Mechanical properties of the wet mixed geopolymer concrete based on CDG and Slag cementitious materials in ambient curing temperature

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Abstract. Although considerable research has been conducted on alkali-activated fly ash cementitious materials for geopolymer concrete production, few of which concentrated on the slag-based geopolymer concrete. This paper presents the results of an experimental investigation on the 7-day & 28-day compressive strength, as well as 28-day flexural strength of the wet mixed geopolymer concrete based on CDG and slag cementitious materials cured at ambient temperature. A total of 90 specimens were tested. The cementitious materials content, sand ratio, as well as the liquid-solid ratio were selected as the main parameters. Besides, the new alkali activator system was adopted to prepare the geopolymer. Effects of these variables on the compressive and flexural behavior of the wet mixed geopolymer concrete are plotted throughout this paper.

Keywords. Geopolymer concrete, Slag, Cementitious material, Compressive strength, Flexural Strength

1. Introduction
Recently, geopolymer concrete has shown great potential in the construction industry due to its environmentally friendly characteristics. The utilization of geopolymer concrete not only reduces the emission of greenhouse gases associated with the global warming problem (Davidovits, 1994; Heath et al., 2014), but also exhibits excellent mechanical and durability performance over the OPC concrete in unregulated disposal of the industrial waste by recycling these materials in geopolymer production (Bernal et al., 2012; Ferone et al., 2015; Zhang, 2013). Since the conventional fly ash-based geopolymer concrete must be cured at high temperatures in the obtaining of sufficient early strength properties, the development of geopolymer concrete in engineering applications has been extremely limited (Mohammed et al., 2016). In this context, researches all over the world have been carried out on the calcium enriched slag cementitious materials. It is shown that the added calcium components could be helpful in solving the problem of geopolymer concrete being cured at ambient temperature (Suwan and Fan, 2014, 2016; Peng et al., 2019; Li et al., 2017; Yip et al., 2008). Since the completely decomposed granite (CDG) mainly consists of aluminosilicates, in which the alumina tetrahedron could react with the silica tetrahedron, under the activation effect of the alkali metal ion. The component CDG can be used as the alumina-silicate precursor in geopolymer manufacturing process.
Besides, study has already shown that the CDG can be used as the main cementitious material in geopolymer (Zha and Zhu, 2018).

In this study, mechanical properties of wet mixed geopolymer concrete cured at ambient temperature on considering the variation of the cementitious materials content, the sand ratio, and the liquid-solid ratio were conducted. Since the strong alkali sodium hydroxide could release large amounts of heat in the geopolymer manufacturing process, the calcium hydroxide and anhydrous sodium carbonate are adopted as the alkaline activator. Besides, the wet mixing technique was adopted to premix the water glass liquid, calcium hydroxide, anhydrous sodium carbonate, and water. The technique made it possible for the alkaline activator to be mixed evenly, which is helpful for the geopolymerization reaction.

2. Materials and methods

2.1. Cementitious materials

In the experiment, the completely decomposed granite (CDG) and the blast furnace slag were used as the main cementitious materials. Details of the cementitious materials are exhibited as follows.

2.1.1. Completely Decomposed Granite (CDG)

The completely decomposed granite (CDG) used in the test came from a construction site in the University Town of Shenzhen, Nanshan District, Shenzhen, Guangdong Province, China. This kind of soil widely exists in the Southern China. According to the Code for Highway Engineering Geological Investigation (JTG-C20-2011), the soil is defined as the quaternary loose deposits remaining in situ after the granite is weathered, called the completely decomposed granite residual soil. Since the soil is usually treated as the waste soil in the foundation excavation or in the site formation works, it belongs to one kind of waste soil. The CDG used in this test contains sand and gravel clay, showing a middling brown red color. After dried the excess liquid, the clod was carefully grinded into a smaller particle size and a higher fitness. This treatment made it easier for the chemical reaction between the CDG and the alkali-activator. The CDG sample used in the test is shown in Figure 1(a).

(a) Completely decomposed granite (b) Granulated blast furnace slag power

Figure 1. Cementitious materials used in the experiment

2.1.2. Blast Furnace Slag

The blast furnace slag used in the experiment was the S-95 grade granulated blast furnace slag powder, a by-product in steel-making industry, which was from Zhengzhou, Henan City. The slag powder sample is shown in Figure 1(b). Based on the X-ray fluorescence (XRF) analyses method, chemical composition of the cementitious materials (CDG and Slag) were successively obtained, and the main chemical components are exhibited in Table 1. It can be seen from the table that the CDG mainly contains SiO$_2$ and Al$_2$O$_3$, while the granulated blast furnace slag mainly contains SiO$_2$, Al$_2$O$_3$ and CaO.
Table 1. Chemical composition of the cementitious materials used in the experiment

| Composition | SiO$_2$ (%) | Al$_2$O$_3$ (%) | Fe$_2$O$_3$ (%) | CaO (%) | MgO (%) | TiO$_2$ (%) | Na$_2$O (%) | K$_2$O (%) |
|-------------|-------------|-----------------|----------------|---------|---------|-------------|-------------|-----------|
| CDG         | 45.71       | 36.92           | 8.96           | 0.49    | -       | 4.40        | -           | 2.96      |
| Slag        | 31.57       | 15.27           | 0.23           | 43.18   | 6.68    | 0.74        | 0.45        | 0.21      |

2.2. Alkaline activator and Aggregates

The water glass solution used in the test was the liquid-4 type liquid water glass with a modulus of 2.31, in which the SiO$_2$ content is 29.84%, and the Na$_2$O content is 13.36%. The calcium hydroxide and the anhydrous sodium carbonate, which are in white color powder and water-soluble, were mainly used to adjust the modulus of the water glass solution. Alkaline activator samples were shown in Figure 2.

![Alkaline activator samples](image)

(a) Liquid Na$_2$SiO$_3$  (b) Ca(OH)$_2$  (c) Na$_2$CO$_3$

Figure 2. Alkaline activator used in the experiment

The coarse aggregate and fine aggregate used in the concrete are the crude gravel and river sand, from the Tanking Mountain in Shenzhen. The particle sizes of the crude gravel were from 5 mm to 25 mm, while the particle sizes of the river sand were from 0 mm to 5 mm.

3. Experimental methods

To solve the great heat released problem in the preparation of CDG geopolymer concrete, the alkali sodium hydroxide was replaced by the calcium hydroxide and anhydrous sodium carbonate, which was also used to verify whether the method was feasible. Besides, the wet mixing technique was adopted to premix the water glass liquid, calcium hydroxide, anhydrous sodium carbonate, and water.

After the alkaline activator and water were mixed and stirred for 60 s in a uniform state, the alkaline activator solution and the concrete aggregate were poured together into the mixer. Subsequently, the mixing process was maintained for 120 s. After that, the stirred CDG geopolymer concrete was poured into a mold of 100 mm × 100 mm × 100 mm with the help of an electric concrete vibrator. Then the fabricated specimen were cured in the natural environment maintenance condition for 7 days or 28 days.

Determination of the specimen’s flexural strength ($R_f$) and the specimen's compressive strength ($R_c$) are illustrated in Figure 3(a) and 3(b). The calculation methods are exhibited as follows.

$$R_f = \frac{2 \times F}{\pi \times A} = 0.637 \frac{F}{A} \quad (1)$$

$$R_c = \frac{F}{A} \quad (2)$$

In which, $F$ is the ultimate load when the specimen is broken, $A$ is the cross-section area of the specimen, $R_f$ is the specimen's flexural strength, $R_c$ is the specimen's compressive strength.
3.1. Mix ratio design of the cementitious materials content

Three groups containing 27 specimens were cast, and were labelled as C1-1, C1-2, and C1-3. The sand ratio and the liquid-solid ratio remain constant, which equal to 40% and 0.65 respectively, while the cementitious materials contents are 420 kg/m$^3$, 450 kg/m$^3$, and 480 kg/m$^3$. Design of the mixture ratio was illustrated in Table 2 as follows.

| Label | CDG (g) | Slag (g) | Ca(OH)$_2$ (g) | Na$_2$CO$_3$ (g) | Na$_2$SiO$_3$ (g) | Fine aggregate (g) | Coarse aggregate (g) | H$_2$O (g) |
|-------|---------|----------|----------------|------------------|-----------------|-------------------|---------------------|----------|
| C1-1  | 2520    | 1680     | 112            | 159              | 1299            | 6800              | 10200               | 1160     |
| C1-2  | 2700    | 1800     | 120            | 170              | 1390            | 6800              | 10200               | 1245     |
| C1-3  | 2880    | 1920     | 128            | 181              | 1481            | 6800              | 10200               | 1330     |

3.2. Mix ratio design of the sand ratio

Accordingly, the 27 specimens in this part were classified into three groups, which were labelled as C2-1, C2-2, C2-3. The cementitious materials content and the liquid-solid ratio remain constant, which equal to 450 kg/m$^3$ and 0.7. The sand ratio varies from 34% to 40%. Details of the mix ratio design were exhibited in Table 3 as follows.

| Label | CDG (g) | Slag (g) | Ca(OH)$_2$ (g) | Na$_2$CO$_3$ (g) | Na$_2$SiO$_3$ (g) | Fine aggregate (g) | Coarse aggregate (g) | H$_2$O (g) |
|-------|---------|----------|----------------|------------------|-----------------|-------------------|---------------------|----------|
| C2-1  | 2700    | 1800     | 130            | 185              | 1500            | 5780              | 11220               | 1335     |
| C2-2  | 2700    | 1800     | 130            | 185              | 1500            | 6290              | 10710               | 1335     |
| C3-3  | 2700    | 1800     | 130            | 185              | 1500            | 6800              | 10200               | 1335     |

3.3. Mix ratio design of the liquid-solid ratio

In this section, four groups containing 36 specimens were cast and labelled as C3-1, C3-2, C3-3, C3-4. The cementitious materials content and the sand ratio remain constant, which equal to 450 kg/m$^3$ and 40%, respectively. The liquid-solid ratio varies from 0.65 to 0.80. Details of the mix ratio design were shown in Table 4 as follows.
Table 4. Mix ratio design of the liquid-solid ratio

| Label | CDG (g) | Slag (g) | Ca(OH)₂ (g) | Na₂CO₃ (g) | Na₂SiO₃ (g) | Fine aggregate (g) | Coarse aggregate (g) | H₂O (g) |
|-------|---------|----------|-------------|------------|-------------|-------------------|---------------------|--------|
| C3-1  | 2700    | 1800     | 120         | 170        | 1390        | 6800              | 10200               | 1245   |
| C3-2  | 2700    | 1800     | 130         | 185        | 1500        | 6800              | 10200               | 1335   |
| C3-3  | 2700    | 1800     | 140         | 200        | 1610        | 6800              | 10200               | 1425   |
| C3-4  | 2700    | 1800     | 150         | 215        | 1720        | 6800              | 10200               | 1515   |

4. Results and discussions

4.1. Influence of the cementitious materials content

After the natural curing was carried out, the specimens were subsequently subjected to the compression tests or flexural tests. Figure 4 clearly presents the 7-day, 28-day compressive strength and the 28-day flexural strength of specimens, considering the variation of the cementitious materials content.

Figure 4. Influence of the cementitious materials content on the specimen's strength

It can be seen from Figure 4(a) that as the cementitious materials content increases from 420 kg/m³ to 450 kg/m³, the flexural strength increases significantly. When it increases from 450 kg/m³ to 480 kg/m³, the flexural strength increases slightly, and the maximum 28-day flexural strength is achieved when the cementitious materials content is 480 kg/m³. These can be explained by the fact that within certain limits the higher cementitious materials contain more SiO₂ and Al₂O₃, the chemical compositions which are helpful for forming more silica tetrahedron and aluminium-oxygen tetrahedron. Therefore, the more stable and complex three-dimensional spatial network structures are easier to be formed. Figure 4(b) shows that, compared with the flexural strength, the compressive strength increases a little slower as the cementitious materials content develops, regardless of the 7-day compressive strength or the 28-day compressive strength. In addition, the compressive strength increases with the curing time, and the 7-day compressive strength was about 70% of the 28-day compressive strength.

4.2. Influence of the sand ratio

The sand ratio has effects on the concrete aggregate gradations and influences the workability and strength of concrete. Regardless of the content of the sand ratio, the fluidity would become poor and the segregation would be occurred. Consequently, the mechanical properties of the geopolymer
concrete were deteriorated. Figure 5 clearly shows the 7-day, 28-day compressive strength and the 28-day flexural strength of specimens, when the variation of the sand ratio was taken into account.

![Figure 5](image1.png)

**Figure 5.** Influence of the sand ratio on the compressive strength and flexural strength

Figure 5(a) indicates that the 28-day flexural strength increases remarkably with the sand ratio ranging from 34% to 40%, and the relationship is approximately linear. Figure 5(b) shows that the compressive strength increases slightly as the sand ratio increases. Additionally, the ultimate 7-day and 28-day compressive strength are achieved when the sand ratio is 40%, which equal to 18.08MPa and 24.60MPa, respectively. The sand ratio has little effects on the compressive strength. When it increases from 34% to 40%, the compressive strength only improves 11.70%. The sand ratio influences the workability of the geopolymer concrete, this can be explained by the fact the sand could fill the gap of the concrete and the free water content would decreases. Consequently, the slump of the geopolymer is improved.

4.3. *Influence of the liquid-solid ratio*

The cementitious materials content and the sand ratio per cubic meter remain constant, while the liquid-solid ratio changes from 0.65 to 0.80. Figure 7 displays the 7-day, 28-day compressive strength and the 28-day flexural strength of specimens, when the variation of the liquid-solid ratio was considered.

![Figure 6](image2.png)

**Figure 6.** Influence of the liquid-solid ratio on the compressive strength and flexural strength
Figure 6(a) shows that the flexural strength and the compressive strength increase firstly and then decrease, as the liquid-solid ratio increases from 0.65 to 0.80, regardless of the natural curing duration. When the liquid-solid ratio is 0.70, the maximum concrete strength is achieved. The 28-day flexural strength is 3.20MPa, the 7-day and 28-day compressive strength are 18.08MPa and 24.60MPa, respectively. Additionally, the 7-day compressive strength is approximately 70% of the 28-day compressive strength. The liquid-solid ratio directly affects the geopolymer concrete strength. With the increases of the liquid-solid ratio, the hydration product silica gel could fill the porous space and the density of the concrete is further dense. When a high proportion of the liquid-solid ratio exists, evaporation of the water from the alkaline activator solution results in pore structures, thus leading to a decline in the geopolymer concrete strength. When the liquid-solid ratio is relatively low, the alkaline activator solution could not react well with the cementitious materials. The reaction of the condensation polymerization is insufficient, which results in the reduction of the geopolymer concrete strength.

5. Conclusion
In this study, mechanical properties of wet mixed geopolymer concrete on considering the variation of the cementitious materials content, the sand ratio, and the liquid-solid ratio were conducted. It can be concluded that the flexural strength and the compressive strength both increase as the cementitious materials content increases from 420 kg/m³ to 480 kg/m³, when the sand ratio and the liquid-solid ratio remain constant. The flexural strength and the compressive strength both increase as the sand ratio increases from 34% to 40%, with the cementitious materials content and the liquid-solid ratio being constant. Moreover, the flexural strength and the compressive strength increase firstly and then decrease, as the liquid-solid ratio increases from 0.65 to 0.80, with the cementitious materials content and the sand ratio being constant. When the sand ratio is 0.70, the 7-day maximum compressive strength and the 28-day maximum compressive strength are achieved which equal to 18.08MPa and 24.60MPa respectively, while the 28-day maximum flexural strength is 3.20MPa.

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References
[1] Davidovits J. (1994). "Global warming impact on the cement and aggregates industries," World Resource Review, 6:2.
[2] Heath A., Paine K., and McManus M. (2014). "Minimising the global warming potential of clay based geopolymers," Journal of Cleaner Production, vol. 78, pp. 75-83.
[3] Bernal SA., de Gutiérrez, RM., and Provis JL. (2012). "Engineering and durability properties of concrete based on alkali-activated granulated blast furnace slag/metakaolin blends," Construction and Building Materials, vol. 33, pp. 99-108.
[4] Ferone C., Liguori B., Capasso I., Colangelo F., Cioffi R., Cappelletto E., and Di Maggio R. (2015). "Thermally treated clay sediments as geopolymer source material," Applied Clay Science, vol. 107, pp. 195-204.
[5] Zhang L. (2013). "Production of bricks from waste materials—a review," Construction and Building Materials, vol. 47, pp. 643-55.
[6] Mohammed Haloob Al-Majidi, Andreas Lampropoulos, Andrew Cundy, Steve Meikle. (2016) "Development of geopolymer mortar under ambient temperature for in situ applications," Construction and Building Materials, Volume 120, Pages 198-211.
[7] Suwan T and Fan M. (2014). "Influence of OPC Replacement and Manufacturing Procedures on the Properties of Self-Cured Geoplymer," Construction & Building Materials, 73(2):551-
561.

[8] Suwan T, Fan M, Braimah N. (2016). "Internal Heat Liberation and Strength Development of Self-Cured Geopolymers in Ambient Curing Conditions," Construction & Building Materials, 114(7):297-306.

[9] Peng H, Cui C, Liu Z, et al. (2019). "Synthesis and Reaction Mechanism of an Alkali-Activated Metakaolin-Slag Composite System at Room Temperature," Journal of Materials in Civil Engineering, 31(1).

[10] Li N, Shi C, Wang Q, et al. (2017). "Composition design and performance of alkali-activated cements," Materials and Structures, 50(3).

[11] Yip C K, Lukey G C, Provis J L, et al. (2008). "Effect of calcium silicate sources on geopolymerisation," Cement and Concrete Research, 38(4):554-564.

[12] Zha X, Zhu J, "Experimental Study on the Effects of Calcium-rich Materials on the Early Compressive Strength of Completely Decomposed Granite (CDG) Base-geopolymer"[C]/4th International Symposium on Hydrogen Energy, Renewable Energy and Materials, HEREM 2018, 2018:2-8.

[13] JTG-C20-2011, Code for Highway Engineering Geological Investigation, China.