Effect of pozzolanic materials in geopolymer mortar using industrial waste material

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Abstract: Geopolymer is one of the new binder technology in the construction where cement is replaced fully by pozzolanic materials such as fly ash, GGBS and alkaline solution. This control the emission of CO$_2$ produced from the cement manufacturing industries. The industrial waste requires disposal is the major problem by utilization of such materials in geopolymer for the benefits of the environmental and eco-friendly process. In this paper, the effect of pozzolanic material in geopolymer mortar using industrial waste material based on oven heating. The optimum percentages of low calcium class F fly ash and GGBS is taken. From the optimum percentage, fine aggregate is partially replaced by iron slag (0%,25%,35%,45%). For enhancing the workability of geopolymer mortar by using poly-carboxylic ether as superplasticizer. The optimum geopolymer mortar mix using industrial waste was concluded based on the compressive test to be studied with conventional.

Keywords: Geopolymer mortar, Pozzolanic materials, Compressive strength, Heatcuring, Iron slag.

1. INTRODUCTION

Geopolymer mortar is produced from utilization of pozzolanic materials, and it is an inorganic polymer [1]. Geopolymers can be formed by treating aluminosilicate materials (such as fly ash, ground-granulated blast furnace slag, etc.) with alkaline activators at high temperatures [8]. These materials are containing high alumina (Al) and silica (Si) content for geopolymerization with alkaline activator [1,3]. The combination of sodium silicate (Na$_2$SiO$_3$) and sodium hydroxide (NaOH) has been used widely as the alkaline activator to produce geopolymer [1,11]. Presently, Portland cement production increases with the increasing demand of the construction industry, which emits one-ton CO$_2$ per one-ton cement [11]. Compared to ordinary Portland cement-based materials, pozzolanic based materials are potentially sustainable for the alternative construction owing to its high strength, rapid curing, excellent fire resistance, and lower CO$_2$ emissions [10]. These pozzolanic materials make environmentally sustainable and eco-friendly approaches points towards the production of geopolymer technology which minimizes energy requirements and controls the emissions of CO$_2$ by using industrial wastes [14,16]. Fly ash is a by-product from burning pulverized coal in electric power generating plants, causing several disposal-related problems [3]. Ground granulated blast slag (GGBS) is a by-product from the blast-furnaces which is used to make iron [5,6,15]. The concentration of the sodium hydroxide solution in the alkaline activator plays a crucial role in the polymerization reaction. The combination of sodium silicate solution to sodium hydroxide solution as the alkaline activator enhanced the reaction between the source material and the alkaline solution. The ratio of sodium silicate solution to sodium hydroxide solution as 2.5 gives maximum strength [16]. The mechanical strength of most pozzolanic materials required heat curing process for enhancing the strength of geopolymer mortar and necessary for pozzolanic materials
geopolymerization[1,2,4,8].

On the other hand, Iron slag also produced in large quantity in India as well as all over the world. About 17 thousand tons of iron slag is produced annually in India. Iron slag requires larger land resources for disposal in open land areas which pose a great threat to living beings and this harmful to the environmental [7,9,12]. The demand for natural sand is increased due to a shortage of natural sand, and this makes ecological problems because of excavation of sand. So, Iron slag is used to solve the shortage of natural sand. Iron slag is a by-product of steel making, are produced during the separation of the molten steel from impurities in steel-making furnaces. Here, Industrial waste is utilized in the Geopolymer mortar to reduce environmental pollution.

2. EXPERIMENTAL PROCEDURE

2.1. Material Selection

In the present investigation, a low calcium class F fly ash(Figure 1) and GGBS(Figure 2) was used as source material. The chemical composition of low calcium class F fly ash (Table 1) and GGBS (Table 2). The fine aggregate was naturally available river sand of maximum size of 4.75mm. The river sand is sieved using I.S. sieves of sizes 2.36 mm, 1.18 mm, 450 microns, and 150 microns. The specific gravity of fine aggregate was 2.62 and fineness modulus of fine aggregates was 2.3. Its grading confirmed to zone II. The Iron Slag(Figure 3) and chemical composition (Table 3) was obtained from the Kamachi Iron and Steel industry located at Gummidipoondi, Tamil Nadu. The specific gravity of fine aggregate was 3.03 and fineness Modulus of Iron Slag Waste was 3.21 and is in black grey colour. Its grading confirmed to zone I. The alkaline solution-to-fly ash ratios were considered as 0.5 for 12 M concentrated sodium hydroxide solutions. The laboratory-grade sodium hydroxide in flake form (97.8% purity) and sodium silicate (50.72% solids) solutions were used as alkaline activators. The alkaline activator solution of sodium silicates and sodium hydroxide ratio is 2.5. Oven curing was done at 75°C each for a heating period of 12 hours duration and tested.

2.2. Low Calcium Class F Fly Ash

![Figure 1. Low calcium class F fly ash](image)

| Chemical composition of Low Calcium Class F Fly ash generated in Thermal Plants |
|-----------------------------|----------------|
| Fly ash | Percentage |
| SiO$_2$ | 77.10 |
| Al$_2$O$_3$ | 17.71 |
| Fe$_2$O$_3$ | 01.21 |
| MgO | 0.90 |
| SO$_3$ | 2.20 |
| Na$_2$O | 0.80 |
| CaO | 0.62 |
| Total chlorides | 0.03 |
| Loss of ignition | 0.87 |
2.3. GGBS

![Figure 2. GGBS](image1)

| Chemical composition of GGBS | GGBS | Percentage |
|-----------------------------|------|------------|
| CaO                         | 37.34|
| Al₂O₃                       | 14.42|
| Fe₂O₃                       | 1.11 |
| SiO₂                        | 37.73|
| MgO                         | 8.71 |
| MnO                         | 0.02 |
| Loss of ignition            | 1.41 |

2.4. Iron Slag

![Figure 3. Iron slag](image2)

| Chemical composition of iron slag | Iron slag | Percentage |
|-----------------------------------|-----------|------------|
| SiO₂                              | 44.67     |
| Al₂O₃                             | 0         |
| Fe₂O₃                             | 16.11     |
| MgO                               | 1.75      |
| SO₃                               | 21.37     |
| CaO                               | 5.52      |
| K₂O                               | 0.33      |
| Na₂O                              | 0.33      |
| Cl                                 | 0.12      |
| MnO                               | 8.06      |
| TiO2                              | 1.60      |
2.5. Preparation of NaOH Solution
Sodium hydroxide solution always depends upon the level of concentration and by adding flakes of sodium hydroxide in a liter of distilled water instead of preparing one-liter solution. Then Sodium hydroxide molarity was found from the laboratory measurements. For, 12M sodium hydroxide solution consists of $12 \times 40 = 480$ grams of NaOH solids per liter of solution as shown in Figure 4. Sodium hydroxide solution was prepared one day before the casting of mortar cubes to cool down the NaOH solution up to the room temperature and combined with sodium silicates as shown in Figure 5 for preparation of the alkaline solution.

2.6. Preparation of Alkaline Solution
Alkaline activator solution for geopolymer is a Catalytic liquid system. The combination of solutions of alkali silicates and hydroxides and besties distilled water. The major role of the alkaline activator solution is to activate the geopolymeric source materials containing Si and Al in fly ash and GGBS. A mixing combination of sodium hydroxide and sodium silicate solutions as the activator (the alkaline liquid). Sodium hydroxide in the form of flakes (NaOH with 98% purity), and sodium silicate solutions ($Na_2O = 10.6\%, SiO_2 = 26.5\%$ and density = 1.39 g/ml at $25^\circ C$) are to be used. The alkaline activator solution should be prepared 24 hours before its use.

3. PREPARATION OF GEOPOLYMER MORTAR
The calculation of the mix ratio of mortar is 1:3. The geopolymer mix proportion is composed of low calcium class F fly ash, and GGBS (550 kg/m$^3$), fine aggregate (1650 kg/m$^3$), and Alkaline solution to Binder ratio is 0.5 Table 4. The geopolymer mortar mix was prepared by varying percentage of iron slag replacing 0%,25 %, 35 %,45 % of fine aggregates with the same amount of pozzolanic materialsand alkaline solution to binder ratio are shown in Table 5. Calculated quantities of low calcium class F fly ash, GGBS, sand and iron slag is well dry mixed until uniform(Figure 6 and Figure 7) and add alkaline solution thoroughly mixed for 2 to 3 minutes to give homogeneous mix were prepared by sodium hydroxide and sodium silicates before 24 hours. Mortar cube size is 70.7mm$\times$ 70.7mm$\times$ 70.7mm mould was cast in three layers. For uniform, mortar cube each layer is well compacted by tamping rod of diameter 20mm. After that compaction of mortar is required, and the top surface was levelled using a trowel, and if any air present inside the mortar is removed by gently tapped the sides of the mould to expel air. All the mortar cubes were removed from moulds(Figure 8 and Figure 9) after 24 hours of casting and then placed in an oven for thermal curing (heating)are shown in Figure 10. Each specimen was weighted for determination of mass density of mortar. The curing period of all the geopolymer mortar mixes was removed after 24 hours from the moulds and placed in a hot oven at a temperature of $75^\circ C \pm 2^\circ C$ for 12 hours.
Table 4. Material quantities of mortar size 70.6 × 70.6 × 70.6 mm with pozzolanic materials

| S.N O | Alkali Solution | NaOH Materials (g) | Na₂SiO₃ (g) | NaOH (g) | NaOH Pellets (g) | Distilled water | Liquid to Solid Ratio | Alkaline solution to binder ratio |
|-------|-----------------|--------------------|-------------|----------|-----------------|----------------|----------------------|-------------------------------|
| 1     | 2.5             | 12                 | 200 0 800 0 | 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 2     |                 |                    | 200 0 800 0 | 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 3     |                 |                    | 200 0 800 0 | 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 4     |                 |                    | 160 40 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 5     |                 |                    | 160 40 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 6     |                 |                    | 160 40 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 7     |                 |                    | 120 80 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 8     |                 |                    | 120 80 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |
| 9     |                 |                    | 120 80 800 0| 71.43    | 28.57           | 13.71          | 14.86                | 1.21169 0.5                   |

Table 5. Material quantities of mortar size 70.6 × 70.6 × 70.6 mm with Iron Slag

| S.N O | Alkali Solution | NaOH Materials (g) | Na₂SiO₃ (g) | NaOH (g) | NaOH Pellets (g) | Distilled water | Liquid to Solid Ratio | Alkaline solution to binder ratio |
|-------|-----------------|--------------------|-------------|----------|-----------------|----------------|----------------------|-------------------------------|
| 1     | 2.5             | 12                 | 160 40 600 200 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 2     |                 |                    | 160 40 600 200 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 3     |                 |                    | 160 40 600 200 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 4     |                 |                    | 160 40 520 280 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 5     |                 |                    | 160 40 520 280 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 6     |                 |                    | 160 40 520 280 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 7     |                 |                    | 160 40 440 360 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 8     |                 |                    | 160 40 440 360 71.43 28.57 14.86 19.43 1.21169 0.5 |
| 9     |                 |                    | 160 40 440 360 71.43 28.57 14.86 19.43 1.21169 0.5 |

Figure 6. Dry mix of pozzolanic materials and sand
Figure 7. Dry mix of pozzolanic materials, sand and iron slag.

Figure 8. Mortar cubes of fly ash and sand.

Figure 9. Mortar cubes of fly ash, sand and iron slag.

Figure 10. Hot oven curing of mortar cubes.

Figure 11. Compressive strength Testing Machine.
Figure 12. Compressive strength Testing Machine with specimen

4. COMpressive strength

Test specimens of size 70.6 × 70.6 × 70.6 mm were prepared for testing the Compressive strength of mortar are shown in Figure 11 and Figure 12. The mortar mixes with varying percentage of pozzolanic materials and iron slag as a replacement of fine aggregate (sand) were cast into the mortar for testing.

In this study, to make mortar, pozzolanic and fine aggregate was first mixed dry to a uniform colour and add the alkaline solution until homogenous mix. The inside surface of the moulds and base plate were oiled before the mortar was placed. After the 24 hours, the specimens were removed from the moulds and placed in a hot oven at a temperature of 75°C ± 2°C. The specimens, so cast were tested after 12 hours of heat curing measured from the time of specimen in a hot oven. For testing in compression, no cushioning material was placed between the specimen and the plates of the machine. The load was applied axially without shock until the specimen was crushed.

Results of the Compressive strength test on mortar with pozzolanic materials and iron slag replacement at 75°C ± 2°C for 12 hours are concluded.

Compressive strength is calculated using the equation:

\[ f_{ck} = \frac{P}{A} \]

Where,

- \( P \) = Failure load (in N).
- \( A \) = Cross-section of the specimen (mm²).

5. RESULTS AND DISCUSSION

Compressive strength on geopolymer mortar with different pozzolanic material having binder to sand ratio showed that 80% fly ash and 20% GGBS based geopolymer mortar with a ratio 0.5 has the highest strength which is 44.2 MPa at 75°C ± 2°C for 12 hours heat curing (Figure 13). The workability is increased with increase in the ratio of alkaline solution to binder above the ratio of 0.5. The alkaline solution to binder ratio is 0.5. Therefore, 80% fly ash and 20% GGBS based geopolymer mortar are concluded for the optimum compressive strength of geopolymer mortar are shown in Table 6.
Compressive strength shows that partial replacement of iron slag in geopolymer mortar having similar binding properties of sand are shown in Table 7. Compressive strength showed that 80% fly ash and 20% GGBS based geopolymer mortar with 35% of iron slag having a ratio of 0.5 has the highest strength which is 43.3 MPa at 75°C ± 2°C for 12 hours heat curing (Figure 14) [7,9,13]. The iron slag replacement doesn’t affect the strengths and gives workability to 80% fly ash and 20% GGBS based geopolymer mortar.

**Table 6.** Compressive strength of mortar size 70.6 × 70.6 × 70.6 mm with pozzolanic materials

| S.no | Alkaline solution | NaOH M | Fly ash | GGBS | Compressive strength |
|------|------------------|--------|---------|------|----------------------|
| 1    | 2.5              | 12     | 100%    | 0%   | 40.91 MPa          |
| 2    | 2.5              | 12     | 100%    | 0%   | 40.33 MPa          |
| 3    | 2.5              | 12     | 80%     | 20%  | 44.14 MPa          |
| 4    | 2.5              | 12     | 80%     | 20%  | 44.42 MPa          |
| 5    | 2.5              | 12     | 80%     | 20%  | 44.10 MPa          |
| 6    | 2.5              | 12     | 60%     | 40%  | 42.07 MPa          |
| 7    | 2.5              | 12     | 60%     | 40%  | 42.75 MPa          |
| 8    | 2.5              | 12     | 60%     | 40%  | 41.77 MPa          |

**Table 7.** Compressive strength of mortar size 70.6 × 70.6 × 70.6 mm with Iron Slag

| S.NO | Alkaline solution | NaOH M | Fly ash | GGBS | Sand | Iron slag | Compressive strength |
|------|------------------|--------|---------|------|------|-----------|----------------------|
| 1    | 2.5              | 12     | 80%     | 20%  | 100% | 0%        | 42.63 MPa            |
| 2    | 2.5              | 12     | 80%     | 20%  | 100% | 0%        | 42.91 MPa            |
| 3    | 2.5              | 12     | 80%     | 20%  | 100% | 0%        | 41.85 MPa            |
| 4    | 2.5              | 12     | 80%     | 20%  | 75%  | 25%       | 43.42 MPa            |
| 5    | 2.5              | 12     | 80%     | 20%  | 75%  | 25%       | 43.01 MPa            |
| 6    | 2.5              | 12     | 80%     | 20%  | 75%  | 25%       | 42.67 MPa            |
| 7    | 2.5              | 12     | 80%     | 20%  | 65%  | 35%       | 42.59 MPa            |
| 8    | 2.5              | 12     | 80%     | 20%  | 65%  | 35%       | 43.52 MPa            |
| 9    | 2.5              | 12     | 80%     | 20%  | 65%  | 35%       | 43.80 MPa            |
| 10   | 2.5              | 12     | 80%     | 20%  | 55%  | 45%       | 41.41 MPa            |
| 11   | 2.5              | 12     | 80%     | 20%  | 55%  | 45%       | 41.89 MPa            |
| 12   | 2.5              | 12     | 80%     | 20%  | 55%  | 45%       | 41.59 MPa            |

![Figure 13. Compressive strength of mortar with pozzolanic materials](image-url)
6. CONCLUSION

- The characteristics of geopolymer mortar strength are being computed in the present work by replacing 100% fly ash by 20% and 40% GGBS with the sand.
- The characteristics of the above geopolymer mortar strength are being computed in the present work by replacing 25%, 35%, and 45% Iron slag with the sand.
- The result is moreover positive in case of increase in compressive comparing with normal fly ash geopolymer mortar.
- Therefore, 80% fly ash and 20% GGBS replacement of pozzolanic materials to cementitious material at 75°C ± 2°C for 12 hours heat curing is overall better in compressive normal fly ash geopolymer mortar, so the optimum percentage of pozzolanic materials is concluded.
- Also, 35% replacement of Iron Slag to sand in geopolymer mortar at 75°C ± 2°C for 12 hours heat curing is given better compressive strength for optimum fly ash and GGBS geopolymer mortar, so the optimum percentage of iron slag is concluded.

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