

Strength Development of Alkali Activator Treated Clayey Sand Soils

Tugba Eskisar
Ege University
Dept. of Civil Engineering
Izmir, Turkey

Abstract:- The focus of this study is the alkali activator treated clayey sand soils under different curing periods. The unconfined compressive strength developments due to this process were investigated. The specimens were subjected to curing periods varying between 7 and 90 days. The effects of activator type, alkali activator application method, curing period and the effect of 3 cycles of freeze-thaw on the unconfined compressive strength of the soils were determined. It has been found that different alkali activator types affect the success of application method. Longer curing periods also helped to increase the strength of the specimens. The untreated clay specimens showed an unconfined compressive strength of 316 kPa, however, with proper treatment application method 2895 kPa was observed after 90 days. The application of 3 freeze-thaw cycles, decreased the strength of the soils. Major loss of strength rate observed was 46%.

Keywords:- Clayey Sand; Alkali Activator; Freeze-Thaw; Unconfined Compressive Strength.

I. INTRODUCTION

In geotechnical engineering applications, it is possible to use alkali activators in the field of soil improvement. Alkali activators are used to create a solid medium and the end product is so-called geopolymers and their performance has been tested and evaluated by researchers in many areas. Further research has shown that the application of the geopolymers in civil engineering studies involving the structural and geotechnical branches had promising results [1].

Obtaining geopolymers by using alkali activators are effective in replacing the cement which is used as a stabilizing material in soil improvement. This innovative product has a much lower carbon footprint than cement and also eliminates the high levels of carbon dioxide released during cement production [2].

Phetchuay et al. [3] investigated the development of the strength of the clay and its carbon footprint by forming a geopolymer made of clay soil, calcium carbide residue, and fly ash. The alkali activator used was a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH). The strength of the clay soil was found to be dependent on the fly ash content and NaOH concentration. The carbon footprints of the alkali activator treated soils were 22-43% lower than cement-stabilized soils.

The clay soils were proven to have the potential to be improved by the addition of sodium silicate. Moayedi et al. [4], treated kaolinite clay with sodium silicate in a stabilization application. The addition of 5 Mol/L sodium silicate showed the highest unconfined compressive strength values.

Ghadir and Ranjbar [5] compared the mechanical performance of clay soil stabilization using volcanic ash based geopolymer and Portland cement. It was observed that Portland cement could be applied successfully in wet environments and geopolymers were more efficient in dry conditions. Increasing the alkali activator and alkali activator / clay molarity increased the compressive strength of the soil. In this study, single phase geopolymerization application with an alkali activator was performed on clayey sand specimens. As can be seen from the literature review, the studies with clayey sand are quite limited. Therefore, alkali activator treatment causing geopolymerization of clayey sand was taken into consideration. Two different ratios of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions were used as alkali activator ingredients. Two different application methods have been tried in which the temperatures were variable during the geopolymerization process. In these methods, the effect of curing period, and the freeze-thaw effect were investigated. The results of this study were interpreted by means of unconfined compressive strength values of the specimens.

II. MATERIALS AND METHODS

Index properties of clayey sand soil is given in Table 1. Relevant ASTM standards were followed when determining the index properties of the soil (ASTM D2487 [6]; ASTM D4318 [7]).

Property	Value
D ₁₀ (mm)	0.05
D ₃₀ (mm)	0.08
D ₆₀ (mm)	0.12
Coefficient of uniformity (C _u)	2.4
Coefficient of curvature (C _c)	1.07
UCSC Symbol	SC

Table 1:- Index properties of clayey sand

Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used to constitute the alkali activator that will trigger the geopolymerization process. The use of 8 moles of sodium hydroxide (NaOH) was preferred [8-9]. Alkali

activator was introduced to the specimens only one time, no secondary treatment was performed. Therefore, this application could be regarded as a single phase geopolymerization. The solution of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) dissolved in water acts as an activator since it triggers chemical reactions in the applied environment. However, the content of the selected activator will change the success of the application. Therefore, the most suitable activator content was determined from the results obtained by working with two different activator contents. The amounts given in percentage herein represent the ratio by weight in the solution:

Activator 1 (ACT1) was composed of 90% sodium silicate (Na_2SiO_3) - 10% sodium hydroxide (NaOH), on the other hand Activator 2 (ACT2) was composed of 70% sodium silicate (Na_2SiO_3) - 30% sodium hydroxide (NaOH). Both activators were prepared in large quantities in glass containers prior to testing and kept in an environment where they would not be affected by daylight and temperature changes, and they could not contact with open air. Thus, it was ensured that the activator contents always came from the same sources during specimen preparation.

Within the scope of the study, the effects of temperature on geopolymerization method were determined by applying these two activators. Geopolymers belong to the group of durable binder materials that harden at temperatures below 100°C [10]. Basically it was considered to investigate the effect of temperatures of 38°C and 20°C . Experiments performed at the beginning of this study, have shown that curing only at 20°C will not be sufficient to demonstrate the effectiveness of the alkali activator. For this reason, two different geopolymerization applications were decided. In the first method, the specimens were stored directly in a special 38°C temperature curing chamber. In the second method, the specimens were first stored in an oven at 80°C for 24 hours, then stored in a curing chamber at a temperature of 20°C (95% r.h.) for the duration of the cure. Keeping the specimens in an oven with a temperature of 80°C for 24 hours had triggered chemical reactions of geopolymerization [11-12].

The specimens were prepared at their standard Proctor densities. For this purpose, in order to determine the optimum water content to be used in the specimens, clayey sand was compacted with standard Proctor energy and compaction curve was obtained (Fig.1). Standard Proctor compaction tests were performed in accordance with ASTM D698 [13]. Activator 1 or 2 was added to the soil at the optimum water content of the soil. The optimum water content of clayey sand soil was 28%. The maximum dry unit weight of the soil was 18.40 kN/m^3 .

During the preparation of the specimens, firstly, the alkali activator equal to the optimum water content of the soil was added to the soil, then it is mixed until a homogeneous soil mixture was achieved. Thereafter, compaction was held in three layers under standard Proctor conditions. Specimens with a diameter of 50 mm and a height of 100 mm were prepared. Specimens were wrapped with stretch film to

protect them from unwanted external factors. The specimens were subjected to unconfined compressive testing either directly at the end of their curing period or after the application of 3 freeze-thaw cycles at the end of their curing period.

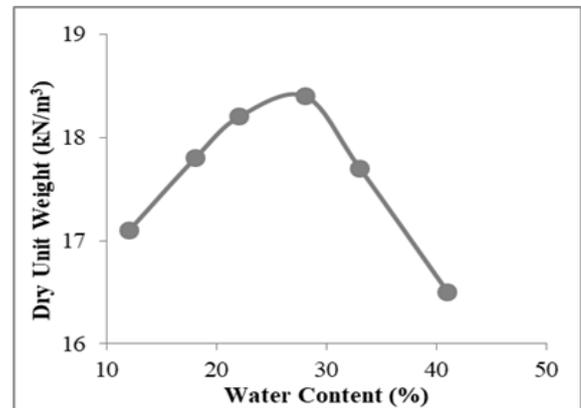


Fig 1:-Compaction curve of the clayey sand.

The unconfined compressive tests were carried out in accordance with ASTM D2166 [14]. Attention was paid that the loading rate was $1\%/min$ to be in the limits of the standard. Care was taken to complete the experiments in less than 15 minutes. All experiments were recorded by a data collector unit and after the maximum strength value was observed, the loading was continued and the decrease of the strength values was confirmed. The amount of maximum deformation was kept as 15%.

A closed system device was used in freeze-thaw experiments. The advantage of this system is that it limits the change in the pore ratio of the soil during freezing and limits the water intake of soils with the potential to swell from the outside during thawing. The use of this system allows a controlled distribution of temperature in the specimen [15-16]. Specimens that completed the curing period were frozen to -18°C . This process took 24 hours. They were then subjected to thawing at 20°C . This process took another 24 hours. A total of 48 hours was 1 freeze-thaw cycle. In this way, each specimen was subjected to 3 freeze-thaw cycles. The axial load and displacement data of the specimen were recorded in unconfined compressive test. The unconfined compressive strength determined from the recorded data was then compared with the specimens that were free of freeze-thaw process and results were achieved as the loss of strength in the specimens.

III. RESULTS AND DISCUSSION

In this study, single phase geopolymerization was applied by using two different methods on clayey sand soils. Two alkali activators composed of different ratios of Na_2SiO_3 and NaOH were used. Thus, it was possible to see which alkali activator was more suitable for which application method of geopolymerization.

Chemical reactions are affected by ambient temperature in geopolymerization [10, 17]. Two methods have been

considered to trigger geopolymerization. In the first method, the specimens were stored in a special curing chamber at a temperature of 38°C during their curing period. In the second method, the specimens were stored in an oven at 80°C for 1 day and then left in a curing chamber at a temperature of 20°C (95% r.h.) [11, 18]. The curing period was counted on a daily basis after the specimens were taken out of the oven. Both geopolymerization methods were compared in terms of unconfined compressive strength. In addition, the freeze-thaw tests was performed with a group of specimens in 3 cycles and the changes in unconfined compressive strength were investigated.

This section examines the effect of temperature, the effect of activator type, the effect of curing period and the effect of 3 freeze-thaw cycles in terms of unconfined compressive strength. Every specimen group reported in this study was composed of at least 5 specimens. The unconfined compressive strengths of at least 3 specimens that had less than 10% difference of strength were used to report the results of this study, otherwise new specimens were prepared and the tests were repeated. After this section, the “specimen” actually refers to the “specimen group” of similar specimens.

A. First Method of Application

Table 2 summarizes the unconfined compressive strength values of clayey sand (CS) specimens prepared by ACT1 and ACT2 and cured at 38°C for 28, 56 and 90 days. In this study, comparisons were made between the first and second method for 28 days specimens. Since application of the first method is at a suitable temperature for summer temperature, it is easy to apply in the field and longer term strength is investigated by this method.

In specimens where ACT1 was added at optimum water content of the soil, strength values were obtained greater than ACT2 added specimens in 28 days. It was concluded that ACT1 addition was effective. In addition, the increase in the amount of Na₂SiO₃ increased the axial displacements corresponding to the highest strength values. This means that mechanical behavior became more ductile. When the first method is applied for soil specimens, the ACT1 is a more effective activator in longer term behavior, consistent with 28 day specimens. The unconfined compressive strength (UCS) of almost 3000 kPa was reached at 90 day specimens.

Specimen	Unconfined Compressive Strength (kPa)				Axial displacement observed at 28 days specimens (%)
	1 Day	7 Days	28 Days	90 Days	
CS	316	-	-	-	2.58
CSACT1	-	585	1075	2895	2.68
CSACT2	-	413	740	2562	1.40

Table 1:- Unconfined compressive strength of specimens at different curing periods (Specimens were geopolymerized with the first method)

B. Second Method of Application

Table 3 summarizes the unconfined compressive strength (UCS) values of clayey sand (CS) specimens prepared with both alkali activators and kept in an oven at 80°C temperature for 1 day and then subjected to curing at 20°C temperature for 7 or 28 days.

It has been found that the application method of geopolymerization significantly affects the unconfined

compressive strength and even the ratio of alkali activator to be used should be selected according to the curing method. In Table 3, the strength values of the specimens which were prepared using ACT2 were greater than those of the specimens prepared using ACT1. This is the exact opposite of the situation discussed in the previous section. However, the strength levels achieved at each alkali activator ratio were also different.

Specimen	Unconfined Compressive Strength (kPa)				Axial displacement observed at 28 days specimens (%)
	1 Day	7 Days	28 Days	90 Days	
CS	316	-	-	-	2.58
CSACT1	-	747	860	1160	2.37
CSACT2	-	890	985	1236	1.42

Table 3:- Unconfined compressive strength of specimens at different curing periods (Specimens were geopolymerized with the second method)

The most significant UCS change was observed in the CSACT2 specimens and the unconfined compressive strength increased by 33%. The specimens reached the highest strength values with smaller axial deformation percentages, in other words, peak strength was obtained with brittle behavior with this application method. In clayey sand

specimens, it was observed that the improvement was achieved when ACT2 was used.

C. Amount of Alkali Activator

The effects of alkali activator addition at different ratios from the optimum water content of the soil were investigated. The results obtained in this section was obtained by working

with 15-28-40% (dry side and wet side of the optimum) of alkali activator in clayey sand specimens. In order to reduce unit costs, the conditions where the least improvement was achieved in the previous sections are represented by using second method of application when ACT1 is used. It was also determined whether it was possible to increase the unconfined compressive strength under these conditions. The curing period of the specimens in this section is 7 days. In Fig.2, it is seen that 320 kPa, 747 kPa, and 120 kPa UCS values were achieved corresponding to the alkali activator percentages of 15%, 28%, and 40%, respectively. Therefore, it was not possible to say that adding more alkali activator above the level of optimum would be beneficial to achieve higher strengths. Although alkali activator is a strong binding solution, its presence more than the optimum has no effect of creating a more rigid medium.

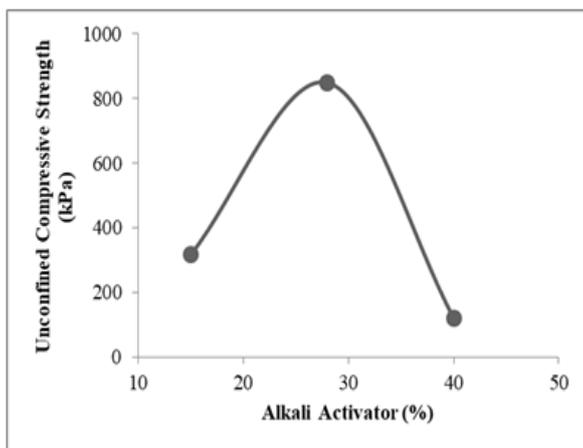


Fig 2:- UCS of 7 days specimens with different alkali activator contents.

D. Freeze-thaw Cycles

The specimens were prepared with the second method were cured for 7 days, and then they were subjected to 3 cycles of freeze-thaw. Then their resistance at the end of freeze-thaw period was determined (Fig.3). The maximum strength reduction after 3 cycles was observed in CSACT2 (46%) specimens, meaning that almost the half of strength could be lost if the soil experienced severe temperature changes during cold season.

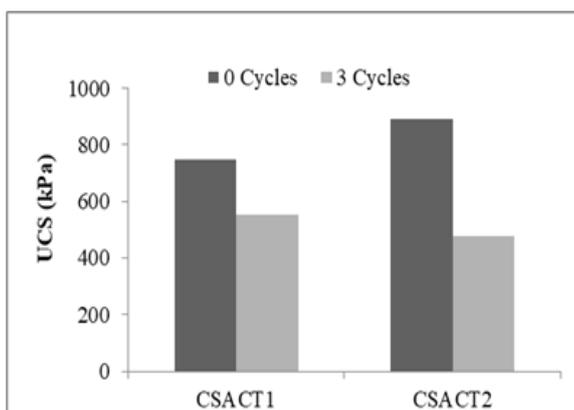


Fig 3:- Loss of strength compared with no cycle and 3 cycles of freeze-thaw.

IV. CONCLUSIONS

In this study, the effect of alkali activators prepared using and 90% Na₂SiO₃-10% NaOH (ACT1) and 70% Na₂SiO₃- 30% NaOH (ACT2), the effect of application method, the effect of changing the amount of alkali activator, the effect of curing period and the effect of 3 cycles of freeze-thaw on the unconfined compressive strength of the specimens were investigated. The main conclusions are summarized below.

- When first method was preferred, using ACT1 resulted in higher UCS values, which means increment of Na₂SiO₃ in the activator would increase the improvement of the soil.
- When first method was applied, the peak strengths obtained in CSACT1 specimens during UCS testing showed that the behavior was more ductile than CSACT2. However, in the second method of application, ACT2 was generally more effective; the peak strengths indicate a brittle behavior compared to CSACT1 specimen group. In short, the application method of geopolymerization have the power to significantly change the performance of the soil.
- In this study, the highest strength value was found to be 1075 kPa in CSACT1 specimens in 28 days. In 90 days, the same specimen group almost reached to 3000 kPa.
- Among 7 days specimens, the maximum strength reduction after 3 cycles of freeze-thaw was determined in CSACT2 specimens. The strength loss was 46%.

As a result, it has been found that the alkali activator addition could remarkably increase the strength of soils when the application method of geopolymerization is selected correctly (considering the effect of temperature). In this way, application of alkali activators in field applications in summer term could be ragerded as a promising soil improvement technique.

REFERENCES

- [1]. M.S., Abdullah, F., Ahmad, and A.M., Mustafa Al Bakri, "Geopolymer application in soil: a short review," Appl. Mech. Mat., vol. 754-755, pp. 378-381, 2015.
- [2]. S., Adhikari, M.J., Khattak, and B., Adhikari, "Mechanical characteristics of soil RAP-geopolymer mixtures for road base and subbase layers," Int. J. Pavement Eng., pp.1-14, July 2018.
- [3]. C., Phetchuay, S., Horpibulsuk, A., Arulrajah, C., Suksiripattanapong, A., Udomchai, "Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer," Appl. Clay Sci., vol. 127-128, pp. 134-142, July 2016.
- [4]. H., Moayedi, B.K., Huat, F., Moayedi, A., Asadi, and A., Parsaie, "Effect of sodium silicate on unconfined compressive strength of soft clay," EJGE, Vol. 16, pp. 289-295, 2011.
- [5]. P., Ghadir, and N., Ranjbar, "Clayey soil stabilization using geopolymer and portland cement," Constr. Build. Mater., vol. 188, pp. 361-371, November 2018.

- [6]. ASTM D2487, “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System),” pp. 1-11, 2017.
- [7]. ASTM D4318, “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils,” pp. 1-20, 2017.
- [8]. K., Somna, C., Jaturapitakkul, P., Kajitvichyanukul, and P., Chindaprasir, “NaOH-activated ground fly ash geopolymer cured at ambient temperature,” *Fuel*, vol. 90, pp. 2118–2124, June 2011.
- [9]. P., Palanisamy, and P., Suresh Kumar, “Effect of molarity in geopolymer earth brick reinforced with fibrous coir wastes using sandy soil and quarry dust as fine aggregate. (case study),” *Case Stud. Constr. Mater.*, Vol. 8, pp. 347-358, June 2018.
- [10]. P., Rovnanik, “Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer” *Constr. Build. Mater.*, Vol. 24, pp. 1176–1183, July 2010.
- [11]. M., Alshaaer, “Two-phase geopolymerization of kaolinite-based geopolymer,” *Appl. Clay Sci.*, Vol. 86, pp. 162-168, December 2013.
- [12]. M.S., Morsy, S.H., Alsayed, Y., Al-Salloun, and T., Almusallam, “Effect of sodium silicate to sodium hydroxide ratios on strength and microstructure of fly ash geopolymer binder,” *Arabian J. Sci. Eng.*, vol. 39(6), pp. 4333–4339, June 2014.
- [13]. ASTM D698, “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³)),” pp. 1-13, 2012.
- [14]. ASTM D2166, “Standard Test Method for Unconfined Compressive Strength of Cohesive Soil,” pp. 1-7, 2016.
- [15]. L., Wong, and M., Haug, “Cyclical closed-system freeze-thaw permeability testing of soil liner and cover materials,” *Can. Geotech. J.*, vol. 28, pp. 784-793, 1991.
- [16]. J.M., Konrad, and M., Samson, “Hydraulic conductivity of kaolinite–silt mixtures subjected to closed-system freezing and thaw consolidation,” *Can. Geotech. J.*, vol. 37, pp. 857–869, 2000.
- [17]. C.Y., Heah, H., Kamarudin, A.M., Mustafa Al Bakri, M., Binhussain, M., Lugman, I.K., Nizar, C.M., Ruzaidi, and Y.M., Liew, “Study on solids – to-liquid and alkaline activator ratios on kaolin – based geopolymers,” *Constr. Build. Mater.*, vol. 35, pp. 912-922, October 2012.
- [18]. M., Bing-hui, H., Zhu, C., Xue-min, H., Yan, and G., Si-yu, “Effect of curing temperature on geopolymerization of metakaolin-based geopolymers,” *Appl. Clay Sci.*, vol. 99, pp. 144-148, September 2014.