GEOPOLYMER-BASED DEEP MIXING OF SOFT SOIL: AN ECO-FRIENDLY ALTERNATIVE TO CEMENT STABILIZATION

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ABSTRACT

Bangladesh, being a low-lying deltaic country in general, is underlain by weak and compressible surface soils that often exhibit poor bearing capacity for structural loads. As a result, deep pile foundations are commonly required, even for structures that are subject to moderate or light loading. Such reliance on pile foundations not only increases construction costs but also raises environmental issues. In consideration of these drawbacks, the current study investigates the feasibility of geopolymer-based deep mixing as an environmentally friendly ground improvement technique, providing an eco-friendly alternative to traditional cement stabilization methods. The reasoning behind this stems from the large amount of carbon emissions related to cement production, which is recognized as one of the prominent industrial sources of CO_2 emissions. In the current research, Class F fly ash, a biproduct of coal-fired power stations and readily available in Bangladesh, was used as the precursor binder. Fly ash in different proportions (10-25% of dry soil weight) was mixed with local soft soils to determine its effectiveness as a stabilization reagent. A chemical activator in the form of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was added to the mixtures to initiate the geopolymeric reaction. The effectiveness of the treatment was determined by Unconfined Compressive Strength (UCS) tests conducted over varying curing ages (14 days, 28 days and 56 days). The experimental results showed a marked improvement in strength in relation to increased binder content and longer curing time, indicating a progressive development of the geopolymer matrix in the soil mix. More than 33 times increase in UCS of treated soil with 25% fly ash has been observed at 56-days curing period than the raw soil when the soil is treated at moisture level of liquid limit. When it is treated at moisture of 125% lquid limit, 122 times increase in UCS has been found. Conversely, an increase in the water-to-binder ratio was observed to have a detrimental influence on the strength development, highlighting the importance of optimizing mix design parameters. It has also been observed that, the treated soil with high strength can undergo lower strain before failure than the low strength soil, which can be a detrimental parameter in foundation design. Overall, the geopolymer-treated soil showed significant strength improvements compared to untreated soil, validating the viability of the method as a novel and green ground improvement method for the soft soils of Bangladesh. The research can be continued with various kinds of soils, geopymeric materials and activators; study on other soil strength and design parameters, mineralogical analysis, laboratry and field scale model; and Artificial Intelligence (AI) based models for the prediction of the strength of geopolymer treated soil.

Keywords: *Deep Mixing, Binder, Activator, Geopolymer, UCS*

1. INTRODUCTION

Bangladesh, being a low-lying deltaic country, is underlain by soft and highly compressible surface soils that possess low shear strength and high settlement potential. Hence, even for low- to medium-rise structure configurations, deep foundations are often required to transfer the load to the stronger strata lying underneath. Despite this, deep foundations are constructed with high financial cost, have environmental concerns, and come with technical complexities. Besides, soft clayey deposits are subjected to excessive settlement, high permeability, and instability, while areas with organic soils, loose sands, or soft clays below the groundwater table are susceptible to liquefaction also (Kitazume & Terashi, 2013). To mitigate these geotechnical problems, lots of techniques of soil improvement have been developed to increase the bearing capacity and stability of problematic soils. The most common methods used for soil stabilization include cement, lime, fly ash, and slag; among them, cement is the most common stabilizer. However, the production of cement involves with significant release of CO_2 worldwide, hence there is a need to find sustainable and eco-friendly alternatives. A promising technique in this respect is the Deep Mixing Method, in which hardening agents are mixed mechanically with in-situ soil to enhance its strength and stiffness.

This paper discusses the feasibility of a geopolymer-based deep mixing technique for sustainable treatment in lieu of cement stabilization. In this approach, Class F Fly Ash, that is one of the biproducts obtained from coal combustion, is treated with alkaline activators that initiate geopolymerization and harden the soft soil. Currently, along with the increased establishment of coal-based power plants across Bangladesh, large volumes of fly ash originate, which have already become an environmental threat because of possible air, surface water, and groundwater contamination. Ground improvement using fly ash reduces waste management problems and protects the environment, leading to sustainable infrastructure.

1.1 Literature Review

Previous studies have shown the performance of many binders and industrial by-products in soft soil stabilization. For example, quicklime-treated marine clay indicated a linear development of UCS with an increase in lime content and curing time (Terashi et al., 1977); similar behaviors were also demonstrated in port clay treated with cement (Saitoh, 1988) Materials containing adequate amounts of silica and alumina can undergo geopolymerization when activated by appropriate alkaline solutions; for example, fly ash and slag have been shown to exhibit potential in this regard by Ye et al. (2014). This results in a cementing matrix that significantly enhances the strength of soils. Wu et al. (2022) showed that the compressive strength of the alkali-activated soil mixture was higher with the addition of more than 50% slag, whereas Nath et al. (2017) found 20% optimum fly ash content for improvement in the UCS of organic soils.

Recently, Miraki et al. (2022) presented proof that a blend of 30% blast furnace slag and 70% volcanic ash, when alkali-activated, works effectively as an alternative option to conventional lime and cement treatment methods. Mohammadinia et al. (2019) conducted an experimental study of alkali-activated fly ash for deep mixed column construction in loose soil and reported significant compressibility changes associated with different initial moisture contents. Similarly, Ekmen et al. (2020) investigated strength and stiffness optimization of fly ash–admixed DMM columns in clayey silty sand with and without the addition of fly ash. The early studies also assessed soil stabilization performance under different binders and moisture conditions. Al-Tabba et al. (2000) concluded that mixtures with 6% cement and 2% bentonite yielded adequate strength and leachability, while excessive moisture resulted in low compressive strength. Further studies by Larsson & Nilsson (2005), Islam & Hashim (2009) and Horpibulsk et al. (2011) have corroborated earlier studies that binder type and soil moisture are the most influential factors affecting the DMM column performance. Kogbara et al. (2013) also found that, for silty sands stabilized with fly ash, a water-to-binder ratio of 0.45 achieved the highest strength and established this as the optimum mix proportion for such mixes.

In developing countries, like Bangladesh, the rapid growth of power plants and other industries has generated huge quantities of biproducts such as fly ash, pond ash, and bottom ash that are rich in alumina and silica. Although a fraction of this material is used by cement manufacturing industries, their safe disposal is still considered an environmental challenge. Geopolymers are a class of inorganic polymers that directly use the aluminosilicate content of industrial by-products, mainly fly ash, as their source material. While geopolymers have recently been found to be useful in ground improvement, most practical applications to date have been restricted to concrete production. On the other hand, ground improvement of weak or problematic soils has traditionally been accomplished using conventional stabilizing agents. In this regard, the effectiveness of the fly ash based geopolymer deep mixing method for enhancement of the strength characteristics of soft soil, determined through the course of a laboratory investigation, is presented in this study. The Unconfined Compressive Strength (UCS) of treated soil has been taken as the primary performance indicator because the increase in the UCS clearly signifies the gain in bearing capacity and general ground stability achieved by the geopolymer treatment.

1.2 Geopolymerization Mechanism

The term "geopolymer" was first used by Davidovits in 1978 to describe a new class of inorganic polymeric materials that resulted from the reaction of aluminosilicate sources with highly alkaline silicate solutions (Davidovits, 2005). Normally, such a geopolymer product is cured at ambient or only slightly elevated temperatures to obtain a hardened binder. This kind of reaction is known as geopolymerization; it forms a three-dimensional polymeric network normally with amorphous to semi-crystalline characteristics. A general empirical formula of a geopolymer may be presented as: $Mn\{-(SiO_2)z\text{–}AlO_2\}\cdot wH2O$,

where, n is the level of polycondensation, z is 1, 2, or 3, and w is the volume of binding water, M is a cation like K^+, Na^+, or Ca^{2+}. It has amorphous to semi-crystalline three-dimensional Si-O-Al polymeric networks.

Geopolymerization is an exothermic process, whereby amorphous aluminosilicate precursors dissolve in a highly alkaline medium and then produce reactive SiO_4 and AlO_4 tetrahedral units. These tetrahedra further undergo polycondensation that forms a robust three-dimensional Si–O–Al framework (Figure 1). This framework contributes to high mechanical strength, durability, and chemical resistance, and geopolymers may be considered a more sustainable option compared to traditional materials based on cementitious binders.

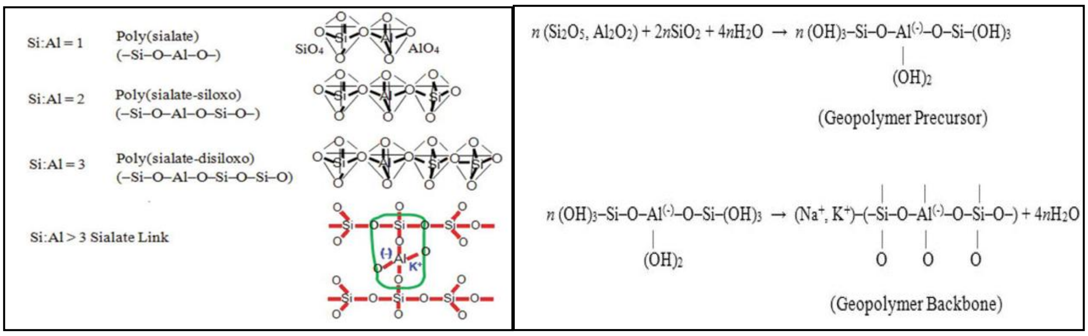

Figure 1: Geopolymerization Mechanism Based on the amount of siloxo Si-O units, geopolymer systems (Bakri et al., 2012)

1.3 Mechanism of the Deep Mixing Method

Deep Mixing Method involves in situ mixing of soil with cement, lime, slag, fly ash, or other hardening agents at a specified depth using regularly spaced augers (Figure2). The method can be implemented either by the wet or the dry technique. The binder is introduced as slurry in the wet method , while in the dry method, it is used in powdered form. Deep mixing is one of the most used soil improvement techniques that are highly effective in soft cohesive soils for enhancing their shear strength and stiffness. This facilitates the construction of superstructures, embankment stability, and the reinforcement of slopes. More importantly, the treatment reduces the permeability of the soil substantially and facilitates the liquefaction mitigation in cohesionless soils (Han, 2015).

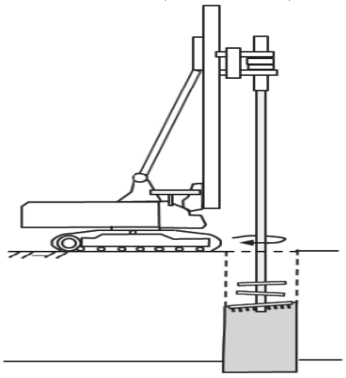

Figure 2: The Process of Deep Mixing Method (Han, 2015)

2. METHODOLOGY

In this experimental investigation, soil with different moisture content was mixed with various amount of alkali activated binder (fly ash). The prepared samples were cured for different age to observe the efficacy of fly ash based geopolymer on the development of strength. The material details and the procedures have been described in following sub-sections.

2.1 Materials

The materials taken for the current study were sandy silt, Sodium Hydroxide and Sodium Silicate as alkali activators, class F fly ash and potable water. The details of materials used are described below.

2.1.1 Soil

Raw soil was collected from Pahartali, Raozan, Chattogram, Bangladesh. Soil was collected from shallower depth, dried, pulverized and sieved through no. 40 (425 µm) sieve to obtain uniform material and stored in dry and sealed condition till next procedure. The soil properties are described in the Table 1 and Figure 3.

Table 1 : Properties of Raw Soil

Properties		Value
Grain Size Distribution [ASTM D 422 – 63]	Fine Content (%)	62.0
Atterberg Limit [ASTM D 4318 – 10]	Liquid Limit (%)	30
	Plastic Limit (%)	23
Specific Gravity (%) [ASTM D 854 – 14]		2.65
USCS Classification. [ASTM D2487 – 11]		ML (Sandy Silt)

2.1.2 Fly Ash

Fly ash is a type of material by-product generated by coal-based power plants. Electrostatic precipitators or other particle filtration equipment in modern coal-fired power plants sort out the fly ash before the flue gases reach the chimneys. Fly ash varies significantly in chemical composition depending on the origin and makeup of the coal being burned. Based on the ASTM standard, there are two different types of fly ash such as class F and class C. The major difference among these groups is in the ash's calcium, silica, alumina, and iron content. Though for the same no active cementing activity was observed, Class F fly ash contains major components silica and alumina. On the other hand, Class C fly ash is a self-cementing ash having more than 20% CaO. (lime). In the current experiment, Class F fly ash was used to produce the geopolymer. Figure 4 shows the grain size distribution curve for the used fly ash in this. study.

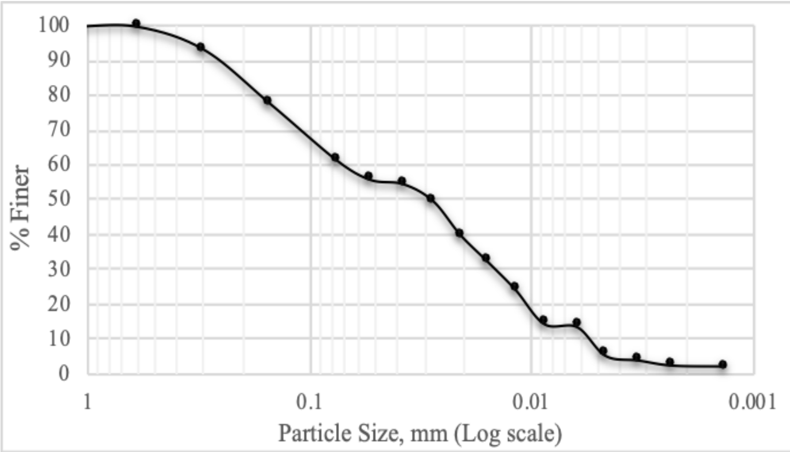

Figure 3: Grain Size Distribution Curve for Soil (Mukta & Aftabur, 2024)

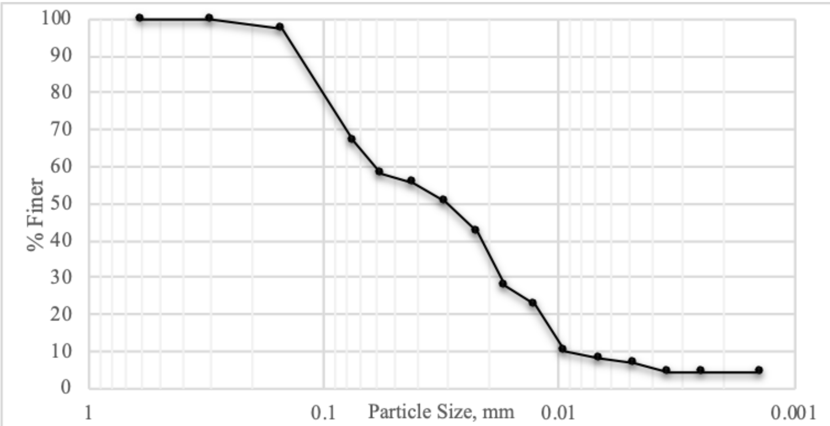

Figure 4: Particle Size Distribution Curve for Fly Ash (Mukta & Aftabur, 2024)

2.1.3 Alkali Activator

The alkaline activator used in this study consisted of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) (Figure 5), combined in a 2:1 ratio. This proportion was selected based on prior research indicating that the most effective performance of fly ash–based geopolymers is typically achieved within the ratio range of 2:1 to 2.5:1 (Bakri et al., 2012). The moisture content of the treated soil was adjusted to 125% of its liquid limit to examine the material behavior under near-liquid conditions. During the mixing process, a water-binder ratio of 0.45 was maintained. Consequently, the total water content, including both the inherent soil moisture and the additional water, relative to the binder content, ranged between 1.69 and 4.20.

2.2 Material Proportion

Soil was taken at two state of moisture content, liquid limit (30%) and 125% of liquid limit (37.5%). Fly ash of 10, 15, 20 and 25% of dry soil have been used as precursor binder in the geopolymer which was activated with alkali activators (NaOH: Na_2SiO_3 =1:2) with activator to binder ratio 9.5. A water-binder ratio of 0.45 was used to make the geopolymer workable. The detailed proportioning of the materials has been tabulated in the Table 2.

Figure 5: Sodium Hydroxide and Sodium Silicate (Mukta & Aftabur, 2024)

Table 2: Proportioning of Material

Soil		Geopolymer					
Dry Soil (%)	Soil Moisture (%)	Binder, P (Fly Ash) (% of dry soil)	Alkali Activator , L(50% of Fly Ash) (NaOH: Na_2SiO_3 =1:2) Total (% of dry soil)	NaOH (%of dry soil)	Na_2SiO_3 (% of dry soil)	Water-Binder Ratio	Total water to binder ratio (Soil moisture + Added water)/ Binder)
100	30	10	5	1.67	3.33	0.45	3.55
		15	7.5	2.50	5.00		2.52
		20	10	3.33	6.67		2.0
		25	12.5	4.17	8.33		1.69
	37.5	10	5	1.67	3.33		4.20
		15	7.5	2.50	5.00		2. 95
		20	10	3.33	6.67		2.235
		25	12.5	4.17	8.33		1.95

2.3 Mixing and Sampling

At first, the soil was mixed with water (30% or 37.5%) to achieve required moisture content. Geopolymer binder was mixed using fly ash, the alkali activator, and water with a water/binder ratio of 0.45 to achieve a workable consistency (Federal Highway Administration Design Manual, 2013). The mixture was left to rest for about 10 minutes to dissipate the heat generated during the exothermic reaction. Then, the geopolymer binder and moist soil were mixed together with an automated machine for approximately 10 minutes to attain homogeneous materials throughout the specimen.

Specimens were prepared in the uPVC cylindrical mold with 38 mm diameter and 76 mm height in three layers with ligt tamping to remove entrapped air. For each mix combination and curing duration, three identical specimens were cast to ensure reproducibility of the results. After sealing and curing under humid conditions, the prepared samples have been tested after 14, 28 and 56 days. Figure 6 shows the sample prior, during and after UCS test.

(a) (b) (c)

Figure 6: (a) Specimen before test, (b) Specimen while testing, (c) Ruptured Specimen

3. RESULTS AND DISCUSSIONS

Unconfined Compressive Strength (UCS) test has been carried out for 14 days, 28 days and 56 days curing periods according to ASTM D2166. The effectiveness of geopolymer treatment on the strength characteristics of soft soil has been illustrated in the sub-sections bellow.

3.1 Effect of Geopolymer on UCS

The UCS test was conducted on both untreated and geopolymer-treated soil samples after 14, 28, and 56 days of curing since strength development in fly ash–based binders usually proceeds at a slower rate than that in cement. The variation of UCS with curing time and binder content is portrayed in Figure 7. The solid lines show the strength of treated soil at moisture level of liquid limit, and the dashed lines are showing for moisture level of 125% of liquid limit. The effect of curing age on the development of strength can be understood clearly from the graph. UCS always increases with the increase in curing time. The difference in strength between 28-days and 56-days strength is lower than that of between14-days and 28-days strength, which indicates that the rate of reaction slows down after 28-days.

The results indicated that UCS increasing progressively with an increase in binder content, with the strength reaching its peak at the highest binder dosage tested, 25% (at soil moisture level of liquid limit). At low binder contents, the rate of gain was relatively moderate, and beyond 15%, the gain showed a steep rise. The UCS value reached the maximum of 1145 kPa at 25% binder content and 56 days of curing, as compared to 34 kPa for the untreated soil, which is approximately a 33.6-fold enhancement of strength. Likewise, for the same mix, the UCS values at 14 and 28 days were 630 and 980 kPa, corresponding to an increase by a factor of 18.5 times and 28.7 times, respectively.

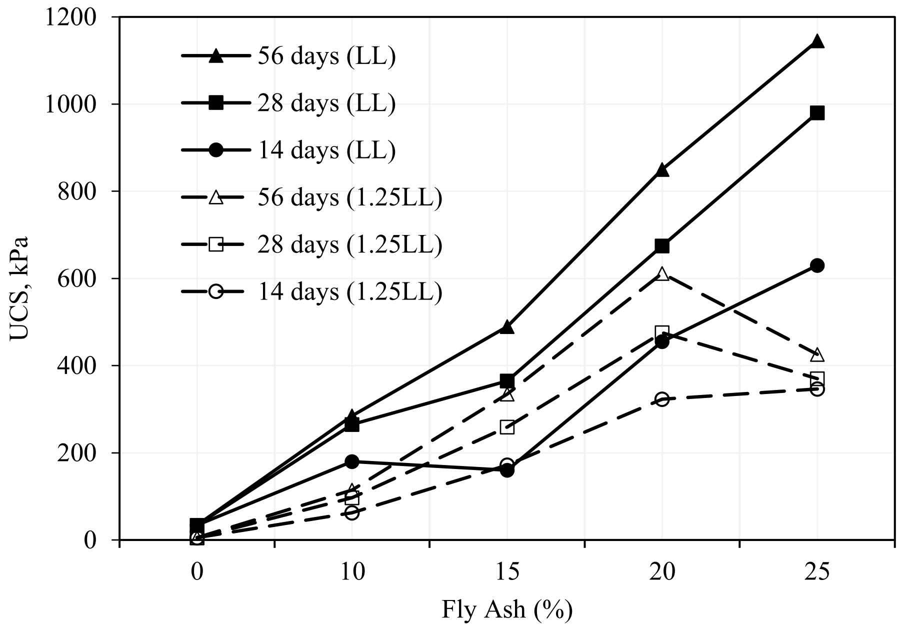

Figure 7: UCS (kPa) at Different Fly Ash (%) at Various Curing Age

It can be seen that the UCS at increases consistently with increasing binder content within the optimum range and then decreases slightly when soil treated at a moisture level of 125% of liquid limit. The strength gained was almost identical for different curing periods as binder content increased up to 20%. Beyond this, the pattern of variation started to differ. For instance, at 14 days, the maximum UCS attained for the treated soil at 25% fly ash was about 346 kPa, which is almost 69 times higher than the untreated soil of 5 kPa, while at 28-day and 56-day curing periods, optimum strength was at 20% fly ash with UCS values of 476 kPa and 612 kPa, which are about 95 times and 122 times higher than the untreated condition. The slight reduction in strength beyond the optimum binder content may be related to the insufficiency of water for complete reaction and restricted ion mobility due to the excessive solid phase. Further, inadequate mixing and the presence of entrapped air voids could also be responsible for the strength reduction, especially since no mechanical compaction was applied during specimen preparation.

3.2 Effect of Water on UCS

The dependence of strength development on total water content, that is the sum of soil moisture and additional water used in the preparation of geopolymers, is shown in Figure 8. The UCS decreases non-linearly with increased water content. This phenomenon is similar to the well-understood strength-water/cement ratio relationship in traditional cement stabilization, as shown in Figure 9. The highest value of UCS occurred at the smallest water-to-binder ratio of 1.69, which suggests that too much water has an adverse effect on geo-polymerization because of increased pore volume and reduced compactness of the stabilized matrix.

3.3 Stress-Strain Pattern

From the stress–strain curves (Figures 10–12), it is observed that geopolymer-stabilized soil with lower strength can undergo greater axial deformation before failure, while soil exhibiting higher strength tends to fail at lower strains, indicating a brittle nature of the treated soil. This structural response is crucial for foundation design on geopolymer-treated grounds. Therefore, a lower strain allowance should be considered for high-strength soils to mitigate the risk of brittle failure, whereas a higher strain margin may be permitted for low-strength soils to ensure ductile behavior and prevent sudden collapse.

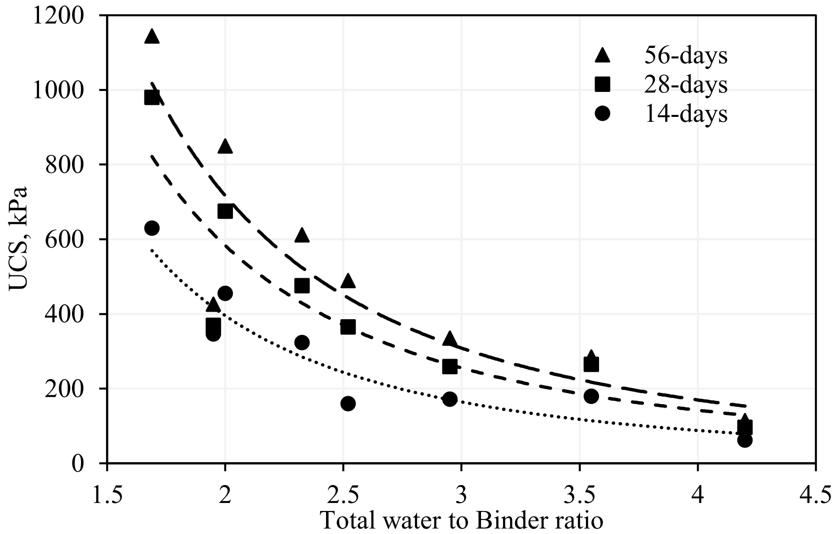

Figure 8: UCS (kPa) at different total water to binder ratio

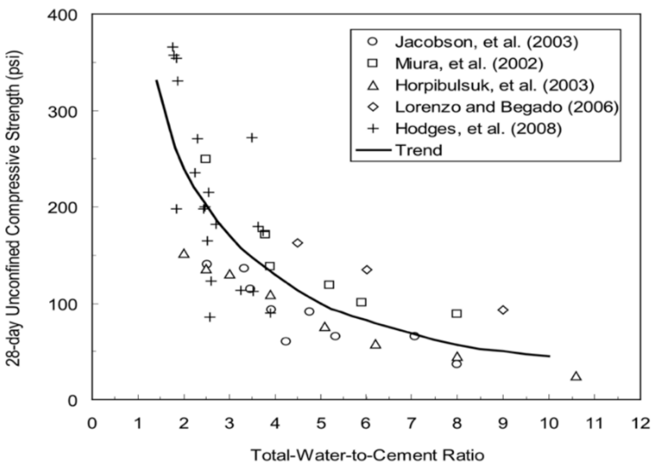

Figure 9: UCS (psi) vs. total water to cement ratio in different studies (Federal Highway Administration Design Manual, 2013)

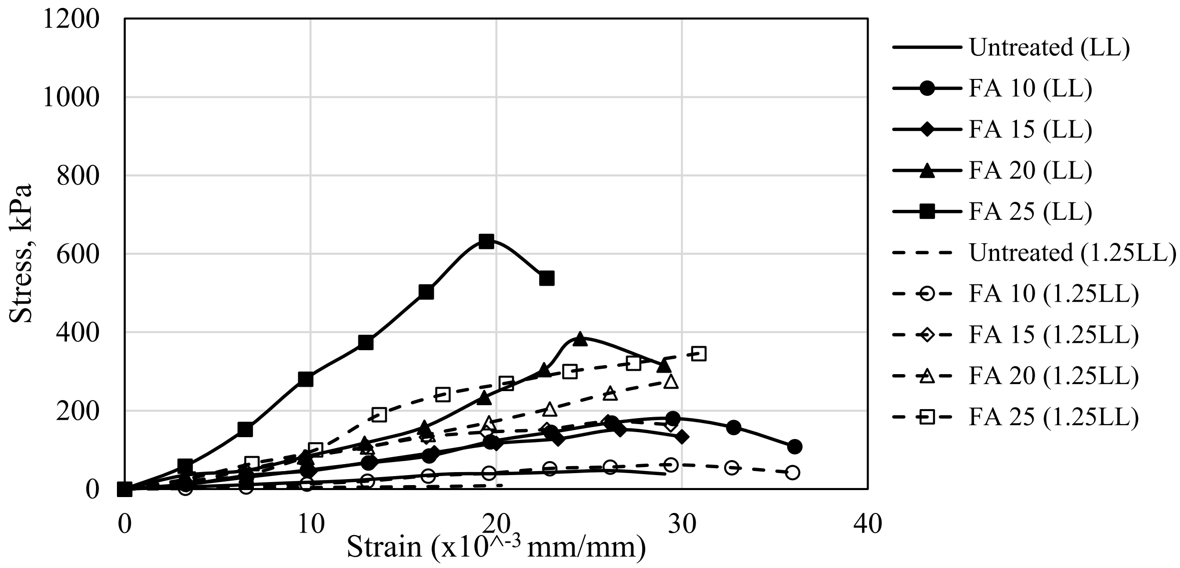

Figure 10: Stress-Strain Curve for 14-days Strength

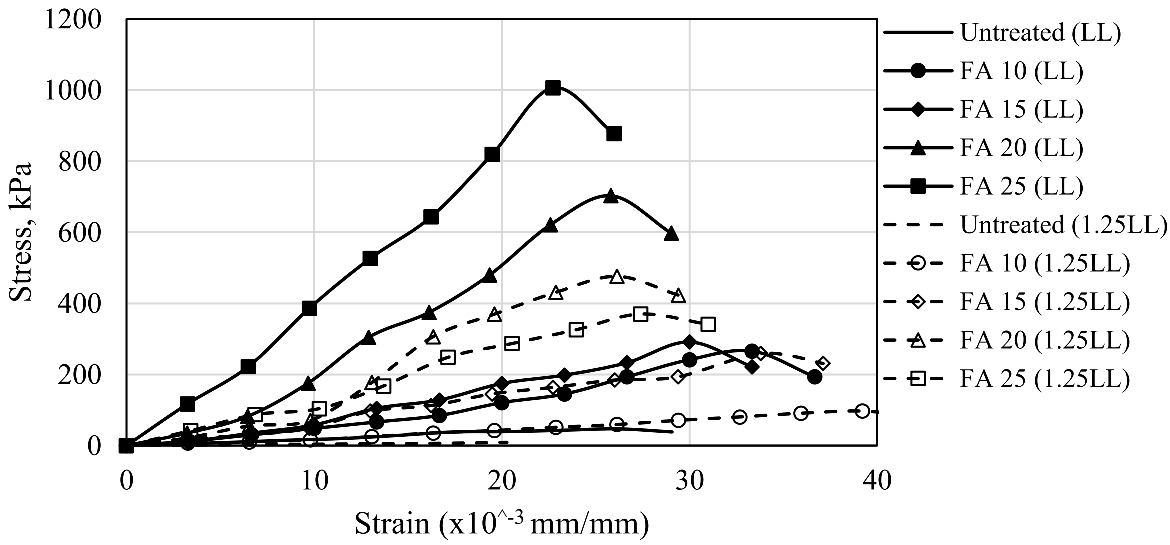

Figure 11: Stress-Strain Curve for 28-days Strength

4. CONCLUSIONS

It has been observed that the geopolymer-based deep mixing method is highly effective for strength improvement in high silt content soils, presenting both economic and environmental benefits. The maximum UCS was obtained at a fly ash content of 25% by dry soil weight at 56-days of curing period when the soil is treated at a moisture content of liquid limit and the alkali activator-binder (L/P) ratio was taken as 0.5. With an increasing moisture level of 125% liquid limit, the fly ash 20% has the maximum UCS. Additionally, the stress-strain behavior analysis provides valuable insight for designers in estimating strain allowances in the design phase. While the UCS obtained for geopolymer-stabilized soils is comparatively lower compared to conventional cement stabilization, the approach has great prospects in view of sustainability in ground improvement. Future large-scale studies covering different types of soils and their moisture conditions with different binder and additive proportions are encouraged in order to better substantiate the performance of geopolymer stabilization

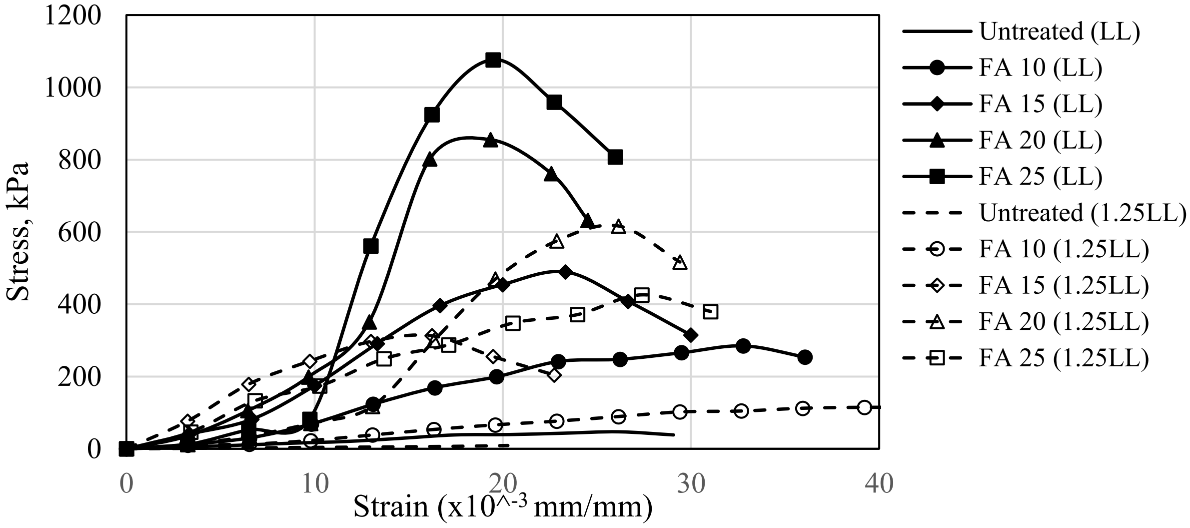

Figure 12: Stress-Strain Curve for 56-days Strength

Being an industrial by-product that can replace cement and, therefore, reduce CO_2 emissions, the use of fly ash in soil stabilization is not only sustainable but also prevents environmental hazards due to uncontrolled fly ash disposal. Further studies can be conducted on wide ranges of soil to observe the impact of geopolymers on the development of compressive strength, shear strength, consolidation, settlement, bearing capacity etc. with detailed mineralogical and microstructural studies using X-ray Diffraction (XRD) Pattern and Scanning Electron Microscopy (SEM) are encouraged for a better understanding of the bonding mechanisms involved. Field-scale studies are also recommended in order to find out about the improvement that such mixtures actually provide to foundation performance under realistic conditions. Efficiency of other kinds of waste materials (such as Blast Furnace Slag, Rice Husk Ash, Cement Clinker Dust etc.) can be observed by using as geopolymer with other activators in soil treatment. Machine learning models can also be developed to predict the geopolymer treated soil strength.

5. ACKNOWLEDGEMENTS

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6. DECLARATION OF USE OF AI

The authors declare that no artificial intelligence (AI) tools were used in the research methodology, data analysis, or experimental processes reported in this manuscript. AI tools (Chatgpt and Quillbot) were used only for language improvement, grammar checking, and formatting assistance to enhance clarity and readability of the manuscript. The scientific content, analysis, interpretation of results, and conclusions are entirely the work of the authors.

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