Stress-strain behaviour and strength properties of ambient cured geo-polymer concrete

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Abstract. Given the high environmental impact of OPC concrete on CO$_2$ emissions, the construction industry is moving towards low carbon alternate binders. In recent years geo-polymer concrete (GPC) has come to the forefront of such efforts. However, challenges remain for GPC to be considered as a main-stream construction material. Since GPC is relatively new material in construction industry, many of its mechanical properties are still not fully understood. The current work looks at the strength properties of ambient cured GPC. This research paper is part of an ongoing investigation on GPC and reports some results of the mechanical properties of ambient-cured GPC. In this study, the stress-strain behavior and compressive strength of such GPC and its dependency on various parameters (ratio and type of activator and proportions & type of pre-cursor materials) is investigated. The results indicate that the compressive strength of GPC is greatly dependent on the proportion of Ground Granulated Blast Furnace Slag (GGBFS) and ratio of activators. It was found that increasing the percentage of GGBFS increased the compressive strength but at the expense of setting time of the mix. The mixes that had GGBFS around 20% of the binder material returned a compressive strength of less than 25 MPa which may not be suitable for structural applications. Whereas, the increase in percentage of GGBFS from 20 to 80% resulted in compressive strength of 40 MPa and higher. The stress-strain relationship of the mixes was compared to two analytical models existed in the literature.

1. Introduction
In the 21st century the concrete industry is facing a challenge to meet the needs of vast infrastructures and housing demand as a result of urbanization and industrialization. At the moment, Portland cement is the favourite option of binder for modern construction industry [1]. However, it is well known that producing Portland cement requires high energy and the CO$_2$ emissions in this process are substantial. These are the major factors contributing to global warming [1, 2]. Global warming to which cement production also contribute, is considered a life-threatening issue that needs to be tackled. On the other hand, there is a need for disposal of millions of tonnes of industrial by products. To solve both these issues one can incorporate industrial by products into concrete production as supplementary cementitious materials (SCMs) [1].

Currently after water concrete is the second widely used material with cement being its main ingredient [3]. The global production of OPC is steadily increasing without sign of slowing down [4], [5]. In the last twenty years’ extensive efforts has been concentrated by the concrete scientific community to decrease the CO$_2$ emissions by searching alternatives to OPC concrete. Being one of the alternatives, GPC concrete sometimes called green concrete have come to the forefront [6, 7]. GPC can be formed by reacting metallic alkaline (such as sodium/potassium hydro-oxide and/or sodium silicate) with materials containing considerable amount of silica (SiO$_2$) and alumina (Al$_2$O$_3$) such as fly ash (FA), GGBFS and rice husk ash [2, 8]. Such binders when mixed with traditional aggregates produce GPC...
which can be engineered with properties similar to or sometimes superior to OPC concrete. Moreover and in contrast to OPC, GPC does not rely on calcining CaCO₃, which is the main source of CO₂ emissions [9–11].

Despite the environmental-friendly characteristic of GPC, good mechanical properties, and high durability, there are several challenges that need to be tackled before it can become a potential mainstream construction material. One such challenge is the need for a high temperature curing regime as reported in literature [6]. However, the main challenge is the dependency of the final product on the activation system and source of the pre-cursor material. There are different types of pre-cursor materials with low and high calcium content [3]. It has been stated in literature that low calcium fly ash has similar properties to OPC concrete, however it requires heat curing for strength development. This research was triggered to take part in overcoming the above-mentioned challenges.

There are several studies available in the literature focusing on the behaviour of heat-cured GPC [10, 13], however, study on the properties of ambient cured GPC is limited [14, 15]. The work presented here is part of an ongoing investigation on the mechanical properties of ambient cured GPC. The key parameters of the study were the binder material content (percentage of FA and GGBFS) and the ratio of sodium silicate to sodium hydroxide (Na₂SiO₃/NaOH).

2. Materials Properties

Inorganic by product industrial waste like FA and GGBFS were used as binders in this study. An XRF test was conducted to specify the composition of the pre-cursor materials and the results are reported in Table 1. The alkaline activators used in the mixes were NaOH & Na₂SiO₃ solutions. Na₂SiO₃ solution had 27% of SiO₂, 8% of Na₂O, and a density between 1.296 and 1.396 gr/ml. NaOH solution (12M) were prepared from 98% purity flakes dissolved in water. The aggregates were combination of coarse and fine. Natural crushed aggregates with maximum size of 10 mm, absorption of 0.7%, and specific gravity of 2.68 was used as coarse aggregates. While fines used in the mixes was a 60% - 40% combination of 5mm crushed aggregates and dune sand (absorption of 1% specific gravity of 2.62).

Table 1. XRF (x-ray fluorescence) test results.

| Material | Na₂O | MgO | Al₂O₃ | SiO₂ | SO₃ | K₂O | CaO | TiO₂ | MnO₂ | Fe₂O₃ |
|----------|------|-----|-------|------|-----|-----|-----|-----|------|-------|
| FA       | 1.045| 7.51| 10.97 | 59.83| 1.545| 1.42| 8.75| 1.08 | 0.175| 7.525 |
| GGBFS    | -    | 6.58| 5.71  | 32.36| 2.38 | -   | 51.01| 0.64 | 0.73  | 0.59  |

3. Specimens Preparation

The mixing procedure of GPC mixes was done at room temperature. First coarse and fine aggregates were mixed with some portion of water then fly ash and GGBFS were added and mixed for two minutes. After that sodium silicate solution was poured to the dry mix and mixed for two minutes. Sodium hydroxide solution was then added to the mix and blended for another two minutes. The remaining of water together with superplasticizer was then added at the end and mixed for additional two minutes. It should be noted that sodium hydroxide solution was prepared at least 24 hrs before casting.

The mix proportions based on the work of Junaid et al [16] were used to cast specimen of this study and are presented in Table 2. A total of three sets containing 15 different mixes of GPC were prepared and cast in 75 cylinders of 100x200 mm. The difference between each set is the Na₂SiO₃/ NaOH ratio (R). Set1 has R=1, Set2 with R=2, and in Set3 R=2.5. In addition, Set3 has less percentage of GGBFS compared to Set1 and Set2. The difference between the mixes within the same set was the percentage of GGBFS added to the mix. For example, Mix1 of Set1 and Set2 has no GGBFS while Mix5 of the corresponding sets has 100% GGBFS but no FA. As mentioned earlier Set3 has less GGBFS content with the maximum of 20% in Mix5. For details of other mixes refer to Table 2. In Table 2 each mix is identified by a specific label representing the designated number of that mix and the number of corresponding sets. For example, S3M1 stands for the GPC Mix1 related to Set3. The water to binder ratio (w/b) was constant at 0.32 for all mixes of the three sets. To calculate the water to binder ratio the following equation was used:

\[
\frac{W_{\text{free}}+ W_{\text{OH}}+ W_{\text{Si}}}{FA+ G+ SO_{\text{OH}}+ S_{\text{Si}}} \]

(1)

2
Where, $W_{free}$ is mass of free water in the mix, $W_{OH}$ is the hydroxide solution water content, $W_{si}$ is the water content of Na$_2$SiO$_3$ solution, $FA$ is the mass of fly ash, $G$ is the mass of GGBFS, $S_{OH}$ is the mass of solid content of hydroxide solution, and $S_{si}$ is mass of solid content in the Na$_2$SiO$_3$ solution.

The cylinders were filled with GPC in three layers and was compacted by manual strokes with a 20 mm steel rod and also vibration table was used for better compaction as shown in Figure 1. The samples were demoulded after 24 hours of casting and placed inside laboratory with a room temperature and RH of 40% until it was tested. It is worth mentioning that during casting the setting times of mixes that had higher percentage of GGBFS was less than the mixes with lower amount of GGBFS.

| Mix ID | Pre-cursor Materials | Activators | Water |
|--------|----------------------|------------|-------|
|        | FA | GGBFS | NaOH | Na$_2$SiO$_3$ | Potable |
| Set1   |     |       |      |               |         |
| S1M1   | 425 | 0     | 82.5 | 82.5          | 58.5    |
| S1M2   | 340 | 85    | 82.5 | 82.5          | 58.5    |
| S1M3   | 212.5 | 212.5 | 82.5 | 82.5          | 58.5    |
| S1M4   | 85  | 340   | 82.5 | 82.5          | 58.5    |
| S1M5   | 0   | 425   | 82.5 | 82.5          | 58.5    |
| S2M1   | 425 | 0     | 55   | 110           | 60      |
| S2M2   | 340 | 85    | 55   | 110           | 60      |
| Set2   |     |       |      |               |         |
| S2M3   | 212.5 | 212.5 | 55   | 110           | 60      |
| S2M4   | 85  | 340   | 55   | 110           | 60      |
| S2M5   | 0   | 425   | 55   | 110           | 60      |
| S3M1   | 425 | 0     | 47   | 118           | 60      |
| S3M2   | 403.7 | 21.3  | 47   | 118           | 60      |
| Set3   |     |       |      |               |         |
| S3M3   | 382.5 | 42.5  | 47   | 118           | 60      |
| S3M4   | 361.3 | 63.7  | 47   | 118           | 60      |
| S3M5   | 340 | 85    | 47   | 118           | 60      |

Aggregates were added with the same proportion in all the mixes (10mm size = 1065 kg/m$^3$, 5mm size = 390 kg/m$^3$, and dune sand = 260 kg/m$^3$)

**Table 2.** Mix proportions of the GPC mixes studied in this paper.

**Figure 1.** Samples preparation; a) casting GPC cylinders and b) compaction of GPC cylinders.
4. Results and Discussion

4.1. Compressive Strength

Compression tests were conducted as per the ASTM C39/C39M-14 standard. The samples were loaded with a pace rate of 2.4 kN/s until failure. Figure 2 shows the average seven and 28-days compressive strength of three samples from each mix.

As can be seen in Figure 2a, for Set1 (with \( R = \text{Na}_2\text{SiO}_3 / \text{NaOH} = 1 \)) with an increase in percentage of GGBFS the compressive strength also increased and reached a maximum value of around 45 MPa at 28 days for mix with 80% of GGBFS. However, there is no noticeable increase in compressive strength of Mix5 compared to Mix4. This indicates that the strength development is not significant by increasing the percentage of GGBFS beyond 80%. On the other hand, the compressive strength of the samples for mixes without GGBFS was less than 5 MPa in all Sets indicating that the mixes with only fly ash is not appropriate for structural concrete.

The average seven- and 28-days compressive strength of Set2 (with \( R = \text{Na}_2\text{SiO}_3 / \text{NaOH} = 2 \)) followed a similar trend as Set1 (see Figure 2b). The samples in this set exhibited higher compressive strength value compared to the samples in Set1 due to the higher amount of silicate solution. Therefore, Mix4 and 5 of Set2 returned a maximum strength of 55 MPa at 28 days which is 10 MPa higher than the corresponding mixes of Set 1. The rate of strength gain with respect to the percentage of GGBFS for this set was a bit steeper than Set1. Nonetheless, the compressive strength of S2M1 and S2M2 are similar to S1M1 and S1M2 and were the lowest in these sets. It may, therefore, be suggested that the mixes with very low proportions of GGBFS are not appropriate for applications in structural engineering.

Mixes in Set3 (with \( R = \text{Na}_2\text{SiO}_3 / \text{NaOH} = 2.5 \)) had lower GGBFS percentage (0, 5, 10, 15 and 20% respectively) compared to the first two Sets (Set1 and Set2 (0, 20, 50, 80, 100%)). As plotted in Figure 2c, the pattern of strength improvement with respect to the percentage of GGBFS available in the mix was almost similar to Set1 and Set2. However the measured compressive strength is quite low which is not suitable for structural applications. The reason for having overall lower strength in this set is the amount of GGBFS content available in the mixes. Even though there is a relatively steep jump in the compressive strength of Mix4 and 5 of Set3 but still not a suitable compressive strength. The maximum GGBFS content in this Set was 20% (S3M5) which is equal to the amount of GGBFS in S1M2 and S2M2. This indicates that for comparison purpose Mix5 of Set3 can be compared to Mix2 of Set1 and Set2. When comparing it can be found that S3M5 exhibited higher compressive strength than S1M2 and S2M2 indicating the effect of higher amount of silicate solution (\( R = 2.5 \)) on compressive strength. It must be noted that higher percentages of GGBFS in mixes with \( R = 2.5 \) resulted in early and sudden setting of the GPC mixes.

In general, it can be inferred from Figure 2 that the average 28-day compressive strength of samples of all sets follow a similar trend to the strength acquired at seven days. However, there is not much gain in strength when curing is increased from seven to 28 days. Therefore, the difference between the seven- and 28-days compressive strength of all the mixes is minor. This agrees with the finding in literature. Earlier research work [17], suggest that strength of GPC develop in the initial days after casting and no further improvement is expected at later stages. In addition, the results of this study may also suggest that strength gain with time depend on the type of precursor materials and type of activator used. For example, from Mix3 and onwards that has higher GGBFS content, the difference in strength of seven and 28 days is a bit higher than the first two mixes of each set, however, to reach to concrete conclusion further studies need to be conducted.
Figure 2. Compressive Strength of the Samples at the age of 7 and 28 days, a) Set1, b) Set2 and c) Set3.

4.2. Stress – Strain Curves

Along with the compressive strength test, the stress-strain behaviour of selected mixes was also studied. From each set the mixes with strength over 15MPa were selected for this purpose. The results of the tests are plotted in Figure 3 a-c. Each curve is representative of two cylinders tested at the age of 28 days in a displacement-controlled loading mode with a loading rate of 0.01mm/sec until reaching half the ultimate capacity of the sample (Figure 4). After which, the loading rate was reduced to 0.005 mm/sec till failure of the sample. The parameters that can be determined from the stress-strain plots are the maximum stress, strain at maximum stress, the maximum strain, and sometimes the residual stress.

As can be seen in Figure 3, the stress-strain behaviour of the mixes within the same set is different due to variation in their compressive strength. The two mixes labelled S1M4 and S1M5, shows a strain magnitude of 0.003 at the maximum load similar to OPC concrete (see Figure 3a). Similarly, the mixes in Set2 that had higher compressive strength (S2M3, S2M4, and S2M5) showed a strain magnitude of around 0.004 at the time of maximum load as shown in Figure 3b which is slightly higher than the strain in OPC concrete. Mixes in Set3 that has overall lower compressive strength, experienced higher level of strains compared to Set1 and Set2 as expected (see Figure 3c). Furthermore, it can be noticed in Figures 3a and 3b that a higher level of FA replacement with GGBFS gives a higher compressive stress but a lower peak strain.
Figure 3. Stress-Strain behaviour of samples, a) Set1, b) Set2 and c) Set3.

Figure 4. GPC cylinder under test; a) compression test b) stress-strain test.

To compare the stress strain behaviour of the mixes investigated in this study with model prediction, two analytical models were considered namely Collins & Mitchel model [18] and Junaid et al. model [12]. Both models take the following form:

$$\sigma_c = f'c \cdot \frac{\varepsilon_c}{\varepsilon_{cm}} \cdot \frac{n}{n-1 + \left(\varepsilon_c / \varepsilon_{cm}\right)^{nk}}$$  \hspace{1cm} (2)
Where $\varepsilon_c$ is strain at stress $\sigma_c$, $f'c$ is peak compressive strength, $\varepsilon_{cm}$ strain at maximum strength. In the Collin model the factors $n$ and $k$ can be found using the following expressions:

$$n = 0.8 + (f'c/17)$$

$$k = 0.67 + (f'c/62) \quad \text{if} \quad \varepsilon_c/\varepsilon_{cm} > 1, \quad k = 1 \quad \text{if} \quad \varepsilon_c/\varepsilon_{cm} \leq 1$$

While the Junaid et al. model proposes the following values for $n$ and $k$ factors:

$$n = 0.7 + (f_c'/23) \quad k = 0.6 + (f_c'/86) \quad \text{when} \quad \varepsilon_c/\varepsilon_{cm} > 1 \quad k = 1.0 \quad \text{when} \quad \varepsilon_c/\varepsilon_{cm} \leq 1$$

In this study a post peak reduction factor of 2.0 was used for Junaid et al model.

Figure 5 shows experimental data obtained by testing GPC cylinders and the prediction by Collins & Mitchel model and Junaid et al. model. From each set only one mix is considered for the comparison with the models’ prediction. It can be inferred from the figure that both models’ prediction is reasonable in the ascending branch. Looking at the descending part, Juniad et al. [12] model seems more accurate.

![Figure 5](image1.png)

**Figure 5.** Comparison of experimental result of Stress-Strain behaviour to the models prediction; a) mix S1M4 and b) mix S2M4.

5. Summary and Conclusions

A total of three sets comprise of 15 different GPC mixes were studied in this research project. The objective was to investigate the strength characteristics of ambient cured GPC and their dependency on activator ratios, the precursor type & proportion, and curing time. The compressive strength along with stress-strain relationship for these mixes was studied. The results found from this investigation shows the feasibility of GPC production. The results also indicate that ambient cured GPC can be made with strength properties similar to ordinary Portland cement concrete.

Based on the results of this study the compressive strength of ambient cured Geo-polymer concrete is highly influenced by both the type and ratios of the precursor material. Having higher percentage of GGBFS in the mix significantly increased the compressive strength but at the loss of setting time. The mixes that had GGBFS around 20% of the binder material returned a compressive strength of less than 25 MPa which may not be suitable for structural applications. Whereas, the increase in percentage of GGBFS from 20 to 80% resulted in compressive strength of 40 MPa and higher. However further increase beyond 80% GGBFS had no impact on the compressive strength. Furthermore, the ratio of activator solutions has a noticeable effect on the strength properties. In all three sets with different R = Na$_2$SiO$_3$ / NaOH, among the three mixes that had equal amount of GGBFS (20 %) as binder, the mix that had higher R ratio, exhibited a higher compressive strength. The stress-strain relationship of GPC can be predicted by several analytical models. In this study two such models were used to predict the stress strain behaviour with satisfactory level of accuracy.
6. References

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