Study on factors affecting the mechanical properties of dry mixing CDG based geopolymer

Xiaoxiong Zha*, Kai Wang, and Jiayuan Zhu

School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen, Shenzhen, Guangdong, China.

zhahero@126.com, cewangkai@126.com, zhujiaoyuan1994@sina.com

Abstract. Cement is the main material for the construction industry. But it produces a large amount of greenhouse gases and consumes a lot of resources. As a new type of green cementitious material, geopolymer materials can replace cement. In order to simplify the preparation process of the geopolymer material, dry-mixing CDG geopolymer materials are prepared by using a dry mixing process technique, using a solid activator material, mixing the dry materials, and adding water to the mixture. In this paper, the completely decomposed granite (CDG) and slag are used as the main cementitious materials, and the geopolymer paste and concrete are prepared by the action of alkaline activator, and the systematic study on the mechanical properties of this new geopolymer material has been carried out.

Keywords. Geopolymer, CDG, Slag, Dry mixing, Mechanical properties

1. Introduction
Cement is the main material of the construction industry, and emits a large amount of carbon dioxide. Geopolymer materials can be used as a new type of green cementitious material to replace some or all of the cement (Davidovits, 1994). Since the introduction of geopolymer by Davidovits, after decades of research and development, the selection of raw materials for production has gradually turned into solid industrial waste (Shi et al., 2013). This not only realizes the secondary utilization of industrial waste, but also greatly reduces the cost in the production process of geopolymer materials. As researchers continue to apply and develop this material, the prices of industrial waste are also rising. Some studies have shown that completely decomposed granite can be used as a raw material for geopolymer, so CDG is used as the main cementitious material in this research (Zha et al., 2018).

The preparation of geopolymer materials under the common process requires the preparation of an activator solution, which leads to a cumbersome preparation process; and the activator solution is corrosive, which also increases safety hazards during the configuration process. This also has some adverse effects on the promotion and development of geopolymer materials at the construction site. In response to this problem, Suwan developed a self-maintenance technology that uses a “pre-dry mix” method (Suwan et al., 2014, 2016) based on the exothermic heat of the geopolymer activator dissolved in water to provide the heat needed for strength development, allowing the geopolymer material to be at ambient temperature. Under the shape can be cured. Bayuaji also proposed a new idea for the production of geopolymer cement technology, which is a mixture of cementitious materials and solid...
activators, similar to bagged commercial cement (Bayuaji et al., 2017). It not only optimizes the preparation process of geopolymer, but also guides the new development direction of geopolymer.

2. Materials and methods

2.1. Cementitious materials

The residual soil of fully weathered granite used in the experiment is widely distributed in southern China. It contains sand and gravel clay and is brownish red. The cohesive soil in the hard plastic state is a kind of construction dregs. The slag used in the test is S-95 grade granulated blast furnace slag powder, which is an industrial by-product. The samples are shown in Figure 1.

![CDG](a) CDG  ![Slag](b) Slag

Figure 1. Cementitious material used in the experiment.

The X-ray fluorescence analyses of the chemical composition of cementitious materials were carried out, and the results are shown in Table 1.

Table 1. Chemical composition of the cementitious materials

|       | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | CaO (%) | MgO (%) | TiO₂ (%) | Na₂O (%) | K₂O (%) |
|-------|----------|-----------|-----------|---------|---------|----------|----------|---------|
| 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

The solid water glass is white granular crystal with a modulus of 3.28, wherein the SiO₂ content was 73.87% and the Na₂O content was 23.25%. Both calcium hydroxide and sodium carbonate are white powdery solids and are mainly used to adjust the modulus of the water glass solution. The samples of the alkaline activator are shown in Figure 2.

![Solid Water glass](a) Solid Water glass  ![Calcium hydroxide](b) Calcium hydroxide  ![Sodium carbonate](c) Sodium carbonate

Figure 2. Alkaline activator used in the experiment.
3. Experimental methods
In order to simplify the preparation method of CDG geopolymer materials, the safety hazards in the preparation process are also reduced. The dry blending technique is used to premix the solid activator with the gelling material. In the preparation process of the construction site, such as ordinary concrete, it is only necessary to add the dry material and aggregate which are mixed in advance to the mixer, and then add water to stir to prepare the geopolymer material.

The solid activator and the gelling material were mixed and stirred for 60 s to uniformly mix the solid activator with the gelling material, and then stirred with water for 120 s. Then, the stirred slurry was poured into a test piece of 40 mm × 40 mm × 160 mm, and placed in a water mold for 1 d at room temperature and cured in water. The flexural strength and compressive strength of the specimens were measured for 28 d and 56 d. The measurement method is shown in Figure 3.

![Figure 3. Test piece strength measurement method](image)

(a) Flexural strength  (b) Compressive strength

The determination of the flexural strength \( (R_f) \) requires a folding clamp, and the method of use is shown in Figure 3(a). The method for measuring the compressive strength \( (R_c) \) of the geopolymer paste is to put the half-cuboid after the fracture test of the fracture test into a compression clamp, so that the pressure receiving surface of the test piece is 40 mm×40 mm, and the use method is shown in Figure 3(b).

\[
R_f = \frac{1.5 \times F_f}{b^3} \\
R_c = \frac{F_c}{A}
\]

In which, \( F_f \) is the load when the test piece is broken, \( l \) is the distance between the two supporting cylinders below the clamp, \( b \) is the length of the square section of the test piece, \( F_c \) is ultimate load when the compressed test piece is damaged, \( A \) is the pressure area of the test piece.

3.1. Mix ratio design of the activator modulus
The ratio of SiO\(_2\)/Na\(_2\)O in the activator was adjusted to 1.0, 1.2, 1.5, 2.0 by changing the ratio of solid water glass to Ca(OH)\(_2\) and Na\(_2\)CO\(_3\). The CDG and slag are mixed at a ratio of 3/2, the amount of Na\(_2\)O of the activator is controlled to be 6% of the cementitious material, the water-to-binder ratio is 0.5, and the blending thereof is shown in Table 2.

| Label | CDG (g) | Slag (g) | Ca(OH)\(_2\) (g) | Na\(_2\)CO\(_3\) (g) | Na\(_2\)SiO\(_3\) (g) | Water (g) |
|-------|---------|----------|-----------------|---------------------|---------------------|-----------|
| C1-1  | 900     | 600      | 78              | 111                 | 120                 | 750       |
| C1-2  | 900     | 600      | 70              | 100                 | 142                 | 750       |
3.2. Mix ratio design of the activator dosage
Solid water glass, Ca(OH)$_2$ and Na$_2$CO$_3$ powder were used as solid activators, and the ratio was adjusted, therefore the ratio of SiO$_2$/Na$_2$O in the solid activator system was kept constant at 1.5. Adjust the proportion of cementitious materials, the total amount of residual soil of fully weathered granite is 60%, and the amount of slag is 40%. The amount of the activator was changed so that the Na$_2$O of the activator system was 4%, 6%, 8% of the cementitious material, and the water-to-binder ratio was 0.5. The specific mix ratio design is shown in Table 3.

| Label | CDG (g) | Slag (g) | Ca(OH)$_2$ (g) | Na$_2$CO$_3$ (g) | Na$_2$SiO$_3$ (g) | Water (g) |
|-------|---------|----------|----------------|------------------|------------------|-----------|
| C2-1  | 900     | 600      | 40             | 58               | 118              | 750       |
| C2-2  | 900     | 600      | 60             | 87               | 117              | 750       |
| C2-3  | 900     | 600      | 80             | 116              | 236              | 750       |

3.3. Mix ratio design of the water-to-binder ratio
The ratio of SiO$_2$/Na$_2$O in the activator was controlled to 1.5, and the residual soil of the fully weathered granite was mixed with the slag in a ratio of 3/2. The amount of the activator was 6% of the cementitious material calculated by Na$_2$O, and the water-to-binder ratio was changed to 0.4, 0.45, 0.5, 0.55, 0.6 respectively. The specific mix ratio design is shown in Table 4.

| Label | CDG (g) | Slag (g) | Ca(OH)$_2$ (g) | Na$_2$CO$_3$ (g) | Na$_2$SiO$_3$ (g) | Water (g) |
|-------|---------|----------|----------------|------------------|------------------|-----------|
| C3-1  | 900     | 600      | 60             | 87               | 177              | 600       |
| C3-2  | 900     | 600      | 60             | 87               | 177              | 675       |
| C3-3  | 900     | 600      | 60             | 87               | 177              | 750       |
| C3-4  | 900     | 600      | 60             | 87               | 177              | 825       |
| C3-5  | 900     | 600      | 60             | 87               | 177              | 900       |

4. Results and discussions

4.1. Influence of the activator modulus
The flexural strength and compressive strength of the test pieces at 28-day and 56-day during the curing age are shown in Figure 4.
It can be seen from Figure 4 that as the molar ratio of SiO$_2$/Na$_2$O in the activator increases from 1.0 to 2.0, the flexural strength of the cleaned specimen gradually increases; the compressive strength of the test piece first increases and then decreases. The maximum 56-day compressive strength of 24.90 MPa is obtained when the modulus is 1.2. This can be attributed to the fact that the water glass with low modulus contains more oligosilicate tetrahedron, which is beneficial to the dissolution of silicon and aluminum components and promotes the geopolymer gel. However, due to the quick reaction, some micro-cracks are generated inside the test piece, resulting in a decrease in the bending strength. However, the compressive strength has no high flexural strength for microcrack sensitivity, so the compressive strength increases as the modulus decreases. When the ratio of Na$_2$CO$_3$ and Ca(OH)$_2$ is too high, too many microcracks leads to a decrease in strength.

4.2. Influence of the activator dosage

After the specimen is demolded, it should be cured in water to the predesigned curing time. Firstly, the flexural strength is measured, then the compressive strength of the two fractured half prism specimens is measured. Details of the strength versus activator dosage is shown in Figure 5.

![Figure 5. Influence of the activator dosage on strength](image)

It can be seen from Figure 5(a) that when the amount of Na$_2$O in the activator increased from 4% to 8% of the cementitious material, the flexural strength of the test piece increases. As the amount of activator increases, the increase of the flexural strength of the test piece from 28-day to 56-day is greater. Since the solid water glass has a low solubility in water under normal temperature and normal pressure conditions, it is required that the water glass solid is continuously dissolved in water to participate in the reaction. Therefore, the reaction is also slow. When the amount of the activator is large, the activator can always participate in the reaction, supplementing the microcracks in the test pieces, thus improving the bending strength.

From Figure 5(b), it can be found that the compressive strength of the test piece increases with the increase of the amount of the solid activator. When the amount of Na$_2$O is 8% of the cemented material, the compressive strength at 56-day is the largest, which can reach 24.38 MPa. This indicates that the amount of the activator has a greater influence on the mechanical properties of the test piece.

4.3. Influence of the water-to-binder ratio

Due to the low strength of the group 3-5 specimens during the 28-day curing period, the flexural strength and compressive strength of the 56-day were not studied. Therefore, there were only four specimens for the 56-day test. The test result data is shown in Figure 6.
It can be seen from Figure 6 that, as the water-to-binder ratio increases, the flexural strength and compressive strength of the test piece increase first and then decrease, the test piece with the water-to-binder ratio equals to 0.45 can obtain the highest strength. The flexural strength of the 56-day is 3.90 MPa and the compressive strength is 22.63 MPa.

When the water-to-binder ratio is relatively high, a large amount of moisture in the test piece remains inside the test piece, forming capillary pores, which reduces the compactness of the test piece, resulting in a decrease in the strength of the test piece. When the water-to-binder ratio is too low, the fluidity of the geopolymer material is poor, the test piece is difficult to form, and the defects in the pouring process would affect the strength of the geopolymer test piece.

5. Conclusion
In order to simplify the preparation process of geopolymer materials, further promoting the development of construction materials, dry-mixed geopolymer materials are prepared through the dry mixing method. Optimizing the geopolymer preparation process can solve the difficulties in transporting alkaline activator solutions.

In this research, a series of studies on the mechanical properties of dry-mixed geopolymer materials were carried out. The effects of the activator modulus, the activator dosage, and the water-to-binder ratio on the mechanical properties were investigated. For the dry-mixed geopolymer paste material, when the molar ratio of the SiO₂/Na₂O to the initiator is 1.2, the compressive strength is the highest. In addition, the flexural strength increases with the increase of the modulus. As the amount of activator increases, the strength of the test piece also increases. When the water-to-binder ratio varies from 0.4 to 0.6, the strength of the geopolymer paste first increases and then decreases. When the water-to-binder ratio is 0.45, the highest 56 d compressive strength 22.63 MPa is achieved. Additionally, during the 56-day curing period, the dry-mixed geopolymer material still has a certain increase in strength.

Acknowledgement
This research is funded by the National Nature Science Foundation of China (Grant No. 51578181), Natural Science Foundation of Guangdong Province (No. 2016A030313665) and Shenzhen Science and Technology Plan Project (No. JCYJ20150327155221857). Acknowledgement is also given to the Shenzhen Carbon Storage Cement-Based Materials Engineering Laboratory.

References
[1] Davidovits J. Global warming impact on the cement and aggregates industries[J]. World Resource Review; (United States), 1994, 6:2.
[2] Shi H, Xia M, Guo X. Research Development on Mechanism of Fly Ash-based Geopolymer and
Effect of Each Component[J]. Journal of the Chinese Ceramic Society, 2013, 41(7):972-980(9).

[3] 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.

[4] Suwan T, Fan M. Influence of OPC Replacement and Manufacturing Procedures on the Properties of Self-Cured Geopolymer[J]. Construction & Building Materials, 2014, 73(1-2):551-561.

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

[6] Bayuaji R, Yasin A K, Susanto T E, et al. A Review in Geopolymer Binder with Dry Mixing Method (Geopolymer Cement)[C]// American Institute of Physics Conference Series. American Institute of Physics Conference Series, 2017:020-022.