Comparative studies on strength properties of flyash based geopolymer concrete incorporating ggbs and alccofine subjected to elevated temperature

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Abstract. Geopolymer concrete is a novel material trying to be implemented in the construction field. Efforts being made by the researchers to unfurl the advantages and application of Geopolymer concrete in engineering fields. Geopolymer concrete does not require cement in making and utilizes industrial waste products. Hence replacing the OPC concrete by GPC, we not only reduce the pollution caused by manufacturing cement, but also use calcium, silica and alumina rich industrial waste. It is important to study the performance of GPC subjected to elevated temperature before considering it for structures like industrial buildings, complexes which are vulnerable to fire accidents. Present study investigates the properties like compressive strength, weight loss/gain, and Thermal energy absorption for GPC subjected to elevated temperature from 100°C, 200°C, 400°C, 600°C and 800°C for exposure time of 1hour and 2hours. We compare these properties of GPCs, one made using Flyash and GGBS as binders named FGGPC and the other using Flyash and Alccofine 1203 named FAGPC. From the results we found that strength of GPC increases with the rise in temperature up to 200°C and then rapidly decreases with further rise in temperature. Use of FAGPC is advantageous than using FGGPC on field vulnerable to fire. 

Keywords: GPC, Flyash, GGBS, Alccofine, Alkaline Activator, FGGPC, FAGPC, Elevated Temperature, Thermal energy.

1. Introduction

Concrete being mostly used construction material and its consumption increasing every day, its use cannot be restricted. Cement is the major component for making concrete but the production of cement contributes a major role in increasing greenhouse gases causing global warming. To limits the usage of concrete made from OPC, researchers investigated and identified a noble material called Geopolymer concrete [1,19]. Geopolymer concrete utilises calcium, alumina and silica rich industrial waste by products as binders which completely eliminates ordinary cement usage. To develop strength in geopolymer concrete an alkaline solution is required which chemically and physically reacts with these calcium, silica and alumina rich mineral admixtures [2,8]. The several mineral admixtures used for producing GPC are Flyash, GGBS, Metakaolin, Silicafume, Nanosilica, Alccofine, Rice husk ash etc.

Polymerization and Alkaline activation are two different processes but combine help in producing geopolymer concrete [9,20]. Polymerisation is a chain reaction process to form polymers from its monomers. Alkaline activation is the process of mixing alumina silicates minerals with alkaline activator solutions to enhance setting and hardening [3,10]. The alkaline activators used for GPC are KOH, NaOH solutions mixed with K2SiO3 or Na2SiO3 solutions. There is no exact mix design to develop GPC, but researchers developing several mix design methods which are in pending to be
approved by the concrete institutions [4,6]. Several applications of GPC which are already being implemented such as railway sleepers, tooling moulds, moulds for thermoplastics etc. [5,7]. The properties of the GPC depends on the several parameters like chemical and physical properties of mineral admixtures used as binders, molarity of alkaline activator solution, ratio of \( \text{Na}_2\text{SiO}_3 \) to NaOH solution, molarity of NaOH solution, alkaline binder ratio etc. [11,16]. At elevated temperature exposure regime the properties of GPC also depend on exposure temperature, time of exposure, rate of rise in temperature, rate of cooling and cooling methods [12,13].

When comes to structures, GPC is less implemented due to lack of proper research and demerits like early setting etc., but mostly used for precast members. But when comes to structures strength, durability properties of concrete need to be studied. It’s also important for a proper investigation is need to be done for GPC at high temperature exposure regime to counteract while at fire accidents. As a part of it, in the present study we compare the strength characteristics of two different GPCs subjected to elevated temperature. The concrete specimens are casted, ambient cured at room temperature then subjected to elevated temperature at 100°C, 200°C, 400°C, 600°C and 800°C for 1hr and 2hr exposure time. Air cooling and Water quenching are adopted for cooling the specimens after fire exposure and then tested. The properties like residual strength, weight loss/gain, thermal energy are observed. The surface temperature and core temperatures immediately after taking out from furnace are observed.

2. Significance of the study

To examine whether the GPC is suitable for high temperature exposures or not. The GPC made with only flyash takes much time to give strength than OPC concrete, hence by replacing it by GGBS and Alccofine separately to some extent, the change in the properties of GPC are observed. To check whether the betterment of performance of GPC with addition of GGBS and Flyash. Effort done to make the GPC concrete to be made to use in field applications in Civil and Structural Engineering.

3. Experimental procedure

The experimental procedure implemented for this project has been adopted from the available literature. In this work we compare the strength properties of two GPCs made from Flyash as major binder and GGBS and Alccofine as minor binders replacing flyash by 20% for economic considerations [2, 18]. Hence we name the GPC made from Flyash and GGBS as FGGPC and GPC made from Flyash and Alccofine as FAGPC.

3.1. Materials

Flyash, GGBS and Alccofine 1203 are used as binders, Alkaline Activator has been used to activate these calcium, silica and alumina rich materials to strengthen and to be concrete [14,15]. Locally available natural fine aggregate and 20mm coarse aggregate are used. Low calcium Flyash and GGBS are collected from the nearby RMC plant and their chemical compositions and physical properties are given in table 1 and table 2. Alccofine 1203 is a low calcium silica based mineral additive manufactured by the Ambuja cements ltd. The percentage replacement of GGBS and Alccofine for Flyash is about 50% from previous works, but we set it to only up to 20% for economic considerations [17].
Figure 1. Flyash, GGBS and Alccofine from left to right

Table 1: Chemical composition of Flyash, GGBS and Alccofine.

| Chemical composition | Flyash | GGBS | Alccofine |
|----------------------|--------|------|----------|
| In Mass (%)          |        |      |          |
| SiO₂                 | 53-57  | 33.28| 30-35    |
| Al₂O₃                | 25-35  | 17.47| 20-22    |
| CaO                  | 4-6    | 35.59| 30-36    |
| Fe₂O₃                | 3-7    | 0.65 | 1.2-2.5  |
| MgO                  | 1.0-2.5| 8.10 | 4-8      |
| Na₂O                 | 0.10-0.25| 0.35| 0-0.5    |
| K₂O                  | 0.10-1.43| 0.48| 0.0-0.75 |
| SO₃                  | --     | --   | 0.1-0.3  |
| TiO₂                 | 1.08   | 0.75 | --       |

Table 2: Physical properties of Flyash, GGBS and Alccofine.

| Property                | Flyash | GGBS | Alccofine 1203 |
|-------------------------|--------|------|---------------|
| Specific Gravity        | 2.4    | 2.8  | 2.86          |
| Fineness (m²/kg)        | 425    | 395  | 1200          |

The Alkaline activator is a mixture of sodium silicate (Na₂SiO₃) and sodium hydroxide solution (NaOH) at a proportion of 2.5:1 and the NaOH solution taken is of molarity 4. The Alkaline activator solution is rested for 24 hours after preparation to ensure all the heat exhausts which produced due to NaOH pellets reaction with water [7, 20]. As per the previous studies the alkaline activator solution should use as early as possible, later which may not give estimated results. It is a colourless sticky liquid.

3.2. Equipment.
Electric furnace with temperature rise up to 1200°C is used for elevated temperature exposure. Compressive testing machine with a loading capacity of 2000kN is used. Digital thermometer with capturing capacity of 1050°C with the help of thermo couple is used. Weighing machines and Concrete mixer are the other major equipment are used.
Figure 2. Electric muffle furnace and its digital meter

3.3. Trail mix
The mix design for preparing GPC of grade equal to M30 being adopted with reference to the work of Dr Mallkarjun Rao [10, 18]. Initially trail mix was done to ensure that the adopted mix design satisfies as per our requirement given in table 3. Test specimens are casted, ambient cured at room temperature (25°C) for 28 days and then tested for compressive strength [2, 11]. The preliminary tests are done for two different alkaline binder ratios for both FGGPC and FAGPC to analyse the workability of the GPCs in the fresh stage. This is to verify the usage and role of superplasticizer in the GPC. The mix design adopted is given in table below. The percentage of Flyash to GGBS/Alccofine is 80% to 20%. The ratio of Na$_2$SiO$_3$ to NaOH is 2.5. Slump and Compressive strength results are given in table 4.

Table 3: Trail mix proportions for the FGGPC and FAGPC.

| Mix Design | Alkali binder ratio | Flyash (A) | GGBS (B) | Alccofine (C) | Binder (A+B+C) | Na$_2$SiO$_3$ (D) | NaOH (E) | Alkaline solution (D+E) | Coarse aggregate | Fine aggregate |
|------------|---------------------|------------|----------|---------------|----------------|------------------|----------|-------------------------|----------------|--------------|
| FGGPC      | 0.4                 | 304        | 76       | -             | 380            | 152              | 43.4     | 108.6                   | 1081           | 787          |
|            | 0.5                 | 284        | 71       | -             | 355            | 177              | 50.6     | 126.4                   | 1081           | 787          |
| FAGPC      | 0.4                 | 304        | -        | 76            | 380            | 152              | 43.4     | 108.6                   | 1081           | 787          |
|            | 0.5                 | 284        | -        | 71            | 355            | 177              | 50.6     | 126.4                   | 1081           | 787          |

Table 4: Slump and Compressive strength for Specimens casted for Trail mix.

| Results of Trail mix design | Alkali binder ratio | Slump in mm | Compressive strength (28 days) |
|-----------------------------|---------------------|-------------|--------------------------------|
| FGGPC                       | 0.4                 | 100         | 31.64                          |
|                             | 0.5                 | 107         | 33.26                          |
| FAGPC                       | 0.4                 | 103         | 33.51                          |
|                             | 0.5                 | 111         | 34.83                          |

From the above results, to further proceed we take alkaline binder ratio to be 0.4 keeping in view of economy in producing concrete. As the increase in alkali binder ratio may increase slump and concrete has better workability for both FGGPC and FAGPC, but we can avoid it by using superplasticizer to some extent. Fosroc conplast SP430 sulphonated naphthalene based super plasticizer is used at 5% to the binder weight [12].

3.4. Elevated temperature exposure regime

Once ensuring and adopting a mix design then we proceed for mass production of specimens as per our requirement. After the 28 days curing, the specimens are subjected to elevated temperatures at 100°C, 200°C, 400°C, 600°C and 800°C for duration of 60 min and 120 min at a rate of temperature rise being 9°C/min. The heated specimens are cooled in two methods which are Air Cooling and Water quenching. Residual Strength properties like Uniaxial Compressive strength, Strength loss/gain and Thermal energy consumption are observed and compared for the FGGPC and FAGPC.

![Image of temperature meter and heated concrete specimens](image1.jpg)

**Figure 3**: Core temperature reading of 530°C for concrete exposed to 600°C for 2 hours.

**Figure 4**: Colour change, unheated left specimen and heated right specimen 400°C

3.4.1. Air cooling. The specimens are removed from the furnace and then they are kept at room temperature for 24 hours and then tested for weight loss and compressive strength test which gives us residual compressive strength.

3.4.2. Water quenching. Immediately after removing specimens from the oven, we immerse them in 5 liters of water for each specimen and the temperature of water is noted at 1, 3, 5, 10, 15, 30 and 60 minutes. Initially the temperature of water rises rapidly and then it falls gradually. Left the specimen in the water until the water comes to room temperature and remove specimens and left it in room temperature for 24 hours and then tested.

4. Results, Observations and Discussions

Surface temperature and core temperature are found to know the change in core temperature to surface temperature for exposure time of 1 hour and 2 hours. The values are listed in the table 5. From the observation it states that the temperature rise and increase in the time of exposure to fire will increase the difference between the surface temperature and core temperature both for FGGPC and FAGPC.
Table 5: Difference between Surface temperature and Core temperature

| Time of exposure | Exposure Temperature | FGGPC | FAGPC |
|-----------------|----------------------|-------|-------|
|                 | Surface temp | Core temp | Difference | Surface temp | Core temp | Difference |
| 1 hour          | 100°C       | 70        | 80         | 10       | 69        | 80         | 11       |
|                 | 200°C       | 135       | 154        | 19       | 137       | 157        | 20       |
|                 | 400°C       | 249       | 300        | 51       | 254       | 303        | 49       |
|                 | 600°C       | 342       | 485        | 143      | 340       | 487        | 147      |
|                 | 800°C       | 458       | 591        | 133      | 463       | 598        | 135      |
| 2 hours         | 100°C       | 71        | 84         | 13       | 72        | 85         | 13       |
|                 | 200°C       | 143       | 161        | 18       | 140       | 163        | 23       |
|                 | 400°C       | 272       | 346        | 74       | 276       | 342        | 66       |
|                 | 600°C       | 345       | 534        | 189      | 346       | 530        | 184      |
|                 | 800°C       | 490       | 620        | 130      | 485       | 623        | 138      |

The surface temperatures and core temperatures for FGGPC and FAGPC are almost similar. A slight colour change is observed from 400°C and above and a dark black colour is observed in the inner core at a temperature of 600°C and above for both FGGPC and FAGPC.

4.1. Air Cooling and Weight Loss:

The specimens are removed from the furnace and then they are kept at room temperature for 24 hours and then tested for weight loss and compressive strength test which gives us residual compressive strength.

Table 6. Weight loss percentage for air cooling method

| Weight loss % | FGGPC | FAGPC |
|---------------|-------|-------|
| Exposure period | Initial weight | Final weight | Change in weight | Change in % | Initial weight | Final weight | Change in weight | Change in % |
| 1 hour        | 100°C       | 2.379 | 2.367 | 0.012 | 0.51 | 2.393 | 2.345 | 0.047 | 1.97 |
|               | 200°C       | 2.413 | 2.390 | 0.023 | 0.93 | 2.415 | 2.350 | 0.065 | 2.69 |
|               | 400°C       | 2.394 | 2.310 | 0.084 | 3.50 | 2.350 | 2.265 | 0.085 | 361 |
|               | 600°C       | 2.283 | 2.283 | 0.104 | 4.34 | 2.348 | 2.232 | 0.116 | 5.94 |
|               | 800°C       | 2.411 | 2.291 | 0.120 | 4.97 | 2.379 | 2.244 | 0.135 | 5.67 |
|               | 100°C       | 2.422 | 2.404 | 0.018 | 0.73 | 2.414 | 2.357 | 0.057 | 2.33 |
| 2 hours       | 200°C       | 2.384 | 2.345 | 0.039 | 1.62 | 2.363 | 2.294 | 0.069 | 2.92 |
|               | 400°C       | 2.399 | 2.299 | 0.100 | 4.15 | 2.356 | 2.226 | 0.130 | 5.51 |
|               | 600°C       | 2.407 | 2.295 | 0.112 | 4.64 | 2.346 | 2.205 | 0.141 | 5.98 |
|               | 800°C       | 2.389 | 2.259 | 0.130 | 5.42 | 2.387 | 2.232 | 0.155 | 6.49 |

Weight loss in FAGPC is dominant than that of FGGPC for all the temperature exposures. From this we can say that the FAGPC forms more pores by relieving moisture more than that of FGGPC. More pores may be lead to loss in strength but sometimes the pressure formed in the pores contributes to enhance the properties. For FGGPC a sudden gap in weight loss is observed from 200°C to 400°C but for FAGPC a gradual weight loss is observed with rise in temperature. Time of exposure also increase the weight loss in both GPCs.
4.2. *Water quenching and Weight Gain:*
Immediately after removing specimens from the oven, we immerse them in 5 litres of water for each specimen and the temperature of water is noted at 1, 3, 5, 10, 15, 30 and 60 minutes. Initially the temperature of water rises rapidly and then it falls gradually. Left the specimen in the water until the water comes to room temperature and remove specimens and left it in room temperature for 24 hours and then tested.

![Image of water temperature recording](image-url)
Table 7. Weight gain percentage for water quenching method.

| Exposure period | Exposure temperature | Initial weight | Final weight | Change in weight | % change | Initial weight | Final weight | Change in weight | % change |
|-----------------|----------------------|----------------|--------------|------------------|----------|----------------|--------------|------------------|----------|
| 1 hour          | 100°C                | 2.393          | 2.448        | 0.055            | 2.31     | 2.376          | 2.432        | 0.047            | 1.97     |
|                 | 200°C                | 2.421          | 2.496        | 0.075            | 3.13     | 2.331          | 2.406        | 0.075            | 3.20     |
|                 | 400°C                | 2.385          | 2.522        | 0.137            | 5.75     | 2.356          | 2.498        | 0.142            | 6.03     |
|                 | 600°C                | 2.389          | 2.553        | 0.164            | 6.89     | 2.343          | 2.510        | 0.167            | 7.09     |
|                 | 800°C                | 2.420          | 2.593        | 0.173            | 7.16     | 2.394          | 2.584        | 0.190            | 7.92     |
| 2 hours         | 100°C                | 2.412          | 2.478        | 0.066            | 2.77     | 2.350          | 2.408        | 0.058            | 2.46     |
|                 | 200°C                | 2.395          | 2.504        | 0.109            | 4.55     | 2.363          | 2.467        | 0.104            | 4.41     |
|                 | 400°C                | 2.405          | 2.567        | 0.162            | 6.75     | 2.307          | 2.468        | 0.161            | 6.99     |
|                 | 600°C                | 2.392          | 2.562        | 0.170            | 7.10     | 2.400          | 2.583        | 0.183            | 7.63     |
|                 | 800°C                | 2.398          | 2.586        | 0.188            | 7.83     | 2.413          | 2.610        | 0.197            | 8.20     |

From the results of water quenching the weight gain for FAGPC is more than that of FGGPC. This may be due to more pores formation in FAGPC for elevated temperature exposure regime. The weight gain percentage is gradually increasing with rise in temperature for both GPCs. As the time of exposure to fire increases the weight gain percentage is also increased.

Figure 8. Bar chart showing Weight Gain % vs Temperature

4.3. Residual compressive strength:
The uniaxial Compression test is done for the specimens of Air cooling and water quenching after they are kept at room temperature for 24 hours. The test results and observations are given in table.
Table 8. Residual compressive strength for GPC post elevated temperature

| Exposure period | Exposure temperature | FGGPC | FAGPC |
|-----------------|-----------------------|-------|-------|
|                 | Air cooling           | Water quenching | Air cooling | Water quenching |
| 1 hour          | 100°C                 | 33.4  | 32.9  | 32.6  | 31.5  |
|                 | 200°C                 | 39.0  | 29.4  | 39.5  | 32.0  |
|                 | 400°C                 | 33.7  | 21.8  | 38.0  | 26.4  |
|                 | 600°C                 | 28.8  | 14.3  | 28.2  | 15.6  |
|                 | 800°C                 | 13.0  | 10.7  | 15.2  | 13.6  |
|                 | 100°C                 | 33.6  | 33.3  | 34.0  | 33.2  |
|                 | 200°C                 | 43.1  | 25.6  | 40.3  | 34.0  |
| 2 hours         | 400°C                 | 31.5  | 19.4  | 37.0  | 22.2  |
|                 | 600°C                 | 26.2  | 13.3  | 26.5  | 14.4  |
|                 | 800°C                 | 12.2  | 9.1   | 14.8  | 13.0  |

4.3.1. Residual compressive strength for Air Cooling:
From the observations residual strength of FGGPC increased up to a temperature rise of 200°C and further rise in temperature, the strength decreased gradually up to 600°C and a sudden drop is observed at 800°C. For FAGPC the strength increased up to 200°C and then decreased but a two-step drop in strength is observed at 600°C and 800°C. FAGPC has better performance for high temperatures and Air Cooling than that of FGGPC. The observation are similar for both exposure times of 60 minutes and 120 minutes, although the increase in exposure time decreases the strength.

Figure 9. Horizontal crack profile on specimen post elevated temperature testing
4.3.2. Residual compressive strength for Water Quenching:
When water quenching was done, strengths of FGGPC gradually decreases with rise in temperature and with increase in exposure time. Strength of FAGPC increases up to 200°C and further gradually decreases. However only at 100°C FGGPC strength is more than that of FAGPC. Further rise in temperature the strength of FAGPC is dominant. It shows that FAGPC is better at high temperatures than that of FGGPC for water quenching. Similar to the Air cooling observations, the increase in exposure time decreases the strength.
For both the GPCs Air cooling method gives better results than water quenching only except for FAGPC at 800°C. Hence water quenching is not a preferable cooling method for GPCs exposed to elevated temperature. FAGPC is a better concrete for a temperature exposure of at 400°C.
4.4. Thermal energy:
The thermal energy concept is done to know the heat absorption of the concrete when exposed to fire. The time at maximum thermal energy for FGGPC is 15 minutes and for FAGPC is 10 minutes. This shows that the FAGPC absorbs energy at a faster rate. The maximum thermal energy values and their corresponding time is given in the table 9. The expression to calculate the thermal energy is given by

\[
\text{Thermal Energy (kcal)} = \text{Mass of water (litres)} \times \text{Specific heat of water} \times \text{Rise in Temperature}
\]

\[
\text{Mass of water taken for cooling} = 5 \text{ litres}
\]

\[
\text{Specific Heat of Water} = 1.0 \text{ cal/g/°C}
\]

\[
\text{Rise in Temperature} = [\text{Initial temperature of water} - \text{Temperature of water after immersing heated specimen in water}]
\]

| Exposure | Thermal energy (min) | Max thermal energy (Kcal) | Thermal energy (min) | Max thermal energy (Kcal) |
|----------|----------------------|---------------------------|----------------------|---------------------------|
| period   | FGGPC                | FAGPC                     | FGGPC                | FAGPC                     |
| 1 hour   | 100°C                | 15                        | 50                   | 10                        | 45                        |
|          | 200°C                | 15                        | 70                   | 10                        | 55                        |
|          | 400°C                | 15                        | 130                  | 10                        | 110                       |
|          | 600°C                | 15                        | 225                  | 10                        | 225                       |
|          | 800°C                | 15                        | 265                  | 10                        | 270                       |
|          | 100°C                | 15                        | 60                   | 10                        | 50                        |
|          | 200°C                | 15                        | 85                   | 10                        | 70                        |
| 2 hours  | 400°C                | 15                        | 165                  | 10                        | 150                       |
|          | 600°C                | 15                        | 240                  | 10                        | 240                       |
|          | 800°C                | 15                        | 280                  | 10                        | 275                       |

The observations tells us that, although FAGPC has a faster rate of energy absorption but the maximum thermal energy for FGGPC is more than FAGPC. It shows that the use of Alccofine improves the pore structure of GPC than using GGBS and further studies on pore structure of the GPCs subjected to temperature rise is important.

4.5. Physical observations:
We can observe a surface color change in specimen subjected to elevated temperature of 200°C and above for both FGGPC and FAGPC as shown in figure 4. The inner core color of the specimen changed to dark black color for FGGPC and FAGPC at and above 600°C as shown in figure 3. We can observe serious cracks on the surface of the specimens at 800°C as shown in figure 5. The specimen showed a horizontal crack while testing for uniaxial compression test using CTM as shown in figure 7.

5. Conclusions
- The Geo polymer concrete can be used for the structures vulnerable to fire exposure.
- The FAGPC gives better performance than FGGPC at and above the exposed temperature of 400°C.
- Air cooling method gives better results than water quenching which did not give expected results.
- The rate of thermal energy consumption for FAGPC is at a faster rate but total thermal energy consumption for FGGPC is more than FAGPC.

6. Future scope of the study
There is much scope for the future studies regarding GPC subjected to elevated temperatures. Durability studies, microscopic analysis, porosity studies on GPC post fire need to be studied. The fly
ash GPC properties are studied replacing different mineral admixtures with different proportions are studied. Deep studies on property recovery of concrete post elevated temperature is required.

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