylinders and prisms were cast. After casting, all specimens were kept at room temperature for one day. For GPC, no water curing is required. Temperature curing for one day is sufficient [9]. So the specimens were placed inside the oven along with moulds and cured at 60^OC 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. After 24 hours of casting, PCC specimens were demoulded and kept immersed in water for 28 days.

E. Testing of Column

Columns were tested using 200T column testing machine under monotonic axial compressive loading. Loading was done using 100kN hydraulic jack. The accurate measurement of applied load was done using 100T capacity digital load cell. Load was applied from the bottom of specimen and load cell was kept at top in order to avoid the self-weight measurement. Axial deformation of specimens was measured at loading intervals of 25kN using two Linear Variable Differential Transformers (LVDT) with range 50mm with least count of 0.001mm. LVDTs were positioned at 150mm gauge length on two faces on opposite sides in order to determine the core deformation. Schematic diagram and actual test set up are shown in fig 1 and fig 2 respectively.

The appearance of tested specimens is shown in fig 3. As the loading was increased cracks initiated at column one third height from the support. With further increase in load, cracks propagated longitudinally along the length of column. It was observed that horizontal cracks developed on the tension side of the column. Ultimately failure of column occurred by the crushing of concrete in the compression zone of the column.

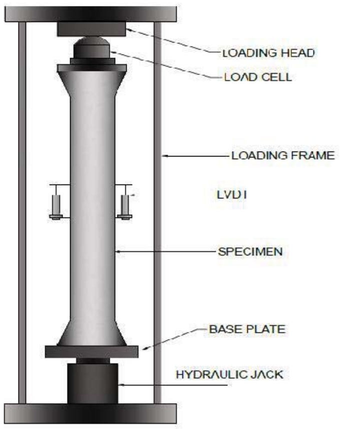

Fig. 1. Schematic diagram of test setup

Fig. 2. Loading arrangement

Fig. 3. Tested column specimens

III. TEST RESULTS

A. Fresh and Hardened Properties

Fresh and hardened properties of all the mixes were studied and are shown in Table 3. From the test results it can be seen that GPC possesses superior mechanical properties compared to PCC. This may be due better bonding of the geopolymer paste [6].

TABLE 3 FRESH AND HARDENED CONCRETE PROPERTIES

Mix	**GPC**	**FRGPC**	**PCC**	**FRC**
Slump (mm)	123	123	123	123
Compacting factor	0.9	0.8	0.92	0.86
Compressive strength (N/mm^2)	37	41.2	35	39.5
Split tensile strength (N/mm^2)	3.56	4.2	3.15	3.6
Modulus of elasticity (N/mm^2)	38148	40157	26678	30149
Flexural strength (N/mm^2)	4.35	4.57	3.77	4.2

B. Ultimate Load Carrying Capacity

Table 4 shows the ultimate load carried by the specimens. It can be seen that the percentage increase in ultimate load for GPC specimens with and without fibre is around 5% compared to corresponding RCC specimens. For fibre reinforced specimens the percentage increase in ultimate load is around 22% in both cases. Thus it can be inferred that the effect of fibres on the strength of GPC is same as that of PCC.

TABLE 4 ULTIMATE LOAD CARRIED BY SPECIMENS

Specimen	Fibre content	Ultimate load carrying capacity (kN)	% increase in ultimate load
GCA0	0	550	4.76
RCA0	0	525	
GCA2	0.5	675	4.97
RCA2	0.5	643	

C. Stress- Strain behaviour

Experimental values of load and deflection were used to determine the stress and strain values. Stress - strain curves for all the columns were plotted and is shown in the fig 4. From the figure it can be seen that both GPC and RCC columns behaved in a similar manner during the initial stages. After reaching the peak stress a sudden dip in the stress -strain curve is observed for GPC and RCC column which implies a sharp reduction in the stiffness value. For fibre reinforced specimens the ultimate stress is higher and also shows more ductile behaviour compared to non fibrous specimens.

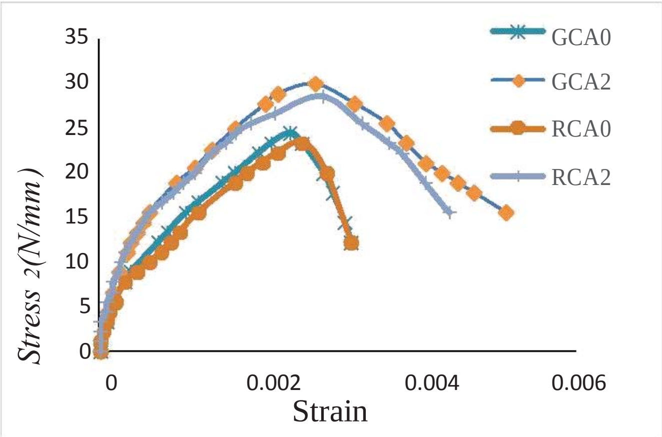

Fig. 4. Stress - Strain Curve for column specimens

D. Energy absorption capacity and Ductility

Energy absorption of the specimens was calculated as the area under the stress - strain curve. The area under the stress - strain curve up to a given value of strain is the total mechanical energy per unit volume consumed by the material in straining it to that value. The energy absorption capacities of all the column specimens are shown in Table 5. From the table it can be inferred that both GPC and RCC specimens the energy absorption capacity increases with increase in fibre content but the percentage increase was more for GPC than PCC.

TABLE 5 ENERGY ABSORPTION CAPACITY

Specimen	**Energy absorption capacity (N/mm^2)**	**% increase in energy absorption capacity of GC compared to RC**
GCA0	0.052	6.12
RCA0	0.049	
GCA2	0.111	18.08
RCA2	0.094	

Strain ductility ratio is defined as the ratio of axial strain of concrete at 85% of peak stress on descending branch (ε_{85}) to strain at peak stress (ε_u) [11]. It is used to make a quantitative assessment of ductility. Table 6 shows the ductility values calculated for all the specimens. From the table it can be seen that effect of fibres on the ductility of columns is almost same for both GPC and RCC columns.

TABLE 6 DUCTILITY VALUES OF THE SPECIMENS

Specimen	**ε_u**	**ε_{85}**	**Ductility ($\varepsilon_{85}/\varepsilon_u$)**
GCA0	0.00248	0.00282	1.18
RCA0	0.0024	0.00280	1.16
GCA2	0.0027	0.00360	1.33
RCA2	0.0028	0.00365	1.30

IV. ANALYTICAL MODELLING

For a better understanding of the stress and strain distribution, GPC columns were modelled and analysed using Finite Element Method. Concrete is modelled as SOLID 65 element and steel reinforcement is modelled as LINK180 element. The parameters used to model GPC columns are given in Table 7.

Material Model Number 1 refers to Solid65 element which requires linear isotropic and multilinear isotropic material properties to properly model concrete. The multilinear isotropic material uses the von Mises failure criterion and Willam and Warnke (1975) model to define the failure criterion of concrete. EX is the modulus of elasticity of the concrete (E_c) and PRXY is the Poisson's ratio.

The compressive uniaxial stress-strain relationship obtained by testing cylinder specimens was used to model the multilinear isotropic stress strain relation of concrete. Fig 5 shows the meshed column.

TABLE 7 MATERIAL MODELS FOR COLUMN SPECIMEN

Material Model number & element type	**Material properties**		
1 (SOLID 65)	Linear Isotropic		
	EX		38149
	PRXY		0.18
	Multilinear Isotropic		
		Strain	Stress (MPa)
	Point 1	0.000005	1.08
	Point 2	0.00055	11.09
	Point 3	0.00105	18.8
	Point 4	0.0016	24.42
	Point 5	0.00215	24.7
	Concrete		
	Open shear transfer coefficient		0.3
	Closed shear transfer coefficient		1
	Uniaxial cracking stress		4.1
	Uniaxial crushing stress		-1
2(LINK 180)	Linear Isotropic		
	EX (N/mm^2)		200000
	PRXY		0.3
	Bilinear Isotropic		
	Yield stress(N/mm^2)		415
	PRXY		0.3

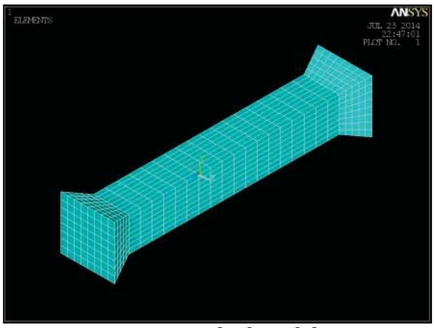

Fig. 5 Meshed model

B. Loading and Boundary conditions

Displacement boundary conditions are needed to constrain the model to get a unique solution. To achieve this, the translations at the nodes (UX, UY and UZ) are given constant values of zero. At the top of the column translations in x and y directions are set to zero allowing displacements to occur along the length 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. The axial pressure can be simulated using the ANSYS load step option. Load step option may be used when the incremental loading is considered. Thus column is loaded upto failure. Failure occurs when the convergence criterion is not satisfied.

C. Stress Distribution

Axial stress distributions at failure load for GPC columns are shown in fig 6 and fig. 7. From the figure it can be seen that uniform stress distribution occurs along the length of the column except at the top and bottom region of the column. At failure load of the column model, stress at top and bottom region is found to be higher than the stress at middle portion for all the columns. This indicates that failure occurred at top and bottom region. Stress distribution in the cross section of the stub indicate that maximum stress occurred in the centre region of the cross section and stress decreases towards the periphery of the column cross section.

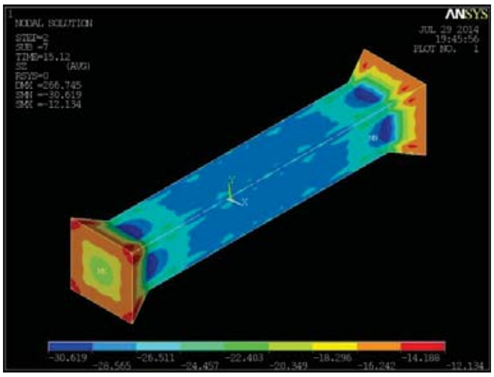

Fig. 6 Stress Distribution in GCA0

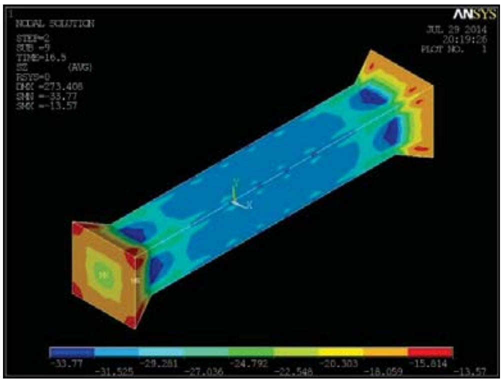

Fig. 7. Stress Distribution in GCA2

D. Stress - strain Relationship

The axial stress-strain curve obtained from ANSYS solution is compared with experimental results and is shown in fig. 8. 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 gives a message specifying large deflection, exceeding the displacement limitation. This indicates the failure of the column. Stress strain relationship obtained from ANSYS shows that the predictions are in close agreement with experimental curves. This indicated that the actual behaviour of confined column specimens with transverse steel and steel fibre under concentric compressive loading can be approximately predicted by the FEM approach.

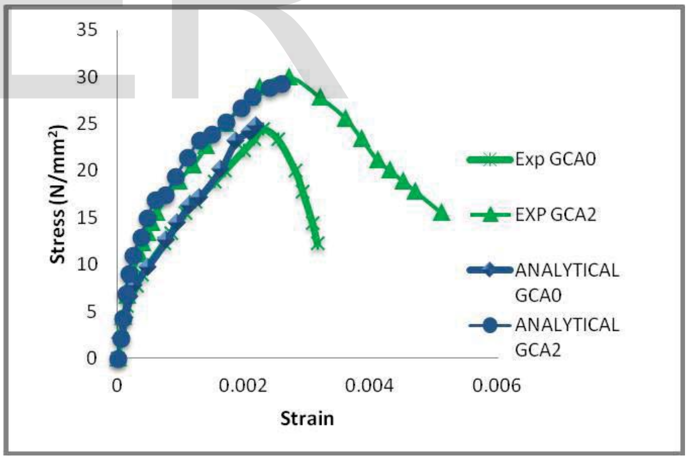

Fig. 8. Comparison of Stress Strain Curves

Table 8 and 9 shows the comparison of the ultimate stress and strain obtained from FEM analysis with experimental results. It shows that close tolerance is achieved between the experimental and FEM results. So the model developed by FEM approach can be used for further analysis of reinforced geopolymer concrete columns.

TABLE 8 COMPARISON OF ULTIMATE LOAD

Specimen	Ultimate Load kN		
	Experiment	*ANSYS*	*% variation*
GCA0	550	546.4	0.65
GCA2	675	709.3	5.1

TABLE 9 COMPARISON OF ULTIMATE STRAIN

Specimen	Ultimate stain		
	Experiment	*ANSYS*	*% variation*
GCA0	0.0024	2	4.35
GCA2	0.0018	0.0017	5.56

V. CONCLUSIONS

From the present study, the following conclusions were obtained.

- Stress-strain behaviour of geopolymer concrete column was found to be comparable to that of conventional concrete column and the post peak behaviour improved significantly with addition of fibres in both the cases.
- Geopolymer concrete and conventional concrete column showed similar failure mode, energy absorption capacity and ductility.
- Finite element model of the reinforced geopolymer concrete column was created. Stress- strain curves obtained from finite element analysis is found to be in good agreement with experimental results.
- Percentage variation between the stress and strain values obtained from finite element analysis and experiment is only less than 6%.
- From the experimental study it can be concluded that geopolymer concrete can be used as an alternative construction material to conventional concrete.

Acknowledgement

The authors would like to thank the financial support by Kerala State Council for Science, Technology and Environment (KSCSTE) for carrying out the experimental investigation.

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