Evaluating the Strength and Durability Properties of Geopolymer-Stabilized Soft Soil for Deep Mixing Applications

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Abstract: - Soft soil poses serious challenges and is unsuitable for engineering projects because of its insufficient bearing capacity, low shear strength, and high compressibility. Deep soil mixing (DSM) is one of the most popular methods of enhancing soft soil qualities, such as increased bearing capacity and reduced settling, which are critical for building any structure. The environmental effects of creating binders such as cement and lime make it crucial to identify alternative materials for geotechnical applications. This study employed fly ash (class C) --based geopolymer to investigate its effectiveness as an environmentally friendly substitute for cement for DSM applications. The experimental program included unconfined compressive strength, flexure strength, and durability tests. The parameters in the study are binder content (10, 15, and 20%) and activator/binder ratio (0.4, 0.6). Results revealed that UCS and flexural strength, GP-treated soil were in the range of 0.9–5.3 and 0.8–1.5 MPa, respectively (depending on the ratio of fly ash and activator). These strengths were even higher than those of cement-stabilized soil. The geopolymer-treated specimens exhibited excellent endurance over the wetting-drying cycle, with a modest weight loss of less than 4.5%. A binder dosage of more than 10% and an AC ratio of 0.6 were recommended to meet DSM application guidelines. The current study concludes that employing a fly ash-geopolymer binder to stabilize soft soil is an effective alternative to cement in DSM applications.

Key-Words: - Fly ash class C, wetting-drying test, UCS, DSM, geopolymer, Flexure, SEM.

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1 Introduction

Soft soil is generally defined as having low permeability, little compressibility, and significant shear strength. It becomes necessary to stabilize it when building structures over them. This can be done using established physical or chemical stabilization techniques to stabilize the treated soil and transfer loads. Deep stabilization techniques like electro-osmosis, grouting, stone columns, preloading with vertical drains, and so forth must be used if the soft soil deposits reach greater depths, [1]. One of these methods is the deep soil mixing (DSM) method, a cutting-edge method with various global applications. To support low- to medium-load structures, this technique essentially entails installing soil binder columns-columns made of mixed binder, either wet or dry—below the ground surface with augers. These columns reinforce the soft ground, enhancing its effectiveness by reducing settlements and increasing bearing capacity, [1], [2]. The DSM approach has several advantages over other deep stabilization systems, including ease of use, a wide variety of applications, the ability to place columns in various patterns such as the wall, block, and grid, and significantly decreased sludge removal during column installation.

For DSM applications, traditional cementitious binders, including cement, lime, and their mixes, are frequently utilized as binders, [3], [4]. However, because ordinary Portland cement (OPC) is incompatible with current and future sustainability and durability criteria, its usage for soil stabilization, precast structural parts, and concrete becomes dubious. In addition, the production of cement and lime poses a serious environmental risk due to its high carbon emissions. For instance, the cement industry produces about seven percent of CO^2 emissions, [5]. Therefore, there is a need for sustainable and cost-effective alternatives to cement. Research on alkaline cement (which is also known as alkaline cement, inorganic polymers, geo cement, alkali-activated binders, and geopolymers) from the last few decades validate these substances as a suitable alternative for traditional cement because they use industrial byproducts such as fly ash, metakaolin, and so on, [6], [7] Alkali-activated binder creates 60-80% less CO2 and requires 60% less energy during manufacture than OPC, [6].

Geopolymers offer several advantages, including high early strength, rapid hardness, low shrinkage and permeability, high resistance to chemical corrosion, and fire resistance, [8]. There are certain drawbacks to geopolymer materials, such as loss of workability owing to alkaline solutions, the hazardous nature of the ingredients utilized in these solutions and issues such as the material's high alkalinity, [9]

Some recent research has been conducted on using geopolymers as soil stabilizers, [10]. Geopolymer binder helped soil particles create a more compact microstructure, improving soil's volume stability and mechanical characteristics, [11]. Fly ash is used as a geopolymer to replace cement for soil stabilization, [12]. The study discussed using activated fly ash to improve soft soils. Cement and geopolymer samples have equivalent unconfined compressive strength (UCS) at curing 28 days. The properties of FA-based geopolymer for high-plastic soil are investigated, [13]. The UCS quickly increased by 400%. Geopolymer stabilization enhances the resilience modulus by increasing the activator dose, [14], [15]. The effects of metakaolin and alkali-activator on the mechanical properties of the geopolymer-clay soil are investigated by [16]. According to the experimental results, the unconfined compression strength of the geopolymer-improved soil improves initially and then declines with metakaolin and alkali-activator content. The geopolymer-improved soil's strength performance and stabilizing effect were investigated further by comparing it to pure clay soil, lime soil, and regular Portland cement soil using unconfined compression strength tests, direct shear tests, and Brazilian split-cylinder tests. The results demonstrate that the geopolymer-improved soil has higher unconfined compression, shear, and Brazilian splitting strength than the other three soil types. [9] Investigated the application of activated high calcium class C fly ash for sand soil stabilization. The results showed that GP-treated soil had higher UCS and flexural strength than cement-stabilized soil. [14], studied the durability and permanent deformation of several fly ash-geopolymer mixtures. Despite varying permanent deformation, soil with different fly ash amendments exhibited equal resilience modulus. SEM images were used to evaluate the interaction of industrial waste and soil particles, the reaction of geopolymer to temperature variations, and the geopolymer proportion. The microstructure of soil-geopolymer reveals that the strong bonding of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) is the explanation for the improved strength, [17]. As a result, the geopolymer can be used for both shallow-depth soil stabilization and deep soil mixing applications, [18], [19]. Although fly ash geopolymers are energy efficient and environmentally friendly, they require a high alkaline atmosphere and high curing temperatures (60-90 °C) to activate reactions. This research project aimed to enhance geopolymer responsiveness by applying fly ash with high Ca content at ambient temperature.

It has been discovered that geopolymers have higher mechanical characteristics. However, nothing is known regarding the long-term performance of soil- geopolymers. The investigation does not indicate the amount of geopolymer required to produce the durability specified for OPC soils. One of the most significant impediments to the widespread adoption of this potential ground improvement technique is a lack of comprehensive study into the durability performance of soil-treated geopolymers. This study aims to assess the durability and strength of soft clay stabilized with geopolymer, compare it to traditional OPC at high binder dosages, and validate geopolymer combinations in fulfilling DSM standards.

2 Experimental Program Materials used Soil

The soil employed in this investigation is low plastic clayey (Cl). The sample was obtained at a depth of around 2 meters. Figure 1 shows the grain size distribution of the soil. Table 1 lists the soil parameters, while Table 2 shows its chemical composition.

3 Geopolymer (GP) Materials

GP binder employed in this investigation was a combination of fly ash and a liquid sodium activator. Fly ash (FA) was derived from coal-fired power plants. Table 2 includes the chemical compositions assessed using energy dispersive spectroscopy (EDS). FA can be categorized as high calcium CFA based on its chemical composition as described in ASTM standard C618 as described in ASTM standard C618, with Al_2O_3, SiO_2, and Fe_2O_3 levels over 50% and Ca content greater than 20%. The activator (hence known as AC) was a mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). NaOH was immersed in distilled water for no less than 24 hours with a molar concentration of 10 M before combining with Na_2SiO_3. To optimize early strength and generate a massively alkaline environment, the mass ratio of Na_2SiO_3/NaOH was set to 2.0, [20].

4 Preparation of Samples and Methodology

Samples were prepared using the same mixing procedure throughout all tests. To ensure uniformity and form the entire dry material, fly ash was mixed with dry soil at a percentage replacement (by weight) for five minutes. Subsequently, an activator was created by combining sufficient NaOH and Na_2SiO_3 for five minutes. To achieve the 10 Molar concentration of the solution, NaOH was dissolved in distilled water for at least 24 hours before mixing with sodium silicate. It was diluted with more free water before mixing with dry materials to create the perfect moisture level for compaction. The final mixture was compressed in layers with controlled weight/thickness so that every sample could reach the correct density. Cement-treated samples were created by mixing cement paste (produced with a water/cement ratio of 0.4) into the soil. Table 3 illustrates the testing schedule for the current laboratory investigation.

The Unconfined Compressive Strength (UCS) test is a fast and simple method to determine how different factors, like the quantity and type of stabilizer, affect the strength enhancement of treated soil. The UCS tests were performed after a 28-day cure time. The UCS test samples were created using cylindrical tubes made of (PVC) measuring 50 mm in diameter and 100 mm in height, providing a 2:1 height-to-diameter ratio as per (ASTM D1633-00, 2007), [21]. The test was conducted using a uniaxial machine with a loading capacity of 50 kN and 0.1 mm per minute displacement rate.

For the flexural strength test, Treated samples were prepared in rectangular molds with dimensions of 50, 50, and 200 mm and tested after 28 days of curing as per ASTM D1635/D1635M-19, [22]. The following equation was used to determine the samples' flexural strength:

$$fs = \frac{3pl}{2bd^2} \tag{1}$$

where fs is the flexural strength (MPa), l is the span of the simple supports (mm), P is the max load (N), b is the width of the sample (mm), and d is the thickness of the sample (mm).

For durability tests, After 28 days of curing, the specimens with 101.6 mm in diameter and 116.4 mm in height were immersed in water for 5 hours of wetting before being oven-dried at 80 °C for 42 hours, completing one cycle of wetting and drying according to ASTM D559-03, [23]. The durability test involved 12 cycles of wetting and drying. The weight of the samples was measured after each wetting-drying cycle to calculate the mass change. The specimens were brushed with a steel brush across their whole surface before being weighed till the cycle was complete. UCS tests were performed on 45x90mm samples after 3, 6, 9, and 12 durability cycles to determine soil residual strength. UCS testing is not a standard technique for evaluating durability; rather, it provides a signal for estimating the deterioration caused by the treated materials.

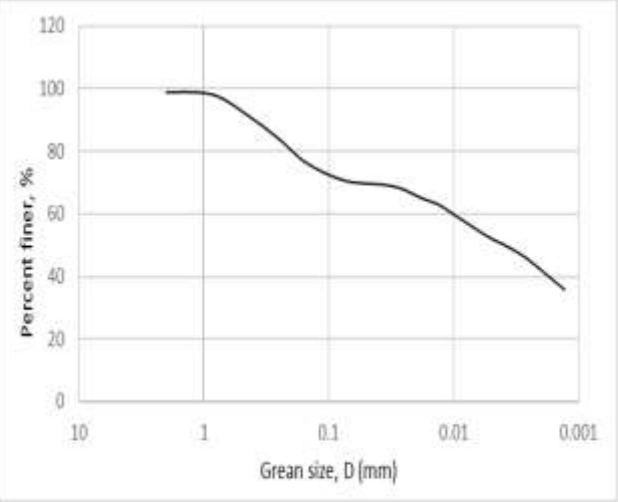

Fig. 1: Particle size distribution curve of the soil

Table 1. Soil properties

Soil property	**Standard**	**Value**
Liquid Limit (LL), %	ASTM D 4318	46.3
Plastic Limit (PL), %		22.2
Plasticity index, %		24.1
Sand content, %	ASTM D 422	29
Clay content, %		40. 9
Silt content, %		30.9
Soil classification	ASTM D 2487	CL
Optimum moisture content, %	ASTMD 1557	12.1
Max dry density (gm/cm³)		1.82
UCS (MPa)	ASTM D1633-00	0.189

Table 2. Chemical compositions of the soil and FA using EDS

Element	Na_2O	MgO	Al_2O_3	SiO_3	K_2O	CaO	Fe_2O_3	other
soil	2.77	8.1	16.89	29.03	5.1	6.65	12.4	19.06
Fly ash	2.02	3.2	19.16	37.08	1.9	25.13	4.09	7.42

Table 3. Materials and testing program

Parameters	**Binders**	
	Geopolmer	Cement
Materials	Fly ash class C	OPC
Activator (AC)	Na_2SiO_3 and NaOH	Water
Binder content (%)	(10,15,20)	10,15,20
Activator/ fly ash or W/C ratio	0.4, 0.6	0.4
Test conducted	UCS, flexure, durability	UCS, flexure, durability

5 Results and Discussion

5.1 Unconfined Compressive Strength UCS

The findings are shown in Figure 2, where it is clear that the specimens treated with GP had more UCS than the specimens treated with cement at the same dose. This is explained by the fact that, in contrast to cement-treated mixes that only had pozzolanic reactions, GP-treated mixes had higher levels of both pozzolanic and polymeric processes. In other, the GP- soil exhibits a higher rate of cementitious product development than the soil- cement. These results are consistent with the outcomes mentioned by [9], [16], [19], [24].

The UCS significantly increased when the activator at geopolymer-treated samples was increased from 0.4 to 0.6. This is because an enhancement in activator content caused an increase in the leaching processes of aluminum and silicon from the fly ash's amorphous phase.

Due to an increase in pH. This, consequently, increased the formation of cementitious products between the soil particles, such as N-A-S-H and C-A-S-H, and, as a result, strengthened the soil even more.

The findings of the UCS test demonstrate that samples treated with 10% fly ash content and an AC ratio of 0.4 could only satisfy the minimal UCS threshold of 1.034 Mpa for DSM applications. As a result, samples treated with 10% fly ash and Ac = 0.4 were not accepted for further testing.

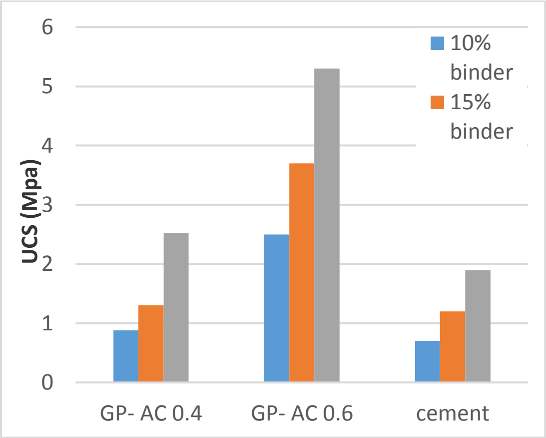

Fig. 2: UCS for mixtures with various geopolymer (GP) binder content and activator (AC) ratios

6 Modulus of Elasticity

The stiffness of the specimens treated with GP and OPC was determined using Secant Modulus (E50), a stress-to-strain ratio referred to as Young's Modulus at 50% UCS. The E50 values for all treated samples follow the same trend as the UCS, as shown in Figure 3. The relationship between the treated specimens' UCS and E50 in this study is seen in Figure 4. It demonstrates a correlation of E50 = 167*UCS for specimens treated with GP and E50 = 184*UCS for specimens treated with cement; these values are in good accord with the range proposed by earlier researchers [19], [25], [26]. [19], results reveal a correlation of E50 = 164*UCS for GP-treated specimens and E50 = 187*UCS for cement-treated specimens.

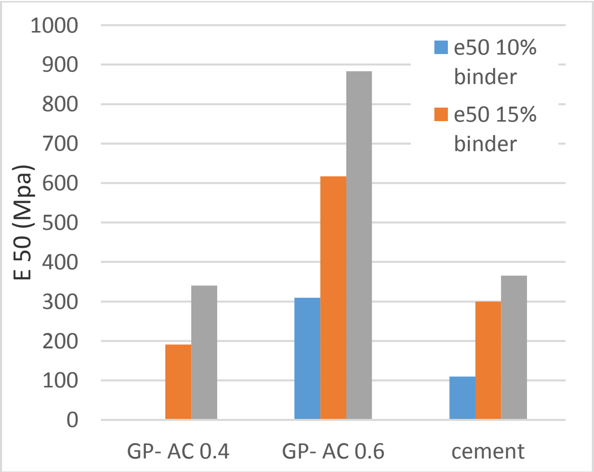

Fig. 3: E50 for mixtures with various binder content

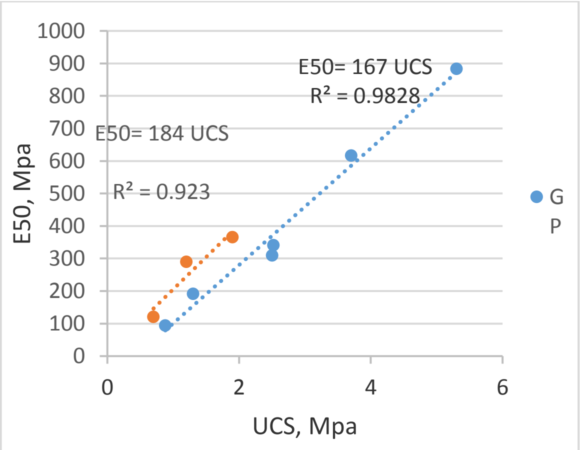

Fig. 4: Variation of *E*50 with UCS for soil-treated mixes

7 Flexural Strength (fs)

After 28 days of curing, rectangular beam specimens treated with 10, 15%, and 20% binder contents were tested for flexural strength at AC ratios of 0.4 and 0.6 (except for FA10%, AC 0.4). Figure 5 shows the results of the flexural strength test. The relationship between fs values and geopolymer content followed a pattern similar to those of UCS values, with a rise in GP content attributed to greater flexural strength.

When comparing the Fs of geopolymer and cement-soil samples. Fs of GP samples exceeded that of OPC-treated samples. When the beams were subjected to flexural testing, the top and lower sections sustained compressive and tensile stresses, respectively. Both tension and compression contributed to the beam failure, while tensile stress had a greater impact on the flexural failure [26]. A previous study has demonstrated that when geopolymer binders were used in concrete, they had both higher and lower flexural strength than cement, depending on the composition and ratio of source materials, [27]. Cement-stabilized mixtures had lower flexural strength than geopolymer-stabilized mixtures, implying that they had lower tensile strength.

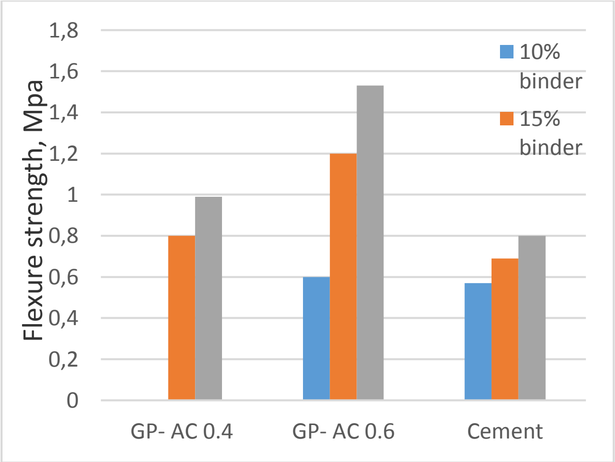

Fig. 5: Flexural strength values for mixtures with different GP binder and cement

8 Durability

As part of the durability assessment process, the specimens treated with cement and geopolymer underwent wetting and drying cycles to determine the mass loss and strength loss of each treatment.

Mass loss

The mass loss (%) of the stabilized samples exposed to the w-d cycles is shown in Figure 6. Figure 6 shows that the samples underwent only a slight weight loss of less than 4.5% during the 12 wetting-drying durability cycles. The geopolymer gel that holds the soil particles together is comparatively strong since the mass loss was not significant.

Regarding mixtures treated with cement, The durability test was not passed by soil treated with 10% cement. As per ASTM D559, soil cement that exhibits a mass change of more than 10% is deemed unsuitable for the durability test. The GP-treated mixes showed better endurance in terms of mass loss than the cement-treated ones. The findings indicate that soft soil treated with a geopolymer binder based on fly ash can pass both wet and dry durability tests.

9 Strength Loss

UCS testing was achieved on samples treated with cement and geopolymer after 3, 6, 9, and 12 durability cycles to investigate strength deterioration for wetting-drying processes of survived treated soil (Figure 7).

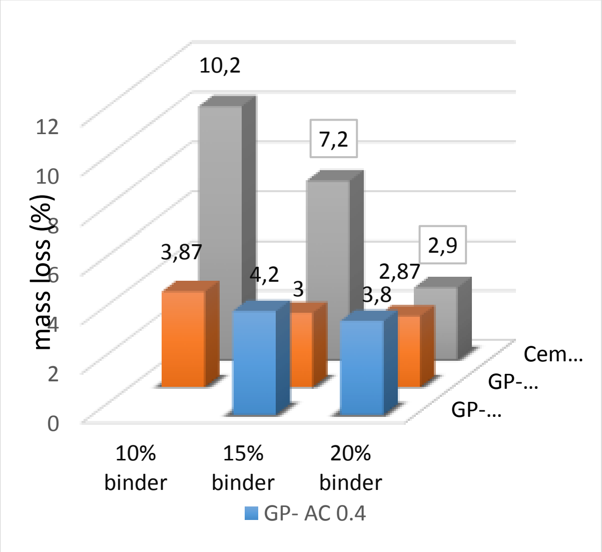

Fig. 6: Wetting-drying changes in mass after twelve cycles for geopolymer-treated soil and cement-soil

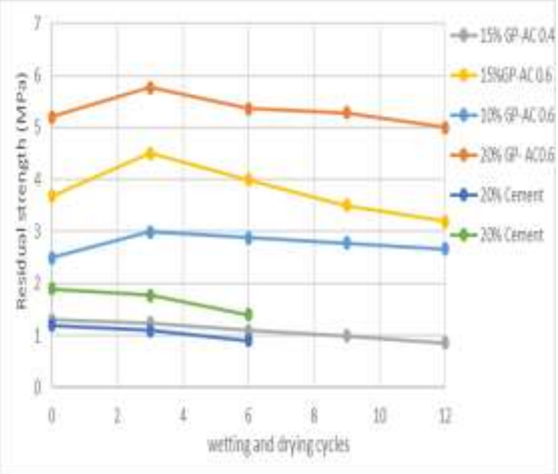

Fig. 7: Effect of wetting-drying cycles on UCS values of soil-geopolymer and soil cement mixtures

After 12 cycles, a deterioration tendency was identified for geopolymer-soil, with an overall value of 23% at the sample with fly ash content of 15% and an activator of 0.4. While the strength increased in the third cycle, there was a slight deterioration in other geopolymer samples. This may suggest that the high temperatures of the durability drying cycle accelerate the geopolymerization and the corresponding gel formation/hardening of the soil, which is then followed by a cumulative effect of the durability cycle that degrades the stabilized soil structure. It should be illustrious that the geopolymerization and subsequent strength growth are accelerated by heat curing, [28]. The alkali activation succeeded in forming denser and less porous/permeable materials, reducing the possibility of water absorption and subsequent sample deterioration owing to shrinkage and swelling caused by wetting–drying cycles. According to Figure 7, all of the GP-treated specimens met the criterion for a minimum UCS of 1.034 MPa. Thus, based on the durability results, the GP-treated specimens were shown to be resistant to wetting and drying in terms of mass loss and residual strength.

10 Microstructure

To further understand the mechanism of geopolymer strength growth, the microstructure texture of geopolymer-treated soil was examined using scanning electron microscopy (SEM).

The composition of the FA-geopolymer is principally determined by the dissolution of aluminum silicate in fly ash by alkaline solutions generated by polycondensation. The geopolymer product is created by leaching Si4+ and AL3+ from activator and fly ash reactions, solidifying over time and cementing soil particles. SEM examination reveals the degree of geopolymerization by identifying etching on FA surfaces (Figure 8). Where the geopolymerization reaction is indicated by the cementitious product offerings on the fly ash surfaces by silica and aluminum decomposition, the etched holes in FA surfaces are often filled with cementitious products and tiny particles, resulting in a compact matrix.

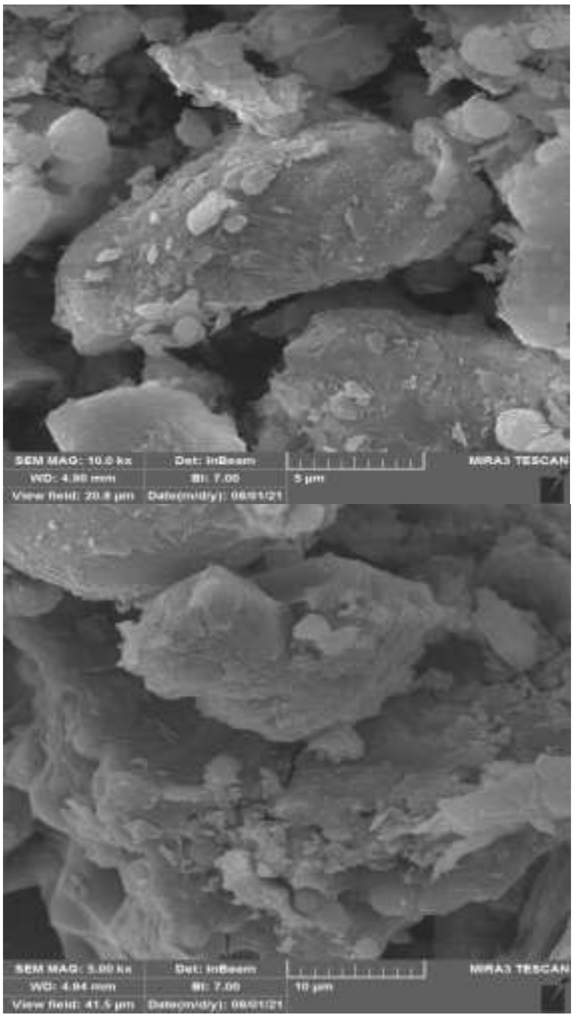

Fig. 8: SEM analysis for soil-geopolymer mixtures

11 Conclusions

The original motivation for the research comes from the following points:

1. As civilization advances and soft soils become more common, soil stabilization becomes increasingly important.
2. The need to look for environmentally friendly and sustainable alternatives to traditional soil stabilization materials (e.g., OPC and lime), as evidenced by the high carbon footprint and other negative environmental effects associated with sourcing and overexploiting non-renewable raw materials.
3. More research is needed to determine the most effective amount of geopolymer components for stabilizing soft soils and improving their mechanical and durability properties.
4. Solutions must address various practical issues with geopolymers, such as processing temperature and high content, which limit their use in the field.

This research has focused on using fly ash with a high calcium concentration (high-calcium Class C fly ash) to increase the reactivity of the geopolymer and maintain efficient ambient temperature curing. Strength and durability tests were conducted on mixtures treated with cement and geopolymer to determine the effectiveness of this stabilizing approach for soft soils. This paper reports on the outcomes of the experimental study. A comparison was also made between the effectiveness of GP-treated and cement-treated specimens under compression, flexure, and wetting-drying cycles.

The current experimental inquiry yielded the following conclusions:

1. In unconfined compression, the GP-treated specimens displayed more UCS than the cement-treated specimens with the same dose, which could reflect the combined effect of GP's geopolymeric and pozzolanic processes.
2. E50 values for all treated samples show a similar pattern to the UCS. GP-treated samples had a lower E50 than cement-treated samples at the same UCS, indicating they were less brittle. There was significant agreement between the correlation established by previous studies and the anticipated relationship between E50 and UCS of treated specimens in this study.
3. The improvement in flexural strength values follows the same trajectory as the increase in compressive strength. The flexural strength of the GP-treated soil was found to be between 0.6 and 1.5 MPa, even greater than those of the OPC-stabilized soil.
4. The geopolymer samples displayed high durability. The treated samples were described successfully, mainly bypassing 12 wetting-drying cycles and a weight change of less than 4.5% with some residual strength.

The findings above suggest that fly ash class C-based geopolymer stabilization can be a more effective method for treating soft soils than cement stabilization. This makes the use of FAC-geopolymer-based stabilizers a sustainable alternative for deep soil mixing applications.

12 Proposed Area for Future Research

Future research on geopolymer-stabilized soils will most likely focus on a few key areas to improve their performance and broaden their uses. Among the possible topics for more research are:

1. Continued study to optimize soil geopolymer mix design, including soil type selection, geopolymer precursors, and activating solutions.
2. Investigating the utilization of alternative waste or byproduct resources as additional cementitious materials or geopolymer precursors.
3. Long-term durability of soil geopolymers was investigated under various environmental and service circumstances, including chemical exposure, high temperatures, and freeze-thaw cycles.
4. Creating established rules and best practices for the large-scale use of soil geopolymers in diverse geotechnical and building projects.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

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Conflict of Interest

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