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Improving the Bearing Capacity of soil Using Alkali activated fly ash-based geopolymer

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Abstract

Geopolymer 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. Geopolymers involve alkaline activation of industrial waste to create cementitious products in treated soils, resulting with in improved soil properties. Due to its low bearing capacity, weak soil presents a problematic ground condition that is almost unsuitable for engineering construction projects. Chemical stabilization is one of the most widely used methods to enhance weak soil properties such bearing capacity. Therefore, this paper investigated the strength of low plasticity silt treated by geopolymer. The results shows that the unconfined compressive strength (UCS) of the low plasticity silt-geopolymer matrix increased significantly in range of with increasing the main ingredient of the geopolymer (FGP), i.e., fly ash (FA). 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 low plasticity silt voids by fly ash, produce geopolymer hydrated gel (C, N–A–S–H) that significantly bonded the soil particles. Therefore, it can be concluded that geopolymer is viable sustainable material to improve such problematic soil for different applications.

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

1. Introduction

Weak soils like soft clay and low plasticity silt cannot support superstructure loads. Loose, compressible, or organic refers to surface soils like soil, sludge, peat, organic soils, and landfill soils with unconcentrated homogeneous or non-homogeneous materials. Soft soil has low undrained shear strength, high compressibility, and low permeability. (Cernica, 1995). Improved or strengthened soil materials, whether natural or breakable, have been processed to improve their geotechnical properties (durability, erosion, compressibility, permeability, porosity, physical characteristics, mechanical properties, etc.) (Flodin & Broms, 1981).

Soil stabilization is the physical or chemical improvement of soil through various methods such as mechanical compaction and the use of various calcium-rich chemicals. (Sherwood, 1993). The past three decades have seen a significant increase in the rate of technology concerning ground improvement strategies, many of which have found widespread use in industrial construction projects. (Huat et al., 2019).

The production of traditional soil stabilizers such as cement and lime, which involves the thermal decomposition of calcium carbonate found in limestone, produces significant amounts of carbon dioxide and energy. For example, one ton of CO_2 is emitted for every ton of cement produced. Global CO_2 production in lime is around 1% and averages 0.95 tons of CO_2 per ton of lime. (Khedari et al., 2005; J L Provis, 2014). The process also necessitates a significant amount of energy to maintain the high temperatures required to produce OPC (450-1550°C) and lime (100-1000°C). Furthermore, raw materials are quickly consumed in cement production. According to Garcia-Lodeiro et al. (2015), producing 2.0 billion tons of cement necessitates the use of more than 3.0 billion tons of raw materials, 70% of which is limestone.

As a result, new soil stabilizers are required as a viable and sustainable alternative to cement in civil engineering applications. Geopolymerization innovations are gaining traction as a solution for solid waste and by-products that provide an advanced and cost-effective solution to many problems where hazardous waste must be treated and stored in critical environmental conditions. (Hamzah et al., 2015).

In the 1970s, the term “FGP” 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 temperature or slightly higher temperatures by alumina and silica-rich solvents (e.g., fly ash, slag, metakaolin, calcined clay) in alkaline activators. FGP is quickly proving to be a promising alternative for soil stabilization, eliminating the environmental challenges that traditional binders face by emitting less CO_2 during construction. One ton of FGP typically produces 0.19 to 0.24 tons of CO_2 and contributes slightly to global warming. (Papadopoulos & Giama, 2007).

Cristelo et al. (2013) FGP (sodium-based alkaline activators and class F fly ash) was used to stabilize low plasticity silty soils, and it was compared to a cement-based binder. The activator-to-FA ratio was between 1-2.5, and the FA ratio was (20, 30, 40%) of total solids. After 7, 28, 90, and 365 days of curing, UCS specimens were prepared and tested. On 365 days of curing, the results showed a significant increase in strength with a lower active/FA ratio of up to 43.4 MPa. At 28 days of curing, the UCS results of the cement and FGP samples were very similar.

Significant improvement occurred in medium and high plastic soils treated using FGP (Adhikari et al., 2019). The UCS of medium plastic soils containing 5% FA was 1.0 MPa, increasing to 2.6 MPa at 25% FA content. However, for high plastic soil, the UCS was unaffected up to 20% FA. However, at 30%FA, the UCS increased 400% in a short period of time (Adhikari et al., 2019). Furthermore, soft soil demonstrated high strength when stabilized with a FGP base on Granulated Blast Furnace Slag (GBFS) and Basic Oxygen Furnace Slag (BOFS) (BOFS) (Salimi & Ghorbani, 2020). They discovered that curing samples at temperatures ranging from 20 to 45°C increased the UCS (42 time) compared to untreated soil. This FGP based on ground granulated blast furnace slag was also used as a sustainable alternative to cement for deep soil mixing applications. As an example, Bhavita Chowdary et al. (2021) The UCS of cement-treated and FGP samples was investigated using GGBS content of 10-30% and activator ratio of 0.5-1.0. GP-treated specimens had higher UCS than cement-treated specimens of the same dosage (except for the mix with A/B = 0.5). This is due to an increase in pozzolanic and geopolymeric processes. Although using FGP has attracted more attention as an eco-friendly material, limited studies have been performed on the use of FGP in the geotechnical applications. As a result, the purpose of this article is to look into the possibilities for geopolymerized FA as a secondary raw material for geotechnical stabilization of low plasticity silt as an alternative to cement and lime. An extensive series of laboratory UCS tests were performed in this study to investigate the strength and stiffness of the FGP-low plasticity silt matrix. Furthermore, scanning electron microscopy (SEM) analysis was used to investigate the microstructural advancement of treated low plasticity silt. Since 2018, this work has been a part of an ongoing project

2. MATERIALS

In this study, soil, FA class c, and activator were mainly used.

2.1 Soil

This study's soil sample was collected in Nasiriyah, Almuhia area, about 343.5 kilometers south of Baghdad, Iraq's capital. Soil samples are collected 1 to 1.5 meters below the existing ground level. To determine the geotechnical properties of soil, specific gravity (Gs), sieve analysis, Atterberg's limits (LL and PL), compaction test, and direct shear test are all used. Table 1depicts these properties. According to the Unified Soil Classification System, the soil is categorized as low plasticity silt soil (ML).

Table 1The physical properties of the soil

Property	Value	Standard of the test
Specific gravity (Gs)	2.73	ASTM D 854
sand %	20	
Fines content %	80	ASTM D 422 and ASTM D 2487
Silt %	55	
Clay %	25	
Soil classification	ML	
Liquid limit %	40	
Plastic limit %	30	ASTM D 4318
Cohesion, c (kPa)	50	
Internal friction angle Ø°	5	ASTM D 3080
γ_{field} (kN/m3)	17.65	
moisture content Wc%	13	ASTM D 2216
Maximum dry unit weight (KN/m3)	18.12	ASTM 698
Optimum moisture content %	15.5	

2.2 Fly Ash

In this study, local fly ash was used, which was supplied by the Nasiriya power generating plant as byproduct waste materials generated during the production of electricity. Figure ***.1***depicts a picture of FA and the particle distribution as determined by the hydrometer test

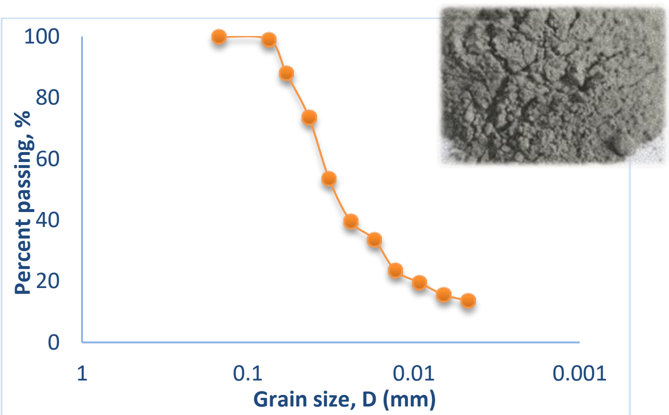

Figure .1The particle size distribution curve of FA

2.3 Alkali activator

Sodium silicate (Na_2Sio_3) and sodium hydroxide (NaOH) were used in this study to form the alkaline activator solution because they were cheaper and more available than a potassium-based solution. Furthermore, NaOH has a high capacity for the release of silicate and aluminate monomers. We obtained 98 percent pure sodium hydroxide pellets. The sodium silicate was purchased in liquid form. To make NaOH solution, a specific amount of sodium hydroxide pellets was dissolved in distilled water. The molarity of the NaOH solution was kept constant throughout the research at 10 M. The molarity of the solution was calculated by dissolving 400 grams of NaOH pellets in one liter of distilled water. The weight ratio of sodium silicate to sodium hydroxide in this study was 2.

3. METHODOLOGY

A series of unconfined compressive strength tests were performed on treated samples that had been cured for 28 days to investigate the compressive strength of FGP-treated soils. The UCS test samples were made from (PVC) cylindrical split tubes 50 mm in diameter and 100 mm in height, with a height-to-diameter aspect ratio of 2:1. Several studies have recommended this type of plastic mold because it is more resistant to the alkali mixture. To facilitate sample extraction, a longitudinal incision was made. To avoid volumetric expansion caused by compaction and movement, the mold was restricted by three stainless steel clamps prior to compaction.

On treated soil specimens, a compressive strength test was performed using a uniaxial machine with a loading capacity of 50 kN in accordance with (ASTM D1633-00, 2007). A load cell and a Linear Variable Displacement Transducer were used to determine the applied load and resulting displacements (LVDT). For all UCS tests, the displacement rate was 0.1 mm per minute. The compression machine is depicted in Figure *.2*

Figure .2alfa unconfined compressive tester

4. Microstructure Analysis

The microstructure samples were examined by using Field Emission Scanning Electron Microscope (FESEM) with Energy-Dispersive Spectrometer (EDS). That test was performed on small prepared samples taken from samples tested by UCS.

5. RESULTS

Several variables influence the effectiveness of fly-ash-based FGP as a binder. The effects of the FA, and activator to FA ratio were examined for soil to determine a practical FGP mixture for soil stabilization and to investigate the reliability of using these new binders in DSM for weak soil. the unconfined compressive strength (UCS) test was selected to examine the degree of reactivity of different FGP components in treated soils.

5.1 Effect of Fly ash Content

Several ratios of coal-fired FA (5,10, 15, 20, 25, and 30%) were investigated for their effect on the strength of the soil-FGP composite at AC/FA values 0.2, 0.4, 0.6, and 0.8. Figure 3 depicts the unconfined compressive strength of low plasticity silt treated with FGP at various FA concentrations.

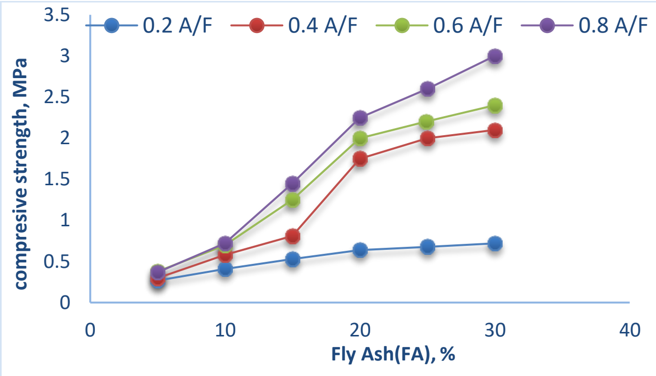

Figure. 3 Variation of unconfined compressive strength with the FA content

Increasing the FA concentration resulted in a considerable increase in the unconfined compression strength of the FGP-treated low plasticity silt for all activator ratios. For example, an activator ratio of 0.2 raised the unconfined compressive strength to 0.27, 0.41, 0.53, 0.64, 0.68, and 0.72 MPa as the FA increased to 5, 10, 15, 20, 25, and 30%. A similar growing tendency was seen with increased FA for different activator ratios. Increasing the FA concentration to 5, 10, 15, 20, 25, and 30%, for example, increased the compressive strength to 0.37, 0.72, 1.45, 2.25, 2.6, and 3 MPa, respectively.

There is no clear ideal proportion of FA because the UCS increases as the rate of FA increases in all investigated soils. However, after the addition of 20% FA, the pace of improvement becomes slower. As a result, it is recommended to employ 20% FA in the FGP, as this content resulted in compressive strength ranging between 0.64 and 2.25 MPa (depending on the activator ratio), which is adequate for most geotechnical applications.

5.2 Effect of Activator Content

Figure 4 depicts the effect of the alkaline activator ratio AC/FA 0.2, 0.4, 0.6, and 0.8. The UCS of all combinations with high FA concentration (20, 25, and 30%) increased constantly as the alkaline ratio increased. For a 30% FA percentage, for example, raising the AC/FA from 0.2 to 0.4, 0.6, and 0.8 improved the UCS by 158%, 195%, and 256%, respectively.

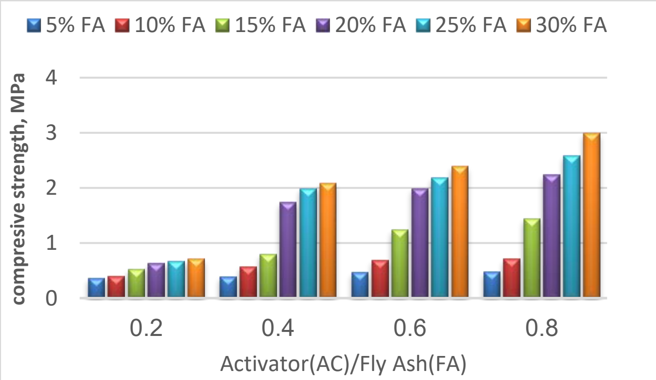

Figure. 4 Variation of unconfined compressive strength with the activator ratio

The reason for the improvement can be attributed to an increase in pH caused by an increase in activator content, which increased the leaching processes of silicon and aluminum from the amorphous phase of the FA, resulting in an increase in the formation of cementitious products such as N-A-S-H and C-A-S-H between soil particles. However, because of its effect on the solubility of FA particles, the production of excessive silica in mixtures obtained due to higher AC/FA led the aforementioned decrease in strength. A similar pattern of activity was documented by (Mustafa et al., 2013).

At a normal curing period of 28 days, a ratio of 0.4 with 20% FA or more yielded a strength range of 1.75 - 2.1 MPa. These ratios' strength performance may meet the needs of most ground improvement applications, such as subbase or subgrade course in road building. (Corps, 1984), Deep soil mixing applications (Puppala et al., 2008). Therefore, this ratio was recommended as a practical percentage to synthesise FGP for soil stabilization.

5.3 Stiffness Behavior of FGP-Treated Soil

The stiffness of FGP-treated soil determined from the unconfined condition may aid in better understanding the effect of various experimental variables (such as FA concentration, activator content, and soil type) on the stiffness of the stabilized low plasticity silt. Figure 5-6 depicts the observed stiffness E50, or secant modulus at 50% peak strength, of FGP-treated low plasticity silt. In general, increasing the amount of FA and activator in the stabilized low plasticity silt enhanced its rigidity. The observed increase in E50 is mostly attributable to the FGP capacity to bind soil particles after hardening, hence enhancing the stiffness of the soil fabric.

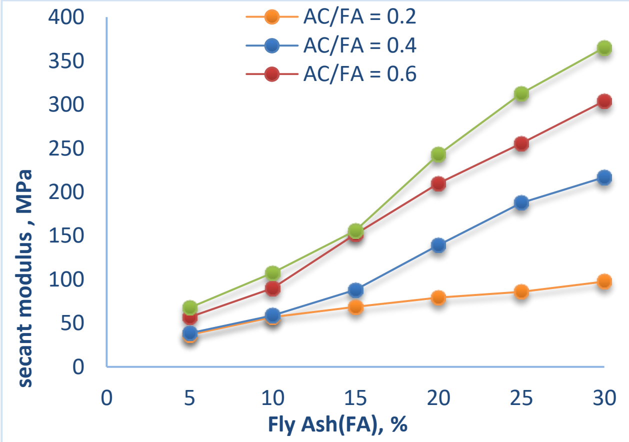

Figure.5 Variation of secant modulus with the FA content

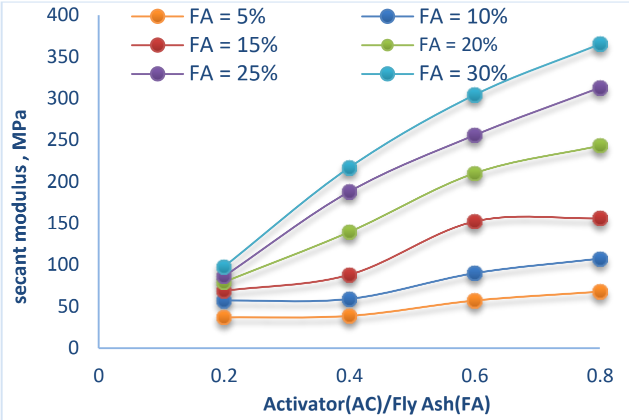

Figure.6 Variation of secant modulus with the activator ratio

5.4 Microstructures Characteristics

SEM testing was performed on a selected sample of soil with a 20% FA content and a 0.4 activator ratio to explore the microstructure of the low plasticity silt-FGP composite. The SEM test was carried out on sections of the same sample as the UCS test. Figure 7 shows a SEM image of soil treated with FGP.

It can be seen that the selected FA content filled the pores of the low plasticity silt and produced thick formations. Furthermore, the added alkaline activator and geopolymerization process resulted in partial dissolving of FA particles and efficiently activated low plasticity silt and FA particles, resulting in a clear change in the texture of the normal low plasticity silty soil. Geopolymerization will eventually result in two chemical structures, 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 from the C-A-H and C-S-H formed by OPC hydration and lime pozzolanic processes, respectively. (García-Lodeiro et al., 2007). As a result of the created Highly connected three-dimensional chain network polymeric bond of sialite, particles of the stabilized low plasticity silt were strongly bonded together, resulting in a stiff crystalline composite. This is consistent with the large rise in soil strength, with the unconfined compressive strength increasing by 15 times.

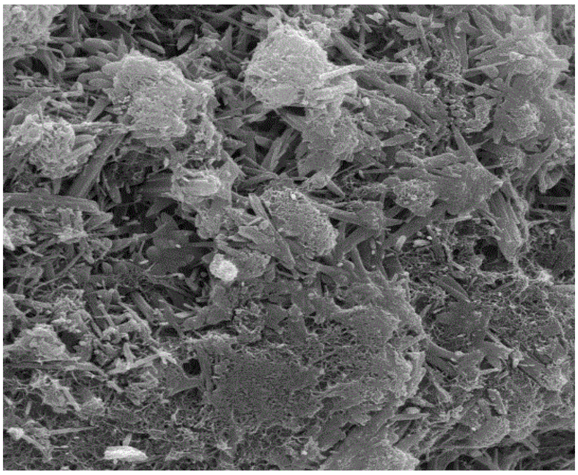

Figure. 7 SEM images of soil-FGP matrix

The FA content was chosen to fill the pores of the low plasticity silt and generate thick structures. Furthermore, the alkaline activator applied to the geopolymerization procedure resulted in efficiently activated low plasticity silt and FA. As a result, the particles of stabilized soil were strongly bound together by the created FGP gel, resulting in a stiff crystalline composite. This is consistent with the large rise in soil strength, with the unconfined compressive strength increasing by 15 times.

Conclusions

Fly-ash-based FGP 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 FGP could be enhanced significantly with the addition of FA. Although experimental study found no optimum FA content, the highest rate of improvement occurred at FA content of 20%. It was found that the strength increases with the increase of the FA content in the mixture for all soil.

Regarding to the effect of alkaline activator, strengths and stiffnesses of low plasticity silt–FGP 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 FA (5-15%) results in decreased the strength with further increase of activator from 0.4 to 0.8.

This improvement is due to the improvement of the microstructure of the low plasticity silt 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 low plasticity silt creating strongly connected three-dimensional chain polymeric network.

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