Improvement the Strength Characteristics of Loose Sandy Soil Using Sustainable Geopolymer

Alaa H. J. Al-Rkaby *[1], Ahmed Katea [2]
*[1] Corresponding author: Professor, Civil Engineering, University of Thi-Qar. e-mail: alaa.astm@gmail.com, alaa.al-rakaby@utq.edu.iq
[2] Civil Engineering Department, Engineering College, University of Thi-Qar

Article Info
Page Number: 660 - 667
Publication Issue:
Vol 72 No. 1 (2023)

Abstract
Loose sand present problematic ground condition, as a result of its low bearing capacity. Therefore, this paper investigated the strength of loose sand treated by geopolymer, which has introduced recently as a novel echo-friendly alternative to the tradition materials of soil stabilization such as lime and Ordinary Portland Cement (OPC) to eliminate their sever impacts on the environment.
The results shows that the unconfined compressive strength of the loose sand-geopolymer matrix increased significantly in range of with increasing the main ingredient of the geopolymer, i.e. fly ash. Similar trend was observe regarding to the secant modulus. However, with increasing the activator ratio, the compressive strength of soil-geopolymer matrix decreased for fly ash content of 20-30% and increased when the fly ash was 5-15%. The improvement in the strength is attributed to the dense and stiff crystalline structure due to fill the sand voids by fly ash, produce gepolymer hydrated gel (C, N–A–S–H) that significantly bonded the soil particles. Therefore, geopolymer is viable sustainable material to improve such problematic soil for different applications.

Keywords: Sustainable material, Shear strength, Geotechnical application, geopolymer, soil stabilization, SEM

Article History
Article Received: *15 October 2022*
Revised: *24 November 2022*
Accepted: *18 December 2022*

INTRODUCTION

Weak soils, such as soft clay and loose sand, have a poor bearing capacity, making them incapable of bearing the load of superstructures that will be imposed on them.

The phrases loose, compressible, or organic relate to soils that make up the surface layers of the soil, such as soil, sludge, peat, organic soils, and soils derived from landfills with unconcentrated homogeneous or non-homogeneous materials. Soft ground is soil with characteristics such as low undrained shear strength, high compressibility, and low permeability (Cernica, 1995). By improving or strengthening a soil material, whether natural or breakable, we imply the processing of this material to improve its geotechnical properties (durability, erosion, compressibility, permeability, porosity, physical characteristics, mechanical properties, etc.) (Flodin & Broms, 1981).

Soil stabilization refers to the improvement of the soil physically or chemically by using various method including mechanical compaction and the use of various calcium rich chemicals (Sherwood, 1993). During the last three decades, a large number of techniques ground improvement have developed rapidly and have found large-scale application in industrial projects (Huat et al., 2019). In general, ground improvement is aimed at:`

1. Methods to improve the engineering properties of the treated soil mass
2. Implemented by modifying the ground's character – with or without the addition of foreign material
3. Properties modified are shear strength, stiffness, and permeability
4. The major function of ground improvement is to:

a. Increase the bearing capacity
b. Control deformations and accelerate consolidation
c. Provide lateral stability
d. Form seepage cut-off and environmental control
e. Increase resistance to liquefaction

The production process of traditional soil stabilizers such as cement and lime, which involves thermal decomposition of calcium carbonate present in limestone, is accompanied by significant carbon dioxide emissions and energy emissions. For example, about one ton of carbon dioxide is emitted per ton of cement production. In lime, global CO_2 production is around 1% and averages 0.95 tons of CO_2 per 1 ton of lime (Khedari et al., 2005; J L Provis, 2014). The process also requires intense energy to maintain the high temperatures needed to produce OPC (450-1550°C) and (100- 1000°C) for lime. Moreover, in cement production, raw materials are quickly consumed. According to Garcia-Lodeiro et al. (2015), the production of 2.0 billion tons of cement consumes more than 3.0 billion tons of raw materials (70% of which is limestone).

Therefore, new soil stabilizers, a viable and sustainable alternative to replace cement in civil engineering applications, are required. The innovations of geopolymerization have attracted more and more attention today as a solution for solid waste and by-products that provide an advanced and economical solution to many problems where harmful waste must be treated and stored in critical environmental conditions (Hamzah et al., 2015).

In the 1970s, the term “geopolymer” was coined for the first time to name the inorganic alkaline aluminosilicate activated materials (Davidovits, 2008; John L Provis, 2009). It is produced at ambient or slightly elevated temperatures by solvents rich in alumina and silica (e.g., fly ash, slag, metakaolin, calcined clay) in alkaline activators. Geopolymer is rapidly showing to be a promising alternative for soil stabilization, eliminating the environmental difficulties encountered by traditional binders by emitting less CO_2 during construction. Typically, one ton of geopolymer produces just 0.19 to 0.24 tons of CO_2 and contributes somewhat to global warming (Papadopoulos & Giama, 2007).

Cristelo et al. (2013) studied sandy clay soil stabilization with geopolymer (the sodium-based alkaline activators and class F fly ash) and compared it with a cement-based binder. The ratio of activators to FA was between 1-2.5, while the fly ash ratio was (20, 30, 40%) from total solids. UCS specimens were prepared, and tests were performed after 7, 28,90, and 365 days of curing. The results showed a significant strength increasing with a lower active/ FA ratio of up to 43.4 MPa on 365 days of curing. The UCS results of the cement and geopolymer samples were very similar at 28 days of curing.

Significant improvement occurred in medium and high plastic soils treated using geopolymer (Adhikari et al., 2019). The UCS of the medium plastic soils with 5% of fly ash was 1.0 MPa and increased to 2.6 MPa at 25% with increasing fly ash content to 25% . However, the UCS was not affected up to 20% FA for high plastic soil. However, at 30%FA, the UCS was rapidly increased by 400% (Adhikari et al., 2019). Moreover, soft soil showed high strength when it stabilized by geopolymer base on Granulated Blast Furnace Slag (GBFS) and Basic Oxygen Furnace Slag (BOFS) (Salimi & Ghorbani, 2020) . They found that after curing samples at temperatures between 20 to 45°C, increasing the UCS (42 time) compared to untreated soil. This ground granulated blast furnace slag-based geopolymer was used also as a sustainable alternative to cement for deep soil mixing applications. For example, Bhavita Chowdary et al. (2021) investigated the UCS of cement-

treated and geopolymer samples considering GGBS content of 10–30% and activator ratio of 0.5-1.0. Results revealed that specimens treated with GP had higher UCS than cement-treated specimens of the same dosage (except for the mix with A/B = 0.5). This is due to the appearance of increased pozzolanic and geopolymeric processes.
Although usingbgeopolymer has attracted more attention as an eco-friendly mataerial, limited studies have been performed on the use of geoplymer in the geotechnical applications. Therefore, this article aims to investigate the opportunities for the geopolymerized fly ash as secondary raw materials to be used in geotechnical stabilization of loose sand as an alternative to the cement and lime. In this study, extensive series of laboratory UCS test was conducted to investigate the strength and stiffness of geopolymer-loose sand matrix. . In addition, the microstructural advancement of treated sand was investigated using scanning electron microscopy (SEM) analysis. This work is a part of an ongoing project since 2018.

RESULTS

Effect of Fly ash Content

Several contents of the coal-fired fly ash (5,10, 15, 20, 25 and 30%) have been considered to investigate their effect on the strength of the composite of soil-geopolymer at AC/FA of 0.2, 0.4, 0.6, and 0.8. Figure 1 shows the unconfined compressive strength of the loose sand treated with geopolymer considering different fly ash contents.

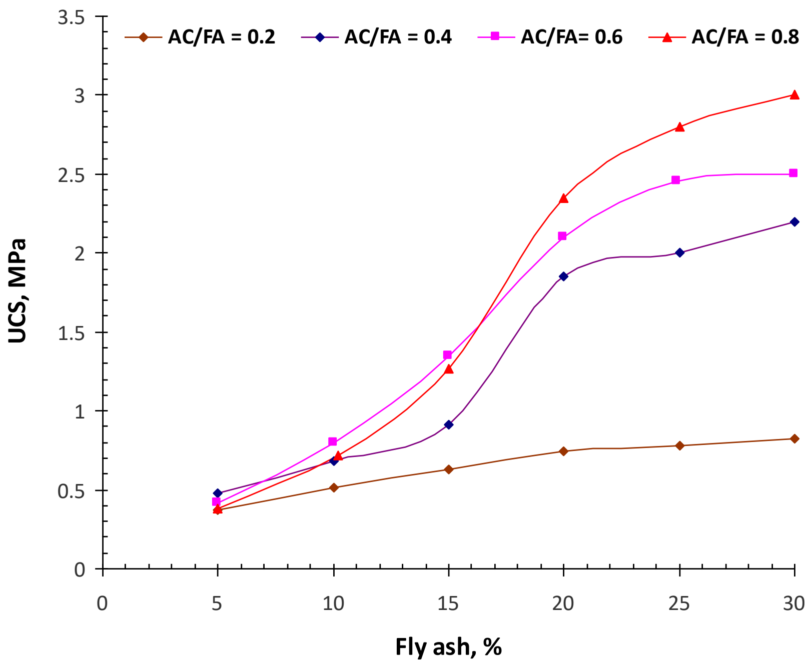

Figure 1: Variation of unconfined compressive strength with the fly ash content

For all the activator ratios, increasing the content of the fly ash resulted in significant increase in the unconfined compression strength of the loose sand treated with geopolymer. For example, for the activator ratio of 0.2, the unconfined compressive strength increased to 0.61, 0.76, 0.82, 0.91, 0.94, and 1.03 as the fly ash increased to 5, 10, 15, 20, 25 and 30%. similar trend of increasing was observed with increasing fly ash for other ratios of the activator. For example, increasing fly ash content to 5, 10, 15, 20, 25 and 30% resulted in increasing the compressive strength to 1.05, 1.58, 1.87, 2.83, 3.17 and 3.24 MPa respectively.

There is no clear optimum percentage of fly ash, as the UCS increases with the increase of the rate of fly ash for all tested soils. However, it can be observed that the rate of improvement after the 20% of fly ash become less. Therefore, it can be recommended 20% of fly ash to be used in the geopolymer, particularly this content led to compressive strength ranging between 0.91 and 2.83 MPa (depending on the activator ratio), which is suitable for most geotechnical applications.

Effect of Activator Content

The effect of the alkaline activator ratio AC/FA 0.2, 0.4, 0.6, 0.8 is shown in Figure 2. It can be observed that the UCS of all mixtures with high fly ash content (20, 25 and 30%) increased continuously with increasing the alkaline ratio. For 30% fly ash content, for example, with increasing AC/FA from 0.2 to 0.4, 0.6 and 0.8, the UCS increased by 168%, 205% and 266% respectively.

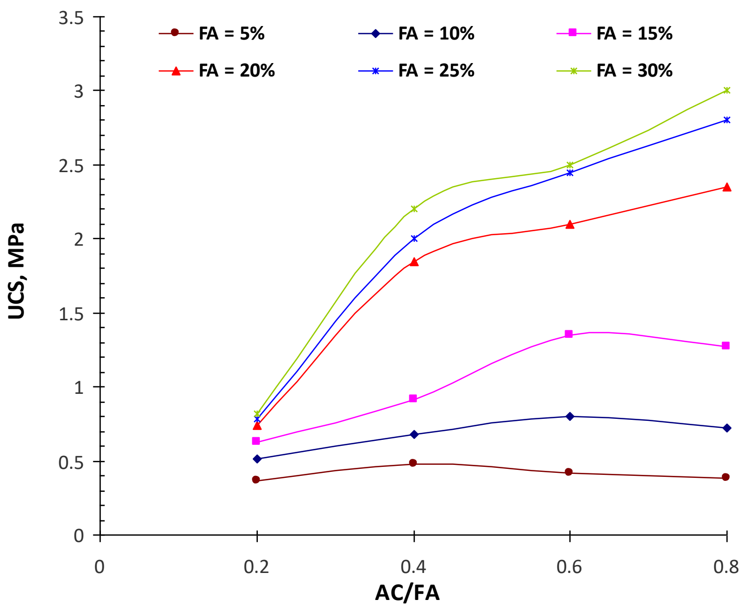

Figure 2: Variation of unconfined compressive strength with the activator ratio

The reason for the improvement can be attributed to the increase in the pH due to increase of the activator content that led to increase the leaching prosses of silicon and aluminum from the amorphous phase of the fly ash, which in turn increases the formation of cementitious products such as N-A-S-H and C-A-S-H between soil particles. However, for the low content of fly ash, the generation of excessive silica in mixtures obtained due to increased AC/FA caused the aforementioned decrease in strength because of its effect on the solubility of fly ash particles. Similar behavior was reported by (Mustafa et al., 2013).

The ratio of 0.4 with 20% fly ash or more was found to give strength range of 1.85 – 2.2 MPa at a typical curing period of 28 days. The strength performance of these ratio may fulfil the requirements of most ground improvement applications, e.g. subbase or subgrade course in road construction (Corps, 1984), Deep soil mixing applications (Puppala et al., 2008). Therefore, this ratio was recommended as a practical percentages to synthesise geopolymer for soil stabilization.

Stiffness Behavior of Geopolymer-Treated Soil

stiffness of geopolymer treated soil estimated from the unconfined condition, might help better understand the influence of various experimental variables (such as fly ash concentration, activator content, and soil type) on the stiffness of the stabilized sand. The measured stiffness E_{50}, the secant modulus at 50% peak strength, of geopolymer-treated sand is shown in Figure 4-11. In general, increasing the content of fly ash and activator increased the stiffness of stabilized sand. The observed increase in E_{50} is primarily due to the geopolymer's ability to bind soil particles after hardening and consequently increasing soil fabric stiffness.

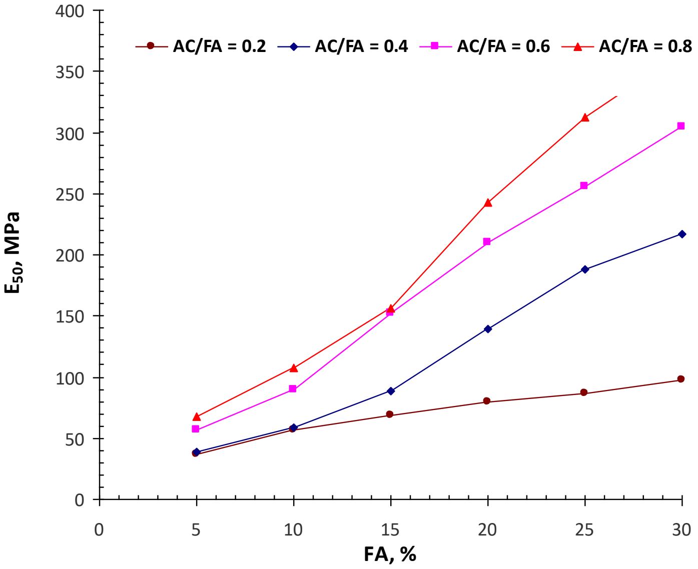

Figure 3: Variation of secant modulus with the fly ash content

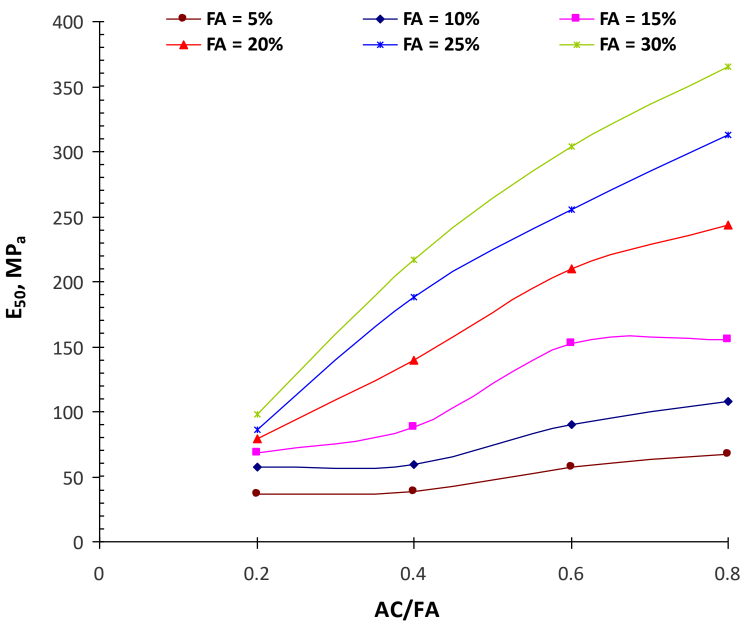

Figure 4: Variation of secant modulus with the activator ratio

Microstructres Characteristics

To investigate the microstructure of the sand-geopolymer composite, SEM testing was carried out on selected sample of soil considering 20% fly ash content and 0.4 activator ratio. SEM test was performed on pieces of the same sample on which the UCS test was performed. SEM image of soil treated with geopolymer is presented in Figure 1.

It can observe that the selected content of the fly ash filled the pores of the loose sand and produce dense structures. Moreover, clear change in the texture of the typical sandy soil was occurred due to the added alkaline activator and geopolymerization process that resulted in partial dissolution of fly ash particles and efficiently activated sand and fly ash particles. Eventually, geopolymerization will produce two chemical structure, Sodium Aluminium Silicate Hydrate (N-A-S-H) or (N, C)-A-S-H (high calcium content N-A-S-H gels). These structures differ than C-A-H and C-S-H produced by hydration of OPC and pozzolanic reactions of lime, respectively (García-Lodeiro et al., 2007). Therefore, particles of the stabilized sand were bonded strongly together by the produced Highly connected three-dimensional chain network polymeric bond of sialite resulting in stiff crystalline composite. This is in line with the significant improvement of the soil strength, where the unconfined compressive strength increased by 15 times.

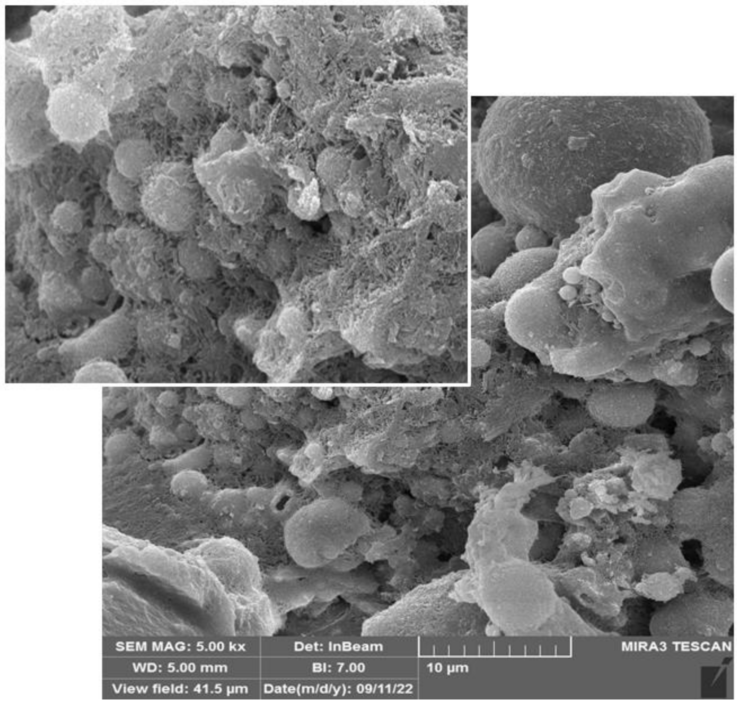

Figure 5: SEM images of soil-geopolymer matrix

The selected content of the fly ash filled the pores of the loose sand and produce dense structures. Moreover, the geopolymerization process resulted in efficiently activated sand and fly ash due to the added alkaline activator. Therefore, particles of the stabilized soil were bonded strongly together by the produced geopolymer gell resulting in stiff crystalline composite. This is in line with the significant improvement of the soil strength, where the unconfined compressive strength increased by 15 times.

Conclusions

Fly-ash-based geopolymers showed great promise as more environmentally and financially sustainable alternatives for OPC and lime in soil stabilization. It was found that the strength and stiffness characteristics of soil treated with fly-ash-based geopolymer could be enhanced significantly with the addition of fly ash. Although experimental study found no optimum fly ash content, the highest rate of improvement occurred at fly ash content of 20%. It was found that the strength increases with the increase of the fly ash content in the mixture for all soil.

Regarding to the effect of alkaline activator, strengths and stiffnesses of loose sand–geopolymer matrix significantly improved with increasing the activator ratio, particularly when using flay ash content in the range of 20 - 30%. However, the solubility effect of high activator ratio on low content of fly ash (5-15%) results in decreased the strength with further increase of activator from 0.4 to 0.8.

This improvemtn is due to the improvement of the microstructure of the loose sand happened by the Sodium Aluminium Silicate Hydrate (N-A-S-H) or (N, C)-A-S-H (high calcium content N-A-S-H gels) occurred eventually during the geopolymerization process. This gel bonded particles of loose sand creating strongly connected three-dimensional chain polymeric network.

References

1. Cernica, J. N. (1995). Geotechnical Engineering: Soil Mechanics. John Wilwy & Sons. Inc., New York.
2. Flodin, N. and Broms, B. (1981). Historical Development of Civil Engineering in soft clays. Elsevier Scientific Publishing Company
3. Sherwood, P. (1993). Soil stabilization with cement and lime. London, UK.
4. Huat, B. B. K., Prasad, A., Kazemian, S., & Anggraini, V. (2019). Ground improvement techniques. CRC Press.
5. Khedari, J., Watsanasathaporn, P., & Hirunlabh, J. (2005). Development of fibre-based soil–cement block with low thermal conductivity. Cement and Concrete Composites, 27(1), 111–116
6. Provis, J L. (2014). Geopolymer schematic. Alkali Activated Materials: State of the Art Report, Rilem TC224-AAM Pp1-9 Springer/RILEM, Dordrecht, 1.
7. Garcia-Lodeiro, I., Palomo, A., & Fernández-Jiménez, A. (2015). An overview of the chemistry of alkali-activated cement-based binders. In Handbook of Alkali-Activated Cements, Mortars and Concretes. Woodhead Publishing Limited. https://doi.org/10.1533/9781782422884.1.19
8. Hamzah, H. N., Al Bakri Abdullah, M. M., Yong, H. C., Zainol, M. R. R. A., & Hussin, K. (2015). Review of soil stabilization techniques: Geopolymerization method one of the new technique. Key Engineering Materials, 660(September), 298–304. https://doi.org/10.4028/www.scientific.net/KEM.660.298
9. Davidovits, J. (2008). Geopolymer Chemistry and Applications. 2nd. Institute Geopolymere, France.
10. Provis, John L. (2009). Activating solution chemistry for geopolymers. In Geopolymers (pp. 50–71). Elsevier.
11. Papadopoulos, A. M., & Giama, E. (2007). Environmental performance evaluation of thermal insulation materials and its impact on the building. Building and Environment, 42(5), 2178–2187.

12. Cristelo, N., Glendinning, S., Fernandes, L., & Pinto, A. T. (2013). Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation. Acta Geotechnica, 8(4), 395–405.
13. Arulrajah, A., Yaghoubi, M., Disfani, M. M., Horpibulsuk, S., Bo, M. W., & Leong, M. (2018). Evaluation of fly ash-and slag-based geopolymers for the improvement of a soft marine clay by deep soil mixing. Soils and Foundations, 58(6), 1358–1370.
14. Adhikari, B., Khattak, M. J., & Adhikari, S. (2019). Mechanical and durability characteristics of flyash-based soil-geopolymer mixtures for pavement base and subbase layers. International Journal of Pavement Engineering, 1–20.
15. Salimi, M., & Ghorbani, A. (2020). Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers. Applied Clay Science, 184, 105390.
16. Bhavita Chowdary, V., Ramanamurty, V., & Pillai, R. J. (2021). Experimental evaluation of strength and durability characteristics of geopolymer stabilised soft soil for deep mixing applications. Innovative Infrastructure Solutions, 6(1). https://doi.org/10.1007/s41062-020-00407-7