EVALUATING SHEAR STRENGTH OF SAND- GGBFS BASED GEOPOLYMER COMPOSITE MATERIAL

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Abstract. Geopolymer has been emerging as a novel and sustainable replacement for the traditional soil improvement materials, such as ordinary Portland cement OPC and lime, which have severe environmental impacts. In this paper, a series of unconfined compression and triaxial tests were conducted on sand and sand - ground granulated blast-furnace slag (GGBFS) based geopolymer. A solution of sodium silicate and sodium hydroxide was employed for the geopolymerization process. Results revealed that adding the GGBFS resulted in a significant increase in the strength properties. This result indicates that geopolymer acted as a cementation agent, providing better bonding between the sand particles and consequently improving the performance of the treated sand.

Keywords: Geopolymer, ground granulated blast-furnace slag, sand, drained triaxial strength, unconfined compression strength.

1. Introduction

One of the recent developments in geotechnical engineering is the application of geopolymers to soil-improvement procedures. Geopolymers have been emerging as an eco-friendly replacement for the traditional materials. These impacts include the emission of large quantities of carbon dioxide, intensive consumption of energy and resources. For example, the production process of one tone of OPC causes a carbon dioxide emission of about one tone and an energy consumption of about 5000 MJ [1–3]. Moreover, one tone of lime results in about 0.86 tons of carbon dioxide.

Geopolymer can be synthesized by activating variety of sources, such as industrial waste (e.g ground blast furnace slag (GGBFS), fly ash) and natural materials (e.g. Metakaoline). A solution of Na_2SiO_3 and NaOH are the most widely available activators used to create a high alkaline environment [4].

Rios et al. [5] studied the behaviour of silty sand mixed with a geopolymer (fly ash, sodium silicate and sodium hydroxide). Their results showed a significant increase in the unconfined compression strength due to the role of the alkaline binder. After 90 days of curing, the strength of the soil mixed with an activator and 15, 20 and 25 % fly ash increased by 16, 31 and 77 times respectively compared with non-stabilized samples [5]. Similar results were found recently by Cruz et al. [6], who found that the unconfined compression strength of soil improved approximately 32 times when Alkali-Activated binder was added. In contrast to the OPC and lime, clayey soil, improved with alkaline activated low calcium fly ash, exhibited a slow increase in the unconfined compressive strength UCS until the 28th day, and then it showed similar or larger UCS than

the conventional stabilizers [7]. A similar trend has been found by Al-Rkaby et al. [8–11].

Dassekpo et al. [12] proposed that the Completely Decomposed Granite (CDG) can be used as a geopolymer source material without the need to add fly ash. They found that the compressive strength, at a 7th day of curing time of the CDG based geopolymer, without an addition of fly ash, was 13.89 MPa compared with 0.36 MPa for the CDG without an alkaline activator.

Regarding the parameters of strength, the angles of the internal friction φ for a soil stabilized by a geopolymer were higher than 50°, associated to cohesion intercepts C higher than 250 kPa [5]. A similar trend was observed by Corrêa-Silva et al [7], who found that the friction angles in the critical state increased by 73.6 % and 50.0 % in the total and effective stress analysis respectively. Moreover, the cohesion increased by two times in terms of total peak strength while it was very low in effective stress [7].

Using a geopolymer made from mixing low calcium fly ash, sodium silicate SiO_2 and sodium hydroxide Na_2O with silty sand led to a very high strength and stiffness [13]. Ratio of $SiO_2/Na_2O = 1$ produced the maximum early strength of the geopolymer concrete [14]. Moreover, the optimum content of the sodium silicate-based additive for improving the low strength clay and high swelling clay was found to be 6.0 % [15]. At this percentage, the UCS of low strength clay and high swelling clay increased by 4.7 and 3.3 times respectively [15].

In addition to the strength properties, studies carried out on geopolymer based soil showed that treated soils have a high durability [14, 16–18]. Similar results have been observed by Corrêa-Silva et al [7] who

found that treated samples induced a strong reduction of sensitivity to water action. Moreover, stabilized samples showed a significant resistance to the wetting and drying tests [19].

The addition of alkali activated stabilizer resulted in reduced volume strains and an overall decrease of compressibility of the treated soil [20]. From an early stage of curing, the geopolymer-soil composite exhibited a deformation modulus two times higher than the untreated samples [6]. After 14 days of curing, the deformation modulus of the geopolymer-soil composite increased to 183.1 MPa compared with 20.0 MPa for the untreated samples [6]. It was found that the compression index (Cc) and swelling index (Cs) decreased from 2.3 and 0.66 for untreated low strength clay and high swelling clay respectively to about 0.5 and 0.2 for treated samples respectively [15]. This is in an agreement with Sargent et al. [21] who found that using ground granulated blast-furnace slag (GGBFS)-NaOH with alluvial soil resulted in decreasing Cc and swelling index Cs from 0.13 and 0.013 to 0.014 and 0.003 respectively.

Abdeldjouad et al. [22, 23] found that the admixtures of a higher kaolinite content with the palm oil fuel ash POFA exhibited higher long term strength than the admixtures without POFA. Similar trend was observed by Teing et al. [24]. The reason for this improvement are the microstructural changes (such as uptake, re-condensation and the presence of glassy phase) taking place in the mixture fabric during the stabilization process [22–25]. Scanning Electron Microscopy SEM showed that voids between soil particles were almost filled with structured aluminosilicate polymerized gel. Therefore, discrete particles of the geopolymer composite material exhibit a denser and more closely bound texture [22–25].

Although good research efforts have been made into enhancing the shear strength and characteristics of soil by a geopolymer, there is little information on the strength characterization of sand - ground granulated blast-furnace slag (GGBFS) based geopolymer. Therefore, this study aims to investigate the strength improvement of sand with Geopolymer incorporating GGBFS.

2. Materials and methods

2.1. Sand

In the city of Perth in Western Australia, sand affords considerable cost savings for infrastructure and buildings because it is the most predominant type of soil in the city and there are many quarries in the surrounding area. As a consequence, soil that is characterized as poorly graded clean sand (SP) according to the Unified Soil Classification System (USCS) is used in the present study, with a coefficient of curvature $C_c = 1.17$ and a coefficient of uniformity $C_u = 1.64$. The physical properties of Perth sand are: maximum void ratio $e_{max} = 0.844$, minimum void ratio $e_{min} = 0.521$, median particle size $D_{50} = 0.43$ and specific gravity $G_s = 2.63$.

2.2. Ground granulated blast-furnace slag GGBFS and the alkaline activator

Calcium rich ground granulated blast-furnace slag (GGBFS) was utilised in this research. Such material is a by-product of the steel and iron industry. Moreover, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used as the alkaline activator. The Na_2SiO_3/NaOH mass ratio was chosen to be equal to 2.0 to create a high alkaline environment and produce the maximum early strength.

2.3. Sample preparation

A total number of forty samples of sand - ground granulated blast-furnace slag (GGBFS) based geopolymer was prepared. In order to prepare these samples, initially, the GGBFS was added to sand at five different volume ratios (10 %, 15 %, 20, 30 & 40 % as a fraction of the total weight), then blended thoroughly in dry conditions until achieving a good distribution and a uniform colour. In this study, the high pH alkaline activator was prepared by adding sodium hydroxide (NaOH) in a pellet form to the sodium silicate solution (Na_2SiO_3) based on predefined mix proportions and mixing them for 15 minutes for a full dissolution. The alkaline activator solution was then added to the sample and mixing continued to obtain a final homogenous mix.

Each sample for the experiment was prepared according to the desired GGBFS content, activator percentage and dry unit weight. For each layer, to produce the desired density, the required amount of sand - ground granulated blast-furnace slag (GGBFS) based geopolymer was determined in advance according to the selected density and the layer volume. In order to compact the mixture, the mould was divided into several layers and, for each layer, the required amount of sand-(GGBFS) based geopolymer was poured into the mould and the surface was flattened by careful scraping. Each layer was then compacted into the mould to the required height. After the compaction, the sand - GGBFS based geopolymer specimens were kept in the laboratory for 24 hours before being soaked for curing. The period of 28 days was chosen as an average curing time.

3. Results

Figure 2 shows the variation of the maximum dry unit weight $(\gamma_d)_{max}$ along the ground granulated blast-furnace slag (GGBFS) content of 5, 10, 15, 20, 30 and 40 % for all activator ratios (Activator/GGBFS=0.2, 0.4, 0.6 and 0.8). It is clear that the 15 % GGBFS exhibited a better performance in terms of the largest maximum dry unit weight. This is due to the fact that such amount of GGBFS fills the voids as inclusions.
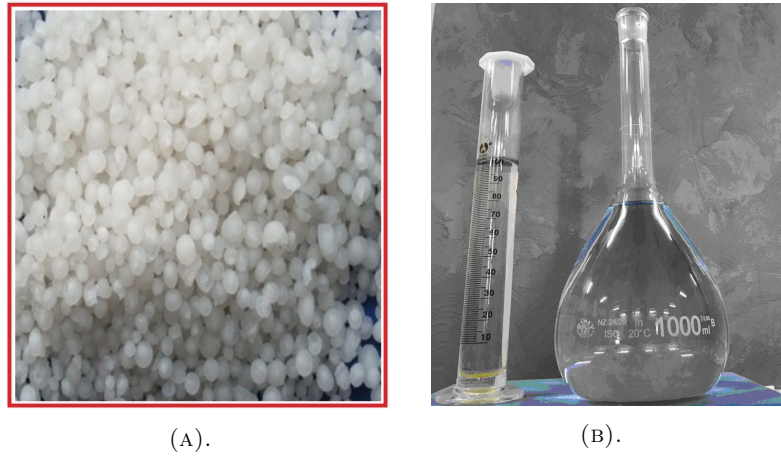
(A).

(B).

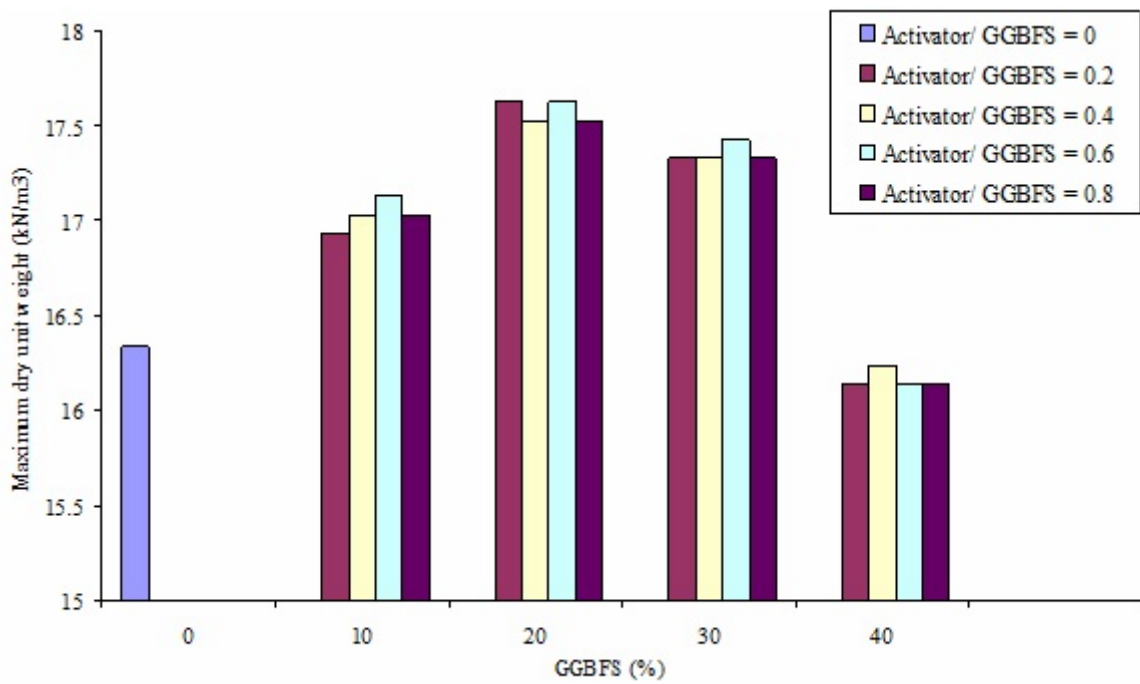FIGURE 1. (a) Sodium hydroxide in pellets form, and (b) Sodium silicate solution.

FIGURE 2. Variation of the maximum dry unit weight $(\gamma_d)_{max}$ with GGBFS content for different activator ratios.
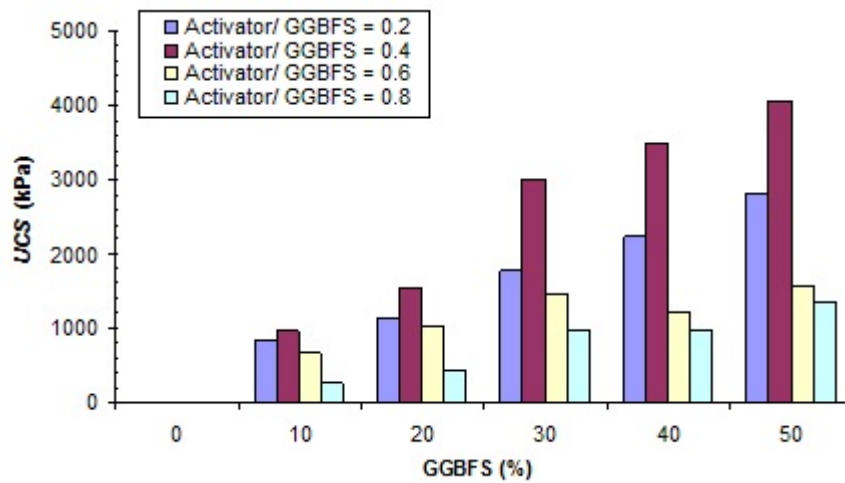

FIGURE 3. Variation of unconfined compression strength UCS with GGBFS content for different activator ratios.
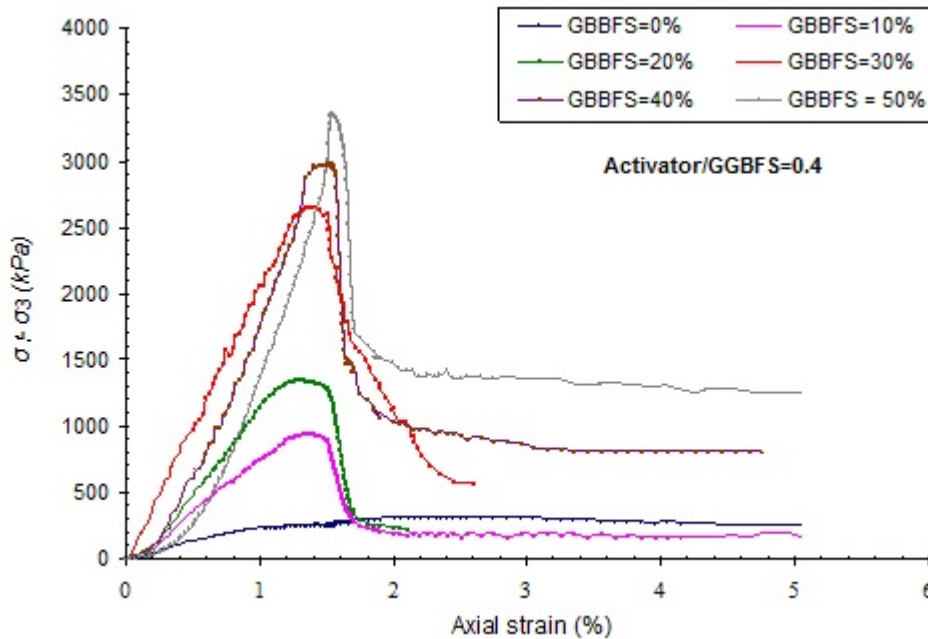
FIGURE 4. Drained triaxail strength – axial strain relationships for Sand-GGBFS based Geopolymer (Activator/GGBFS=0.4).

Figure 3 shows the variation of the unconfined compression strength UCS of a sand- GGBFS -based geopolymer with the GGBFS content for different activator ratios. Results revealed that there is a significant difference in the unconfined compression strength UCS due to a variation in the contents of the GGBFS and activator ratio. The unconfined compression strength UCS increased continuously with the increasing GGBFS content. The rate of increase was greatest when the GGBFS content was increased from 20 to 30 % while the rate increased more slowly as the GGBFS content was increased from 30 to 40 and 50 %. An activator ratio of 0.4 produced the largest *UCS* (981.0 – 4056.5 kPa), while the minimum of 276.5 – 1342.7 kPa occurred with the activator ratio being 0.8. This trend is similar to the results presented in Sukmak et al. [26].

Regarding the triaxial tests, the trend is similar to that of pure sand (UCS), where the composite is strengthened as the GGBFS increases for all activator ratios. For clarity, Figure 4 showed the relationship between the drained triaxail strength and axial strain for a selected activator ratio (Activator/GGBFS = 0.4). Moreover, the variations of maximum drained triaxial strength against the content of the GGBFS and activator ratios are plotted in Figures 5 and 6. For the activator ratio of 0.2, 0.4, 0.6 and 0.8, the drained triaxial strength of the 10 % GBBS-sand increased by 2.7, 3.3, 2.3 and 1.4 times respectively when compared with raw sand. For the same ratios of the activator, the drained triaxial strength of 40 % GBBS-sand increased by 7.6, 10.8, 5.3 and 4.3 times respectively when compared with raw sand.

The drained triaxail strength increased by almost 21.1 - 53.5 % (depending on GBBS) as the activator ratio changed from 0.2 to 0.4. However, increasing the activator ratio to 0.6 and 0.8 was associated with a significant decrease in the drained triaxail strength by 8.6-36.3 % and 34.4- 53.9 % respectively. Moreover, the combination of the largest GBBS content (50 %) and the optimum activator ratio of 0.4 resulted in the maximum improvement.

The observed improvement is due to the geopolymerization process, which consists of a series of chemical reactions between the calcium – aluminosilicate rich slag GGBFS and the alkaline activator. This leads to the formation of geopolymeric gel, which spreads and hardens in a three-dimensional space. Such layers of the geopolymeric gel cover and bind the sand particles. The increase in the strength that occurred with the mixture sand is related to the ability of the geopolymer to resist the applied stress. It is clear that the benefit of the geopolymer depends mainly on the binding effect that could improve the performance of the composite samples in terms of decreasing the deformation and increasing its strength. The benefits of adding the GGBFS and activator to the strength of sand can be explained by its role as a binding agent and cushioning material. The geopolymer acts as a binding agent and provides a significant cohesion to the sand particles. From this conceptual standpoint, the inclusion of this binding agent works to provide a better bonding between the granulate particles of sand, producing a bonded, stable composite. The effect suggests a better performance of sand-based geopolymer under different types of stresses.
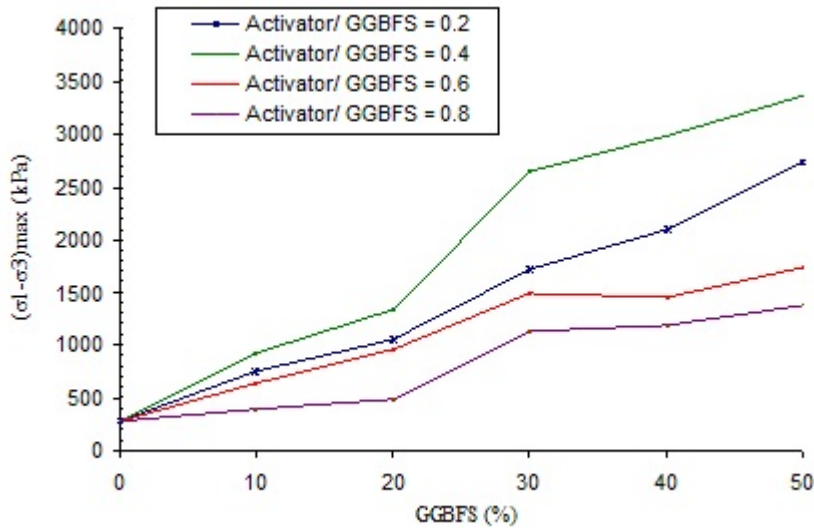
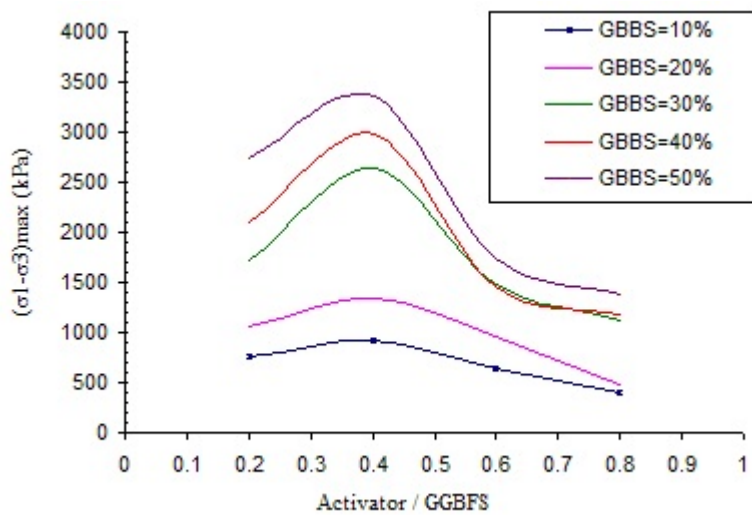FIGURE 5. Variation of maximum triaxail drained strength against GGBFS content for different activator ratios.

FIGURE 6. Variation of maximum triaxail drained strength against activator ratio content for different contents of GGBFS.

GGBFS (%)	Activator/GGBFS							
	0.2		0.4		0.6		0.8	
	C (kPa)	φ (°)	C (kPa)	φ (°)	C (kPa)	φ (°)	C (kPa)	φ (°)
10	142.7	53.2	172.2	54.6	164.7	52.4	131.6	52.4
20	167.5	56.4	215.7	56.8	207.7	53.3	141.8	52.3
30	189.9	56.3	256.3	58.5	243.6	54.8	196.6	53.7
40	192.0	57.5	284.7	58.8	280.2	54.5	203.7	53.6
50	191.9	57.1	297.2	59.5	271.9	56.2	222.9	53.8

*For untreated sand, $C = 0\,\text{kPa}$, $\varphi = 46°$

TABLE 1. Strength parameters of sand-geopolymer based.

4. CONCLUSIONS

In this study, a series of unconfined compression strength and triaxial tests were conducted on samples of sand and Sand- GGBFS Based Geopolymer Composite Material. Some conclusions can be drawn as follows:

(a) The gepolymesation process results in dissolving Si and Al, forming semi-firm gel of aluminum silicate hydrate, which finally turns into a crystal framework gel. This gel can fill a high percentage of the pores that exist in the untreated sand. Therefore, the maximum dry unit weight of samples increased as the GGBFS content increased to 20 %, and then decreased. However, the difference in the maximum dry unit weight due to variation in the activator content was insignificant.

(b) The structured aluminosilicate polymerized gel acts as a binding agent and provides significant cohesion, better bonding between the discrete particles of sand, producing a bonded, stable composite. Therefore, the inclusion of the GGBFS resulted in a significant increase in the *unconfined* compression *strength, cohesion and friction angle* for all activator contents. Drained triaxial strength of sand increased by 2.7, 3.8, 6.2, 7.5 and 9.9 times as the GGBFS increased from 0 % to 10, 20, 30, 40 and 50 % respectively.

Accordingly, such geopolymer material can be used as an important technique in many geotechnical applications. However, due to the limited time and other constraints, there are a number of aspects (such as curing time, permeability, durability, dynamic properties) that require a further research.

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