IMPROVEMENT OF WEAK SOIL USING SUSTAINABLE ADDITIVE

Alaa H. J. Al-Rkaby1 and and Alaa Salim[2]
[1]Professor at Civil Engineering Department, University of Thi Qar, Iraq, 64001
[2]Postgraduate Student at Civil Engineering Department, University of Thi Qar, Iraq, 64001
[1]alaa.astm@gmail.com, [1]alaa.al-rakaby@utq.edu.iq and [2]alaasalim9047@utq.edu.iq

ABSTRACT

Deep soil mixing columns (DSMC) is becoming an increasingly popular and effective soil improvement technique. Portland cement and lime have historically been the most often used binders in such improvement type. However, Geopolymer has been emerging as a innovative and environmentally friendly substitute for such conventional soil binders, which have negative effects on the environment. This paper investigated the effect of the Alkali-activated fly ash content, that referred to the "geopolymers, and the activator/fly ash ratio on the unconfined compressive strength of the sandy soil. Moreover, in this study, an attempt was made to improve the bearing capacity of soil by DSM columns using geopolymer considering various replacement area was investigated. Results exhibited that the Alkali-activated fly ash results in significant improvement of the soil strength. This strength increased with increasing the fly ash content and the activator/fly ash ratio. Moreover, using the geopolymer as a binder in the deep mixing soil columns showed significant improvement in term of increasing bearing capacity and decreasing the settlement.

Keywords: Geopolymer; sustainable materials; bearing capacity.

1. INTRODUCTION

Weak soils, which characterized by low shear strength and high compressibility, are commonly found around the world. This type of soil is a major challenge faced by the engineers for heavy loaded structures resting on such soils. Soil stabilization is a process that improves the shear strength parameters, durability, and workability of soil and thus increases soil bearing capacity. It is required when the soil available for construction is unsuitable for carrying the structural load. Stabilization processes widely used include chemical and mechanical stabilization of the system. Moreover, deep structural elements (e.g. piles) or deep stabilization can be used to stabilize such weak soil. Deep soil mixing is one of the most methods become popular, because its economics and rapid in implementation.

The conventional binders of Ordinary Portland cement OPC and Lime are typically not an environmentally sustainable materials, despite being widely used and recognized for stabilizing fine-grained soils. This is because the manufacture and use of such binders are connected with high energy and carbon emissions footprints. With the growing need for environmentally friendly options and preserve the environment in the construction sector today, it becomes imperative to use alternative sustainable materials that do not have a negative impact on climate and global warming, do not consume high energy and that do not cause high carbon emissions. Therefore, define geopolymer as sustainable material has become popular in recent period, because it is including an industrial waste material in its compostion.

Deep mixing method (DMM) with two classification parts (wet and dry mixing methods) (Dehghanbanadaki et al., 2013), is an in-situ soil treatment in which native soils or fills are blended with cementitious or other stabilizing agents (binders), such as cement, lime, slag, and fly ash (Bruce & Geosystems, 2000). The advantages of the DMM include economics, flexibility, savings of material and energy by exploiting the properties of the soil at the site, small vibrations, low construction noise, and low costs with rapid installation (Bruce & Geosystems, 2000; Chen et al., 2013; Holm, 2003; Indraratna et al., 2015). There for, it has been widely applied in Japan, Europe, China, Singapore, Hong Kong, and America as the foundation of various structures such as tanks, towers, bridge abutments, embankments, underground facilities, retaining structures, excavation support walls, reinforcement piles, breakwaters and high-rise buildings (Bruce & Geosystems, 2000; Terashi, 2005, Al-Rkaby et al., 2017, 2019, 2020).

Deep mixing method is a type of the chemical stabilization that is used to improve the engineering properties of problematic soils. Most specifically, it seeks to increase strength, reduce compressibility, improve stability characteristics, and increase the durability of unsuitable soils (Karol, 2003; Kirsch & Bell, 2012). This technique has been a beneficial and cost-effective alternative to more costly soil replacement or deep foundations used widely by the construction industry, especially in Japan, United States, China, and Iraq, among other countries (Nicholson, 2014).

Lime is commonly used for geotechnical applications. These applications include pollutant encapsulation, slope stabilization, and foundation improved performance, such as lime aggregate particles or lime-mixing soil columns (Little, 1995). It refers to the pozzolanic reaction where the materials of lime respond to the production of cement compounds in the presence of water. The influence could be either quicklime (CaO) or hydrated lime Ca(OH)2. On dry soils, slurry lime can also be used in conditions where there is water necessary to achieve compaction. When a large amount of lime is applied to the soil, the high hydroxyl ion concentration is released from the hydrated lime, the pH of the mixture is elevated, forming a robust basic solution (pH >12). This solution dissolves the silica and alumina sheets from the soil, which reacts with the calcium liberated from the hydrated lime, in a process referred to as a pozzolanic reaction (Little, 1995). This reaction produces Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A- H), which adhere to soil particles, thereby stabilizing the soil (Das, 2010).

Beside the lime, ordinary Portland cement (OPC) is also the most widely used soil stabilization additive. Hydratation and pozzolanic reactions are common for OPC-soil interaction. When OPC comes into contact with the moisture in the soil treated, hydration occurs, the hydration phase begins immediately, promoting enhanced engineering properties. (C-S-H) and (C-A-H) are the reaction products, similar to the reaction products of the lime reaction but more highly produced amounts and high formation rates. Such products stabilize the soil by creating a solid structure around the soil particles (Sargent, 2015).

Although such ordinary Portland cement (OPC) and lime are the widely used stabilizing binders, the carbon footprint associated with producing these conventional stabilizers has generated significant environmental concerns in recent decades. Globally, the production of OPC and lime accounts for 8-10% of anthropogenic CO_2 emissions each year (Garcia-Lodeiro et al., 2015). Considering these emissions and other negative environmental impacts associated with the sourcing and over exploration of nonrenewable raw materials (Sargent et al., 2016), alternatives to traditional binders are necessary for reducing the environmental impacts without compromising the strength, stiffness, and long-term performance of the materials.

Geopolymer, which was coined by Davidovits in the late 1970s, has been emerging as a new, more sustainable, eco-friendly, and low-energy alternative to traditional binders in engineering applications. Geopolymers are cementitious binders produced by combining industrial by-products and waste products possessing high amorphous Al and Si contents, such as fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin (MK), etc., with a liquid alkaline activator (like sodium/potassium hydroxide and sodium/ potassium silicate), rich in soluble metals, like sodium and potassium (Cristelo et al., 2011; Krivenko et al., 2014; Sargent, 2015; Singhi et al., 2016). Geopolymer may contribute to an 80% reduction in CO2 emissions (Duxson, Provis, et al., 2007) while also consuming 70% less energy compared to OPC manufacturing (Tempest et al., 2009).

The use of fly-ash in geopolymers for soil stabilization is particularly significant in Iraq, where the power plants and the new industrial cities generate large amount of it, with it is dumped directly into landfill (Mohammed & Saeed, 2018).There have been very few published papers on Class C fly ash geopolymer (CFA). Hence, it would be beneficial to investigate the feasibility of applying the Class C fly ash-based geopolymer for soil stabilization at ambient temperatures, opposite class F fly ash which is requires elevated curing temperatures up to 80oC (Liew et al., 2012; Palomo et al., 1999).

While many studies dealt with the unconfined compressive, flexural and durability tests of geopolymer used as a binder in deep soil mixing methods (Adhikari et al., 2021; Bhavita Chowdary et al., 2021), opposite, plate load test for pilot field model, were few (or not found). There for, one of the objectives of this study was researched for this purpose. Scanning electron microscope (SEM) and Atomic force microscope (AFM) are one of the common methods for it was performed to examine microstructure, morphology and surface photograph of soil-geopolymer mixtures, to better understand the function of variables influencing strength development ,and to study the interaction between soil particles and industrial waste and the growth of geopolymerization products.

While there have been significant research endeavors to improve the shear strength and properties of soil using geopolymer, there is very limited studies available on using the sustainable materials in the deep soil mixing. Hence, the objective of this research is to investigate the improvement of the weak soil using deep mxing soil-geopolymer columns.

2. MATERIALS AND METHODS

2.1. Soil

The soil utilized in this experimental study was locally available sand, classified according to the unified soil classification system (USCS) as poorly graded sand (SP). The grain size distribution of the sand is shown in **خطأ! لم يتم العثور على مصدر المرجع.** .لم يتم العثور على مصدر المرجع. **خطأ! لم يتم العثور على مصدر المرجع.** shows the essential index properties of sandy soil determined using ASTM standard steps, including particle size distribution, specific gravity, and dry density.

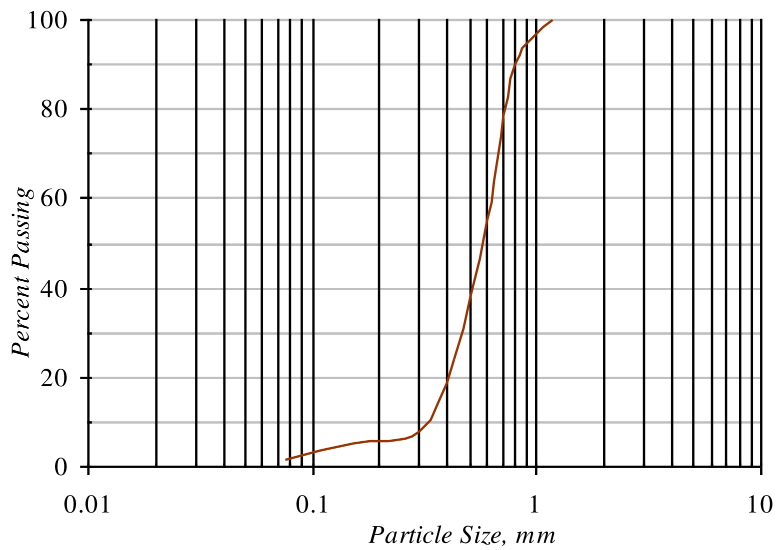


Figure 1: Grain size distribution of the used sand

Table 1: Physical properties of the used soil

Soil property	Specification	Value
Coefficient of uniformity (Cu)	ASTM D 422	2.75
Coefficient of curvature (Cc)		0.81
Mean effective diameter (D_{50})		0.443
Specific gravity (Gs)	ASTM D 854	2.65
Maximum dry Density (gm/cm³)	ASTM D 4253	1.703
Minimum void ratio (e_{min})		0.558
Minimum dry Density (gm/cm³)	ASTM D 4254	1.357

Maximum void ratio (e_{max})		0.84
Internal friction angle φ (°)	ASTM D 3080	36
Relative density (%)		30

2.2. Geopolymer Ingredients

2.2.1. Fly Ash

The fly ash was used in this study which was supplied from local power generating plant as by product waste materials result of during production of electricity. The fly ash could be classified into Class C or high calcium fly ash based on its chemical composition as specified in (ASTM C618, 2000).

2.2.2. Alkaline Activator

The alkaline activator solution involving sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) was chosen because they were less cost and more readily available than potassium-based solutions. Furthermore, NaOH has shown to have an excellent capability for liberating silicate and aluminate monomers. Sodium hydroxide with a purity of 98 % was purchased in pellet form. In contrast, sodium silicate was purchased in liquid form. NaOH was dissolved in distilled water to achieve the required Molar (M) concentration and left the solution for at least 8-24 hours before adding the sodium silicate. Throughout the research, the molarity of the NaOH solution was kept constant at 10M. A 400g of NaOH pellets were dissolved in one liter of distilled water to produce a 10 M solution, using molarity calculations (10*40 = 400 g, where 40 is the molecular weight of NaOH). Based on what was aforementioned in chapter two, the weight ratios of sodium silicate to sodium hydroxide were used in this study 1.5, 2, 2.5 for sand soils. However, it was two for clayey soils. solution was kept constant at 10M. A 400g of NaOH pellets were dissolved in one liter of distilled water to produce a 10 M solution, using molarity calculations (10*40 = 400 g, where 40 is the molecular weight of NaOH). Based on what was aforementioned in chapter two, the weight ratios of sodium silicate to sodium hydroxide were used in this study 1.5, 2, 2.5 for sand soils.

2.3. Construction of DSM Columns

Tests have been performed in 10 sections, each section has dimension of 2m*20m. The top 20cm of the soil was removed, and then the sections were marked to label column locations for mixing.

The geopolymer was prepared by mixing the fly ash with the activator and the water on site using a mixing unit. Soil mixing was performed by the wet-method, where the prepared geopolymer was mixed with water forming a slurry before it was pumped into the soil. Different number of columns were done using column diameters of 100mm and length of 1800mm. Figure 2 shows the site work and the configuration of the deep soil mixing columns.

There are a variety of methods of pumping binders into the soil. In this study, the common way was used, that consists injecting part of the geopolymer slurry through outlet holes in the drag bit of the hollow auger as the auger is penetrating the soil. As the mixing auger penetrates, it loosen the soil in order to facilitate combination. The other part of the slurry geopolymer was pumped as the auger is withdrawn from the soil.

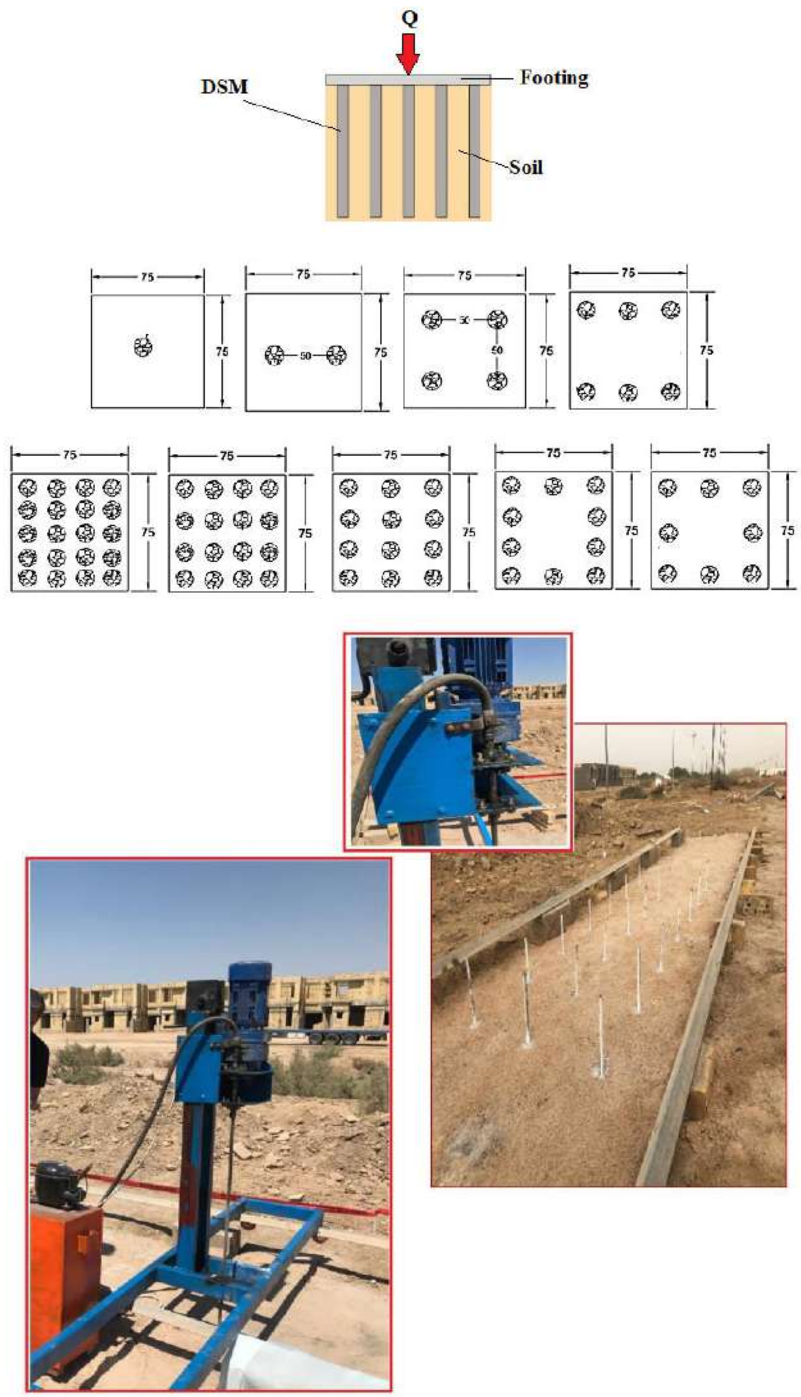


Figure 2: Configuration of the field tests and site work

2. RESULTS AND DISCUSSIONS

2.1. Effect of Fly ash Content

The influence of various amounts of coal-fired fly ash as the main source material on the strength of soil-geopolymer mixtures was studied by considering different proportions of fly ash (5,10, 15, 25and 30%) for sandy soil at activator to fly ash ratio (AC/FA) of 0.25, 0.5, 0.75 and 1.0. From Figure 3, it can be seen that the increase in fly ash content resulted in a significant difference in the unconfined compression strength values for the geopolymer- sand soil for all activator ratios. For example, at AC/FA 0.5, the UCS increased by (about 170%) from 2.2 MPa to 6.1 MPa as FA increased between 5 to 30%. With increasing the activator ratio to 1.0, the improvement of the UCS becomes more significant as it increased to 370%. This make approximates the linear relationship between FA content and UCS of soil-geopolymer. This increase in strength is related to the availability of more geopolymer binders in the structures of treated sand.

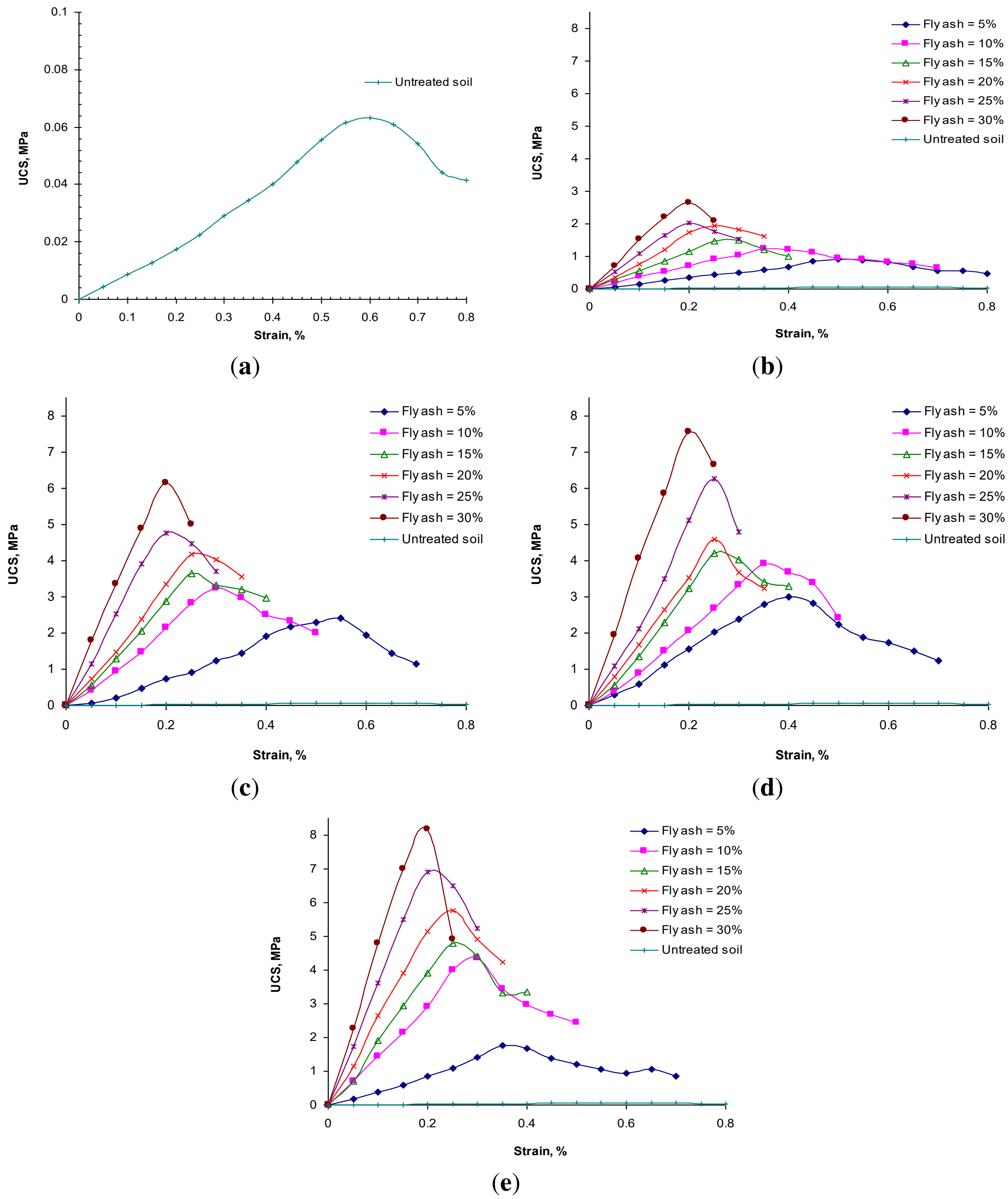


Figure 3. Stress-strain relationships of geopolemerized sand considering different fly ash content at : (**a**) untreated soil; (**b**) AC/FA=0.25; (**c**) AC/FA=0.5; (**d**) AC/FA=0.75; (**e**) AC/FA=1.0.

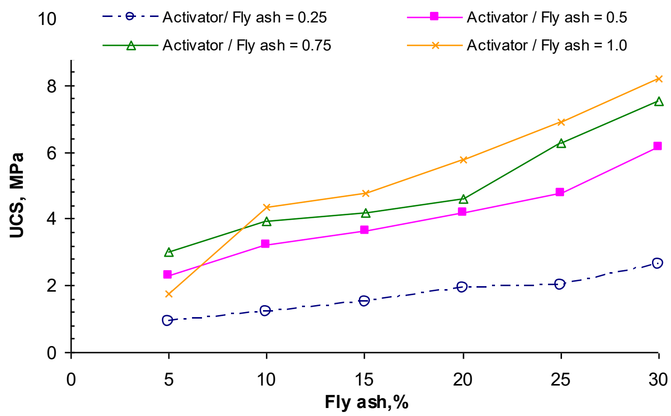


Figure 4: Variation of UCS with the fly ash content considering different activator ratios

2.1. Effect of Activator Content

Figure 5 illustrates the alkaline ratio's effect on the UCS of sand-FA geopolymer specimens for different AC/FA ratios (0.25, 0.5, 0.75, 1.0). It can be observed that the UCS of all mixtures increased with increasing the alkaline ratio except the case of 5% fly ash. For example, increasing AC/FA from 0.25 to 1.0, increases UCS by 90%, 258%, 219%, 199%, 240 and 208% for fly ash content of 5, 10, 15, 20, 25 and 30%, respectively. The reason for this is that the increase of the activator content led to increasing leaching prosses of silicon and aluminum from the amorphous phase of the fly ash due to increased pH, which increased the formation of cementitious products, such as N-A-S-H and C-A-S-H between soil particles, and consequently further increases the strength of the soil. However, as AC/FA increased to 1.0, the improvement decreased for soilwith 5% fly ash. The generation of excessive silica in mixtures obtained from (FA, soil, and high alkaline activator) caused this decrease in strength because of its effect on the solubility of fly ash particles.

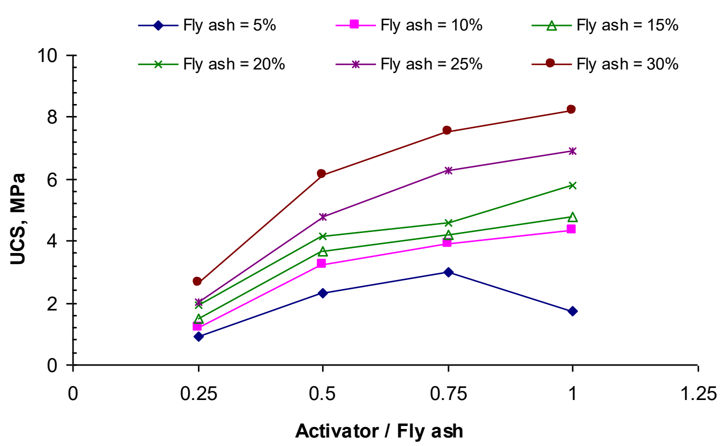


Figure 4: Variation of UCS with activator ratios considering different fly ash contents

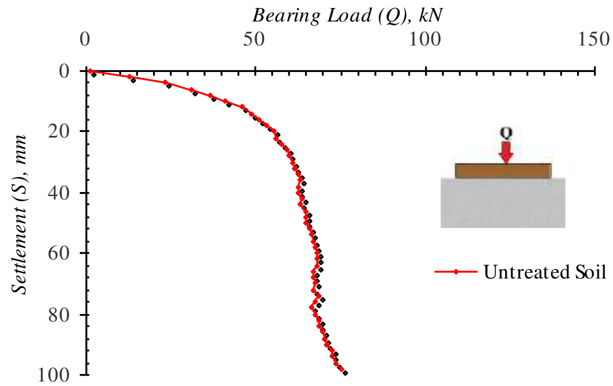
2.1. Effect of the Number of the DSM Columns

The bearing capacities of loose sand improved by deep soil – geopolymer columns have been studied through a series of plate load tests on pilot field models. It is important to mention that the deep mixing column has been installed initially at 1.8 m depth and based on the aforementioned percents of fly ash (20%) and activator (AC/FA 0.5). In many geotechnical applications, single or group of deep soil mixing columns are used to improve the characteristics of the soil. Therefore, a series of loading tests has been carried out on a group of pilot field deep soil mixed columns. Due to time and cost issues, deep mixed column with diameter of 100mm has been selected to be used in this investigation considering .

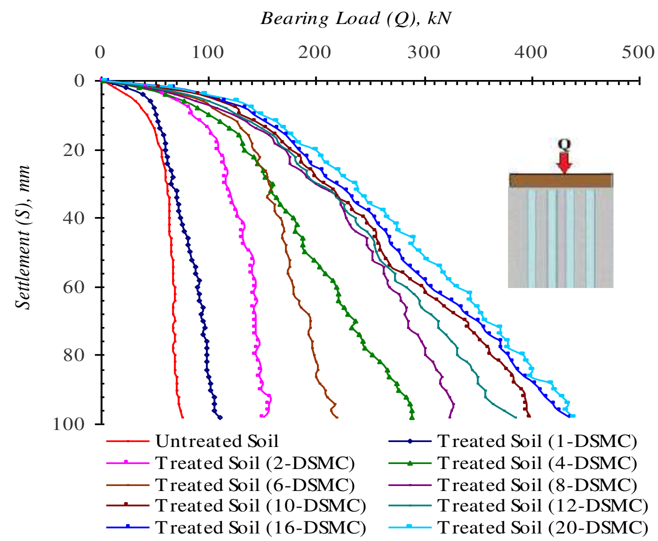
The bearing pressure – settlement relations have been plotted in خطأ! لم يتم العثور على مصدر المرجع. that showed the increasing of the number of DSM columns resulted in significant increase in the bearing pressure. The ultimate bearing capacity of the deep soil-geopolymer mixed column increased from 101 kPa for the untreated soil to 124, 186, 266, 266, 382, 408, 408, 462 and 462 KPa for soil with 1, 2, 4, 6, 8, 10, 12, 14 and 18 DSM columns respectively. The rate of improvement was significant until eight DSM columns, then such rate of improvement became steady.

The group of such deep mixed columns reinforce the soil and make such composite as reticulated geopolymerized mixed columns network to resist the applied load. This network of columns served to circumscribe and internally strengthen the reinforced soil composite.

Moreover, the ultimate bearing pressure of the native soil was selected to compare the develop settlement for the different cases as it the common pressure between the differenced stress -settlement relationships. Under such applied stress (101 kPa), the induced settlement reduced from 22 mm for untreated soil to 20mm for soil treated with single DSM column and to 2-6mm for soil treated with group DSM columns.



(a)



(b)

Figure 5. Relationship between the bearing load and the settlement of: (a) untreated soil; (**b**) soil treated with different numbers of DSM columns

2.1. SEM-EDS ANALYSIS

Geopolymers synthesized from different materials, such as fly ash are mixtures of crystalline aluminosilicate particles and amorphous aluminosilicate gel. As a mixture of amorphous and crystalline phases, the physical and mechanical properties of geopolymers should be the result of both the amorphous gel phase as a binder and the crystalline aluminosilicate particles as fillers. Therefore, an understanding of the microstructure characterization of geopolymers is important in the development of improved geopolymers. This section presents and discusses the microstructure character of geopolymer soil samples, considering the different percentages of fly ash and alkaline solution on (SEM) observations. The EDS has used analysis and X-ray mapping to investigate the chemical compositions of the geopolymers.

The composition of the fly ash-based geopolymer is mainly derived from the decomposition of aluminum silicate in the fly ash by alkaline solutions, which are generated by polycondensation. When an alkaline activator comes

into contact with a source of aluminosilicate (FA), it breaks the bonds of aluminosilicate in fly ash to liberation active Si^{4+} and AL^{3+}. These active Si^{4+} and AL^{3+} compose nuclei and aluminosilicate oligomers formation of AlO_4 and SiO_4 tetrahedral, aluminum silicate chains highly depend on the ratio Si/Al. In other words, the geopolymer product is Sodium Aluminum Silicate Hydrate gel generates from the leaching Si^{4+} and AL^{3+} of reactions fly ash and activator, which harden with time and cement the soil particles.

The rate of geopolymerization of fly ash can be observed in geopolymer samples by etching on fly ash surfaces, detected by SEM analysis. **خطأ! لم يتم العثور على مصدر المرجع.** reveal the SEM analysis images for soil geopolymer. The 28-day age microstructures of the geopolymer system were used to compare and analyze the differences in the changes in fly ash and activator/fly ash ratios.

The microscopic images of the samples treated with geopolymer showed a compact and stable structure, leading to improved engineering properties. This primary reinforcement is attributed to the deposition and development of industrial reinforcement products of the bonds within soil particles. As discussed in the literature review, the silica and alumina oxides at the high hydroxyl (OH−) concentration (high pH) provided by an alkaline medium get dissolved from the fly-ash particles within geopolymer, and this forms a substance classified as Sodium Aluminum Silicate Hydrate (N-A-S-H), which in turn harden with time and cement the soil particles. Few partially reacted fly ash particles were found in the microstructures sample

The "A" area in Figure 6 shows the morphology changes of a reactive fly ash sphere due to the alkali-activated dissolution. The sphere seems broken in the highly alkaline condition, and part of the alumina-silicate dissolves from the fly ash. Further, the inner area of the broken fly ash appears to be filled with many microparticles of the reaction products.

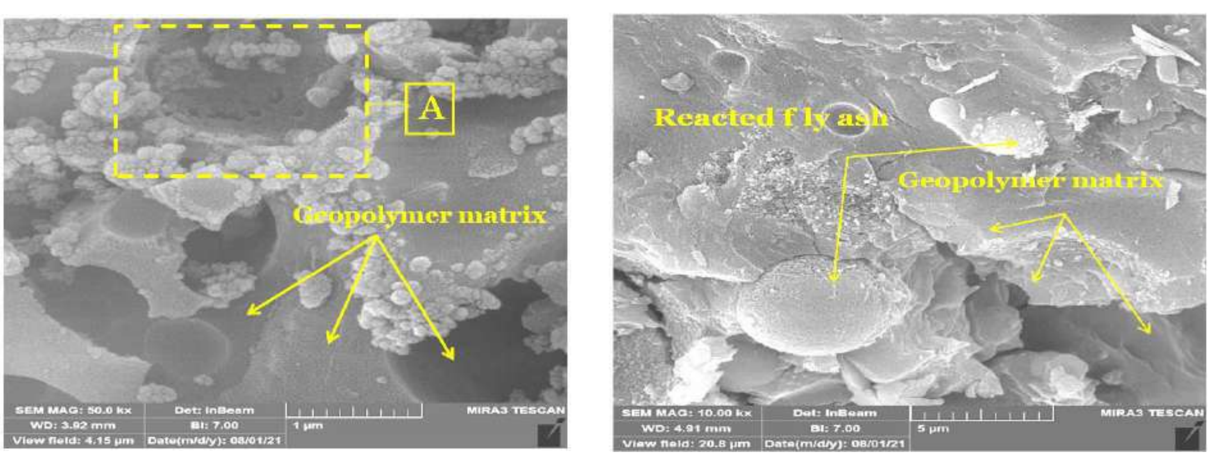


Figure 6. SEM of geopolymerized soil (Fly ash=20%, Ac/FA=0.5)

3. CONCLUSIONS

The use of the Deep Soil Mixing technique has been proven to improve natural strength and stiffness properties and improve the behavior of an engineering system. When using deep soil mixing for supporting soil foundation, the economics and ease of construction have been compared with other techniques. Geopolymer is a cementitious material that can replace ordinary Portland cement in several geotechnical engineering applications, such as soil stabilization, with much lower harmful emissions and energy consumption. Despite these advantages, the use of fly ash-based geopolymer for soil stabilization as a stabilizer is still not widely recognized within the geotechnical industry. The following three man conclusion can be drawn:

1. The strength enhancement of sand soil treated with different combinations of fly-ash, activator, was evaluated and 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 and activator. However, this experimental study found no optimum fly ash content. It was found that the strength increased with the increase of the fly ash content in the mixture for soil.
2. In general, using geopolymer as a binder for deep soil mixing techniques to improve sandy soils has increased the ultimate bearing capacity of foundations at the ultimate load. The bearing capacity of the soil increased by 17, 76, 141, 151, 260, 285, 285, 336 and 336% of soil improved by single, 2, 4, 6, 8, 10, 16 and 20 columns respectively, compared with 110 kPa of the untreated soil.
3. The microscopic images exhibited compact and stable structure, which is attributed to the deposition and development of industrial reinforcement products of the bonds within soil particles. Such bonds consist of Sodium Aluminum Silicate Hydrate (N-A-S-H), which is formed from dissolving the silica and alumina oxides (from the fly-ash particles) at the high hydroxyl (OH−) concentration (high pH) provided by an alkaline medium. This (N-A-S-H) will harden with time and cement the soil particles.

REFERENCES

1. Al-Rkaby, A. H., Chegenizadeh, A., & Nikraz, H. R. (2019). An experimental study on the cyclic settlement of sand and cemented sand under different inclinations of the bedding angle and loading amplitudes. European Journal of Environmental and Civil Engineering, 23(8), 971-986.
2. Dawood, A. O., Sangoor, A. J., & Al-Rkaby, A. H. (2020). Behavior of tall masonry chimneys under wind loadings using CFD technique. Case Studies in Construction Materials, 13, e00451.
3. Al-Rkaby, A. H., Nikraz, H. R., & Chegenizadeh, A. (2017). Stress and deformation characteristics of nonwoven geotextile reinforced sand under different directions of principal stress. International Journal of Geosynthetics and Ground Engineering, 3, 1-11.
4. Al-Rkaby, A. H., Odeh, N. A., Sabih, A., & Odah, H. (2022). Geotechnical characterization of sustainable geopolymer improved soil. Journal of the Mechanical Behavior of Materials, 31(1), 484-491.
5. Afrin, H. (2017). A review on different types soil stabilization techniques. International Journal of Transportation Engineering and Technology, 3(2), 19-24.
6. Adhikari, B., Khattak, M. J., & Adhikari, S. (2021). Mechanical and durability characteristics of flyash-based soil-geopolymer mixtures for pavement base and subbase layers. International Journal of Pavement Engineering, 22(9), 1193–1212.
7. 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), 1–10.
8. Bruce, D. A., & Geosystems, E. C. O. (2000). *An introduction to the deep soil mixing methods as used in geotechnical applications*. United States. Federal Highway Administration. Office of Infrastructure ….

9. Cristelo, N., Glendinning, S., & Teixeira Pinto, A. (2011). Deep soft soil improvement by alkaline activation. Proceedings of the Institution of Civil Engineers-Ground Improvement, 164(2), 73–82.

10. Chen, J.-J., Zhang, L., Zhang, J.-F., Zhu, Y.-F., & Wang, J.-H. (2013). Field tests, modification, and application of deep soil mixing method in soft clay. Journal of Geotechnical and Geoenvironmental Engineering, 139(1), 24–34.

11. Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & van Deventer, J. S. J. (2007). Geopolymer technology: the current state of the art. Journal of Materials Science, 42(9), 2917–2933.

12. Dehghanbanadaki, A., Ahmad, K., Ali, N., Khari, M., Alimohammadi, P., & Latifi, N. (2013). Stabilization of soft soils with deep mixed soil columns–General perspective. *Electronic Journal of Geotechnical Engineering*, *18*, 295–306.

13. Holm, G. (2003). State of practice in dry deep mixing methods. In Grouting and ground treatment (pp. 145–163).

14. Indraratna, B., Chu, J., & Rujikiatkamjorn, C. (2015). Ground improvement case histories: chemical, electrokinetic, thermal and bioengineering. Butterworth-Heinemann.

15. Garcia-Lodeiro, I., Palomo, A., & Fernández-Jiménez, A. (2015). An overview of the chemistry of alkali-activated cement-based binders. Handbook of Alkali-Activated Cements, Mortars and Concretes, 19–47.

16. Krivenko, P., Garcia-Lodeiro, I., Kavalerova, E., Maltseva, O., & Fernández-Jiménez, A. (2014). A review on alkaline activation: new analytical perspectives. Mater. Construcc, 64(315), e022.

17. Karol, R. H. (2003). Chemical grouting and soil stabilization, revised and expanded (Vol. 12). Crc Press.

18. Kirsch, K., & Bell, A. (Eds.). (2012). Ground improvement. CRC Press.

19. Liew, Y. M., Kamarudin, H., al Bakri, A. M. M., Bnhussain, M., Luqman, M., Nizar, I. K., Ruzaidi, C. M., & Heah, C. Y. (2012). Optimization of solids-to-liquid and alkali activator ratios of calcined kaolin geopolymeric powder. Construction and Building Materials, 37, 440–451.

20. Little, D. N. (1995). Stabilization of pavement subgrades and base courses with lime.

21. Nicholson, J. C. (2011). Design of wind turbine tower and foundation systems: optimization approach (Doctoral dissertation, The University of Iowa).

22. Sargent, P., Hughes, P. N., & Rouainia, M. (2016). A new low carbon cementitious binder for stabilising weak ground conditions through deep soil mixing. Soils and Foundations, 56(6), 1021–1034.

23. Terashi, M. (2005). Keynote lecture: design of deep mixing in infrastructure applications. Proc. Int'l Conf on Deep Mixing-Best Practice and Recent Advances, 2005.