Impact of the Activating Agent Concentration in Geopolymer on the Bearing Capacity of Soft Clay Soil

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ABSTRACT

This study investigates the effect of different geopolymer concentrations (11%, 13%, 15%, 17%, and 19%) on soft clay stabilization over treatment periods of 7, 14, and 28 days. The materials, sourced from Baghdad Governorate, Iraq, were analyzed for their physical and chemical properties. Laboratory tests, including compressive strength, flexural strength, and bearing capacity were conducted. The results demonstrated that the addition of geopolymer and Fly Ash (FA) significantly improved soil properties by increasing bearing capacity and reducing settlement. The most effective concentration was identified at 15%. Furthermore, the study examined multiple injection depths of geopolymer materials with depth ratios (*L/D*) of 3, 4, and 5. The highest depth ratio (*L/D* = 5) exhibited the greatest improvement, indicating a positive correlation between the depth ratio and soil enhancement. Additionally, a progressive increase in improvement was observed over the treatment period, with the most significant results achieved after 28 days. Based on these findings, geopolymer and FA are considered effective materials for enhancing the properties of weak Clay Soils (CLs).

Keywords-fly ash; soft clay; settlement; bearing stress; activators

I. INTRODUCTION

CLs often exhibit unfavorable engineering properties, such as high shrinkage and swelling tendencies, limited bearing capacity, and high susceptibility to moisture. These limitations pose significant challenges in construction, thus soil stabilization is a widely adopted solution to improve such problematic soils [1]. This technique utilizes chemical, biological, physical, mechanical, or standard methods to modify natural soil to meet the requirements of engineering applications [2]. Several studies have demonstrated that stabilization can enhance soil strength and mitigate issues including road collapse in construction projects, by strengthening weak CL layers [3, 4].

In pavement engineering, it is essential to optimize the use of native soils to meet the nation's specific road specifications. The demand level is often influenced by challenges, such as limited supply, exceptional material quality, and considerations regarding transportation and economic constraints. Pavement constructions over weak soil layers reveal rapid and damaging disturbances leading to premature pavement deterioration. If the replacement of foundation materials with high-quality alternative soil is not feasible, stabilization using various additives, like lime, cement, FA, and other chemicals in a combined manner becomes crucial.

Many researchers have investigated the enhancement of construction materials and soil properties through the use of different additives. For instance, authors in [5] optimized the performance of compressed earth blocks with coconut shell ash, a cheaper substitute for cement. In [6], the combination of 6% sodium chloride and 10% silica fume facilitated an appreciable reduction of the soil plasticity while increasing strength, with a California Bearing Ratio (CBR) of 8%. Similarly, authors in [7] found that the addition blending 15% waste marble dust with 8% corncob ash improved the stabilizing soil properties with a CBR of 15.53% while reducing swelling potential by 87.5%. Additionally, authors in [8] investigated the impact of geopolymers originated from industrial byproducts, such as alum sludge and rice husk ash, in improving soil stability. These geopolymers established durable aluminosilicate networks, which optimized mechanical performance while reducing CO_2 emissions compared to conventional stabilizers. Weak soils can be stabilized using 10% or lesser cement or lime, otherwise the cost increases significantly, and FA becomes a better alternative. An experimental study [9] explored the potential of using polymer fiber material to strengthen and stabilize the geotechnical characteristics of soft CL. Furthermore, the employment of byproducts, like FA, offered numerous advantages, including technical, economic, and environmental benefits [10].

A geopolymer is a three-dimensional inorganic polymer formed through the chemical reaction between alumina and silicate materials with alkaline solutions [11]. These reactions typically occur at temperatures below 100 °C [12]. The main precursor material is aluminosilicate, which polymerizes into aluminosilicate gels, generally known as geopolymers [13]. Geopolymerization is similar to zeolite production; however, the key difference is that while zeolites have a three-dimensional crystalline framework, geopolymers are non-crystalline materials [14, 15]. The polymerization process begins with a chemical reaction between the geopolymer components and an alkaline solution, leading to the formation of a tertiary structure. This structure is described by polymeric chains bonded by Si-O-Al-O [16]. Two major types of bonds, Si-O-Al-O and Si-O-Si (siloxane bonds), determine the structural integrity and conductivity of geopolymers. Siloxane bonds, which arise from the linkage of silicon and oxygen atoms, are enhanced by the presence of aluminum, facilitating the formation of the Si-O-Al-O framework. This interaction, sometimes referred to as "salination," further stabilizes the geopolymer matrix [17]. The final performance of the geopolymer product and its composition will be greatly affected by the Si/Al ratio. This ratio determines also the type of the resulting structure: for a ratio of 1 poly(silicate) is formed, for a ratio of 0.5 poly(silicate-siloxy) is attained, and for a ratio of 0.33, poly(silicate) is obtained. If the ratio is 1, the compound is poly(silicate). Geopolymer has remarkable properties, such as exceptional fire and heat resistance, low CO_2 content, strong durability, corrosion resistance, and remarkable strength achieved within a short period [18]. The production of geopolymer consists of two main stages. The initial stage involves the dissolution of alumina silicate, found in raw materials, such as FA, into an alkali compound. The second stage continues with the collection and condensation of the dissolved molecules, leading to the formation of various compounds consisting of aluminates and silicates. This technique is essential to verify the physical properties of the geopolymer, where the pore distribution and microstructure organization of the geopolymer are determined. Authors in [19], confirmed the necessity of the sequential stages to form a geopolymer gel bond.

The primary objective of this study is to evaluate the feasibility of using FA-based geopolymers to enhance soil cohesion. FA is an easily accessible material in Iraq and is viewed as waste with harmful effects on the environment. The novelty of this research lies on the method of geopolymer injection into pre-drilled holes of soft CL samples at varying depths with different concentrations to enhance the soil geotechnical properties.

II. MATERIALS AND METHODS

A. Materials

1) Soil

A clayey soil sample was collected from a site west of Baghdad, Iraq, namely Al-Ghazaliya. Preliminary tests were conducted in the laboratory at the College of Engineering, Mustansiriya University to determine and classify soil properties. The physical properties are presented in Table I, while the chemical composition is detailed in Table II. The soil was classified as CL with low plasticity. Figure 1 illustrates the soil sample used in the research. Clay samples of a constant weight and different WCs were prepared to evaluate the Unconfined Compressive Strength (UCS) of soft clay. Distilled water, at laboratory temperatures of 25-30 °C, was added to the sample of known weight to determine WC. Then, the soil with the added water was well-mixed to ensure homogeneity. Once a uniform consistency of twenty was attained, the formed samples were placed into cylindrical molds with a length twice its diameter. The dough created was extracted and placed in an unconfined compression tester to obtain the value (Cu) necessary to make the CL soft. All samples were dried at a temperature of 105 °C in an oven for 24 hours. Additionally, for consistency verification, the samples were also molded using iron or wooden cubic molds with dimensions of $25 \times 25 \times 25$ cm, as part of the experimental setup.

Fig. 1. The utilized soil sample.

TABLE I. PHYSICAL PROPERTIES OF SOIL

Property	Soil	Standard designation
Liquid Limit (LL) (%)	45	ASTM D4318
Plastic Limit (PL) (%)	20	ASTM D4318
Plasticity Intex (PI) (%)	25	ASTM D4318
Specific Gravity, G_S	2.27	ASTM D854
Organic Content (OC) (%)	3.09	ASTM D2974
Color	brown	-
Unified Soil Classification System (USCS)	CL	ASTM D2487
Water Content (%)	21.60	ASTM D2216
Sand (%)	13	ASTM C778
Gravel (%)	0	ASTM C778
(Clay + Silt) %	86	ASTM C778

TABLE II. CHEMICAL CONTENT OF SOIL

Oxide Composition	Sulfur Trioxide (SO_3)	Gypsum Ratio (GYP)	Organic Materials (ORG)	Acidity and Alkalinity (pH)
Soil (wt%)	0.86%	1.84%	3.09%	7.8%

2) Alkaline Activator

The alkaline solution contained sodium hydroxide (NaOH) crystals in the form of plates, as shown in Figure 2(a), and sodium silicate solution (Na_2SiO_3), as depicted in Figure 2(b). NaOH exhibits a purity of 98%, with a molecular weight of 40 g/mol, a preferred quantity for geopolymer production due to its abundance, and high alkalinity compared to other components.

In order to make NaOH, a suitable quantity of crystals was dissolved in distilled water and mixed until total dissolution was achieved. Subsequently, the necessary proportion of Na_2SiO_3 was incorporated and thoroughly blended for 10 minutes to achieve a uniform mixture. Five percentage ratios of NaOH, 11%, 13%, 15%, 17%, and 19% were employed in the manufacturing of geopolymer to treat weak CLs before adding the solution to the dry mixes.

(a)

(b)

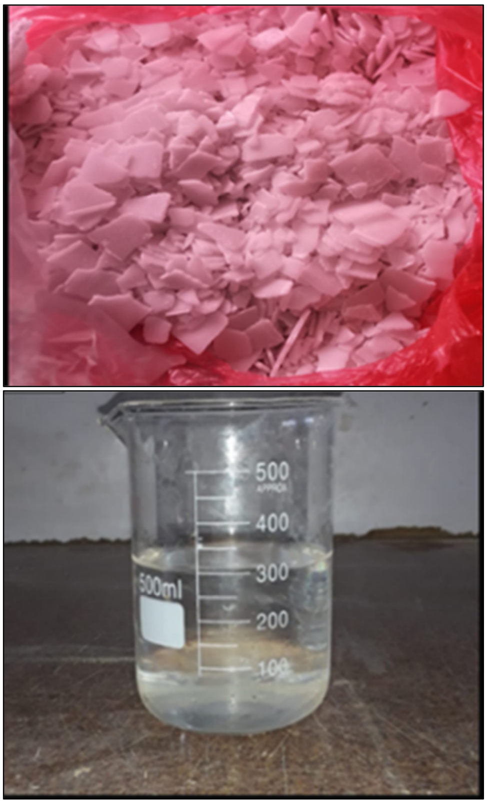

Fig. 2. (a) sodium hydroxide (NaOH), (b) sodium silicate solution (Na_2SiO_3).

3) Sand

Fine aggregate with a gradation of 0.08-0.25 mm (Sika Company/Baghdad) was employed as part of the requirements for this research.

4) Super Plasticizer

The workability of the mix was enhanced by using a superplasticizer (Concrete Viscosity 180), at a dosage of 2% by weight of the binder (FA). This superplasticizer is classified as Type G in accordance with ASTM C494/C494M standards. The detailed specifications of the superplasticizer, as provided by the manufacturer, are listed in Table III.

TABLE III. SUPERPLASTICIZER PROPERTIES

Composition	Aqueous-modified polycarboxylate solution
Packaging	1000 L Intermediate Bulk Container (IBC)
	20 kg pail
Storage Conditions	Dry environment
	+ 5 °C to + 35 °C
	Shield from direct sunlight
	Recirculation needed for extended storage
Color	Light brownish
Specific Gravity, G_S	1.065 ± 0.02 g/cm³
pH	4-6

5) Fly Ash

The FA used in this research was obtained from a local supplier in Baghdad and is illustrated in Figure 3. According to the ASTM C618 standard, the material was classified as class F. The alkaline solution was prepared 24 hours before use, and the raw materials (sand, FA, and Na_2 SiO_3) were mixed manually for 5-10 minutes. The alkali liquid, blended with the superplasticizer, was then added to the dry mix, followed by an additional 5 minutes of mixing. To ensure homogeneousness, the total mixing time was 10-15 minutes. Different weight percentages of 11%, 13%, 15%, 17%, and 19% replaced the FA. After mixing, the geopolymer slurry was poured into steel molds of different shapes and dimensions (cubes and cylinders) depending on the test requirements. Before pouring, molds were covered with a thin layer of oil to prevent any adhesions between the mixture and the inner surfaces of the molds. The pouring process was carried out in three layers, and each one was shaken for 1-2 minutes depending on the type of mold, to remove the trapped air from the mixture. After casting, the surface of the mold was smoothed and then left for 24 hours at ambient temperature. The same procedure was carried out to prepare other samples to evaluate the effect of the reactive powder on the physical and mechanical properties.

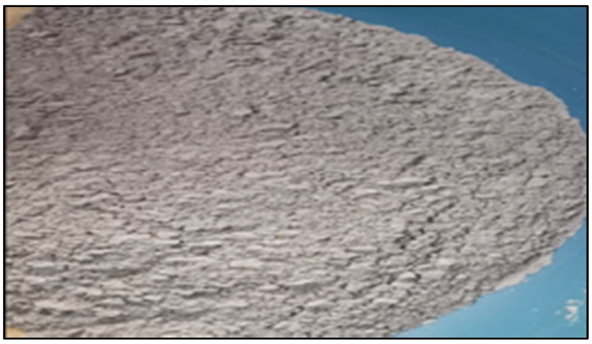

Fig. 3. The FA material.

B. Methods

1) Sample Injection

After the preparation of the samples (soft clay) and the geopolymer materials, a hole with a diameter of 1 in was drilled in the middle of a box. The additives were then injected through a mechanically operated pressure machine, and the injection took place at a pressure of 0.5 bar, ensuring that the material reached the required depth, as shown in Figure 4. This procedure was done at different depths (*L/D* = 3, 4, 5) and varying mixing ratios. The necessary tests were performed at 7, 14, and 28 days.

Fig. 4. Injection of the sample

2) Curing Process

The curing technique was carried out at ambient temperature for 7, 14, and 28 day. Figure 5 displays the 28-period curing method.

Fig. 5. Sample curing at ambient temperature for 28 days.

3) Compressive Strength

The compressive strength test was conducted according to ASTM C109/C109M [20]. This procedure for each mixture was determined by taking the average of three cubic samples with dimensions of 50 × 50 × 50 mm. The samples were analyzed at the initial stages, specifically at 7, 14, and 28 days. A universally applicable pressing machine was utilized, as depicted in Figure 6. The examination occurred in the Laboratory of the Department of Civil Engineering at Mustansiriyah University.

Fig. 6. Universal tecnotest device (compressive strength test)

4) Flexural Strength

The flexural strength of the geopolymer mortar was assessed in accordance with established protocols [21]. Three prismatic specimens, with dimensions of 160 × 40 × 40 mm, underwent testing after 7, 14, and 28 days of curing. The testing process was performed in the Laboratory of the Department of Civil Engineering, Mustansiriya University, as evidenced in Figure 7.

Fig. 7. Universal tecnotest device (flexural strength test).

5) Bearing Test

To evaluate the degree of soil improvement, a bearing test was carried out by applying loads to a square area of 8 × 8 cm in the center of the box. By this way, the geopolymer material and the surrounding soil were examined, and the proportions were recorded using the dial gauge reading obtained when each load was applied, as can be seen in Figure 8. The boundary conditions did not affect the distribution of stresses within the soil. This is attributed to the distance of the wall edge of the sample box, which was 12.5 cm away from the center when applying the relationship *1.5B*, where *B* represents the width of the square pallet and equals to 8 cm. Therefore, the stresses transmitted through square soil and soil treated with geopolymer will be weak and far from the edges. It should be noted that the above relationship (*1.5B*) was used in the case of natural, untreated soil since, when treated, the geopolymer materials participate in the load, and thus the pressures transferred from the edges were very low [22].

(a)

(b)

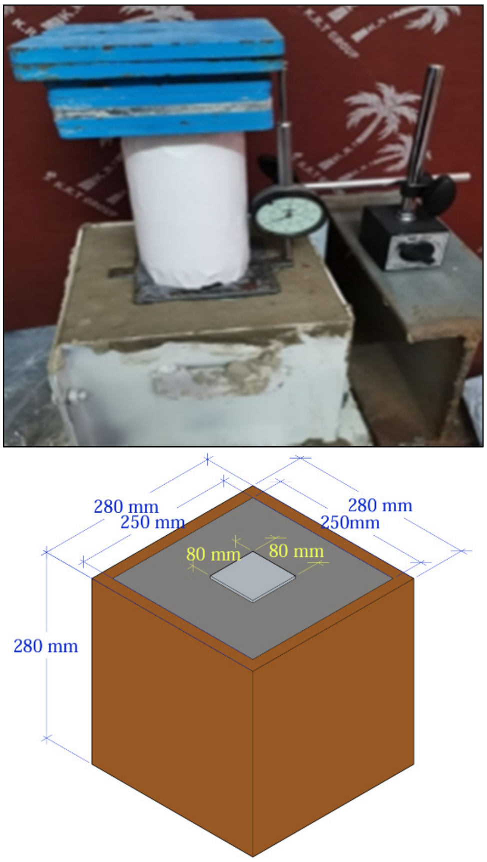

Fig. 8. (a) Bearing test, (b) box.

III. RESULTS AND DISCUSSION

This section presents the outcomes of the experimental investigation, focusing on selecting the appropriate concentration of geopolymer for soil stabilization. The increase in alkaline solution concentration would induce the raw materials to produce more dissolved ions in the geopolymer pastes. The compressive strength of the material is directly affected by its density, (higher density leads to higher compressive strength.) The FA presence enhances the compressive strength by effectively filling the voids and holes inside the structure. Figure 9 illustrates the compressive strength of geopolymer mortar at concentrations of 11%, 13%, 15%, 17%, and 19% over 7, 14, and 28 days of curing. The results indicate that compressive strength increases with a geopolymer concentration up to 15% after which the improvement begins to plateau and eventually decline. The optimum concentration was observed at 15%, especially for 28 days of curing. The reason for the decline in strength above 15% is that the ratio of SiO_2 to Al_2O_3 is constantly larger in this scenario due to the higher alumina content in the source material, which in turn leads to a decrease in the compressive strength value [23].

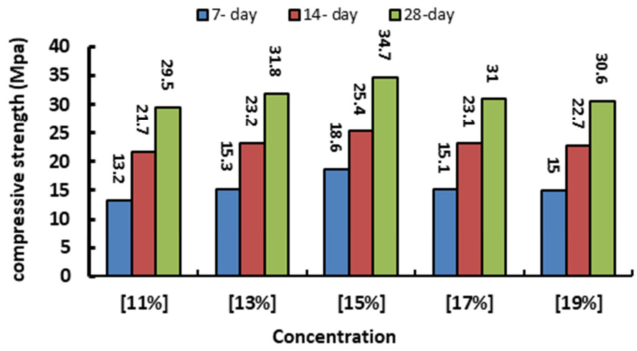

Fig. 9. Compressive strength results of geopolymer mortar with different concentration ratios under different processing conditions.

Additionally, Figure 10 presents the flexural strength of geopolymer mortar at various concentrations and curing periods. Flexural strength peaked at 15%, similar to compressive strength, with the most significant improvement having occurred after 28 days. This highlights the role of geopolymers in enhancing both load-bearing capacity and resistance to bending and deformation.

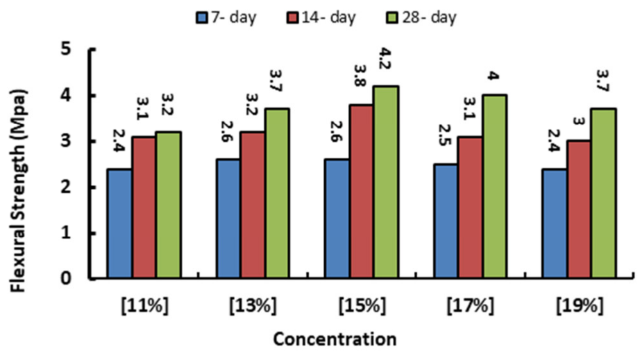

Fig. 10. Flexural strength findings of geopolymer mortar at different concentration ratios and different processing conditions.

After identifying the optimal geopolymer concentration of 15%, the effect of varying injection depth ratios (L/D = 3, 4, 5) on improving CL stability was examined. Figures 11-13 present the relationship between the stress ratio and settlement ratio for the samples treated with 15% geopolymer and cured for 7, 14, and 28 days. The results indicated a decrease in settlement with increased curing time, reaching its lowest value after 28 days, even under high stress levels. Additionally, the highest depth ratio (L/D = 5) exhibited the most substantial reduction in settlement, indicating that deeper geopolymer injection enhanced soil stability more effectively. Bearing capacity tests further confirmed that 15% of geopolymer concentration, combined with a 28-day curing period and a depth ratio of *L/D* = 5, achieved maximum bearing capacity while minimizing settlement.

From the results, after taking more than one depth ratio (*L/D*) and during different treatment periods, it was found that increasing the depth ratio (*L/D*) leads to an increase in the surface area of the treated soil. With geopolymer, after 28 days of curing, the latter will harden significantly and behave like a concrete column embedded in CL. Therefore, as the length or depth ratio increases, the surface area increases, and this leads to an increase in lateral friction.

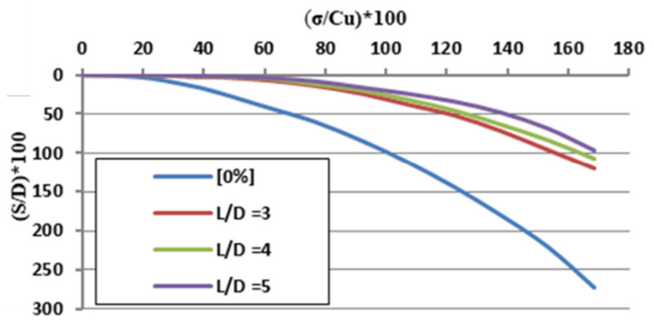

Fig. 11. The relationship between the stress ratio and the settlement ratio for 7 days of curing, with a 15% concentration of geopolymer.

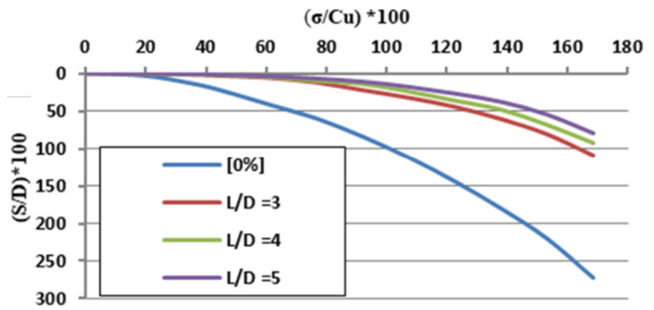

Fig. 12. The relationship between stress ratio and settlement ratio for 14 days of curing, with a 15% concentration of geopolymer.

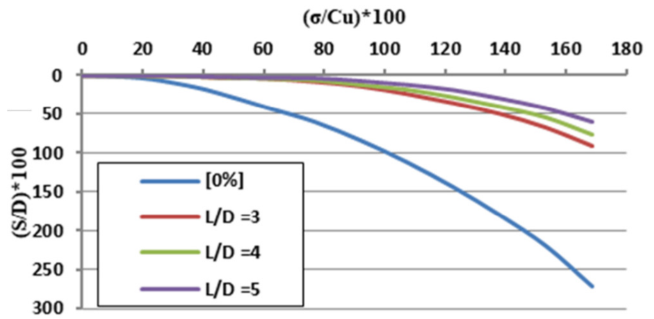

Fig. 13. The relationship between stress ratio and settlement ratio for 28 days of curing, with a 15% concentration of geopolymer.

IV. CONCLUSION

This study investigated the effect of different activating agent concentration in geopolymer-treated soft clay, with a focus on soil strength, settlement, and bearing capacity. The key conclusions are:

- Geopolymer is an effective stabilizing material for weak Clay Soils (CLs) enhancing bearing capacity and reducing settlement.
- An increase in bearing capacity was observed when the percentage of geopolymer was increased from 11% to 15%. A concentration of 15% was identified as the optimal mixing ratio.
- The improvement percentage decreased when the geopolymer percentage exceeded 15%. Thus, any further increase in geopolymer concentration leads to reductions in strength improvement and increased costs.
- The improvement of bearing capacity using geopolymer depends on time periods ranging from 7 days to 28 days.
- The effectiveness of stabilization is also influenced by injection depth. The bearing capacity increased as the depth ratio (*L/D*) increased from 3 to 5.
- *L/D* = 5 was the optimum depth ratio for additives to increase bearing capacity.

In summary, this study confirmed the effectiveness of activating agents for improving soil stability and bearing capacity. Future research should focus on field validation and long-term performance assessment.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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