Studies on Mechanical properties of High Calcium Fly ash based sustainable Geopolymer concrete

Vijaya Prasad B1, Anand N 1, P D Arumairaj 2, M Sanath Kumar3, T Dhillip4, GSrikanth4

1 Department of Civil Engineering, Karunya Institute of Technology & Science, Coimbatore, India-641114
2 Geotechnical & Structural Consultant, AlZUM GeoCivil Integrated services, Coimbatore, India-641025
3 Department of Civil Engineering, Siddhartha Institute of Technology & Science, Hyderabad, India-501301
4 Department of Civil Engineering, University College of Engineering, Osmania University, Hyderabad, India-500007

Corresponding author E-mail id: b.vprasad104@gmail.com.

Abstract. Geopolymer concrete (GPC) is a Sustainable construction material, in which cement is completely replaced by Fly ash as binder. To control emission of CO₂ during the production of cement, it is advisable to use alternate sustainable Cementitious material. The development of GPC become a major interest to use for in-situ and precast applications. The present study aims to develop High calcium fly ash based GPC with aid of alkaline liquids such as sodium Hydroxide (NaOH) and Sodium silicate (Na₂SiO₃). Different molarities i.e 4M, 6M, 8M and 10M are used to develop the GPC under ambient and oven curing process. In the present investigation the Fresh properties of GPC and Mechanical properties such as compressive strength, Tensile strength, Flexural strength and Elastic modulus of GPC are investigated. An increase of alkaline activator in in the mix decreased the workability of GPC. The developed GPC mix of 8M is found to be the optimum for gain in compressive strength. A polynomial relationship is obtained for the mechanical properties of GPC developed under ambient and oven curing. The development cost of GPC can be reduced up to 11.25 to 16.5% as compared with conventional concrete grade of M25.

1. Introduction
Human activities, such as burning coal, oil, gas and deforestation, are some of the reasons for increased concentrations of CO₂ in the atmosphere. Production of cement contributes to the generation of greenhouse gases, i.e the development of CO₂ when calcium carbonate is pyrolyzed to produce lime. The production of cement is an energy-intensive method in which large quantities of greenhouse gases are developed and contaminating the environment [1]. For the development of sustainable environment, concrete with low carbon having good mechanical and durable properties to be used for construction. It is possible to achieve with an alternative waste materials such as Fly ash, Ground granular blast furnace slag (GGBS) for replacing the cement, these cementitious martials can be used for the development of GPC [2]. Generation of power in the thermal power plant with the use of coal has become an additional backbone to increase the power generation capacity.

The utilization of fly ash is an important requirement, because it cannot be disposed of in the field because as it pollutes the groundwater, soil, and air. Presence of Lightweight particles in the fly ash causes respiratory problems, air pollution and also affects the agriculture, horticulture and forest fields. Disposal of fly ash in sea, river or pond will damage aquatic life and huge land is required for making the ash pond[3]. From the last few decades, Fly ash has been used as eco-friendly resource material utilized for the development of high-performance concrete. According to the report of Central Electricity
Authority (CEA)[4], during the year 2018-19, the total utilization of fly ash was approximately 77.59%, and the unused fly ash was 22.41% as shown in figure 1. Therefore, more efforts are required to utilise fly ash for the development of sustainable concrete[3]. The use of locally available geopolymers decreases the demand for Cement, which is the cause of higher CO₂ emissions. Furthermore, during the production of Geopolymers, low greenhouse gas emissions and low energy demand arises as it as environmental friendly sustainable construction material [3].

![Figure 1. Percentage of Fly ash utilization in the Year 2018-19[4].](image)

The term Geopolymer material distinguished given by Daidovits in 1994 [2]. GPC is an innovative and environmentally beneficial building material and an alternative to cement concrete. GPC is an alkali-activated binder, produced by a polymeric reaction of the alkaline solution with the silicon and the aluminium oxides. Supplementary cementitious material such as Flyash, GGBS, Metakaolin, etc are used with alkaline solution create the Geo-polymerization process to form a 3D inorganic chain by a fast chemical reaction between the aluminosilicates [3].

Typically, fly ash is divided into two types, such as low calcium fly ash (LCF) and high calcium fly ash (CFA) [5]. These two materials exhibit different particle chemistry and morphology, which influencing the mechanical properties of the resulting GPC. Based on the composition, the main difference between CFA and LCF is the variation in calcium content [5].

Thus far, the development of geopolymer was based on a precursor derived from LCF produced by burning bituminous coals to improve the mechanical properties of GPC[6,7]. Whereas CFA is known to contain reasonable amounts of silica and alumina[5]. Generally, the annual production of CFA is 1.20 million tons but in recent times, the production of lignite and sub-bituminous coals is increasing in India. Also few research work has been reported on the development and strength assessment of GPC with CFA as a source material and manufactured sand (M-sand) as fine aggregate[7,8]. Hardjito and Rangan (2005) also informed that one ton of LCF can be utilised to produce 2.5 cubic metres of GPC [6].

The objective of this study is to develop CFA based geopolymer concrete using M-sand as fine aggregate. In general, fly ash-based GPC requires oven curing for the development of early strength. To extend the use of GPC for cast-in-situ applications CFA is used as source material. CFA has 10-20% of CaO content, 50-70% of Si and Al content in the material. An attempt has been made to develop GPC under ambient and oven curing conditions with different NaOH molarities like 4M, 6M, 8M and 10M. Effect of different NaOH molar concentrations on CFA based material under ambient and oven curing conditions on strength gain was investigated. Compressive strength, tensile strength, flexural strength and elastic modulus of GPC were investigated. A cost analysis was done to compare the developed GPC with conventional strength grade of M25.
2. Experimental procedure

2.1. High Calcium Fly ash
In this study, CFA was used as the main raw material for developing the GPC binder as per IS 3812:2013 [9]. CFA was collected from the Neyveli lignite power plant, Tamil Nadu, India. The specific gravity of CFA is 2.36. Scanning electron microscope (SEM) micrographs of CFA is shown in figure 2a.

2.2. Aggregates
The locally available Manufactured Sand (M-sand) belongs to Zone II was used as fine aggregate. Density, fineness modulus, specific gravity and water absorption values are 1730 kg/m$^3$, 2.8, 2.79 and 0.7% respectively. Coarse aggregate of size 12 to 20 mm belongs to Zone II was used. Density, fineness modulus, specific gravity and water absorption values are 1380 kg/m$^3$, 2.1, 2.87 and 0.5% respectively. Fine and coarse aggregate are tested following the guidelines of IS 383:2016[10]. SEM image of M-sand is shown in figure 2b.

2.3. Alkaline solution
A mixture of sodium hydroxide (NaOH) and sodium silicate (Na$_2$SiO$_3$) solution was used as the activator solutions. Distilled water was used to prepare the desired concentration of 4M, 6M, 8M and 10M NaOH solution by mixing 97-98% pure NaOH pellets and stirred until all the pellets were thoroughly dissolved. The NaOH solution was then placed for 24h before use. Na$_2$SiO$_3$ solution was purchased from a local commercial producer.

2.4. Details of Mix proportion and Development of GPC
2.4.1. Mix design and Casting of GPC. To develop CFA based GPC, the total aggregate content i.e., fine and coarse aggregate together used as 77% in the GPC mix. Several trials are conducted to develop the appropriate GPC mix, which is shown in Table 1. NaOH concentration of 4M, 6M, 8M and 10M was used and it mixes is denoted as GPC-4M, GPC-6M, GPC-8M and GPC-10M respectively. The mixing process was selected based on the past investigation used to develop LCF based GPC [6]. The process begins with mixing of fly ash with the prepared NaOH solution for 3-5 minutes. The fine and coarse aggregates were then added to the binder and mixed for 3-5 minutes. The Na$_2$SiO$_3$ solution was then added to the prepared mixture and the mixing was continued for another 3-5 minutes.
Table 1. Details of Mix proportion

| Materials          | Density (kg/m³) |
|--------------------|-----------------|
| Flyash             | 381             |
| Fine Aggregate     | 495             |
| Coarse Aggregate   | 1181            |
| NaOH               | 49              |
| Na₂SiO₃            | 122             |
| NaOH/Na₂SiO₃       | 2.5             |
| Al: CFA ratio      | 0.45            |

2.4.2 Curing of Specimens. Two types of curing conditions were adopted in the process of developing GPC. In the ambient curing (AC) condition, all GPC specimens were kept at room temperature for 28 days prior to strength test. The second curing condition is oven curing (OC) in which 60°C is mentioned for 24 h followed by AC conditions for 28 days. In both cases curing conditions, the moulds of GPC specimens were demoulded after 24h.

3. Experimental investigation

Workability of the GPC mixes were evaluated by slump test as per IS :1199-1959 guidelines [11]. Mechanical properties such as, compressive strength, tensile strength, flexural strength and elastic modulus of samples i.e., for GPC-4M to GPC-10M were examined after 28 days, for both AC and OC conditions.

![Images of test samples](image1.jpg)

**Figure 3.** (a) Compressive strength test (b) Tensile strength test (c) Flexural strength test (d) Elastic Modulus test.

Cube specimens were cast of size 150× 150 mm were used to evaluate the compressive strength of GPC as per IS 516:2004[12]. Computerised load controlled compression testing machine with a capacity of
2000 kN was used to test the cubes and cylinders as shown in figure 3a and 3b respectively. The rate of loading was maintained for cube compression test as 140 kg/cm²/min. Tensile strength and elastic modulus tests were conducted using cylinder specimens of 150mm diameter and 300mm height as per IS 5816:1999 [13] and IS 516:2004. Computer controlled Universal testing machine of 100kN capacity was used to test Elastic modulus of GPC as shown in figure 3c and the rate of loading was maintained as 180kg/min until failure. Flexural strength of the GPC was tested using the prism of length 500mm and size of 100 × 100mm as per IS 516:2004. Two point loading was applied on prism specimens as shown in figure 3d and the rate of loading was maintained as 180kg/min until failure.

4. Results and discussions

4.1 Workability
The slump values of GPC for various concentration of NaOH is shown in figure 4. From the figure it is understood that for the GPC with higher NaOH content, the slump values were found to be decreased. The slump values of mixes with GPC-4M, GPC-6M, GPC-8 M and GPC-10M of NaOH were 95 mm, 88 mm,80 mm and 75 mm respectively. The increase of molarities increased the viscosity and leaching of silica and alumina of fly ash particles thus decrease the workability [6].

![Figure 4. Workability of GPC at different Molarities](image)

4.2 Compressive Strength
Compressive strength of GPC developed under AC and OC condition with different concentrations of NaOH from GPC-4M to GPC-10M is shown figure 5. At 28 days, the compressive strength obtained in AC for GPC-4M, GPC-6M, GPC-8M and GPC-10M are 22.96 MPa,23.85 MPa,29.03 MPa and 30.46 MPa. In case of OC condition, the compressive strength obtained for GPC-4M, GPC-6M, GPC-8M and GPC-10M are 21.2 MPa,23.4 MPa,25.6 MPa and 27.8 MPa . As compared to AC condition, the OC based GPC had shown marginal variation in compressive strength. It was also observed from the test results that with an increase of NaOH concentration from GPC-4M to GPC-10M under AC and OC the compressive strength of GPC is increasing. Past studies reveals that the rate of reaction in CFA was higher when it is activated with alkaline solutions. This reaction promotes the initial dissolution of the Si : Al and Ca particles in the CFA and formation the rapid of strength-bearing phases, mostly C-(A)-S-H and N-(A)-S-H gels in CFA[14,15]. The availability of silicate ions in the system enhances the mechanical strength of CFA to the greater extent under ambient curing [16].
Figure 5. Compressive strength of GPC with different molarities under AC and OC

4.3 Tensile strength
Splitting tensile strength test is an indirect method, which has been extensively practiced to test the tensile strength of concrete. Experiments are conducted to check the tensile strength of GPC specimens under AC and OC with different concentration of NaOH (GPC-4M to GPC-10M). From figure 6a, shows the tensile strength of GPC developed under AC and OC at 28 days with different concentrations of NaOH (GPC-4M to GPC-10M). Tensile strengths of GPC obtained under AC for GPC-4M, GPC-6M, GPC-8M and GPC-10M are 1.95 MPa, 2.15 MPa, 3.07 MPa and 3.23 MPa. In case of OC, tensile strengths are 1.78 MPa, 2.6 MPa, 2.9 MPa and 2.98 MPa. As seen from the results of compressive strength of GPC, the tensile strength under AC is found to be marginally higher as compared to OC condition. This increase may be due to Pattanapong et al (2015) conformed that, with an increase in molarity i.e., NaOH concentrations of 10M, 15M and 20M the tensile strengths of GPC were relatively high [17]. This may be due to the strong development of high calcium geopolymer matrix of C-(A)-S-H and N-(A)-S-H gels and interfacial zone of the aggregate [15]. It can be seen from the figure 6b that, a better correlation has been found between tensile and compressive strength of GPC for both AC and OC conditions.

Figure 6 (a) Tensile strength of GPC (b) Relation between Compressive strength and Tensile strength of GPC.

4.4 Flexural strength
Flexural strength is the measure of force needed to withstand the bending failure of concrete section. Flexural strength of GPC developed under AC and OC at 28 days with different concentrations of NaOH
from (GPC-4M to GPC-10M) is shown figure 7a. Flexural strengths of GPC are found to be ranging between 13.7% and 16.4% of the compressive strength of GPC for different molarities (GPC-4M to GPC-10M). Increase of NaOH concentration from GPC-4M to GPC-10M under AC and OC increased the flexural strength of GPC confirmed by Hardjito et al (2005)[6]. Figure 7b shows the relationship between the compressive strength and flexural strength of GPC. It is observed that the R² value is found to be nearly one, confirming the positive correlation.

![Figure 7](image)

**Figure 7.** (a) Flexural strength of GPC (b) Relation between Compressive strength and Flexural strength of GPC

4.5 Elastic Modulus

Increase in compressive strength of concrete increase the elastic modulus. It is the important material property decides the strength of structural elements. Higher the Elastic modulus lesser the deformation of concrete element. Elastic modulus of the GPC developed under AC and OC with different concentrations of NaOH (GPC-4M to GPC-8M) is shown in figure 8a. The elastic modulus of GPC under AC is increased as the molarities increases to GPC-6M, GPC-8M and GPC-10M; this increase in elastic modulus are 12.9%, 21.3%, and 23.2% as compared to GPC-4M of NaOH concentration. For OC condition, for GPC-6M, GPC-8M and GPC-10M; the increase in elastic modulus are found to be as 9.6%, 22.8% and 26.4% as compared to GPC-4M of NaOH concentration. The studies of Darshan et al.(2020) confirmed the increase in Elastic modulus for the varying concentration of alkaline activator[16]. It was also confirmed by the studies of Pattanapong et al (2015). that with the increase in molarity of NaOH concentrations (10M, 15M and 20M) increased the Elastic modulus at 28days for both AC and OC condition[17]. A relationship is proposed between compressive strength and Elastic Modulus of GPC under AC and OC with different molarities as shown in figure 8b. A strong positive correlation is found to exist based on the relationship.
4.6 Cost Analysis
As GPC is the sustainable building material, and it is observed from the experiments that the developed GPC has attained the required mechanical properties. Concrete with OPC and GPC mixes of same grade (M25) has been considered for the comparison of cost[18].

The cost for producing 1m$^3$ of GPC and OPC is calculated based on the prices of the necessary ingredients to assess the socio-economic feasibility. CFA is a waste material obtained for free of charge from the power plant, the values of the fly ash are excluded.

It is noted that, for the grade of M25, the production cost of concrete with GPC is found to reduce between 11.25% and 16.5% than conventional concrete with OPC. Variation in the cost may be due to the change in alkaline solution content. However, this cost is considered based on the availability of raw materials and its market value in the particular location. Hardjito, and Rangan, has informed that the cost of alkaline solutions that are needed to manufacture the GPC is cheaper than the cost of one ton of cement[6].

5. Conclusion
Geopolymer concrete contributes to the reduction of greenhouse gas emission by avoiding the requirement of cement with the utilisation of industrial waste. Based on the data obtained from the experiments, the following conclusions are drawn. The results of this study showed that CFA was found to be suitable for the production of GPC in ambient curing due to the presence of calcium content in the CFA.

- The workability is found to decrease in GPC with increasing the concentration of NaOH from GPC- 4M to GPC-10M.
- With increase in the concentration of NaOH from GPC- 4M to GPC-10M. Under AC and OC conditions, the compressive strength, tensile strength, flexural strength and elastic modulus of the CFA based GPC increases. It is due to the formation of N-(A)-S-H gel and C-(A)-S-H gels.
- The attainment of target compressive strength for the optimum mix of GPC is found to be 29.03MPa for Ambient curing and 25.6MPa for Over curing conditions.
- A proportionate gain in tensile and flexural strength of GPC was observed in case of both AC and OC conditions.
- It is confirmed from the results that, the fresh and hardened properties were satisfied for the developed sustainable GPC.
Reference

[1] Claudio Durastanti and Laura Moretti 2020 applied sciences Environmental Impacts of Cement Production : A Statistical Analysis 3 1–25
[2] J. Davidovits 1994 High-alkali Cements for 21st Century Concretes Concr. Technol. Past, Present Futur. P. K. Mehta, ACI, 144 383–93
[3] Meyer C 2009 The greening of the concrete industry Cem. Concr. Compos. 31 601–5
[4] Anon 2019 Central Electricity Authority
[5] Ranjan Senapati M 2011 Fly ash from thermal power plants-waste management and overview Curr. Sci. 100 1791–4
[6] Hardjito D and Rangan B V 2005 Development and Properties of Low-calcium Fly Ash Based Geopolymer By Faculty of Engineering Curtin University of Technology 48
[7] Vijaya Prasad and Arumairaj. 2019 Recent Advancements in Geopolymer Concrete using Class-F and Class-C Fly Ash Int. J. Innov. Technol. Explor. Eng. 8 5879–84
[8] Guo X, Shi H and Dick W A 2010 Compressive strength and microstructural characteristics of class C fly ash geopolymer Cem. Concr. Compos. 32 142–7
[9] IS:3812 2013 Specification for Pulverized fuel ash, Part-1: For Use as Pozzolana in Cement, Cement Mortar and Concrete Bur. Indian Stand. New Delhi, India 1–12
[10] IS383 2016 Coarse and fine aggregate for concrete Indian Stand. Code Third edit 1–17
[11] IS:1199-1959 2004 Indian Standard Methods of sampling and analysis of concrete Bur. Indian Stand. New Delhi 1199–959
[12] IS : 516 - 1959 (Reaffirmed 2004) 2004 Method of Tests for Strength of Concrete IS 516 - 1959 (Reaffirmed 2004) New Delhi,India
[13] IS:5816 1999 Method of test splitting tensile strength of concrete Indian Standard Code
[14] Chindaprasirt P, Charerat T, Hatanaka S and Cao T 2011 High-Strength Geopolymer Using Fine High-Calcium Fly Ash J. Mater. Civ. Eng. 23 264–70
[15] Li C, Sun H and Li L 2010 A review: The comparison between alkali-activated slag (Si + Ca) and metakaolin (Si + Al) cements Cem. Concr. Res. 40 1341–9
[16] Kumarappa D B and Peethamparan S 2020 Stress-strain characteristics and brittleness index of alkali-activated slag and class C fly ash mortars J. Build. Eng. 32 101595
[17] Topark-Ngarm P, Chindaprasirt P and Sata V 2015 Setting time, strength, and bond of high-calcium fly ash geopolymer concrete J. Mater. Civ. Eng. 27 1–7
[18] Daniel Paul Thanaraj, Anand N and Arulraj G P 2019 Post-fire damage assessment and capacity based modeling of concrete exposed to elevated temperature vol 0