Journal of Engineering Science and Technology
Vol. 20, No. 6 (2025) 1813 - 1826

STRENGTH ENHANCEMENT OF FLY ASH-BASED GEOPOLYMER STABILISED SOFT SOIL

AHMED J. HAMZA[1,*], SARAH AL-QUTAIFI[2]

[1]Department of Reconstruction & Projects, University of Thi-Qar, Nasiriyah, Iraq
[2]Department of Surveying and Geomatics Engineering, College of Engineering, University of Thi-Qar, Nasiriyah 64001, Iraq
*Corresponding Author: ahmed.jabbar@utq.edu.iq

Abstract

The environmental damage resulting from producing lime and cement has led to an improvement of some alternative materials in the construction field, especially for geotechnical applications. As a result, developing low-carbon sustainable materials by replacing lime and cement with geopolymers (GPs) derived from recycled waste can have environmental and economic benefits. This paper focuses on investigating stabilising clayey silt soil using class C fly ash (FA) cured at the surrounding temperature. The parameters studied were different fly ash percentages of 10%, 15%, and 20%, as well as two activator/binder ratios of 0.6 and 0.4. The experimental program involved evaluating the California Bearing Ratio (CBR), unconfined compressive strength (UCS), in addition to durability tests. Furthermore, microstructural analysis was performed using an SEM test. The results reveal that GP-soil specimens demonstrated a high UCS of 1-5 MPa as well as a superior CBR value of approximately 144%. The GP-treated specimens also demonstrated high durability performance with a slight weight loss as low as 1.53% in the wetting-drying cycle. Finally, the microstructural investigation demonstrated that the development of dense gel was the principal cause of strength enhancement. According to the findings of this study, the incorporation of GPs for soil enhancement purposes is a more effective and feasible substitute than the addition of cement in geotechnical applications.

Keywords: California bearing ratio, Fly ash, Geopolymer, Stabilised soft soil, Strength, SEM, Wetting-drying cycles.

1. Introduction

During construction and service durations, the insufficient strength of soft soil poses complications in supporting the weight transferred by the superstructure, and this can result in uneven settlement in addition to cracking [1, 2]. Inorganic cementing substances, like lime and cement, are commonly employed in engineering as chemical stabilisation techniques to improve soil strength and durability [3, 4]. However, the main issue with traditional stabilisers is that their producing process uses much energy and emits massive greenhouse gases. It was reported that approximately 1 ton of CO_2 could result from the production of one ton of cement [5, 6]. Consequently, emphasis has been placed on the application of waste constituents resulting from aluminosilicate byproducts as potential sustainable and low-energy alternatives to cement [7].

Geopolymers (GPs) are inorganic polymer cementitious materials with a three-dimensional network of silica-aluminates. Geopolymer is often produced from aluminosilicate-rich mineral materials like kaolin, feldspar, and zeolite, as well as industrial byproducts or waste like metakaolin (MK), fly ash (FA), and ground granulated blast furnace slag (GGBFS) in highly alkaline environments [7-9]. The geopolymer development process is known as geopolymerization and it consists of several steps: firstly, dissolving solid aluminosilicate oxides in an alkaline medium with a high hydroxyl ions (OH^-) concentration; secondly, dispersion of dissolved aluminium and silicon compounds; thirdly, polycondensation involving residual alkali cations (i.e., Na^+); fourthly, gel formation; fifthly, reorganisation; and finally the evolution of resulted gel over curing time and crystallisation into a hardened state [8, 10].

GPs have many benefits, such as low permeability and shrinkage, high early strength, rapid hardness, and excellent heat and corrosion resistance [11-14]. Furthermore, the CO_2 emissions from geopolymer production are only one-sixth of cement [8]. Considering all these benefits, GPs can be a possible effective substitute for Portland cement (OPC) in the construction industry in the near future. Therefore, several investigations have been recently carried out on the applications of GPs as soil stabilisers [15-18]. The GP-based binder supports particles of soil, leading to a dense microstructure that enhances volume stability as well as the soil's hardened properties. Consequently, the geopolymer can be utilised as a stabiliser for shallow-depth applications, such as shallow foundations, base or sub-base layers in pavement, airport construction, and dams [19].

Several vital parameters, such as source substances, activator chemical properties, temperature, curing temperature and its duration, can impact the geopolymer's hardened properties. Among these essential factors, curing condition is considered the most critical factor that can impact the extend of the application of GPs in the construction domain [12, 20]. Usually, GPs are treated between 60 and 90 °C [21, 22]. Geopolymer soil can be applied at room temperature for geotechnical engineering applications, as it is not practical to process it at elevated temperatures. Geopolymerization occurs more slowly at low temperatures, resulting in lower initial strength and requiring a longer timescale than soil treated with cement [23, 24].

Consequently, compared to Ordinary Portland Cement (OPC), higher activator concentrations are needed to increase the usefulness and efficacy of the application of GPs for soil stabilisation purposes. Nevertheless, the overall cost of this stabilisation strategy rises when activator content is used in large quantities. So far,

class F fly ash (FFA) has been applied as a cementitious material in studies on a FA-soil stabilisation [25]. Basically, the calcium dosage is the main distinction between CFA and FFA. Nonetheless, silica and alumina are frequently present in considerable amounts in both [26, 27].

Most previous investigations on GP-stabilised soils (GPSS) have been concentrated on improving hardened properties in terms of compressive strength. However, the long-term resilience of soils stabilised with geopolymers has received minimal attention. Specifically, research conducted on the ideal addition of GPs for the durability aspect is still infrequent. A primary obstacle to the widespread practice of this effective strategy for ground enhancement is the dearth of comprehensive studies on the durability performance of GP-stabilised soil with geopolymer.

Therefore, this study aimed to investigate the effect of using fly ash with a high calcium content (CFA) to improve the geopolymer's reactivity, to decrease the activator percentage and curing temperature to reduce the cost and improve the feasibility consideration. Furthermore, the current paper will assess the strength as well as durability performance of soft soil stabilised with GPs. The strength and durability were evaluated using a UCS test, CBRT test, and wetting/ drying test. The mechanism of strength improvement is investigated through the use of SEM analyses.

2. Experimental Program

2.1. Materials

2.1.1. Soil

In this study, the utilised soil was clayey silt with a trace of sand, collected from Al Nasiriya refinery, Thi-Qar Province, Iraq, located about 380 kilometres to the South-East of Baghdad City, Iraq. The satellite map shown in Fig. 1 displays the location of soil sampling inside the red circle. The soil specimens were collected between 0.5 and 1 meters below the surface. Based on the Unified Soil Classification System (USCS), the specimen was categorised as clayey silt (ML) with low plasticity.

Fig. 1. The location of the investigated soil.

Figure 2 displays the size distribution of utilised soil grain. According to the ASTM standard test, the geotechnical parameters of ML are revealed in Table 1.

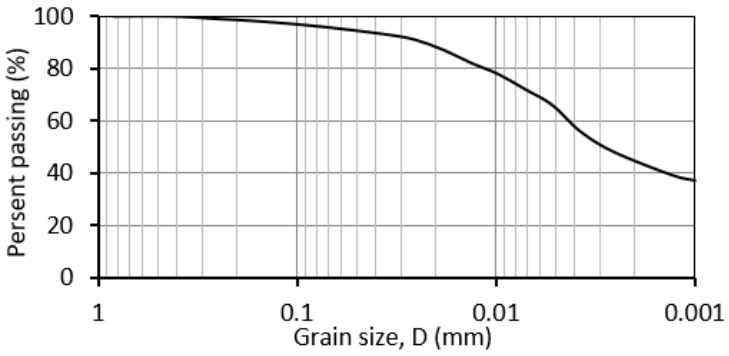

Fig. 2. Testing results of the particle size distribution of the utilised soil.

Table 1. The properties of utilised soil.

Soil property	standard	Value
Liquid Limit (LL), %	ASTM D 4318	46
Plastic Limit (PL), %		34
Plasticity index, %		12
Sand content, %	ASTM D 422	4
Clay content, %		43. 9
Silt content, %		52.1
%Passing sieve no. 200		96
Soil classification	ASTM D 2487	ML
Optimum moisture content, %	ASTMD 1557	19.7
Max dry density (gm/cm³)		1.59
UCS (MPa)	ASTM D1633-00	0.128
CBR, %	ASTM D1883-07	6.5

Figures 3(a) and 3(b) reveal high-resolution pictures of fly ash and soil, respectively, because of a scanning electron microscope (SEM). The SEM shows that the used CFA consists of many spherical particles of different sizes.

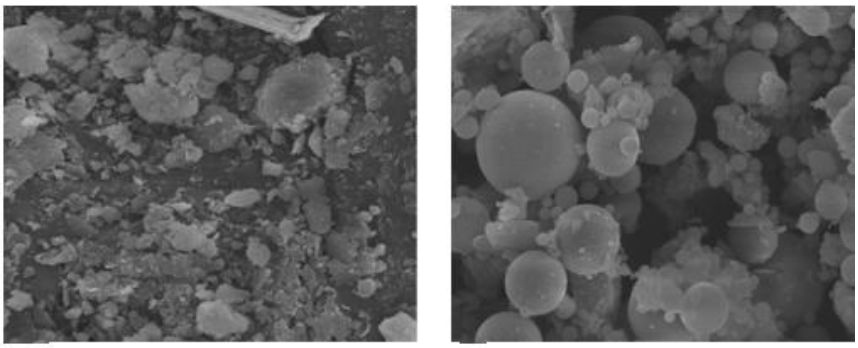

Fig. 3. SEM images of (a) soil and (b) fly ash.

2.1.2. Geopolymer ingredients

The geopolymer binder utilised in the present study was a mixture of FA and alkaline activator (AC) solution. The utilised FA was provided from the Nasiriya power station of production of electricity production as byproduct waste materials, as shown in Fig. 4(a). Table 2 contains the chemical constitutions of FA analysed using energy dispersive spectroscopy (EDS). Based on testing results in Table 2 and the specification of ASTM standard C618, the utilised FA can be classified as high calcium CFA, as the contents of Al_2O_3, SiO_2, and Fe_2O_3 are greater than 50%, and the Ca percentage is greater than 20%.

Table 2. Chemical constitution of applied fly ash.

Element	SiO_3	CaO	Al_2O_3	Na_2O	MgO	K_2O	Fe_2O_3	Others
Fly ash	37.65	26.13	17.18	2.72	3.5	1.5	4.09	7.5

Most researchers have recommended the alkaline activators (AC) of a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), shown in Fig. 4(b), solutions to synthesise geopolymers for soil stabilisation and geotechnical applications [19, 28]. The activator used in this study is Na_2SiO_3 and 10 Molar concentrated NaOH in a fixed mass proportion of Na_2SiO_3/NaOH of 2. This ratio was chosen due to previous literature as it is an optimal ratio to improve strength development [29]. NaOH of 10M concentration was made by melting pellets of NaOH in water for at least 24 hr prior, as seen in Fig. 4(c).

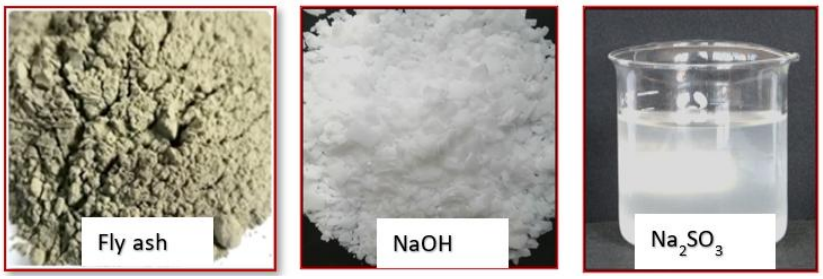

Fig. 4. The Geopolymer binder used in the mixture.
(a) Fly ash, (b) NaOH, and (c) Na_2SO_3.

2.2. Sample preparation

The mixing technique was similar for all involved mixtures. First, three proportions (10%, 15%, and 20%) of fly ash (CFA) were added into dry soil as percentage replacement by weight and then mixed for five minutes to confirm uniformity. After that, an activator was made by mixing adequate NaOH and Na_2SiO_3 for five minutes. The alkali activator was prepared in two ratios of 0.4 and 0.6, referred to here as AC/FA.

Before being mixed with dry materials, it was diluted with extra water to realise the highest moisture level for ideal compaction. The mixture identifications were defined by M (FA, AC/FA). For each specimen, a mixture was compacted into layers with a specified weight/thickness to produce the desired density. For more details, Table 3 presents the proportion of the mixtures used.

Table 3. The mixture proportion of GP-treated soil.

Mixture No.	FA (%)	AC/FA
M*(10,0.4)	10	0.4
M(15,0.4)	15	0.4
M(20,0.4)	20	0.4
M(10,0.6)	10	0.6
M(15,0.6)	15	0.6
M(20,0.6)	20	0.6

* M is a shortened form of the word "Mixture"

2.3. Testing strategy

2.3.1. Unconfined compressive strength

UCS tests were performed after a 28-day curing time. The cylindrical split tubes made of PVC, with a diameter of 45 mm and a height of 90 mm, were utilised to form the UCS test samples, yielding a 2:1 height-to-diameter ratio [30]. A uniaxial loading machine of 50 kN capacity was used to conduct the UCS test on the soil. Each UCS test was performed at a 0.1 mm/min displacement rate.

2.3.2. Durability test

The durability performance was evaluated in terms of wetting-drying cycles (WDCs) tests, which were performed according to (ASTM D559-03) [31]. The samples, 116.4 mm in height and 101.6 mm in diameter, were cured for 28 days. They were subjected to elevated temperature (oven curing) of 70 °C for 42 hr. and submerged in water for five hours. The specimens' weights were measured after every wetting-drying cycle to determine the corresponding weight variation. This process of wetting and drying cycles was represented 12 times. A steel brush was utilised to brush over the entire surface of each specimen each time before being weighed until the end of the cycle. To evaluate the residual strength of soil, a set of dimensions (45 × 90 mm) samples were subjected to UCS tests after being subjected to wetting–drying cycles of 3, 6, 9, and 12. However, the test of UCS is not a typical practice for evaluating durability performance; nevertheless, it offers an indicator for quantifying the deterioration suffered by the treated samples [16].

2.3.3. California bearing ratio (CBR)

CBR of GP-treated soil (GPTS) was determined based on the standard specification ASTM D1883-07. Following 28 days of soaking, geopolymer-treated specimens (GPTS) were evaluated using a CBR tester machine (CEHI-CBR-02) with a 50 kN proving ring.

3. Results and Discussion

3.1. Unconfined compressive strength

Figure 5 represents the effect of the addition of GP into soil on its stress-strain behaviour based on the UCS result. Soil treated with geopolymer typically displayed brittle yielding, where stress peaked just before an abrupt failure. The results are comparable to the findings stated by [16, 32]. This improvement is associated with the cementitious products' formation. The diluted activator creates

high pH levels inside the geopolymer, and that leads to dissolving the alumina and silica oxides existing in the particles of CFA. This results in the GP gel product, which eventually solidifies and cements the soil particles.

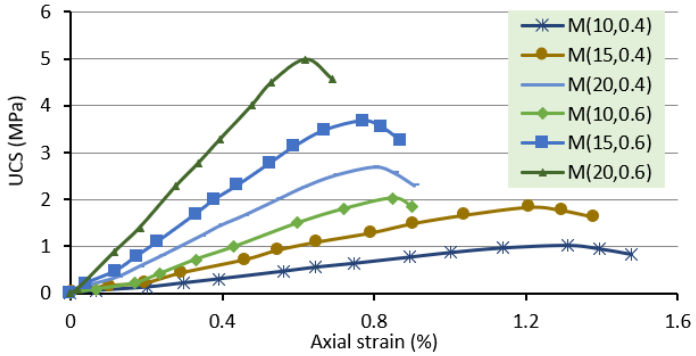

Fig. 5. Unconfined stress-strain behaviour.

3.2. Durability

Temperature and moisture impacts are field-related factors that must be studied to confirm the binder-soil mixture's durable effectiveness. To assess the durability performance, the mass and strength loss of GPTS were estimated by exposing the samples to many WDCs. Figure 6 illustrates the WDCs of the GPTS for different mixture proportions. It can be shown that at (AC/FA 0.4), the clayey silt soil required at least 20% FA (M (20, 0.4)) to achieve the desired 12 durability cycles. This performance for soil may be linked to creating a stable matrix surrounding the particles of treated soil after being hard, and it can withstand the stress created throughout multiple WDCs.

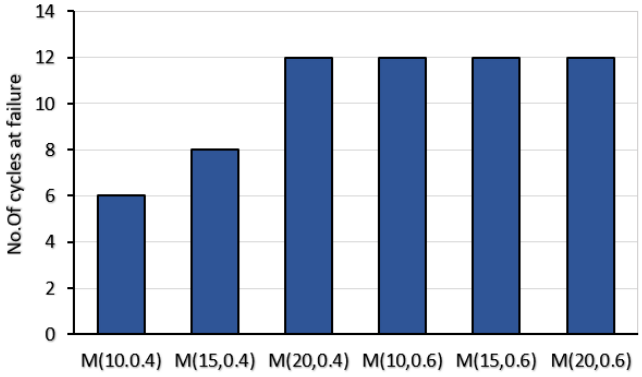

Fig. 6. Different geopolymer-stabilised soil mixtures' wetting-drying durability cycles.

Nevertheless, with low fly ash percentages, i.e., 10% and 15% (M (10, 0.4), and M (15, 0.4)), such treatment level is demonstrated to be insufficient, with early failure at cycles. However, the mixture (AC/FA 0.6) passed 12 targeted durability cycles at all fly ash contents. Figure 7 depicts a picture of the durability

performance of GPTS. The disintegration observed at low addition of GP (e.g., M (15, 0.4)) can belong to the previously mentioned limited form of soil clusters and cementitious products within the treated soil mass, as seen in Figs. 7(a) and 7(b). It was observed that the high durability performance of soil-geopolymer mixtures increased at higher geopolymer content (i.e., M (20, 0.4) and M (15, 0.6) mixtures), as shown in Figs. 7(c) and 7(d). For the weight changes, a durable soil geopolymer that survived the 12 wetting-drying cycles was observed. Table 4 includes the outcomes of the weight variations. Overall, the specimens performed well during the 12 WDC, with a slight weight loss of less than 1.53%. It was indicated that brushing does not cause considerable sample deterioration.

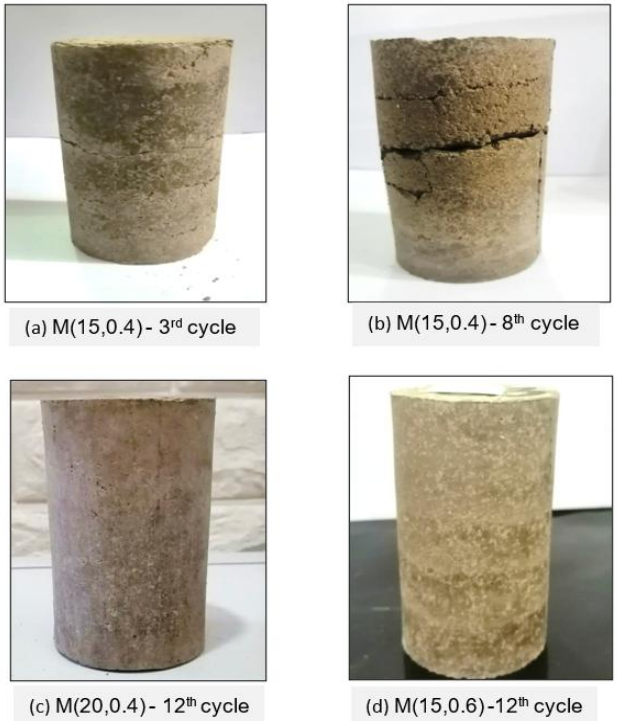

Fig. 7. Changes in geopolymer samples exposed to wetting-drying cycles: (a) M(15,0.4) - 3rd cycle, (b) M(15,0.4) -8th cycle, (c) M(20,0.4) -12TH cycle, and (d) M(15,0.6) -12TH cycle.

Since the mass loss was insignificant, the GP gel connecting the particles of soil is relatively high. UCS testing was achieved on geopolymer samples after 3, 6, 9, and 12 WDC to inspect the strength degradation due to the process of WDCs of treated soil, as shown in Fig. 8. A damage tendency was recognised for GP soil after 12 WDCs, with a total rate of 22% (M (20, 0.4)). Whereas the strength improved in the third WDC, a slight deterioration for (M (15, 0.6) and M (20, 0.6)) specimens was observed. This might propose that the high temperatures of the durability drying cycle speed up the geopolymerization process in addition to the corresponding gel formation in the treated soil. Then, it is followed by a cumulative impact of the durability cycle that damages the structure of stabilised soil. It has to be recognised that thermal curing stimulates the geopolymerization and strength

development [29]. The alkaline activation formed denser materials and reduced the water absorption possibility and subsequent specimen degradation because of shrinkage and swelling resulting from WDSs.

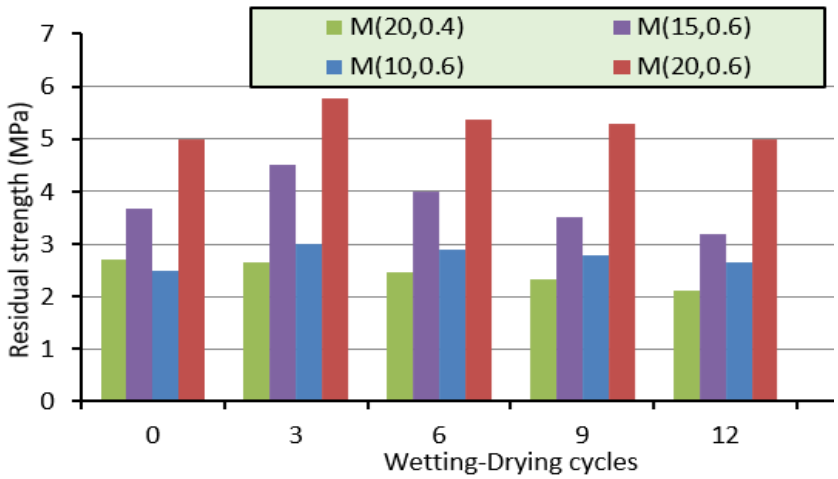

Fig. 8. Influence of wetting-drying cycles on the residual stress results of GPTS mixes.

3.3. California bearing ratio

Geopolymer mixtures at 0.4 activator ratio, AC/FA, resulted in a strength range between 1-2.7 MPa for clayey silt soil after curing for 28 days. All samples tested for CBR are performed on soaked samples. The UCS performance of prepared mixes could meet the minimal demands for most applications for ground improvement, i.e., subgrade or subbase courses in pavement construction. According to IRC 37-2012 specifications, UCS must be at least 0.8 and 3.0 MPa, respectively, to construct low- and high-volume roads.

CBR tests were performed on GP-treated soil (GPTS) at FA percentages of 10%, 15%, and 20% as well as AC/FA of 0.4. Figure 9 shows a rapid increase in the value of CBR for the treated specimens compared to the untreated ones. The CBR value of soil-geopolymer initially increased from 6.5% to 60.7% at 10% FA. Furthermore, the value of CBR increased gradually with incremental dosages (i.e., 15% and 20% of FA) up to the maximum value of 144%, which was reached at 20% FA. The dense microstructure of the treated samples, caused by enhanced gel formation, increases CBR values. These findings align with the results in [33].

Table 4. The effect of WDC on mass changes after twelve cycles in GP-treated soils.

Mixture ID	No. of cycles	% Mass change
M (20,0.4)	12	1.53
M (10,0.6)	12	1.452
M (15,0.6)	12	1.41
M (20,0.6)	12	1.37

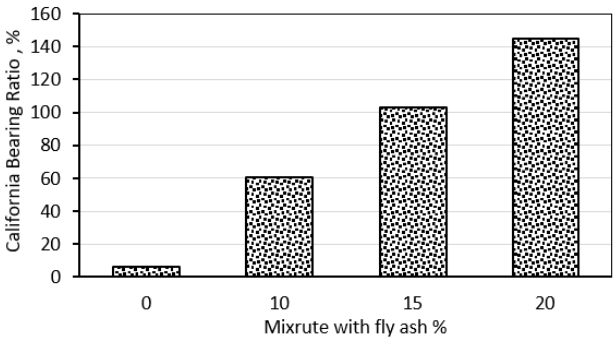

Fig. 9. The California bearing ratio results.

3.4. Microstructure

The microstructure texture of GP-treated soil (GPTS) was analysed with SEM to comprehend the mechanism of its strength development. The FA-geopolymer's composition is primarily derived from the dissolution of silicate and aluminium existing in FA by Activator solution (AC) produced by polycondensation. GP binder is a resultant reaction of FA reactions and Si^{4+} and Al^{3+} from AC, which harden over time to form soil cement particles.

SEM analysis demonstrates the rate of geopolymerization by detecting etching on the surfaces of FA particles [34]. Figure 10 shows the microstructure of GPTS synthesised at 15% FA and AC/FA of 0.4 and 0.6. In the microstructures of (M (15, 0.4)), there were limited partially reacted FA particles, as shown in Fig. 10(a). Under the current activator content, it was indicated that the Si and Al of the FA seem to be partially decomposition. The current finding agrees with the results of Phummiphan et al. [35], who revealed the gradual response of FA with an AC at various contents within GPTS, as shown in Fig. 10(b).

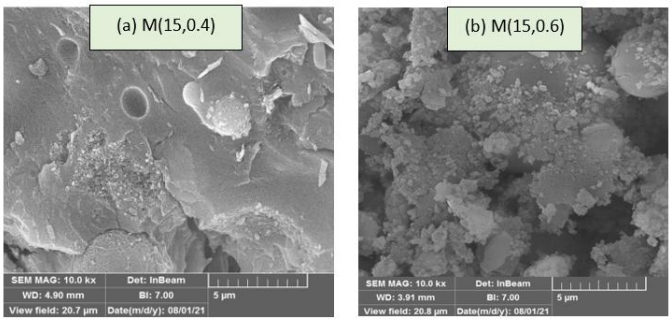

Fig. 10. SEM analysis for soil-GP mixtures (a) M(15,0.4), and (b) M(15,0.6).

Increasing the ratio of alkaline materials corresponding to more NaOH and Na_2SiO_3 resulted in a high rate of Geopolymerization [35]. Where the cementitious agent existed on the surfaces of FA particles by aluminium and silica decomposition indicates the degree of geopolymerization reaction; the etched holes in the surfaces of fly ash particles are frequently filled by small particles and cementitious agents, creating a dense matrix as seen in Fig. 11.

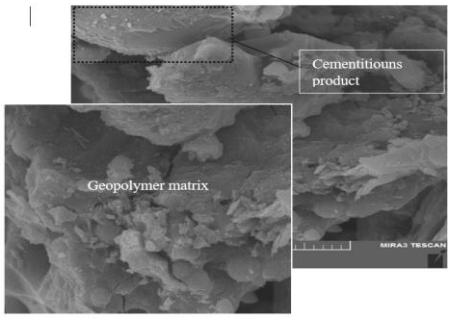

Fig. 11. SEM of geopolymer soil, matrix of geopolymer.

4. Conclusion

The current research investigated the efficacy of stabilising clayey silt soil with geopolymer based on CFA. Several tests were conducted to evaluate the CBR and UCS of four mixture proportions of geopolymer-treated soil (GPTS). The microstructural formation of the soil-geopolymer was examined using SEM analysis. Additionally, the ability of GPTS to resist wetting-drying cycles (WDCs) was evaluated. The following findings were obtained from the current experiment as follows:

- Under unconfined compression, the response of predominant stress-strain for GPTS was a brittle yield, with the stress peaking prior to an abrupt collapse. The response stiffens (e.g., decreases axial strain and increases unconfined force) as the GP replacement percentages rise.
- The CBR of soil-geopolymer mixtures improved with the increase in geopolymer percentage; the addition of 20% FA exhibits a maximum CBR value of 144%.
- The specimens of GPTS demonstrate satisfactory durability performance. The specimens of GPTS were designated effectively, essentially bypassing 12 WDCs and less than 1.52% weight variation with some residual strength.
- SEM analysis of geopolymer-stabilised soils showed improved fabric homogeneity and increased strength gain as geopolymer content increased.

Abbreviations

AC	Alkaline Activator Solution
CBR	California Bearing Ratio
CFA	Class A Fly Ash
FA	Fly Ash
FFA	Class F Fly Ash
GP	Geopolymers
GPTS	Geopolymer-treated soil
ML	Silty Soil
PVC	Polyvinyl Chloride
SEM	Scanning Electron Microscopy
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
WDC	Wetting-Drying Cycles

References

1. Kempfert, H.-G.; and Gebreselassie, B. (2006). *Excavations and foundations in soft soils*. Springer-Verlag.
2. Sim, L.W.; Katman, H.Y.B.; Baharuddin, I.N.Z.B.; Ravindran, G.; Ibrahim, M.R.; and Alnadish, A.M. (2024). Global research trends in soft soil management for infrastructure development: Opportunities and challenges. *IEEE Access*, 12, 73731-73751.
3. Karol, R.H. (2003). *Chemical grouting and soil stabilisation*. Marcel Dekker, Inc.
4. Roshan, M.J.; and Rashid, A.S.B.A. (2024). Geotechnical characteristics of cement stabilised soils from various aspects: A comprehensive review. *Arabian Journal of Geosciences*, 17(1), 1.
5. Al-Qutaifi, S.; Ethaib, S.; and Awei, Y.R. (2022). Evaluating the impact of inclusion metakaolin and silica fume on the green and mechanical properties of low calcium fly ash concrete. *Annales de Chimie-Science des Matériaux*, 46(6), 323-331.
6. Amer, A.A.; and El-Hoseny, S. (2017). Properties and performance of metakaolin pozzolanic cement pastes. *Journal of Thermal Analysis and Calorimetry*, 129(1), 33-44.
7. Davidovits, J. (2008). *Geopolymer chemistry and applications*. Institut Géopolymère.
8. Sargent, P. (2015). *The development of alkali-activated mixtures for soil stabilisation*. In Pacheco-Torgal, F.; Labrincha, J.A.; Leonelli, C.; Palomo, A.; and Chindaprasirt, P. (Eds.), *Handbook of alkali-activated cements*, *mortars and concretes*. Elsevier, 555-604.
9. Al-Qutaifi, S.; and Bagheri, A. (2021). Evaluating fresh and hardened properties of high-strength concrete including closed steel fibres. *The Open Civil Engineering Journal*, 15(1), 104-114.
10. Al-Qutaifi, S.; K. Hanan, A.; and Hamza, A.J. (2025). The influence of molarity activity on the green and mechanical properties of geopolymer concrete. *Construction Material*, 5(1), 16.
11. Davidovits, J. (1989). Geopolymers and geopolymeric materials. *Journal of Thermal Analysis*, 35(2), 429-441.
12. Xu, H.; and Van Deventer, J.S.J. (2003). Effect of source materials on geopolymerization. *Industrial & Engineering Chemistry Research*, 42(8), 1698-1706.
13. Siciliano, U.C.C.S.; Zhao, J.; C. Trindade, A.C.; Liebscher, M.; Letichevsky, S.; De Avillez, R.R.; Mechtcherine, V.; and De A. Silva, F. (2025). Metakaolin-based geopolymer composites using hybrid particulate additives and targeted high-temperature, high-pressure curing conditions. *Ceramics International*, 51(19), 28546-28560.
14. Fernández-Jiménez, A.; Palomo, A.; and Criado, M. (2005). Microstructure development of alkali-activated fly ash cement: A descriptive model. *Cement and Concrete Research*, 35(6), 1204-1209.
15. Nanda, R.P.; and Priya, N. (2024). Geopolymer as stabilising materials in pavement constructions: A review. *Cleaner Waste Systems*, 7, 100134.

16. Abdullah, H.H.; Shahin, M.A.; and Walske, M.L. (2019). Geo-mechanical behavior of clay soils stabilised at ambient temperature with fly-ash geopolymer-incorporated granulated slag. *Soils and Foundations*, 59(6), 1906-1920.
17. Al-Rkaby, A.H.J. (2019). Evaluating shear strength of sand-GGBFS based geopolymer composite material. *Acta Polytechnica*, 59(4), 305-311.
18. Fattah, M.Y.; Rahil, F.H.; and Al-Soudany, K.Y.H. (2013). Improvement of clayey soil characteristics using rice husk ash. *Journal of Civil Engineering and Urbanism*, 3(1), 12-18.
19. Zhang, M.; Guo, H.; El-Korchi, T.; Zhang, G.; and Tao, M. (2013). Experimental feasibility study of geopolymer as the next-generation soil stabiliser. *Construction and Building Materials*, 47, 1468-1478.
20. Khan, Q.S.; Mumtaz, T.; Qazi, A.U.; and Pham, T.M. (2024). Influence of alkaline activators on mechanical properties of environmentally friendly geopolymer concrete under different curing regimes. *Environmental Science and Pollution Research*, 31(50), 60619-60639.
21. Fang, Y.; Wang, C.; Yang, H.; Chen, J.; Dong, Z.; and Li, L.-Y. (2024). Development of a ternary high-temperature resistant geopolymer and the deterioration mechanism of its concrete after heat exposure. *Construction and Building Materials*, 449, 138291.
22. Gianoncelli, A.; Zacco, A; Struis, R.P.W.J; Borgese, L.; Depero, L.E.; and Bontempi, E. (2013). *Fly ash pollutants, treatment and recycling*. In Lichtfouse, E.; Schwarzbauer, J.; and Robert, D. (Eds.), *Pollutant Diseases, Remediation and Recycling*. Springer International Publishing, 103-213.
23. Al-Adhadh, A.R.; Abbas, B.J.; and Hamza, A.J. (2021). Analysis and evaluation of landslide failure and using different techniques to the mitigation. *IOP Conference Series*: *Materials Science and Engineering*, 1090(1), 012008.
24. Corrêa-Silva, M.; Araújo, N.; Cristelo, N.; Miranda, T.; Gomes, A.T.; and Coelho, J. (2019). Improvement of a clayey soil with alkali activated low-calcium fly ash for transport infrastructures applications. *Road Materials and Pavement Design*, 20(8), 1912-1926.
25. Abdullah, H.H.; Shahin, M.A.; and Walske, M.L. (2020). Review of fly-ash-based geopolymers for soil stabilisation with special reference to clay. *Geosciences*, 10(7), 249.
26. Cristelo, N.; Glendinning, S.; Miranda, T.; Oliveira, D.; and Silva, R. (2012). Soil stabilisation using alkaline activation of fly ash for self-compacting rammed earth construction. *Construction and Building Materials*, 36, 727-735.
27. Kadhim, Y.M.; Al-Adhamii, R.A.J.; and Fattah, M.Y. (2022). Geotechnical properties of clayey soil improved by sewage sludge ash. *Journal of the Air & Waste Management Association*, 72(1), 34-47.
28. Sreelakshmi, S.; Huchegowda, B.K.; Chithaloori, S.; and Kumar, G.K. (2020). *Strength and durability behaviour of geopolymer-stabilised soil*. In Latha Gali, M.; and P., R.R. (Eds.), *Geotechnical Characterization and Modelling*. Springer Singapore, 585-591.
29. Odeh, N.A.; and Al-Rkaby, A.H.J. (2022). Strength, durability, and microstructures characterisation of sustainable geopolymer improved clayey soil. *Case Studies in Construction Materials*, 16, e00988.

30. D18 Committee. (2007). *Test methods for compressive strength of* molded *soil-cement cylinders*. ASTM International.
31. D18 Committee. (2003). *Test methods for wetting and drying compacted soil-cement mixture*s. ASTM International.
32. Yu, J.; Chen, Y.; Chen, G.; and Wang, L. (2020). Experimental study of the feasibility of using anhydrous sodium metasilicate as a geopolymer activator for soil stabilisation. *Engineering Geology*, 264, 105316.
33. Murmu, A.L.; Dhole, N.; and Patel, A. (2020). Stabilisation of black cotton soil for subgrade application using fly ash geopolymer. *Road Materials and Pavement Design*, 21(3), 867-885.
34. Fernández-Jiménez, A.; Palomo, A.; Sobrados, I.; and Sanz, J. (2006). The role played by the reactive alumina content in the alkaline activation of fly ashes. *Microporous and Mesoporous Materials*, 91(1-3), 111-119.
35. Phummiphan, I.; Horpibulsuk, S.; Sukmak, P.; Chinkulkijniwat, A., Arulrajah, A.; and Shen, S.-L. (2016). Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer. *Road Materials and Pavement Design*, 17(4), 877-891.