SAND-GEOPOLYMER MIXTURE ON STRENGTH DEVELOPMENT OF SOFT SOILS: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

Soft soils with high percentage of silts have a low bearing capacity and have become a problematic concern for deltaic countries like Bangladesh due to the presence of such soft soils to a considerable depth. The problem is associated with huge foundation costs as most structures on such soft soil require pile foundation. Considering this fact, research has been conducted extensively to find a rational method of improving the strength of soft soils. Replacing soft soils with binding agent, like cement or lime, has long been used despite their detrimental effects on the environment.

Realizing the context, a recent trend has been looking to utilize waste materials with soft soils, keeping the primary aim to enhance the shear strength of soils. Fly Ash, a by-product from coal-based power plant, are available in huge quantity; to date, no significant environmental threat has been recognized. Sand is also an available geo-material found through many geological processes or extracted by dredging the riverbed or sea. Therefore, an attempt can be made to partially replace the soft soils by combining fly ash and sand.

Adding a binding agent may enhance the strength to a considerable limit, as proven by many researches. Summing up the findings, this research conducts a series of experimental investigations using different combinations of sand and geopolymer mixture. Sand percentage has been varied from 5 – 15% by weight, while geopolymer contents have been considered between 5-25%. An unconfined compression test has been carried out on the composite soils at two different curing days.

The result shows considerable strength development with the increasing percentage of sand-geopolymer mixture. From the wide range of experimental observations, the sand-geopolymer mixtures having 10% sand provide the maximum strength development. The maximum geopolymer of 25% has shown the greatest result in soil-sand-geopolymer mix while 15% geopolymer has the maximum strength in soil-geopolymer mix without sand which gives an understanding about the proportion of geopolymer mix while stabilizing the soil with or without sand.

From the stress-strain behaviour, greater strain at failure has been found for lower strength soil mix and vice-versa. It can be suggested to consider the design strength of soil for strain allowance while designing structure on geopolymerized soil. At higher strength, low allownace of strain should be provided while higher strain allowance can be applicable for lower strength. Further investigation, to be specific microscopic investigation, will provide insight into the strength development procedure.

Keywords: *Bearing capacity, Ground improvement, Soft soils, Sand-Geopolymer, UCS*

1. INTRODUCTION

Soft silts are a type of soil components that obstruct the design and construction processes due to their low bearing capacity. As a result, investors and engineers typically decide against investing in construction projects in locations with soils having such problems. Construction on problematic soils is now becoming the primary option in heavily populated places. These soils have very low strength to carry the load of the structures eventually demand deep pile foundation for a low to medium rise building. Besides, soft soil with montmorillonite clay mineral can absorb water, even tiny changes in moisture content cause the soil's volume to alter significantly. This behaviour of the clay soil results in swelling and shrinkage, which creates hazardous conditions for infrastructures built on the foundation of the soil. Therefore, soil stabilization is essential for eliminating this restriction. To adjust a soil's geotechnical properties to match project requirements, the stabilization technique involves mixing two or more different soils, or combining a soil with another geomaterial or chemicals.

Power plants and other industries in developing nations like Bangladesh have the opportunity to expand quickly, producing enormous quantities of industrial by-products like fly ash, pond ash, bottom ash, etc. that are enriched with both alumina and silica. Although some of these by-product materials are used by cement companies, it is still difficult to dispose of them safely because of environmental concerns. Members of the inorganic polymer group known as geopolymers directly utilise the alumina-silicate obtained from materials like fly ash as their foundation material. Although recent research is being done to employ geopolymer for ground enhancement, its field applications are yet only for concrete. On the other hand, the most typical method for enhancing problematic soil is the application of conventional soil stabilizing admixtures. The goal of the current study is to investigate the possibility of geopolymer stabilization for a particular soft soil that has been carried out specifically in the laboratory by slurry method with varying proportion of geopolymer and sand.

1.1 Literature Review

Researchers have been looking for effective and inexpensive remedial techniques because soft soils provide a risk for structures to fail. Numerous methods have been developed to this point, and the performance of those methods have been confirmed by experimental and in-situ applications. One method to solve the differential swelling issue is to partially replace soft soils with hard soil. In addition, treating soft soils with stabilizing agent(s) is a wise strategy in effectively reducing the related problem. The geotechnical qualities of soil are improved when common agents like lime, cement, and industrial wastes like fly ash and slag are added. However, due to the lack of binding agent present, the stabilizing agent by itself is unable to enhance the characteristics of soils. In the current situation, adding some additives together with the stabilizing agent helps to speed up the binding process and, in many cases, increases in strength.

In a study, the use of alkali-activated fly ash for the building of deep mixed columns in loose soil relation showed the effects of the initial moisture content of the compacted soil sample and the compressibility before & after fly ash treatment ere also observed (Mohammadinia et al., 2019). In order to compare the effects of deep soil mixing with and without the addition of FA, a study was undertaken on Strength and stiffness optimization of fly ash-admixed DSM erected in clayey silty sand (Ekmen et al., 2020).

Numerous studies have been done on the subject of alkali additive effects on boosting soil hardness and effectiveness. In addition, numerous researchers have used a variety of binders and additives in their experimental investigations to stabilize loose soils using the Deep Soil Mix (DSM) approach. The ideal soil-grout mixture met the strength and leachability requirements and contained 6% cement and 2% bentonite. Two types of binders were utilized in another study, one made of cement and finely ground fuel ash, and the other of cement and bentonite (Al-Tabba et al., 2000). Additionally, they demonstrated how the samples' compressive strength decreased as the moisture level increased.

In a different study, Deep Soil Mix columns performances were obsereved when lime and cement were mixed (Larsson & Nilsson, 2005). The impact was examined on different binders, including as cement, bentonite, mining sand, and calcium colored, on hand-mixed soil columns (Islam & Hashim, 2009). An investigation was made to observe how cement admix affected Bangkok clay in order to identify the crucial elements influencing the strength of DSM columns (Horpibulsk et al., 2011).

Shear strength can be improved with geo-polymerisation process. A study on sand stabilsation with geopolymer made from alkali activated ground granulated blast-furnace slag (GGBFS) has shown that consolidated drained tri-axial shear strength increases with increasing geopolymer content (Al-Rkaby, 2019). The maximum strength has been found at maximum of 40% of geopolymer content with 0.4 activator to GGBFS ratio and the maximum strength is 800% of soil without GGBFS. Another study on clay stabilization with fly ash and egg shell powder has shown maximum unconsolidated undrained shear strength at soil with 15% fly ash and 5% egg shell powder with 10 Molar NaOH (Diana et al., 2023).

The present study is aimed to observe unconfined compressive strength development pattern on sand-geopolymer stabilized silty soil and the stress-strain pattern

1.2 Geopolymerization Mechanism

Davidovits invented the term "geopolymer" in 1978. Geopolymer generally, an inorganic polymeric substance created when aluminosilicate sources mix with a very alkaline silicate solution. This reaction is then dried at room temperature or just a little higher. Geopolymerization reaction is the name given to the formation process.

Emperical Formula of Geopolymer:

$$Mn\{-(SiO2)z-AlO2\}\cdot wH2O \qquad (1)$$

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 Ca2+. It has amorphous to semi-crystalline three-dimensional Si-O-Al polymeric networks.

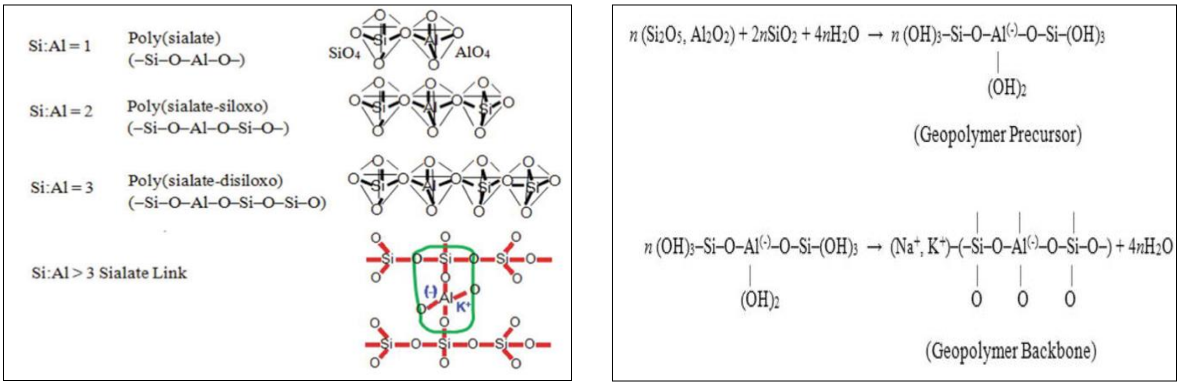


Figure 1: Schematic diagram of geopolymer formation (Bakri et al., 2012)

In order to create three-dimensional polymeric networks from amorphous aluminosilicates, chemical reactions must take place. Geopolymerization is an exothermic process. The aluminosilicate sources disintegrate into SiO_4 and AlO_4 tetrahedral units in a very alkaline media, and these units eventually take part in the polycondensation process.

2. METHODOLOGY

In this investigation, different amounts of sand (5%, 10%, and 15%) were added to soil samples. Different soil-sand mixes were then mixed with water of optimum moisture content for the current study. Afterward, samples were treated by adding different percentages of fly ash based geopolymer. The detailed discussions on the materials used, test program and procedures are given in the subsequent sections.

2.1 Materials

The materials adopted for present research was clayey soil, locally available sand, alkali activators and class F fly ash. The details of materials used are described below.

2.1.1 Soil

Soil sample was collected from the Mohamuni Pahartali, Raozan, Chittagong . Soil was collected from shallow depth, dried, pulverized and sieved through no. 40 sieve and stored in a sealed condition up to next step. From observing the raw soil, field identification and laboratory experiments, the soil was classified as soft sandy silt.

(a) (b)

Figure 2: Parent soil (a) before and (b) after drying

Table 1: Field Identification result [ASTM D-2488]

Test	Result	Probable Identification
Dry Strength	Low	Silt
Dilatancy	Slow	Silt
Plasticity	Low	Silt

Table 2: Index Properties of Parent Soil

<table>
<tr><td>Grain Size Distribution [ASTM D 422 – 63]</td><td>Fine Content (%)</td><td>57.58</td></tr>
<tr><td rowspan="2">Atterberg Limit [ASTM D 4318 – 10]</td><td>Liquid Limit (%)</td><td>40</td></tr>
<tr><td>Plastic Limit (%)</td><td>31</td></tr>
<tr><td colspan="2">USCS Soil Classification [ASTM D2487 – 11]</td><td>ML (Sandy Silt)</td></tr>
<tr><td colspan="2">Specific Gravity (%) [ASTM D 854 – 14]</td><td>2.66</td></tr>
<tr><td>Standard Proctor Test [ASTM D698 − 12]</td><td>Optimum Moisture Content, (%)</td><td>23.15</td></tr>
</table>

2.1.2 Sand

Local sand with an FM of 1.60 was used in soil geopolymer mix. The Grain size distribution curve of the sand is illustrated in figure.

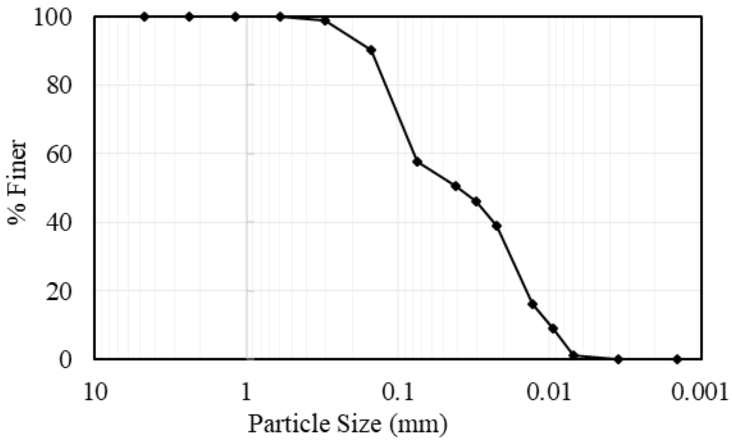


Figure 3: Grain Size Analysis of Parent Soil

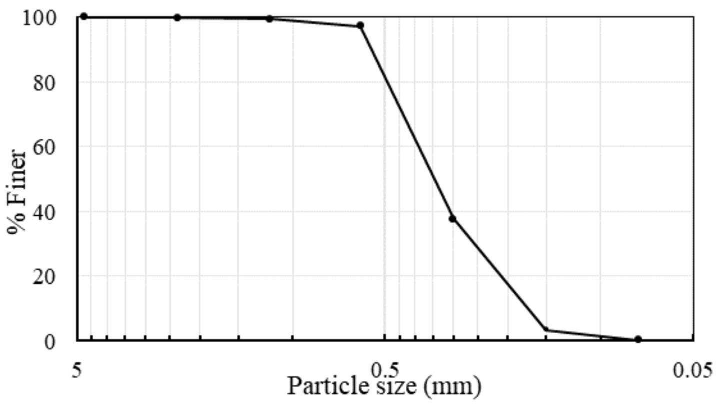


Figure 4: Grain Size Analysis of Sand

2.1.3 Fly Ash

Fly ash is a type of material by-product created by coal-based power plants. Before the flue gases reach the chimneys, electrostatic precipitators or other particle filtration equipment in modern coal-fired power plants sort out fly ash. Depending on the origin and makeup of the coal being burned, the chemical composition of fly ash varies significantly. According to ASTM standard, there are two different classifications of fly ash: class F and class C. The primary difference between these groups is the ash's calcium, silica, alumina, and iron content. Although no active cementing activity was seen for the same, Class F fly ash comprises silica and alumina as major components. On the other hand, Class C fly ash is a self-cementing ash with more than 20% CaO. (lime). Class F fly ash was used to create the geopolymer in the current experiment.

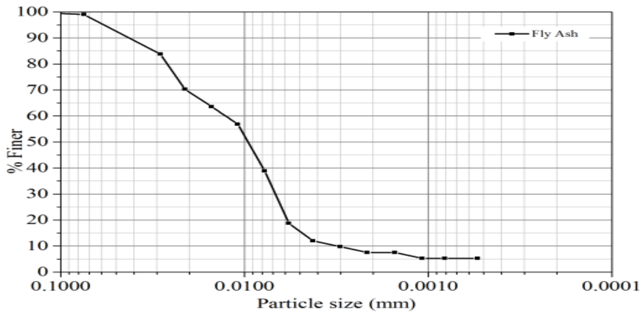


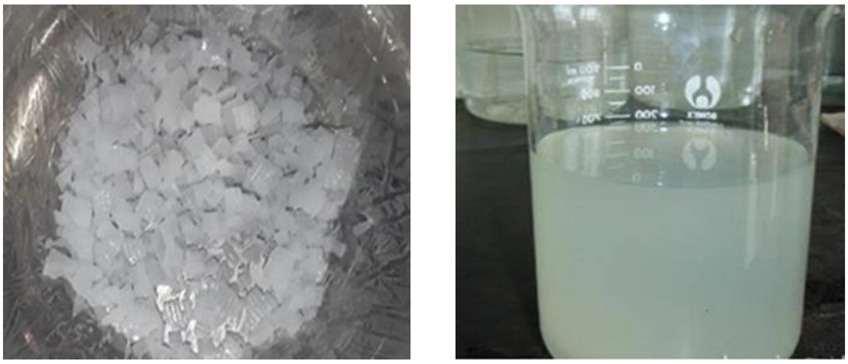
Figure 5: Grain Size Analysis of fly ash (Debanath, 2019)

2.1.4 Alkali Activator

The sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) utilized as the alkali activator in this work were purchased from a nearby market. The inorganic solid chemical sodium silicate is white in hue. The bulk density of sodium hydroxide (NaOH), a solid pellet-type substance that is corrosive in nature, is 930 kg/m3. To make sodium hydroxide solution for application, sodium hydroxide pellets were dissolved in water which. Finally, an alkali solution was made by combining these two chemicals in a 1:2 (NaOH: $Na_2SiO_{3)}$ ratio to create the geopolymer employed in this work.

2.2 Material Proportion

All the materials are taken as the precentage of dry parent soil. Sand was used as 0%, 5%, 10% & 15% of dry weight of soil. Fly ash of 5%,10%,15%, 20% & 25% were mixed with 50% alkali activator by weight of fly ash. The mix of sodium hydroxide (NaOH) and sodium silicate (Na_2SO_3) at a ratio of 1:2 was taken as alkali activator. Sample designation and properties are listed in the Table 2.



(a) (b)

Figure 6: (a) Sodium Hydroxide pellets; and (b) Sodium Silicate solution

2.3 Mixing and Sampling

At first, the soil was brought to the Optimum Moisture Content level by mixing 23.15% water. Alkali activator and water of 0.45 water to binder ratio to get a workable mix (Nabi et al., 2023). The mix was kept for approximately 30 minutes to eliminate the heat generate by chemical reaction. Geopolymer was prepared by mixing Fly Ash (FA) and the alkaline solution. Then the geopolymer, moist soil and sand were manually mixed for 10 minutes so that homogenity could be obtained throughout the mix.


(a)


(b)

Figure 7: Cured sample before testing; (b) Sample is being tested on Unconfined Compressive Strength Testing machine

Sample was prapred in a 38mm by 76mm cylindrical mold in 3 layers. Mild tamping was done to eliminate the air bubbles. 3 identitical samples were prepared for each combination and each curing age. Then the samples were kept sealed in a humid condition for curing for 14 and 28-days. The results of three samples were averaged.

Table 3: Proportioning of Material

Sand (% of dry soil)	**Binder (Fly Ash) (% of dry soil)**	**Alkali Activator (% of dry soil) ($NaOH: Na_2SO_3$ =1:2)**		
		Total (%)	**NaOH (%)**	**Na_2SO_3 (%)**
0	5	2.5	0.83	1.67
	10	5	1.67	3.33
	15	7.5	2.50	5.00
	20	10	3.33	6.67
	25	12.5	4.17	8.33
5	5	2.5	0.83	1.67
	10	5	1.67	3.33
	15	7.5	2.50	5.00
	20	10	3.33	6.67
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	10	5	1.67	3.33
	15	7.5	2.50	5.00
	20	10	3.33	6.67
	25	12.5	4.17	8.33

3. ILLUSTRATIONS

Unconfined compressive strength (UCS) is tested for 14-days and 28-days curing periods according to ASTM D2166. The effect of geopolymer treatment on the strength characteristics of soft soil is illustrated in the following subsections.

3.1 Effect of Geopolymer on UCS

The unconfined Compressive Strength (UCS) has been found to be increasing with the increase of geopolymer content in presence of sand. Maximum geopolymer content of 25% has shown the maximum strength.

Sand has an impact on strength development which is illustrated in the figure. If there is no sand in geopolymer mix, the strength is higher than the soil geopolymer mix with sand. Without sand, soil geopolymer mix has shown increasing strength at lower geopolymer content up to 15% and tends to decrease after this optimum level. At 25% of geopolymer content, strength has fallen and becomes lower than soil-geopolymer-sand mix both for 14- days and 28- days curing age (figure 8-9). The surplus of geopolymer content compared to the soil and water might be the possible cause of the strength reduction.

The optimum amount of sand has been found to be 10% of dry soil. Strength tends to decrease when the amount is increased or decreased from this optimum level. Sand provides an interlocking bond with the geopolymer which results in growth in strength. At a lower than optimum level, the interlocking is minimum whereas at greater than optimum level, excess sand causes less geopolymer-soil bond results in lower strength development.

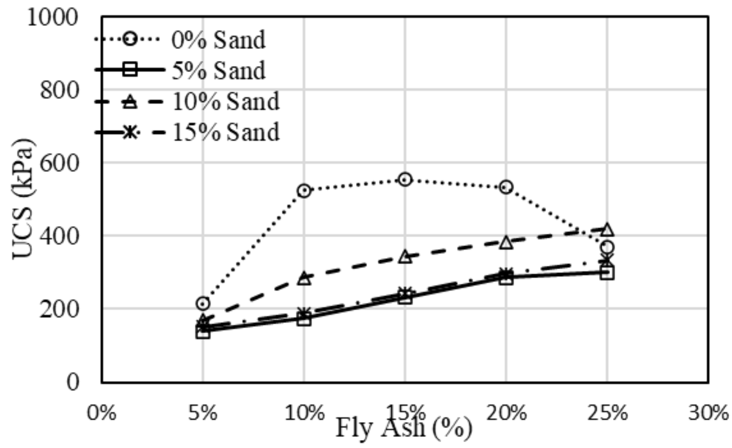


Figure 8: UCS (kPa) at different Fly Ash (%) at 14-days Curing age

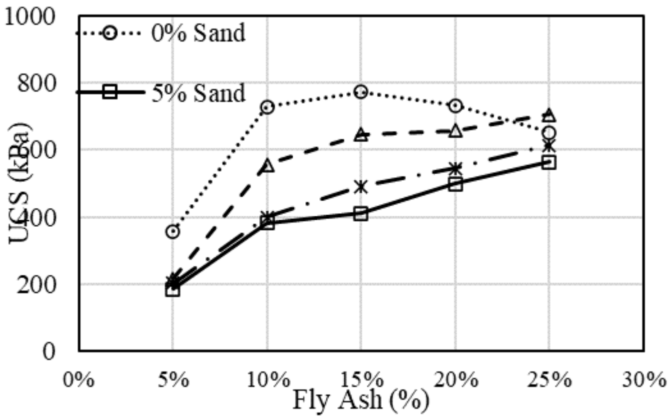


Figure 9: UCS (kPa) at different Fly Ash (%) at 28-days Curing age

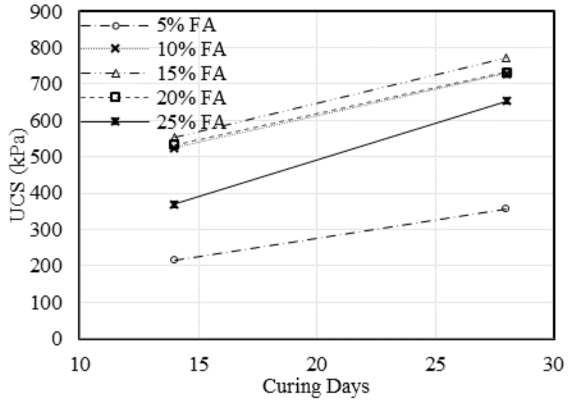
Geo-polymerisation with sand shows almost a linear increasing in strength with increasing geopolymer content while 5% sand proportion shows a slight decreasing rate at higher geopolymer content of greater than 20% for 14 days curing period. At 28-days strength, initial rate of increament is higher with the increase in geopolymer. When the soil mix has 5% sand, rising rate of strength increases initially which decreases after 10% of geopolymer and again rises after 15% geopolymer. At 10% sand, the rate of strengthening reduces at 10% and increasing again after 20% geopolymer content. The variation in strengthening rate might be caused by the presence of void and insufficient reaction due to less contact between soil and geopolymer caused by void.

The effect of fine content on geo-polymerisation process can also be observed from the above discussion. The stabilized soil shows maximum strength at maximum geopolymer content without sand. After adding sand, the strength decreases compared to the soil geopolymer mix without sand. The possible cause might be the lower surface area of coarser particles of sand hinders the reaction with geopolymer. Hence, soil mix with 10% sand shows higher strength than 5% sand. The voids present between the soil and sand might be higher in 5% sand mixed with soil-geopolymer which results in lower strength.

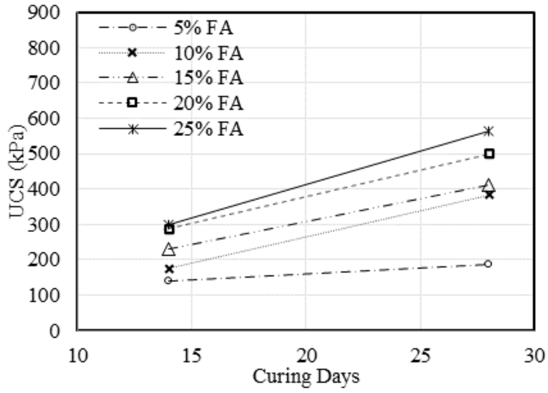
3.2 Effect of Curing age on UCS

The unconfined compressive strength tends to be increasing with the increase of curing time. At a very low geopolymer content (i.e. 5%), slight increase in strength has been observed with increasing curing days form 14 days to 28 days as there has been a little reaction to form bonds between soil and geopolymer (figure 10).

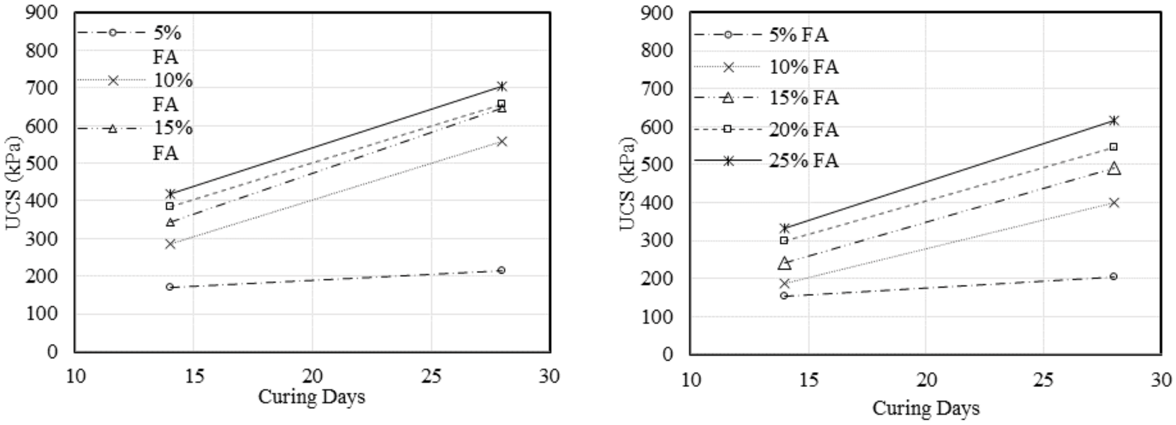
With the increase in geopolymer content, the rate of strength development also increases with curing age. When the geopolymer content increases to 10% or greater, the rate of rising the UCS increases and 28 days strength has been found to be increased more than 200% than 14 days strength in soil geopolymer mix with 10% sand.`



(a)



(b)



(c) (d)

Figure 10: UCS (kPa) at Geopolymerized soil (a) without sand, (b) 5% sand, (c) 10% sand and (d) 15% sand

3.3 Stress-Strain Pattern

From the Stress-Strain curve in figure 11-16, it can be seen that the geopolymerized soil undergoes a longer strain before failure when the breaking stress is lower. As the strength is higher for longer curing period, the failure strain is also lower at 28-days curing age than that of 14-days. At the minimum of 5% geopolymer content, maximum strain has been found 6.7% before its failure stress at 14-days curing age and 6.2% at 28-days age when there is 15% sand. At 5% sand, 6.33% and 4.67% strain have been observed for 14-days and 28-days curing age restively whereas the values are 4.83% and 4.22% for 10% sand which is the optimum sand proportion.

The strain at the maximum failure strength at maximum geopolymer content of 25% has been found to 4% at 14-days age and 2.5% at 28-days curing age when the sand content is 5%. 2.83% strain for 14-days and 2% strain for 28-days have been observed for maximum stress at optimum sand fraction of 10% whereas 4.5% strain has been shown by the Geopolymerized soil with 15% sand irrespective of curing age.

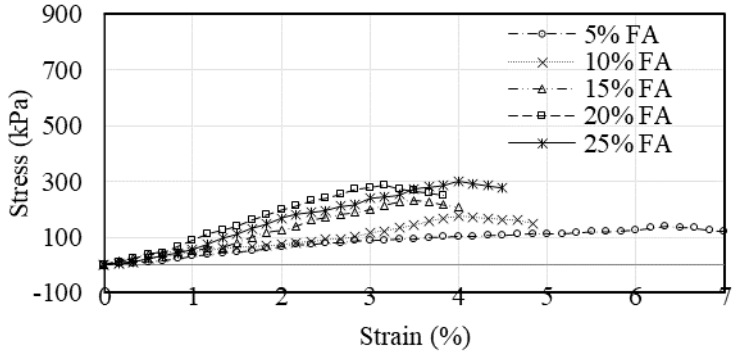


Figure 11: Stress-Strain Curve for 5% Sand at 14-days curing period

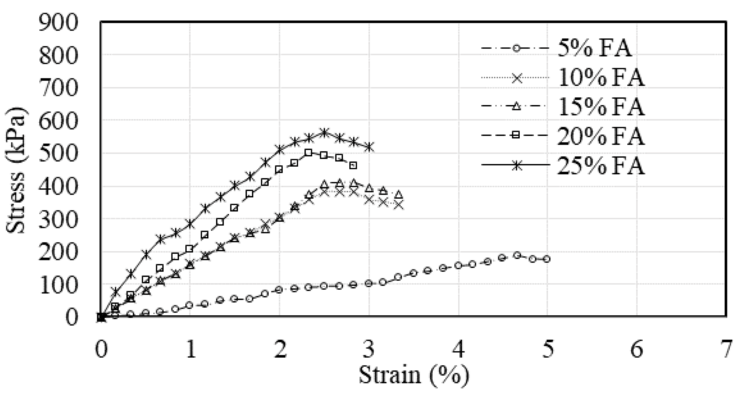


Figure 22: Stress-Strain Curve for 5% Sand at 28-days curing period

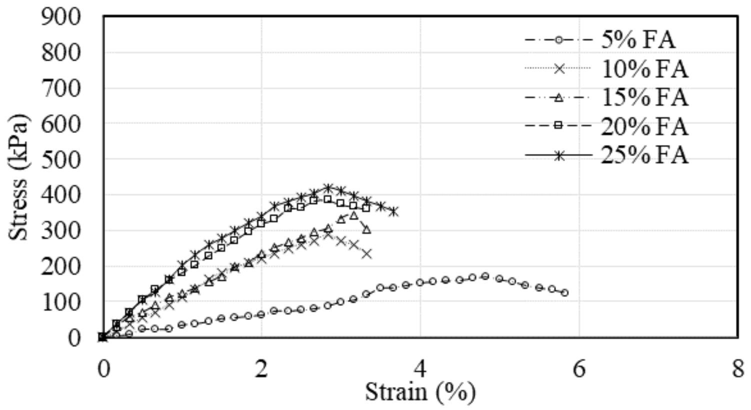


Figure 33: Stress-Strain Curve for 10% Sand at 14-days curing period

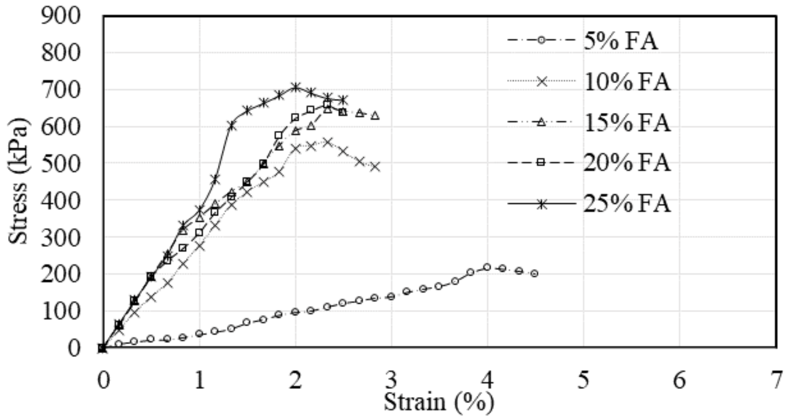


Figure 44: Stress-Strain Curve for 10% Sand at 28-days curing period

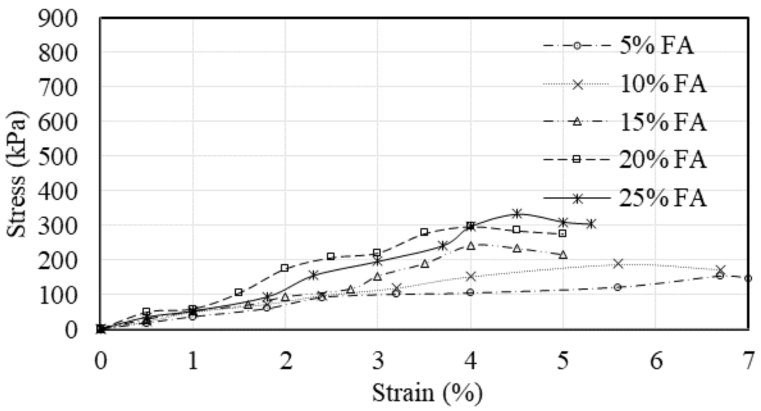


Figure 55: Stress-Strain Curve for 15% Sand at 14-days curing period

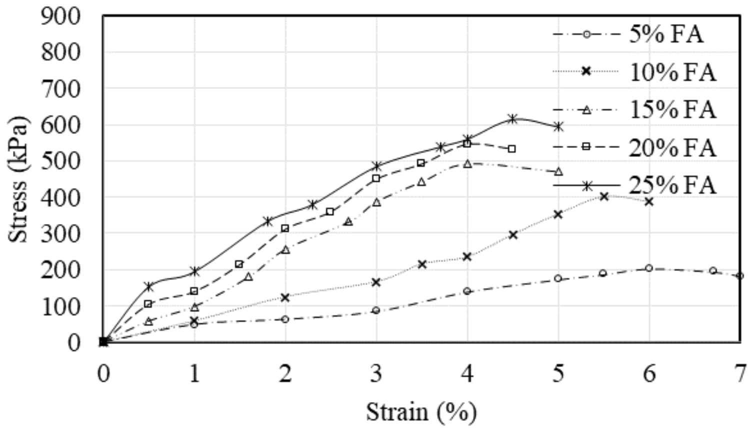


Figure 66: Stress-Strain Curve for 15% Sand at 28-days curing period

4. CONCLUSIONS

From the above discussion, it can be concluded that the increasing geopolymer proportion results in increase in strength to a maximum of 15% geopolymer for the silt type soil when there no sand is added. If sand-geopolymer mix is used, optimum amount of sand (i.e. 10% of dry soil) should be used with maximum possible geopolymer proportion to get the maximum strength. Sand-geopolymer based stabilization can be carried out when the soil has some plasticity and strength requirement is not much higher as sand decreases the strength. Using sand with geopolymer can also be an approach where sand is easily available and cost effective approach is requirement.

Since Shear strength is dependent on cohesion and angle of internal friction and previous studies showed considerable increase in shear strength in geopolymer stabilization of clay and, it is expected to increase shear strength in silty soil with geo-polimerisation process. Further investigation on shear strength development pattern in sand-geopolymer stabilized on silt can be carried out to observe the effectiveness of geopolymer.

Soil mix with higher strength undergoes lower strain which can be considered in design. The suggestion for strain allowance while designing structure on geopolymerized soil is to consider the design strength of soil. At higher strength, low allownace of strain should be provided and higher strain for lower strength. Further investigation can be carried out with different kind of soil (i.e clay, sand, organic soil etc.) and different amount of alkali additives and water. Mineralogical analysis can be carried out for the analysis of microstructural bond formation.

5. ACKNOWLEDGEMENTS

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REFERENCES

Al-Rkaby, A. H. J. (2019). Evaluating Shear Strength Of Sand-Ggbfs Based Geopolymer Composite Material. Acta Polytechnica, 59(4), 305–311. Https://Doi.Org/10.14311/Ap.2019.59.0305

Al-Tabba, A., Ayotamuno, J., & Martin, R. J. (2000). Soil Mixing Of Stratified Contaminated Sands. Journal Of Hazardous Materials , 72(1), 53–75.

Bakri, A. M. Mustafa Al., Kamarudin, H., M., Bnhussain, A., Rafiza, R., And Zarina, Y. (2012). Effect Of Na2sio3/Naoh Ratios And Naoh Molarities On Compressive Strength Of Fly-Ash-Based Geopolymer. 109(5), 503–508.

Debanath, O. C. (2019). Performance Evaluation Of Geopolymer Stabilized Soil. Department Of Civil Engineering, Chittagong University Of Engineering And Technology. .

Diana, W., Hartono, E., Pratama, W. E., & Wardani, W. I. (2023). Shear Strength Characteristic Of Geopolymer Fly Ash And Egg Shell Powder Stabilized Clay Soil. E3s Web Of Conferences, 429. Https://Doi.Org/10.1051/E3sconf/202342904024

Ekmen, A. B., Algin, H. M., & Özen, M. (2020). Strength And Stiffness Optimisation Of Fly Ash-Admixed Dcm Columns Constructed In Clayey Silty Sand. Transportation Geotechnics, 24. Https://Doi.Org/10.1016/J.Trgeo.2020.100364

Horpibulsk, S., Rachan, R., Suddeepong, A., & Chinkulkijniwat, A. (2011). Strength Development In Cement Admixed Bangkok Clay: Laboratory And Field Investigations. In Soils And Foundations (Vol. 51, Issue 2). Japanese Geotechnical Society.

Islam, Md. S., & Hashim, R. (2009). Bearing Capacity Of Stabilized Peat Column Using Hand Operated Cone Penetrometer. Journal Of Applied Sciences, 9(10), 1968–1973.

Larsson, S., & Nilsson, L. (2005). Findings Of The Work On Influencing Factors On The Installation Process For Lime-Cement Columns.

Mohammadinia, A., Disfani, M. M., Conomy, D., Arulrajah, A., Horpibulsuk, S., & Darmawan, S. (2019). Utilization Of Alkali-Activated Fly Ash For Construction Of Deep Mixed Columns In Loose Sands. Journal Of Materials In Civil Engineering, 31(10). Https://Doi.Org/10.1061/(Asce)Mt.1943-5533.0002878

Nabi, M. H., Acharjee, S., Banu, M. M., & Rahman, M. A. (2023). Effect Of Geopolymer Contents On Strength Development Of Soft Soils. Architecture And Civil Engineering, 12–14.