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EXPERIMENTAL TESTING, FE MODELLING AND ANALYSIS OF GEOPOLYMER CONCRETE COLUMNS WITH STEEL REINFORCEMENT (CSCE'21)

[a]Adal Imtiaz, [b]Faheem Butt, [c]Rana Muhammad Waqas*

a, b, c: Department of Civil Engineering,
University of Engineering and Technology, Taxila,
a*: rajaadall@gmail.com
b: faheem.butt@uettaxila.edu.pk
c: rana.waqas@uettaxila.edu.pk

Abstract- This paper focuses on experimental testing and Finite Element (FE) modelling of steel reinforced Ordinary Portland Cement-OPC and Geopolymer Concrete-GPC columns. GPC was prepared by combining Fly Ash-FA, furnace slag-SG and adding steel fibres SF with volume fraction of 0.75%. Twelve 200x200mm columns having length of 1000mm with concrete cylinder compressive strength (fc') of 40 MPa were casted and tested for static loading on 5000KN Universal Testing Machine (UTM). Experimental results were validated through FE modelling on commercial software ABAQUS. Concrete Damaged Plasticity (CDP) model was used to define behaviour of concrete. It was found that axial load-deflection response closely matched with the laboratory results for columns loaded with zero eccentricity while load capacities for columns loaded with different eccentricity were over predicted in FE Model. It has been observed that load bearing capacity of GPC columns is lower than corresponding OPC columns but can be improved by addition of steel fibre. A constitutive model derived for high strength concrete has shown close agreement with experimental results [1] [2] [3].

Keywords- FE modelling, geopolymer concrete, quarry rock dust, steel fibres.

1 Introduction

Development of geopolymer concrete (GPC) has been increased due to growing demand of its being environmental friendly and alternative to OPC with better durability and curtails emission of carbon dioxide (CO2) during the production of cement used in OPC. GPC is a well-known cementitious material based on alumina-silicate and the main constituents are mainly industrial waste residuals such as fly ash (FA) and ground granulated blast-furnace slag (SG). Using by-products of industries as partially replacing cement is encouraged to enhance the physical, chemical and mechanical properties of concrete. Dense gel structure of geopolymer concrete makes it more durable than the OPC concrete [4]. Various Investigations have endorsed the use of slag (SG) to achieve encouraging outcomes at ambient curing conditions [5]. Fibres are generally included in concrete to control cracking due to plastic and drying shrinkages and decrease the permeability of concrete by decreasing bleeding water. Mechanical properties especially splitting tensile and flexural strength are also improved by addition of Steel fibre (SF) [6]. Adding SFs at 0.25, 0.5 and 0.75% of concrete (by volume) improves the ductility and load bearing capacity of GPC specimens [7]. Under different loading conditions, fibre reinforced GPC column specimen exhibit higher peak axial load and bending moment than those without steel fibres [8].

In order to validate experimental findings, behaviour of reinforced concrete columns was simulated through finite element analysis (FEA). It is commonly accepted that concrete damaged plasticity model has proved to be appropriate in modelling the reinforced concrete structures. Using Concrete damage plasticity (CDP) model in ABAQUS for FEA for prediction of the response of reinforced GPC and OPC concrete columns presented decent match between experimental curves and predicted load–displacement responses [9]. ABAQUS has been found to be an accurate tool for conducting FEA. This study focuses on experimental and numerical analysis to investigate steel reinforced OPC concrete and GPC columns prepared by low calcium fly ash and Slag (SG) with and without addition of 0.75% SF (by volume of composites). Total three types of reinforced concrete columns (Table 1) were prepared with different composition with four samples of each type tested for eccentricity 0, 15, 35 and 50 mm. Thus total of twelve samples of columns were prepared for experimental investigation through static load testing and FE modelling through ABAQUS for validation of experimental results.

2 Experimental Procedures

In order to cast steel reinforced columns made with OPC and Geopolymer concrete, the ingredients i.e. coarse aggregate, fine aggregates and binders (FA, SG) were mixed as per ratios given in Table 1.

Table 1- Mix proportion of OPC and GPC mixtures

Group ID	Specimen ID	Mix proportions (%)				Mix quantities (kg/m^3)								
		SF	OPC	FA	SG	Sand	OPC	CA	SG	FA	Na_2SiO_3	NaOH	SP	Water
OPC	CC-0F	0	100%	-	-	640	370	1201	-	-	107	53	4	170
GPC	GC-0F	0	-	50%	50%	643	-	1206	200	200	107	53	8	-
	GC-0.75F	0.75%	-	50%	50%	647	-	1214	200	200	107	53	12	-

Note: SF(Steel Fibres); OPC(Ordinary Portland Cement); FA (Fly ash); SG (Blast Furnace Slag); CA (Coarse Aggregates); SP (Superplasticizers); GPC (Geopolymer Concrete),

Mix design of all the mixes was prepared for 28-day compressive strength (fc') of 40 MPa. Four specimens of steel reinforced columns (200mm x 200mm x 1000mm) were casted for every type of mix. Ambient curing was carried out for columns and UTM of 5000 kN capacity was used for testing under static loading at eccentricity 0, 15, 35 and 50 mm. Load deflection behaviour was obtained for each type of column through experiment for validation by finite element modelling using ABAQUS.

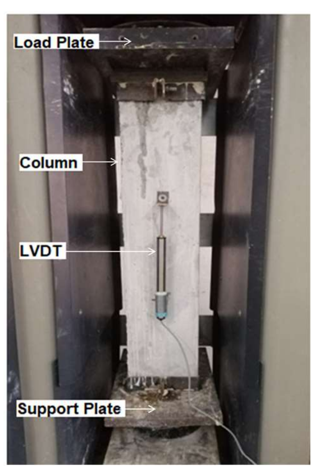


Figure 1: Experimental Setup

2.1 Materials.

To prepare specimen of conventional concrete, Type-II cement OPC conforming to ASTM C-150 [10] was used. GPC mixtures were prepared by using different proportions of binders i.e SG and FA. Fine aggregate's fineness modulus conformed to ASTM-C-136-06 [11] whereas water absorption and specific gravity was conforming to ASTM-C128-15 [12]. The Specific gravity of coarse aggregate (CA) was conforming to ASTM-C127-07 [13]. The commercially available hard-drawn, hooked end wire (steel) fibres (MasterFiber® S 65), conforming to the provisions of ASTM A820 [14], Type 1 were used. Grade 60 deformed steel bars conforming to ASTM A615 [15] were used as column reinforcement.

3 Finite Element Model

3.1 Methodology.

Commercially used software known as ABAQUS was used for numerical simulations of reinforced concrete columns. Concrete material and end steel plates (50mm thick) were modelled as a 3D solid homogeneous section while steel bar and rectangular ties were modelled as 3D deformable wire element with truss section having cross section area of 113.1 and 28.27 mm^2 respectively. In order to define concrete compressive behaviour, CDP model was used. Bottom of all columns was fixed and top end remained free for axial load application. Displacement controlled loading in form of displacement of 10 mm was applied at eccentricity 0, 15, 35 and 50mm for each type of column. Load deflection curves were obtained for each column and compared with the experimental results. No lateral loads have been studied.

3.2 Geometry of Model, Meshing and Boundary Conditions.

Reinforced concrete columns as per dimensions shown in Figure 2 were modelled in ABAQUS. Parts comprising of concrete column, steel plates and steel reinforcement were then assembled and connected through tied and embedded region constraints respectively. Steel plates were tied through master and slave surface concept i.e. bottom surfaces of top steel plate and column were taken as master surfaces whereas top surfaces of bottom steel plate and column were considered as slaves for equal distribution of applied load. Meshing of columns were carried out with reduced integration (C3D8R), 3D stress linear and quadratic hexahedral elements while steel bars were meshed using standard linear 3D truss elements (T3D2). Accuracy of results was calibrated for mesh size of 25mm. Point load in the form of displacement of 10 mm was applied axially to the column at eccentricity equal to 0, 15, 35 and 50 mm from centre of the column. Detail of geometry and meshed model along with application of constraints for steel-reinforced columns are shown in Figure 2.

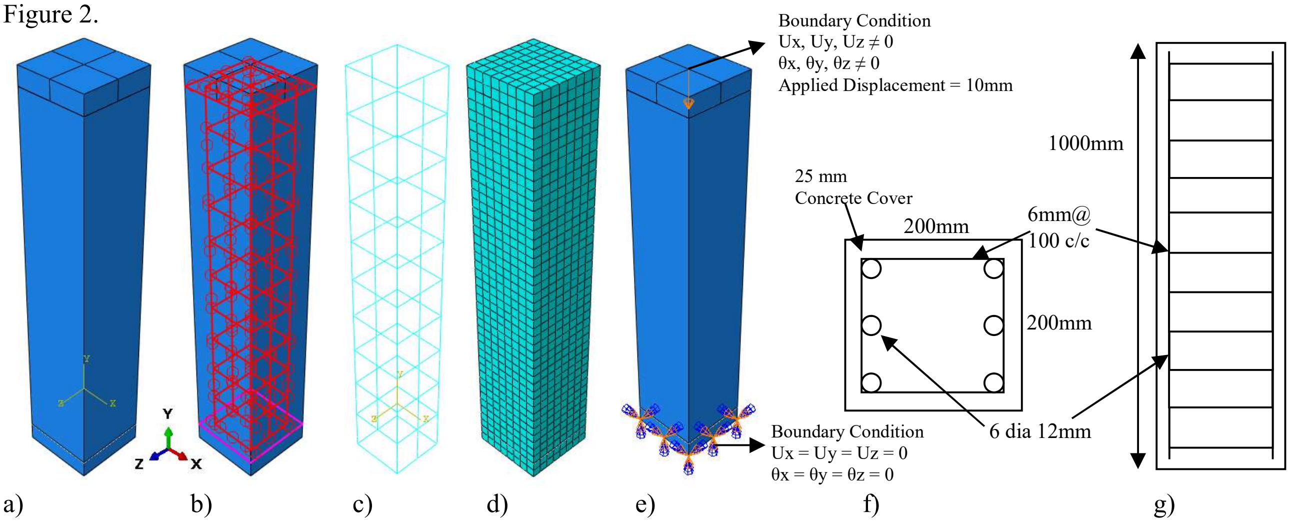


Figure 2: FEA Model of Column, a. Geometry, b. Embedded region constraints, c. Steel mesh, d. Meshing, e. Boundary Conditions f. Column Cross Section and g. Longitudinal Section of Column

3.3 Material Properties.

In order to define the concrete behaviour, CDP model proposed by Liu and Chen [16], as shown in Figure 3 and 4, which describes the relationship between inelastic and plastic strain, and compression stress of concrete. Liu and Chen parameters [16] were used to determine values of damage parameter dc, inelastic strain ε_{in} and plastic strain ε_{pl}. Linear elastic behaviour was assumed in the reversible regime, whereas damage plasticity behaviour in irreversible regime for both GPC and OPC concrete. For modelling of linear elastic behaviour, properties of concretes and steel reinforcement are tabulated in Table 2.

Table 2-Different properties of concrete and steel

Material	Density, ρ (tonne/mm^3)	Poisson ratio, υ	Young's modulus, Ec (MPa)	Max Stress, MPa
OPC	$2.4\text{x}10^{-9}$	0.2	29725	fc'=40
GPC	$2.42\text{x}10^{-9}$	0.23	30150	fc'=40
GPC-SF	$2.42\text{x}10^{-9}$	0.23	34129.1	fcf'=40
Steel Bars	$7.85\text{x}10^{-9}$	0.3	200,000	fy=420
End Plates	$7.85\text{x}10^{-9}$	0.3	200,000	-

For concrete in irreversible regime, concrete damaged plasticity (CDP) model is used to define two failure mechanisms known as crushing due to compression and cracking due to tension. To model plastic behaviour of concrete, recommended values of the dilation angle (ψ)=36°, yield shape surface (Kc=2/3), and eccentricity (e=0.1) were used [17]. The value of stress ratio σ_{b0}/σ_{c0} is taken as 1.12, which is also quantified by Papanikolaou and Kappos [18] through proposed equation $\sigma_{b0}/\sigma_{c0} = 1.5\, f_c'^{-0.075}$ based on a large statistical data. Constitutive model derived for high strength concrete by Collin et al [3] was used to model compressive behaviour of both OPC and GPC concrete as per Table 3.

Table 3-Equations for material properties and constitutive model for GPC and OPC concrete

Material Property	GPC		OPC	
Elastic Modulus, Ec	$Ec_{GPC} = 4907.5\sqrt{fc'}$ [19]	(1)	$Ec_{OPC} = (3320\sqrt{fc'} + 6900)$ [21]	(2)
	For Steel Fibre Reinforced-SFR GPC			
	$Ecf_{GPC} = 21500 \text{ x } (\frac{fc'}{10})^{\frac{1}{3}}$ [20]	(3)		
Peak Strain, ε_{cp}	$\varepsilon_{cp} = 18.97 f_c' + 623.6$ [19]	(4)	$\varepsilon_{cp} = \frac{f_c'}{E_c}\frac{n}{n-1}$ [3]	(5)
	For SFR GPC [22]			
	$\varepsilon_{cpf} = \left[0.00050 + 0.00000072 \left(\frac{v_f\, l_f}{d_f}\right)\right](f_{cof})^{0.35}$	(6)		
Tensile Strength	$f_t' = 0.7\sqrt{fc'}$ [23]	(7)	$f_t' = 0.33\sqrt{fc'}$ [24]	(8)
	$f_t' = 0.6\, \eta\, (fc')^{\frac{2}{3}}\, V_f \frac{l_f}{d_f}$ [22] (For SFR GPC)	(9)		

Cracking Strain $\varepsilon_{cr} = 0.000065 f_{ct}^{\ 0.54}$ [23] (10) $\varepsilon_{cr} = 0.000065 f_{ct}^{\ 0.54}$ (11)

Constitutive Model [1] [2] [3]

$$\sigma_c = f_c' \frac{n\ (\varepsilon_c / \varepsilon_{cp})}{n - 1 + (\varepsilon_c / \varepsilon_{cp})^{nk}} \quad \text{(MPa)} \tag{12}$$

Where,
fc'= Peak / Maximum stress
ε_{cp} = Strain at peak / maximum stress
$n = 0.8 + (f_c'/17)$
$k = 0.67 + (f_{cm}/62)$ when $\varepsilon_c/\varepsilon_{cp} > 1$
$= 1.0$ when $\varepsilon_c/\varepsilon_{cp} \leq 1$

For Steel Fibre Reinforced Concrete [25]

$$n = \beta = 1.093 + 7.4818(3V_f \frac{l_f}{d_f})^{-1.387} \tag{12}$$

V_f=Steel fibre fraction in Volume
l_f , d_f = Length and diameter of fibre, respectively
η = Orientation factor of fibre which is taken as 0.5

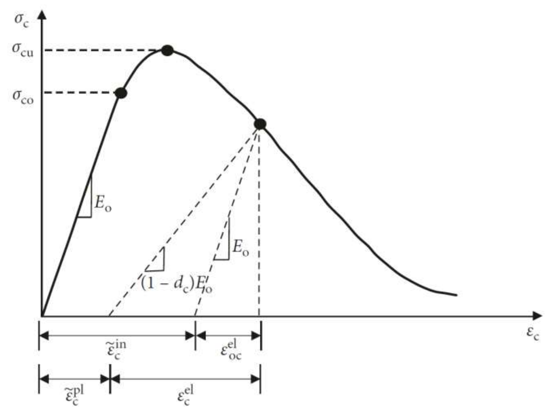


Figure 3: The plain concrete damaged plasticity model

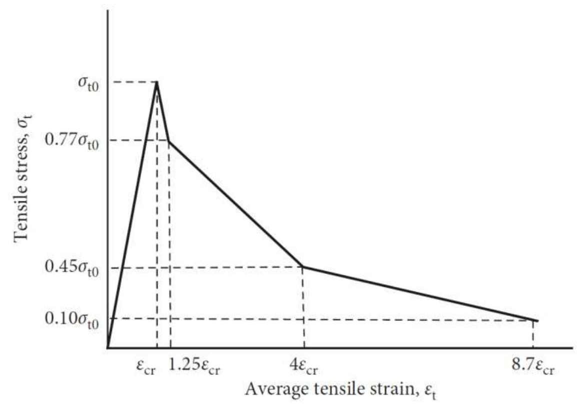
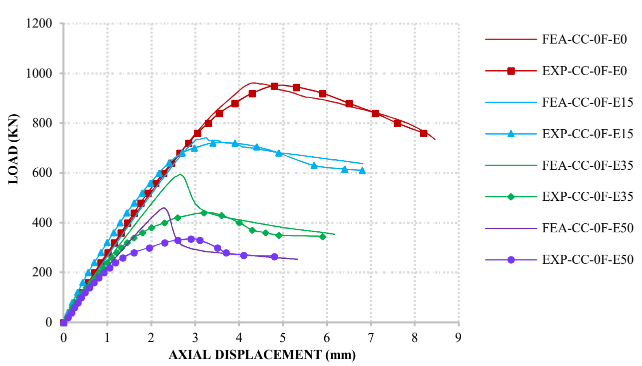


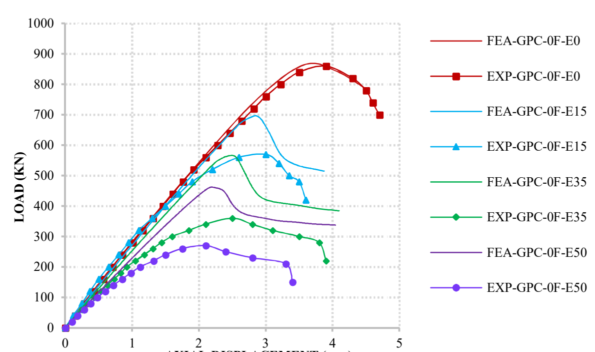
Figure 4: Modified tension stiffening model

4 Results and Discussions

Experimental results depicts that peak load capacity of GPC columns was reduced by 9.4%, 20.8%, 18.2%, 19.4% than corresponding OPC concrete columns for application of load on eccentricity 0, 15, 35 and 50mm, respectively. However, it was improved by 18%, 29.8%, 27.7% and 29.6% with addition of 0.75% of steel fibre fraction by volume in GPC columns. After comparison of results, obtained from experiments and FE modelling through ABAQUS, it has been observed that load deflection curve for concentrically loaded column were in good agreement with experimental curve.



a)



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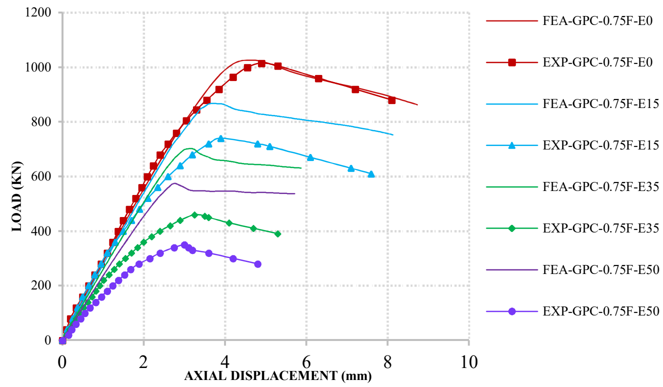

c)

Figure 5: Load vs Displacement Curve for a. OPC Column, b. GPC Column, and c. GPC Column with addition of 0.75% SF

Difference in peak load for the concentrically loaded column was 1.15%, 0.4% and 0.9% for OPC, GPC and GPC with Steel fibres, respectively. Notably, accuracy of 99% has been achieved by the model for accurately predicting concentrically loaded columns. However, load capacities for eccentrically loaded column were over predicted by the FE model and over prediction had a rising trend as the eccentricity of column is increased. Difference in axial deflection for peak load was 9.09%, 8.54% and 3.17% for concentrically loaded columns of OPC, GPC and GPC with 0.75% steel fibres respectively. Overestimation in results for eccentrically loaded columns was due to opening of laps of tie reinforcement resulting in discrepancies. Moreover, even small eccentricity resulting due to error in construction or imperfect geometry of material is of vital importance as it can significantly reduce ultimate axial capacity of columns.

5 Conclusion

Following conclusions can be made from the conducted study:

- FE Model has been found in good correlation with the practical results for concentrically loaded column with an accuracy of 99%. Difference in peak load and axial deformation for all three types of concentrically loaded columns is 1% and 3-9% respectively.
- The eccentrically loaded columns over predicted peak load carrying capacity of column due to opening of lap for rectangular ties used in experimental setup. Therefore, it is recommended to model ties in FE model accordingly for future studies.
- Load carrying capacity and ductility of GPC columns improves by addition of steel fibres in 0.75% volume fraction.
- The model can be used for further parametric studies and improvement for validation of experimental results for concentrically loaded columns.

References

[1] S. Popovics, "A numerical approach to the complete stress-strain curve of concrete," *Cement and Concrete Research,* vol. 3, no. 5, pp. 583-599, 1973.

[2] E. Thorenfeldt, "Mechanical properties of high-strength concrete and applications in design," *Material Science,* 1987.

[3] M. P. Collins, D. Mitchell and J. G. Macgregor, "Structural Design Considerations for High-Strength Concrete," *Concrete International,* vol. 15, no. 5, pp. 27-34, 1993.

[4] A. S. Genikomsou and M. A. Polak, "Finite element analysis of punching shear of concrete slabs using damaged plasticity model in ABAQUS," *Engineering Structures,* vol. 98, pp. 38-48, 2015.

[5] P. Nath and P. K. Sarker, "Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," *Construction and Building Materials,* vol. 66, pp.

163-171, 2014.

[6] A. Islam, U. J. Alengaram, M. Z. Jumaat, N. B. Ghazali, S. Yusoff and I. I. Bashar, "Influence of steel fibers on the mechanical properties and impact resistance of lightweight geopolymer concrete," *Construction and Building Materials,* vol. 152, pp. 964-977, 2017.

[7] P.SaranyA, P. Nagarajan and A.P.Shashikala, "Behaviour of GGBS-dolomite geopolymer concrete short column under axial loading," *Journal of Building Engineering,* vol. 30, p. 101232, 2020.

[8] N. A.Farhan, M. N. Sheikh and M. N.S.Hadi, "Behaviour of Ambient Cured Steel Fibre Reinforced Geopolymer Concrete Columns Under Axial and Flexural Loads," *Structures,* vol. 15, pp. 184-195, 2018.

[9] M. Elchalakani, A. Karrech, M. Dong, M. S. M. Ali and B. Yang, "Experiments and Finite Element Analysis of GFRP Reinforced Geopolymer Concrete Rectangular Columns Subjected to Concentric and Eccentric Axial Loading," *Structures,* vol. 17, pp. 273-289, 2018.

[10] ASTM C150-07, "Standard Specification for Portland Cement," *ASTM International,* 2007.

[11] ASTM C136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," *ASTM International,* 2006.

[12] ASTM C128-15, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate," *ASTM International,* 2015.

[13] ASTM C127-07, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate," *ASTM International,* 2007.

[14] ASTM A820-11, "Standard Specification for Steel Fibers for Fiber-Reinforced Concrete," *ASTM International,* 2011.

[15] ASTM A615, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," *ASTM International.*

[16] W. X. M. Liu and Z. Chen, "Parameters calibration and verification of concrete damage plasticity model of Abaqus," *Industrial Construction,* vol. 44, pp. 167-213, 2014.

[17] "Abaqus User Manual".

[18] V. K.Papanikolaou and A. J.Kappos, "Confinement-sensitive plasticity constitutive model for concrete in triaxial compression," *International Journal of Solids and Structures,* vol. 44, no. 21, pp. 7021-7048, 2007.

[19] S. Chitrala, G. J. Jadaprolu and S. Chundupalli, "Study and predicting the stress-strain characteristics of geopolymer concrete under compression," *Case Studies in Construction Materials,* vol. 8, pp. 172-192, 2018.

[20] Comite Euro-International Du Beton;, "CEB-FIP MODEL CODE 1990: DESIGN CODE," 1993.

[21] ACI 363 (1992), "State-of-the-Art Report on High-Strength Concrete (ACI 363R-92)," *ACI Journal Proceedings, 92(Reapproved).*

[22] N. A. Farhan, M. N. Sheikh and M. N. S. Hadi, "Axial Load-Bending Moment (P-M) Interactions of Geopolymer Concrete Columns Reinforced with and without Steel Fiber," *Structural Journal,* vol. 117, no. 1, pp. 133-144, 2020.

[23] D. Hardjito, S. Wallah, D. Sumajouw and B. Rangan, "The stress-strain behaviour of fly ash-based geopolymer concrete," *Development in Mechanics of Structures and Materials,* vol. 35, pp. 831-834, 2004.

[24] EN 1992-1-1 , "Design of concrete structures - Part 1-1 : General rules and rules for buildings," *Eurocode 2,* 2004.

[25] T. T.Tran, T. M.Pham and HongHao, "Experimental and analytical investigation on flexural behaviour of ambient cured geopolymer concrete beams reinforced with steel fibers," *Engineering Structures ,* vol. 200, p. 109707, 2019.