Improving the Performance of Soil Using Sustainable Geopolymer

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Improving the Performance of Soil Using Sustainable Geopolymer

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Abstract: *Soil stabilization is a common technique to improve the mechanical properties of the soil in term of increasing its strength and decreasing the associated settlement. The new sustainable materials have been emerged as alternative to the traditional binders such as the cement and the lime. These materials can be used in the shallow and deep soil mixing. This paper reviewed the mechanism of the soil stabilization, the traditional binder and the sever impacts on the environment, the new echo-friendly materials, deep soil mixing technique, and the geopolemerization. The results showed significant enhancement of the shear strength of the geopolymerized silt where the strength was increased by more than 6 times. This enhancement may be attributed to the developed geopolymer-jel NASH that filled the voids, surrounded and cemented the soil particles. Consequently, this matrix considered as a novel precursor for using in the soil injecting and grouting technique.*

Keywords: *Geopolemerization, Soil Stabilization, Weak Soil, Deep Soil Mixing Columns.*

1. INTRODUCTION

Technological advancements and persistent population growth, especially in developing countries, have necessitated the construction of high-rise buildings and other infrastructure, including roads and bridges, in coastal regions, characterized by weak soil that resembles marine clay (Al-Rkaby, 2019a, 2019b; Al-Rkaby et al., 2019, Abed et al., 2024). The excessive settlement and poor bearing capacity of weak soils, however, render them unsuitable for these applications. Consequently, prior to commencing construction activities on such perilous soil types, soil improvement becomes necessary. To accomplish this, it is the duty of academic and construction engineers to develop techniques for reinforcing feeble soils so that they can be utilized as foundation material, Deep stabilization techniques, including but not limited to stone columns, grouting, electroosmosis, and preloading with vertical drains, are required to prepare the ground for construction when weak soil deposits extend to greater depths. One instance of such a methodology is the deep soil mixing method (DSM), an advanced approach that finds application in a multitude of countries worldwide. The foundation of this methodology consists of the installation of soil-binder columns or piles, which serve to fortify the weak adjacent soil and enhance its overall functionality (by minimizing settlements and increasing bearing capacity to support the heaving load structures). These columns are created by mixing binder, either dry or wet with weak soil using special augers (Kitazume&Terashi, 2013; Porbaha, 1998; Puppala & Pedarla, 2017, Li et al., 2024). lime and

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ordinary Portland cement (OPC) are the most common methods that used in a variety of soil stabilization techniques, shallow or deep stabilization. this is because of its simplicity of use, broad range of applications, ability to arrange columns in a variety of patterns, such as walls, blocks, grids, etc., and much less soil extraction during column installation.

However, an excessive reliance on cement has led to significant CO_2 emissions, the depletion of natural resources, and dust pollution, among other environmental issues. The production of OPC uses a lot of energy (5000 MJ/t PC), which results in CO_2 emissions of 0.70–1.10 tonnes per each tonne of OPC (Bosoaga et al., 2009; Fatehi et al., 2018). CKD is a substantial quantity of a byproduct material generated as a byproduct of cement production; between 0.6 and 0.7 tonnes of CKD are produced per tonne of cement manufactured, (Al-Refeai& Al-Karni, 1999; Puppala&Pedarla, 2017). Weak soils are frequently stabilized through the use of reinforced earth, pile or explosion compaction, excavation and replacement, and well point systems, among others. Numerous variables—soil condition, desired compaction levels, construction process, maximum compaction depth, project completion deadline, equipment, and material availability—influence the estimation of the optimal method. Employing conventional methods to enhance soil quality can lead to various issues, including economic and environmental concerns. Cement is the most ancient binding agent in the history of soil stabilisation. Because it can be employed in isolation to achieve the necessary stabilising effect, it could be categorised as a primary stabilising agent (Sherwood, 1993).In the course of the hydration process, cement reaction occurs. Cement is mixed with water and other components to produce a substance that undergoes a hardening phenomenon, which initiates the process. As cement hardens (sets), it will encase soil as an adhesive. Typically, just a tiny quantity of cement is used, yet this quantity is sufficient to enhance the soil's engineering qualities by reducing flexibility and volume change and increasing strength (Al-Tabbaa&Perera, 2005, Sun et al., 2024; Wang et al., 2024; Xie et al., 2024).Lime application offers a cost-effective method for stabilizing soil and has the potential to substantially enhance engineering properties through both stabilization and modification. The right amount of lime added to the soil stabilises it and results in a significant boost in its long-term strength through a pozzolanic reaction. Calcium silicate hydrates and calcium aluminates are created when the calcium in the lime combines with the aluminates and silicates that have been dissolved in the soil. Slurry lime can also be used where water may be required to accomplish adequate compaction in parched soil conditions, (Hicks, 2002). Upon being combined with moist soils, quicklime promptly absorbs as much as 32% of the water by weight from the adjacent soil in order to produce hydrated lime; (Sherwood, 1993).Stabilization can lead to significant enhancements in shear strength and resilient modulus values, sustained strength accrual over extended periods of operation, and long-lasting durability spanning decades.Lime stabilization technology finds its most extensive implementation in the domains of environmental and geotechnical sciences. Its applications include the encapsulation of contaminants, the rendering of backfill, the capping of highways, the stabilization of slopes, and the improvement of foundations, (Ingles & Metcalf, 1972). Sulfur and organic substances, nevertheless, have the potential to impede the lime stabilization procedure. The swelling caused by sulphate (e.g., gypsum) reacting with lime may affect the strength of the soil. The country's rapid development, together with its great economic performance, has led to the creation of extensive infrastructures. However, weak soils are usually widely distributed all over the world and thus the low bearing pressure of the soil becomes a significant challenge to the engineers. Chemical and mechanical soil stabilization is widely used for the geotechnical problems. Chemical binder promotes a variety of chemical reactions that result in long-term improvement of the soil engineering properties. Several different chemical stabilizing binders used for soil stabilization, including OPC, lime, cement kiln dust, fly ash, and bitumen. However, the soil stabilization by cement and lime resulted in significant amount of the project's overall cost may be incurred due to the required soil stabilization. Moreover, such materials (cement and lime) have a sever impacts on the environment as they are the main consequences of 8-10% of the emitted CO_2.The geo-polymer was introduced recently as an environmental-friendly material as it results in less CO_2 during construction, where one ton of geo-polymer produces just 200kg of CO_2 (Papadopoulos &Giama, 2007). Fly-ash is a byproduct of fine material from burning pulverized coal in many industrial activities. The main ingredients of such products are the oxides of silica, aluminum, and calcium oxides. As fly ash contains of high silica and alumina, two major sources of the geopolymerization process, it can be used efficiently in geopolymer-soil stabilization. For example, increasing the fly ash content from 20% to 50% increased the strength of enhanced soils by 50-120 % (Sreelakshmi et al., 2020). The role of the activator in the geopolymerization process is to initiate a reaction and increase the kinetics of such reaction. Individual materials such as calcium hydroxide, sodium hydroxide, or a combination of NaOH and Na2SiO3, a combination of potassium hydroxide and potassium silicate can be used as an activator (Cristelo et al., 2012; Rangan et al., 2005; Zhan et al., 2024). Therefore, it is important to investigate the performance of the soil improved by the new sustainable materials such as geopolymer. In this research, the compressive strength of the clay soil improved by the geopolymer considering different contents of the fly-ash has been investigated. This work is part of an ongoing project since 2018.

2. MATERIALS AND METHODS

Soil and Geopolymer Ingredients

1. Soil

In Thi-Qar, weak soils are usually widely distributed all over the Thi-Qar governorate, thus, such silt supports more than 80% of the various civil engineering applications in Thi-Qar. As a consequence, such soil that is characterized as high plasticity silt MH based on the Unified Soil Classification System (USCS) was investigated in herein.

2. Fly-ash and the Alkali Activator

Fly-ash was utilized in this investigation which is available locally. The chemical compositions of the used F-ash are depicted in Table 1. Sodium hydroxide (NaOH) is a chemical compound that dissolves in water and is used in wide fields. Sodium silicate is an important chemical compound with the formula (Na_2SiO_3) also known as water glass.

Table: chemical compositions of the used F-ash

Element	*Concentration (% weight)*										
	C	*O*	*F*	*Na*	*Mg*	*Al*	*Si*	*S*	*K*	*Ca*	*Fe*
Fly ash	2.1	13.8	Nil	3.8	1.9	9.3	77.53	1.2	3.2	22.1	1.3

Sample Preparation

Different percentages of fly-ash (3.0, 6.0, 9.0, 12.0, 15.0, and 18%) and activator ratios (0.15, 0.3, 0.45, and 0.6) were considered to investigate the influence of such elements on the strength of the treated silty soil.

The samples of geopolymerized soil were prepared by blended the proportions of F-ash with the dry silt. Then the alkaline solution with free water was blended with the dry clay-fly-ash matrixes until achieving homogeneous mixtures. The prepared mixtures were compacted based on the max. dry density. After completing the preparation, the samples were wrapped and cured for 28 days.

3. RESULTS

Influence of Fly-ash Content

Different contents of the fly-ash 3.0, 6.0, 9.0, 12.0, 15.0 and 18% have been added to the native silt in order to study their impact on the unconfined compressive strength (UCS). Figures 1 and 2 show the relationship curves between the UCS and the secant modulus with the fly ash content added to the silty soil, respectively.

Irrespective of the activator ratio, the increase of the fly ash content resulted in improvement the behaviour of the geopolymerized mixtures in term of increasing the unconfined compressive strength qu. However, the level of the improvement was not same for all the mixtures. For example, for the activator ratio (AC) of 0.15, a compressive strength improved from 0.10 MPa for the native silt to 0.38, 0.43, 0.60, 0.8, 0.95, and 1.0 as the fly-ash increased to 3.0, 6.0, 9.0, 12.0, 15.0 and 18% respectively. For high ratio of the activator, 0.6, the compressive strength increased significantly to 0.65, 1.53, 1.67, 1.87, 2.0, and 2.37 MP corresponding to adding 3.0, 6.0, 9.0, 12.0, 15.0 and 18% of a fly-ash respectively. This enhancement can be attributed to the generation of cementations-jel products between soil particles.

Similar to the studies on the OPC, no optimum content of F-ash after which the UCS decreased with the increasing the F-ash for all tested-silts. However, for the most geotechnical application, the required range of the unconfined compressive is 1.0 - 2.0 MPa, and accordingly the best fly-ash content can be determined.

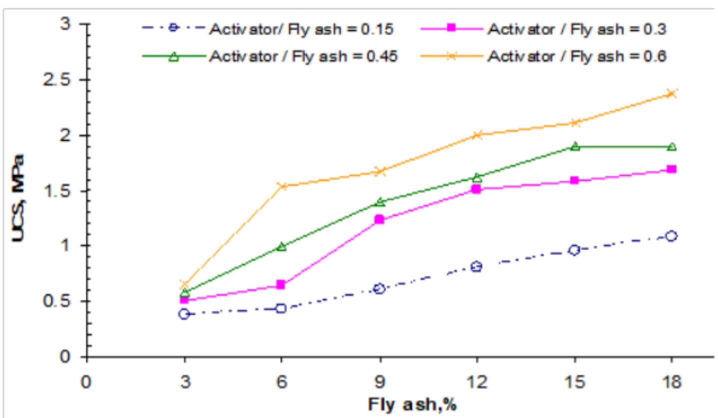

Figure 1: Relationship of the UCS with the F-ash Content.

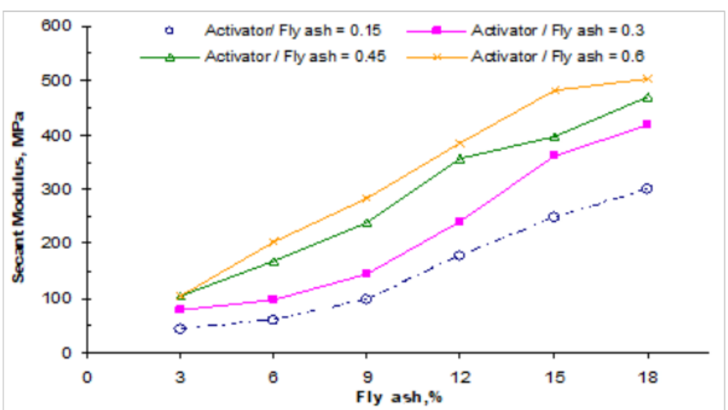

Figure 2: Relationship of the Secant modulus with the Fly-ash Content.

Influenceof Activator Content

The fly-ash is an inactive material and the reaction process needs an activator agent to initiate the geopolymerization and increase the kinetics of such reaction. Therefore, the role of the AC of 0.15, 0.3, 0.45, and 0.6 on the improvement of the strength has been investigated as shown in Figures 3 and 4 that showed the variation of the UCS and the secant modulus with the activator content added to the silty soil, respectively.

For a mixture with high fly ash content (18%), the UCS for all matrixes increased with increasing the AC ratio. However, the improvement of the geopolymer mixture with less fly-ash content (3.0, 6.0, 9.0, 12.0 & 15.0) increased at increasing the AC ratio AC/FA to 0.45 then kept constant. For 18% fly-ash content, for example, with increasing AC/FA from 0.15 to 0.3, 0.45 and 0.6, the UCS increased by 68%, 89%, and 137% respectively.

However, for the least fly-ash content (5%), the improvement was 31% as the alkaline ratio AC/FA increased to 0.3 then the improvement became 52% and 71% with increasing AC/FA to 0.6 and 0.8 respectively. This enhancement can be justified based on the developing of cementitious products between soil particles.

Aluminum silicate is the primary active component among these substances. These compounds are present in an extensive variety of substances, including CKD, fly ash, metakaolin, blast steel slag and rice husk. The variability in properties of geopolymer products can be attributed to various factors, including particle size, chemical composition, and constituents of mixtures.

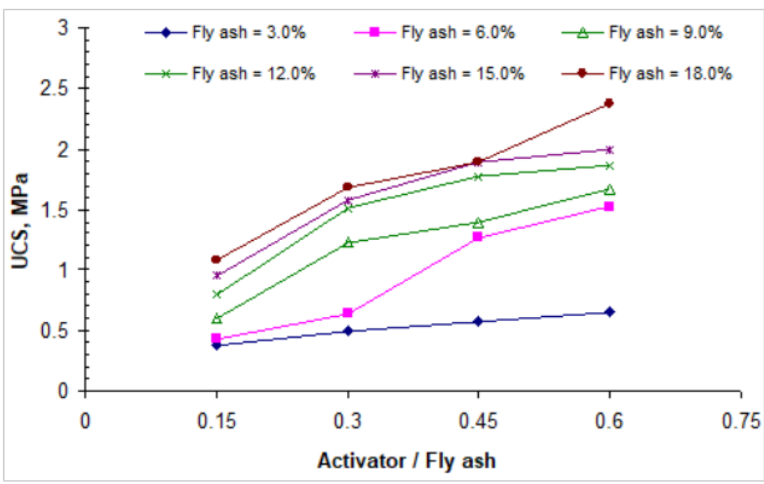

Figure 3: Relationship of the UCS with different Activator Content.

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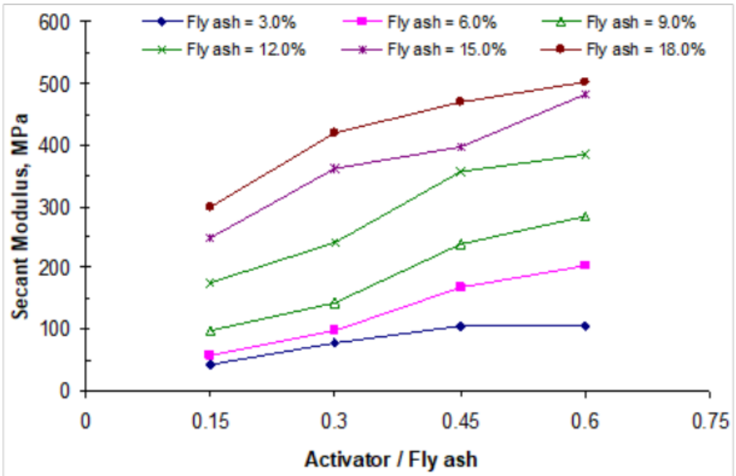

Figure 4: Relationship of the Secant modulus with different Activator Content.

According to (Diaz et al., 2010), an elevated concentration of the glass phase results in improved geopolymerization, subsequently causing an increase in compressive strength. Moreover, smaller fly ash particles result in a comparatively larger surface area for contact, ensuring increased reactivity. The aforementioned effect is augmented even more by increased combustion temperatures and fly ash grinding. In addition, a greater proportion of alkali activators is necessary for the fly ash to accommodate the trace amount of unburned coal that is present (Diaz et al., 2010).

The principal precursors utilised in the geopolymer reaction are silica and alumina. Significantly affecting the geopolymer's properties is the proportion of silicon (Si) to aluminium (Al). By keeping the mass ratio of silicon oxide to aluminium oxide in the source material between 2.0 and 3.5, it is possible to produce an optimal product. The studies conducted by (Duxson et al., 2007), investigated the influence of Si/Al ratios on the properties and microstructure of geopolymer. In accordance with the findings, the geopolymer displaying a uniform microstructure and a Si/Al ratio of 1.9 possessed the most desirable properties. However, geopolymer materials were synthesized by(Fletcher & Ross, 2018),encompassing a range of Si/Al ratios from 0.5 to 300. The researchers noted that the mechanical characteristics of the specimens exhibited a discernible elastic response as the SiO2 concentration escalated, specifically when the Si/Al ratio exceeded 24. A study conducted by (Hardjito et al., 2004), the geopolymer concrete contains silicon (Si) and aluminium (Al) in molar ratios of approximately 1.779 and 1.883, respectively.

4. CONCLUSIONS

a. The weak soil spreads over the world and is characterized by its low shear strength and large settlement. This type of soil is considered a big challenge to the engineer and can result in many problems for the structures built on it.

b. It is common and efficient to increase the shear strength and deformation of such soft and loose soils through soil stabilisation. Nevertheless, the utilisation of conventional binders, including OPC and lime, results in significant environmental consequences due to the substantial quantities of CO2 emitted and energy consumed.

c. By-product materials such as fly ash has been recognized as new sustainable materials which can be used for soil stabilization. These materials can be activated to be binders with high strength, low deformation, and durability.

d. By means of geopolymerization, an alkaline activator such as Na2SiO3 or NaOH can produce a cementations material with enhanced mechanical strength. The activators merely facilitate the solidification and formation of the solution's siliceous and aluminous components.

e. Activated fly ash can be utilised as a binder in the deep soil mixing technique to strengthen weak deep soil by forming various patterns of deep stiff columns.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11