Civil and Environmental Engineering
Vol. 20, Issue 2, 978-992, DOI: 10.2478/cee-2024-0071

THE EFFECT OF ADDING MIXTURE OF GYPSUM-LIME WITH GEOPOLYMER ON THE PROPERTIES OF SWELLING SOIL

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Abstract

This study was to investigate the influence of adding optimum percentages of gypsum (G) - lime (L) mixtures (i.e. 6% lime and 4% gypsum) with three percentages of fly ash geopolymer (FAG) (i.e. 6%, 9%, and 12%) on some engineering properties of expansive soil. The tests results indicated that adding the percentages for the gypsum-lime mixture (6% lime + 4% gypsum) affected the soil's properties by decreasing the plasticity index, swelling potential, and swelling pressure by 48.2%, 85%, and 87.9%, respectively. Adding (6% L + 4% G + 12% FAG) decreased the plasticity index, swelling potential, and swelling pressure of prepared expansive soil by about 66.1%, 96.4%, and 96.9%, respectively. The California bearing ratio increased up to 33.3% and 95.1% with the addition of (6% L + 4% G) and (6% L + 4% G + 12% FAG), respectively. Also, adding the same percentages of gypsum-lime mixture and gypsum-lime mixture with geopolymer caused increasing in Unconfined compressive strength value by 109.5% and 322.6%, respectively. The results show the significant effect of gypsum-lime mixture with geopolymer on compaction parameters of the prepared soil, so there was a decrease from 22% to 18% for the optimum moisture content and an increase from 1.473 g/cm^3 to 1.516 g/cm^3 for the maximum dry density.

Keywords:

Expansive soil;
Gypsum-lime mixture;
Geopolymer;
Engineering properties;
Swelling potential.

1 Introduction

Swelling soils are problematic in nature because of the abundance of clay minerals called montmorillonite. It has a strong ability to change volume in response to moisture content changes, which is referred to as swelling potential. This expansion has a major impact on sidewalks, pipelines, basement floors, building foundations, and other structures. Numerous foundations have needed to be repaired and renovated as a result of the swelling's indirect effects, which have caused enormous damage. Expansive soils have been improved by the application of several procedures, including dewatering, soil stabilization, and earth reinforcement. One way to improve expansive soils is by soil stabilization, which involves changing the characteristics of the soil to satisfy particular engineering specifications [1].

Ameta et al. [2] looked at the cost analysis, swelling characteristics, and plasticity of bentonite with various proportions of gypsum-lime mixes. It is discovered that a combination consisting of 2% lime and 4% gypsum is more cost-effective in lowering the plasticity index, liquid limit, and swelling pressure.

Tilak et al. [3] carried out a study on bentonite modified with gypsum and lime. Based on the results, Bentonite with 8% lime increased maximum dry density and optimum moisture content by adding (0.5, 1, 2, 4, 8 %) gypsum. In addition, the UCS of bentonite with 8% lime cured for (3, 7, 14, and 28 days) increased with adding gypsum percentages up to 4% and decreased with adding 8% gypsum. The modulus of subgrade reaction, California bearing ratio, and coefficient of consolidation for bentonite increased with the addition of (8% lime + 4% gypsum).

Kiliç et al. [4] were able to investigate the influence of the addition of (3%, 6%, 9%, 12%, and 15%) gypsum, lime, and gypsum-lime mixtures (50% gypsum + 50% lime) at curing periods of (7, 28, 90 days) on the unconfined compressive strength and swelling properties of high plasticity clay. As a result of the experimental study, the swelling pressure and swelling percent decreased with the increase in additives percent, while the strength increased. For gypsum, the lowest improvement ratio was obtained. The optimal mixture was obtained at 6% lime, which corresponds to a 191.87% increase in unconfined compressive strength, a 98.98% decrease in swell pressure, and a 99.55% decrease in swell percent for 90 days.

Mohammed Shafiqu [5] looked into the effects of adding lime (L) and cement kiln dust (CKD) with polyacrylamide (PAM) polymer on the characteristics of clayey expansive soils. When PAM polymer was added to the lime and CKD mixture instead of only lime and CKD, the study discovered that the expansive clay soil's characteristics were much improved. After testing various combinations, it was found that 3% lime, 8% CKD, and 5% PAM produced the best results. These combinations reduced free swell by 94.5%, increased Unconfined Compression Strength (UCS) by 262% after 7 days, increased UCS by 400% after 28 days, and improved the California Bearing Ratio (CBR) from 5.45% to 27%.

Mohammed Shafiqu and Abass [6] focused on using lime (L) and cement kiln dust (CKD) to stabilize highly plastic soils in order to lessen swelling and improve geotechnical characteristics. According to the study, adding (6% L + 16% CKD) reduced the soil's swelling potential to 2% from 19%, and adding (9% L + 16% CKD) produced the greatest CBR value by about 35.95%.

Khadka et al. [7] studied the stabilizing of high sulfate expansive soil by adding lime and gypsum to the geopolymer. With the use of an expansion test, creating cementation products has been capable of withstanding volume changes and determining the optimal dose corresponding to the minimum expansion amount.

Al-Jeznawi et al. [8] used laboratory tests to show that adding 10% CKD, (5%, 10%, and 15%) silica fume, and (5%, 8%, and 10%) polyethylene polymer (PEHD) to expansive soil samples significantly reduced swelling potential, increased the plastic limit, and reduced the plasticity index and liquid limit. In particular, adding (10% CKD + 10% silica fume + 10% PEHD) resulted in a 2.1% swelling potential decrease from 21.23%.

Al-Jeznawi et al. [9] demonstrated that adding polypropylene polymer significantly improved the properties of expansive soils, with optimal results obtained at lower percentages of 0.4% and 0.8% of the polymer, leading to increased plasticity index, liquid limit, maximum dry density, and unconfined compressive strength, while reducing swelling potential. However, higher percentages of Polypropylene polymer (1.2%, 2%, and 4%) resulted in a decrease in these properties.

It has been observed from the previous studies on improvement soils by using traditional stabilizers and non-traditional stabilizers like geopolymers that there were a lot of studies with respect to using lime to improve expansive soils but little studies were observed that used gypsum as stabilizer and scarce studies in the field of enhancement of expansive soil using mixture of gypsum-lime with geopolymer materials. This study aims to investigate how adding gypsum-lime mixture with geopolymer affects the properties of swelling soil including, swelling and plasticity properties, unconfined compressive strength with curing periods of (0, 7, and 14 days), California bearing ratio, and compaction parameters.

2 Materials

2.1 Natural Soil

The soil used in the present study was obtained from Al-Zafaraniya, southeast of Baghdad, at a depth of (2-2.5) m below the soil surface. This soil was lean clay (50% clay + 44% silt + 6% sand). The chemical composition of natural soil is shown in Table 1.

Table 1: Natural soil's chemical composition.

Si [%]	Sb [%]	Al [%]	Ca [%]	Mg [%]	Ru [%]	Pt [%]	C [%]	O [%]	Na [%]	Fe [%]	K [%]
27.13	25.99	11.17	7.32	5.67	5.28	4.97	3.97	2.77	2.04	1.84	1.84

2.2 Bentonite

The bentonite used in this study was obtained from Wadi Hauran in Anbar governorate, western Iraq. It was used to prepare the highly expansive soil. Table 2 shows the chemical composition of bentonite.

Table 2: Bentonite's chemical composition.

Si [%]	Sb [%]	Al [%]	C [%]	Ca [%]	O [%]	Fe [%]	Pt [%]	Mg [%]	Ba [%]	Co [%]
40.07	17.21	12.05	8.86	5.19	4.35	3.76	3.58	2.29	1.39	1.25

2.3 Prepared soil

(40%) of bentonite and (60%) of natural soil were mixed to prepare artificial expansive soil to study the effect of adding gypsum-lime mixture with different percentages of geopolymer on the characteristics of expansive soil. The swell% of prepared soil was (18.77 %) using an odometer test, and the soil classification was (CH) according to ASTM D2487 [10]**.** The chemical composition of prepared soil is shown in Table 3. A chemical analysis was conducted at the National Center for Construction Laboratories and research on the prepared soil and the results are shown in Table 4. The grain size distributions of natural soil, bentonite, and prepared soil are shown in Fig. 1.

Table 3: Prepared soil's chemical composition.

Sb [%]	Si [%]	Ca [%]	Al [%]	C [%]	Mg [%]	Fe [%]	O [%]	Pt [%]	K [%]	Co [%]	Cl [%]
30.91	29.29	9.49	8.93	6.18	3.36	3.32	3.09	2.15	1.79	0.85	0.66

Table 4: Chemical tests results of prepared soil.

Property	Results
SO_3 [%]	0.823
T.S.S [%]	3.190
Gypsum [%]	1.598
pH	8.03
Organic materials [%]	0.664

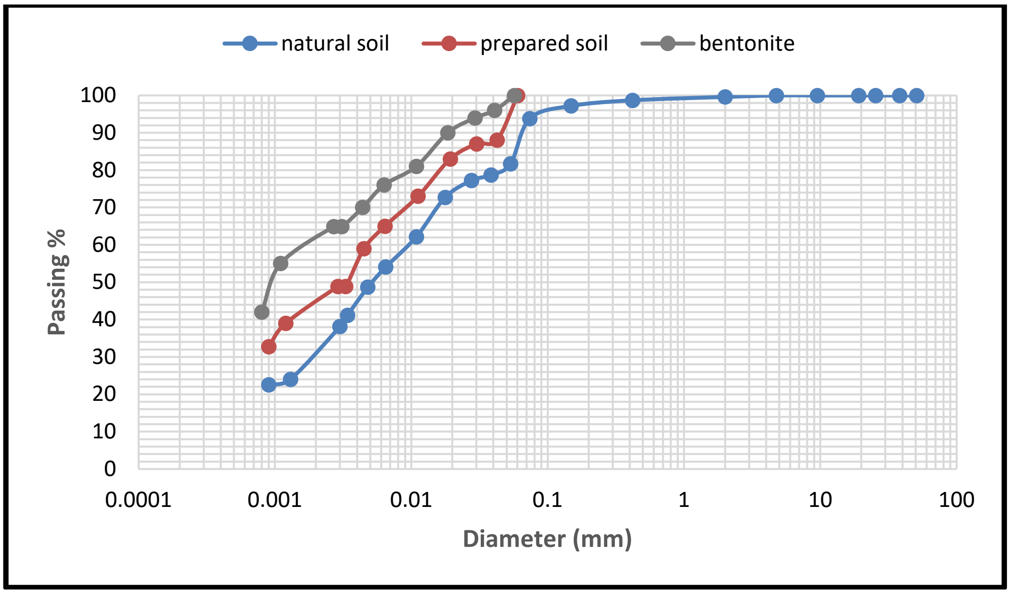

Fig. 1: The grain size distribution of natural soil, prepared soil, and bentonite.

2.4 Gypsum

The mineral gypsum is made up of hydrated calcium sulfate. The chemical formula is calcium sulfate dihydrate ($CaSO_4$. 2(H_2O)). When it comes to fire resistance, low cost, resistance to biological factors and chemicals causing deterioration, and resistance to air pollution, gypsum has superior qualities than organic additions [11]. Gypsum utilized in this study was manufactured by Romil Company Ltd. in the UK. The chemical composition of gypsum is shown in Table 5.

Table 5: Gypsum's chemical composition.

Sb [%]	S [%]	Ca [%]	C [%]	O [%]
51.97	21.55	15.64	9.40	1.45

2.5 Lime

Many projects have successfully used lime stabilization to reduce swelling and increase the workability and plasticity of the soil. Typically, the top few inches of soil are treated with 3 to 8% by weight of hydrated lime. flocculation agglomeration, Cation exchange, pozzolanic reaction, and lime carbonation are some of the main reactions. All fine-grained soils could be somewhat modified to exhibit reduced plasticity and increased workability with the application of lime treatment. The lime type, soil type, percentage of lime, and curing conditions (temperature and duration) all have a significant impact on the strength properties of soil treated with lime [1]. The lime utilized in the present study was hydrated lime manufactured in Iran. The chemical composition of lime is shown in Table 6. The natural soil, bentonite, gypsum, and lime used in this study are illustrated in Fig. 2.

Table 6: Lime's chemical composition.

Sb [%]	Ca [%]	Mg [%]	Pt [%]	C [%]	Si [%]
70.60	22.02	3.04	1.95	1.67	0.72

Fig. 2: Natural soil, bentonite, gypsum, and lime used in this study.

2.6 Geopolymer

The geopolymers can often be synthesized from a wide range of materials with a high aluminosilicate concentration. The precursors of geopolymer that have a high content of silica (Si) and alumina (Al) minerals, like GGBFS and FA, are highly recommended for geopolymerization in applications of soil stabilization. All materials of aluminosilicate have to be activated by a second raw material that is referred to as the alkali activator solution. Diffusion, leaching, polymerization, reorientation, and condensation are all steps in the integrated process of geopolymerization [12].

2.6.1 Fly ash

Burning coal produces fly ash, an industrial byproduct that is usually divided into class F and class C. Class F fly ash (FFA) is a typical form of fly ash produced by burning bituminous coal that has a low percentage of CaO. Additionally, class C fly ash (CFA) with a high percentage of CaO is produced by lignite and sub-bituminous coal [13]. The composition of Class F fly ash is comparable to that of naturally occurring volcanic ash [14]. Because Class C fly ash contains more CaO than Class F, it is comparatively more pozzolanic. Because of its self-cementitious qualities, Class C fly ash doesn't need additional materials for pozzolanic reactions. Class F fly ash needs additional materials like cement or lime to start pozzolanic reactions. Fly ash, whose microscopic shape is fine spherical particles, is an extensively utilized raw material for the preparation of geopolymers and is widely available worldwide [15]. Since FA lowers construction costs and greenhouse gas emissions, replacing cement with FA is excellent for the environment [16,17]. Fly ash utilized in this study was Class F and manufactured by Euro Build Construction Chemicals and Coatings Company in UAE as illustrated in Fig. 3. The chemical composition of fly ash is shown in Table 7.

Fig. 3: Fly ash utilized in the study.

Table 7: Fly ash's chemical composition.

Si [%]	Al [%]	C [%]	Sb [%]	O [%]	Ca [%]	Ba [%]	Mg [%]	Pt [%]	Fe [%]	K [%]
34.67	23.37	16.07	11.49	4.62	3.26	2.08	1.73	1.27	0.83	0.60

2.6.2 Sodium Silicate

A chemical material with the formula Na_2SiO_3 is Sodium Silicate. Originally, it was a liquid. It is utilized in many various applications and is also referred to as liquid glass or water glass. The sodium silicate used in this study was manufactured in UAE as shown in Fig. 4. The characteristics of the sodium silicate employed in this investigation are shown in Table 8.

Fig. 4: Sodium Silicate used in the study.

Table 8: Characteristics of the sodium silicate used in this study.

Property	Value
Na_2O [%]	13.1–13.7
SiO_2 [%]	32–33
Density-20 Baum	51 ± 0.5
Specific gravity (Gs)	1.534–1.551
Viscosity (CPS) 20 [°C]	600–1200
Net Weight [kg]	30

2.6.3 Sodium hydroxide

An organic substance having the formula NaOH. Another name for it is caustic soda. Many types of sodium hydroxide are available. This study employed the flake form. To attain the desired molar concentration, the flakes must dissolve in water at a particular weight. The sodium hydroxide used was manufactured by Loba Chemie Pvt. Ltd. in India, as shown in Fig. 5. The physical characteristics of sodium hydroxide are shown in Table 9, and the specification of sodium hydroxide is shown in Table 10.

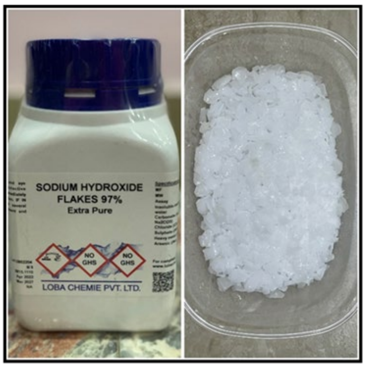

Fig. 5: Sodium Hydroxide used in the study.

Table 9: Physical characteristics of sodium hydroxide used in this study.

Property	Value
Color	White flakes
Odor	Odorless
Physical state at 20 [°C]	Solid
Boiling point [°C]	1390 [°C]
Melting point/Freezing point [°C]	318 [°C]
Vapor pressure 20 [°C]	< 24 hPa at 20 [°C]
pH value	13–14
Density [g/cm^3]	2.13
Vapor density	> 1
Solubility in water [%weight]	111 g/100 g of water

Table 10: Specification of sodium hydroxide used in this study.

Component	Limits
Assay	Min. 97 [%]
Carbonate (as Na_2CO_3)	Max. 2 [%]
Insoluble matter in water	Max. 0.05 [%]
Sulphate (SO_4)	Max. 0.05 [%]
Chloride (Cl)	Max. 0.05 [%]
Heavy metal (as Pb)	Max. 0.005 [%]
Iron (Fe)	Max. 0.005 [%]
Arsenic (As)	Max. 0.0003 [%]

3 Preparation of Test Samples

Bentonite was mixed with natural soil to prepare artificial expansive soil. In an oven set at 105 °C, the natural soil and bentonite were dried for a whole day. Next, the natural soil was pulverized by the Los Angeles machine. By dry mass, 40% bentonite was mixed with 60% natural soil. These percentages were chosen to get an appropriate swell percentage for the research.

The alkaline activator in this study has been prepared in two steps. First step, flakes of sodium hydroxide (NaOH) were dissolved in distilled water to obtain a concentration of 10M to create a sodium hydroxide solution. Water and sodium hydroxide react exothermically, necessitating a cooling-off interval. second step, the resultant solution was completely blended with liquid sodium silicate (Na_2SiO_3) for 7 to 10 minutes at an equal percentage of sodium silicate and sodium hydroxide according to previous research [18]. The alkali solution was not mixed or stored using metal instruments since they may react and cause metal corrosion, which could contaminate the solution. Hand gloves must be worn when preparing the solution for safety requirements, as the chemical solution can harm the skin.

Prepared soil samples treated with a gypsum-lime mixture with geopolymer were first prepared by mixing fly ash in proportions (6%, 9%, and 12%) with the activated alkaline solution in proportions (10%) of the dry weight of the mixture, based on the previous studies [18,19]. The activator solution was mixed with Fly ash for 5-10 min until a homogeneous geopolymer slurry was obtained [7]. Then, the activated fly ash was added to the mixture of the soil and the optimal percentages of the gypsum-lime mixture (6% lime + 4% gypsum). Finally, the water needed to obtain the optimum moisture content from compaction test was added to each sample. The optimum percentages of the gypsum-lime mixture were chosen according to reference [2]. In this study, percentages of geopolymer indicate the amount of fly ash present in geopolymer, such as 6% geopolymer, which means the mixture includes 6% fly ash and 10% alkali activator solution.

4 Testing program

Compaction test [20], Atterberg limits test [21], free swell and swelling pressure test [22], California bearing ratio test [23], and unconfined compressive test [24] are carried out to investigate the effect of adding various percentages of fly ash-based geopolymer (6%, 9% and 12%) with the optimum percentages of gypsum-lime mixture (6% lime + 4% gypsum) on the properties of prepared soil. About 40 samples were prepared and tested in this study.

The standard proctor compaction tests were conducted using ASTM D 698 method A [20], using a standard proctor and mechanical hammer to compact samples into three layers, with 25 blows applied to both treated and untreated expansive soil. Based on ASTM D4318 [21], liquid and plastic limits are determined on prepared soil, natural soil, and treated soil. The liquid limit is conducted using the Casagrande device. The plasticity index (PI) of soil is the difference between the liquid and plastic limits of soil. The swelling test was conducted according to ASTM D4546-96 [22] by using odometer test apparatus. The specimens were compacted at their optimum moisture content and maximum dry density from compaction test inside the consolidation ring (75 mm diameter and 20 mm height), with the specimen height set 4 mm lower than the ring's height. The specimen was allowed to swell freely under 1kPa pressure. A dial gauge with a division of 0.002 mm was used to record the rise in sample height. In accordance with ASTM D1883-87 [23], the potential strength of laboratory compacted specimens is determined using the California Bearing Ratio (CBR). With three layers and 56 blows per layer, this test procedure gives the (CBR) at optimum moisture content and maximum dry density that correspond to the values found in the 6" standard proctor mold. The procedure of the unconfined compressive strength test was achieved according to ASTM D 2166 [24] by compacting specimens inside mold (38 mm diameter and 76.3 mm height) using a manual hammer to achieve optimum moisture content and maximum dry density from the compaction test. Double nylon bags were used to allow samples to cure. After curing for 0, 7, and 14 days, the nylon bags were removed, and the specimens were tested using a digital unconfined compression tester. The properties of natural and prepared soil are illustrated in Table 11.

Table 11: Properties of natural soil and prepared soil.

Property	Natural soil	Prepared soil	Standard method
Liquid limit [%]	37	85	ASTM D4318
Plastic limit [%]	19	29	ASTM D4318
Plasticity index [%]	18	56	ASTM D4318
Sand [%]	6	0	ASTM D422
Silt [%]	44	41	ASTM D422
Clay [%]	50	59	ASTM D422
Maximum dry density [g/cm^3]	1.730	1.473	ASTM D698
Optimum moisture content [%]	16	22	ASTM D698
Swelling [%]	1	18.77	ASTM D4546-96
Swelling pressure [kPa]	NA	735.75	ASTM D4546-96
California bearing ratio [%]	NA	12.13	ASTM D1883-87
Unconfined compressive strength (without curing) [kPa]	NA	211.946	ASTM D 2166
Unconfined compressive strength (7 days curing) [kPa]	NA	281.267	ASTM D 2166

Unconfined compressive strength (14 days curing) [kPa]	NA	351.309	ASTM D 2166
Classification according to the Unified Classification System (UCS)	CL	CH	ASTM D2487

5 Results and discussions
5.1 Plasticity index

The influence of adding various percentages of fly ash geopolymer (6%, 9%, and 12%) with a gypsum-lime mixture (6% L + 4% G) on plasticity index (PI) value for the prepared soil is studied as shown in Table 12 and Fig. 6. From the findings of this figure, the values of plasticity index decreased with increasing fly ash geopolymer content up to 12% FAG. The maximum reduction in plasticity index is found by adding (6% L + 4% G + 12% FAG). Adding (6% L + 4% G) to prepared soil decreased the plasticity index to 29%. While the addition of (6% L + 4% G + 12% FAG) to prepared soil results in a decrease in plasticity index to 19%. This might result from a decrease in the amount of clay in the soil and a change in grading due to the fly ash's coarser particle size and lower liquid limit when compared to the soil mixture [25].

Table 12: The influence of adding gypsum-lime mixture with geopolymer on the plasticity index.

Sample	PI [%]	PI reductions [%]
Prepared Soil + 6% L + 4% G	29	48.2
Prepared Soil + 6% L + 4% G + 6% FAG	24	57.1
Prepared Soil + 6% L + 4% G + 9% FAG	22	60.7
Prepared Soil + 6% L + 4% G + 12% FAG	19	66.1

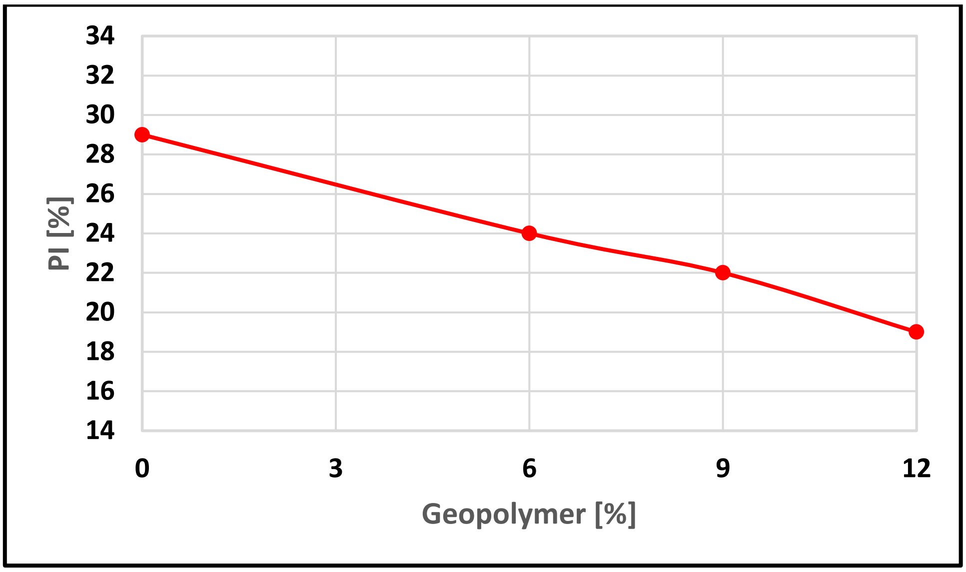

Fig. 6: The influence of adding gypsum-lime mixture with geopolymer on the plasticity index.

5.2 Compaction parameters

The values of optimum moisture content (OMC) and maximum dry density (MDD) were determined for various treated soil samples. Table 13 summarizes the results for compaction parameters. It is noted that the addition of gypsum-lime mixture with geopolymer affected the OMC and MDD of all percentages of treated expansive soil, and the optimum moisture content decreased with the addition of fly ash geopolymer, as shown in Fig. 7, While maximum dry density increased as shown in Fig. 8. The chemical activators used in the geopolymer mixture, which function as lubricants to lessen repulsion forces and promote sliding between the clay particles, and this may be attributed to the increase in MDD [26]. The lubrication induced by the activator can lower the volume of free water needed to reach the optimum compaction, which can lower the OMC. The silty properties of fly ash in the geopolymer can decrease the overall surface area related to clay particles and, consequently, the water demand because of the partial replacement of clay through additives during treatment [27]. The compaction curves are illustrated in Fig. 9.

Table 13: The influence of adding gypsum-lime mixture with geopolymer on the compaction parameters.

Sample	OMC [%]	MDD [g/cm^3]
Prepared Soil + 6% L + 4% G	26	1.386
Prepared Soil + 6% L + 4% G + 6% FAG	20	1.480
Prepared Soil + 6% L + 4% G + 9% FAG	19	1.492
Prepared Soil + 6% L + 4% G + 12% FAG	18	1.516

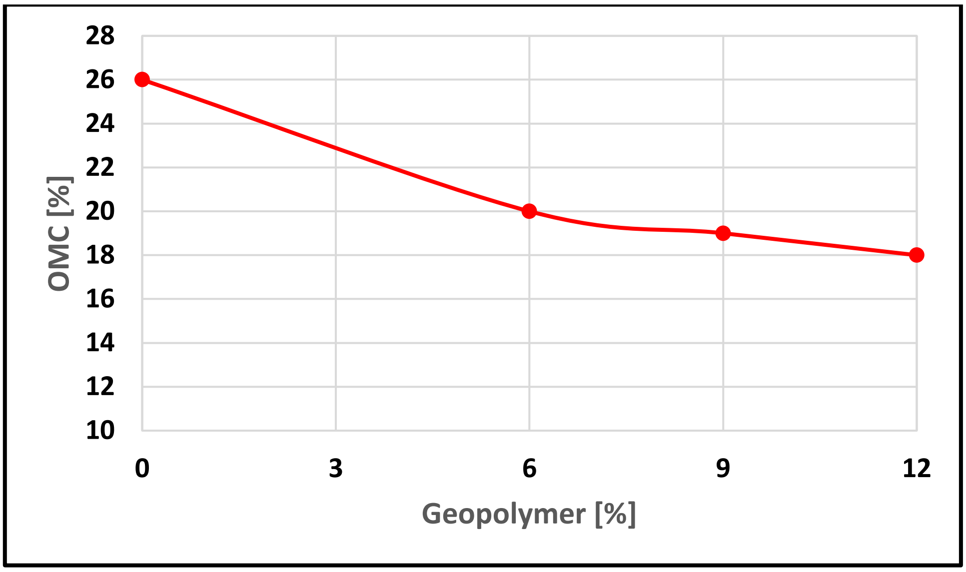

Fig. 7: The influence of adding gypsum-lime mixture with geopolymer on the optimum moisture content.

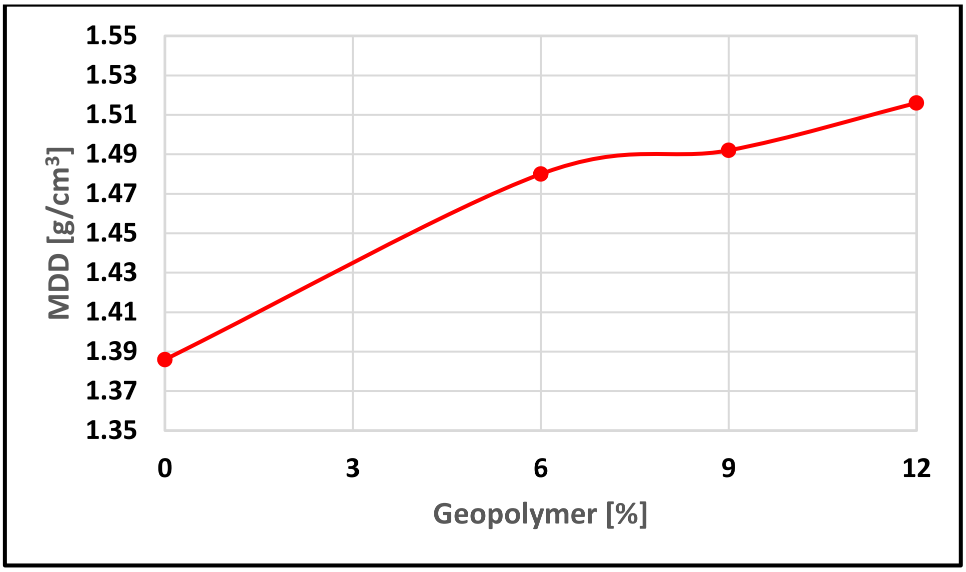

Fig. 8: The influence of adding gypsum-lime mixture with geopolymer on the maximum dry density.

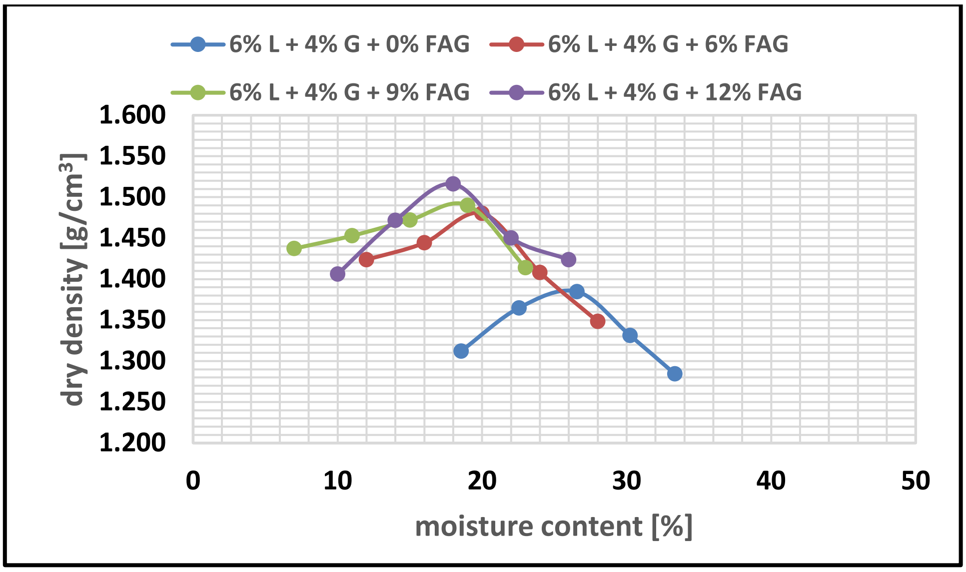

Fig. 9: The influence of adding gypsum-lime mixture with geopolymer on the moisture content-dry density relationship.

5.3 Free swell percentage and swell pressure

The influence of adding various percentages of fly ash geopolymer (6%, 9%, and 12%) with a gypsum-lime mixture (6% L + 4% G) on the free swell and swell pressure value for the prepared soil is investigated as shown in Table 14. Adding the various percentages of fly ash geopolymer with gypsum-lime mixture causes decreasing in the swell percent and swell pressure value, as shown in Fig. 10 and 11, respectively. From the results, it has been indicated that the maximum reduction in free swell and swell pressure is obtained with the percentages (6% L + 4% G + 12% FAG). The swell percent and swell pressure reduced to 2.81% and 89.18 kPa, respectively, with a percentage of improvement of about 85% and 87.5% by the addition of (6% L + 4% G). While the addition of (6% L + 4% G + 12% FAG) leads to a reduction in swell percent and swell pressure to 0.68% and 22.30 kPa, respectively, with a percentage of improvement of about 96.4% and 96.9%, respectively. The decrease in swell percent and swell pressure by adding geopolymer to the mixture due to the formation of cementation products could resist the volume change [7]. The swell percent-time relationships are plotted in Fig. 12.

Table 14: The influence of adding gypsum-lime mixture with geopolymer on the free swell and swelling pressure.

Sample	Swell [%]	Free swell reductions [%]	Swell pressure [kPa]	Swell pressure reductions [%]
Prepared Soil + 6% L + 4% G	2.81	85	89.18	87.5
Prepared Soil + 6% L + 4% G + 6% FAG	2.10	88.8	78.03	89.1
Prepared Soil + 6% L + 4% G + 9% FAG	1.30	93.1	55.74	92.2
Prepared Soil + 6% L + 4% G + 12% FAG	0.68	96.4	22.30	96.9

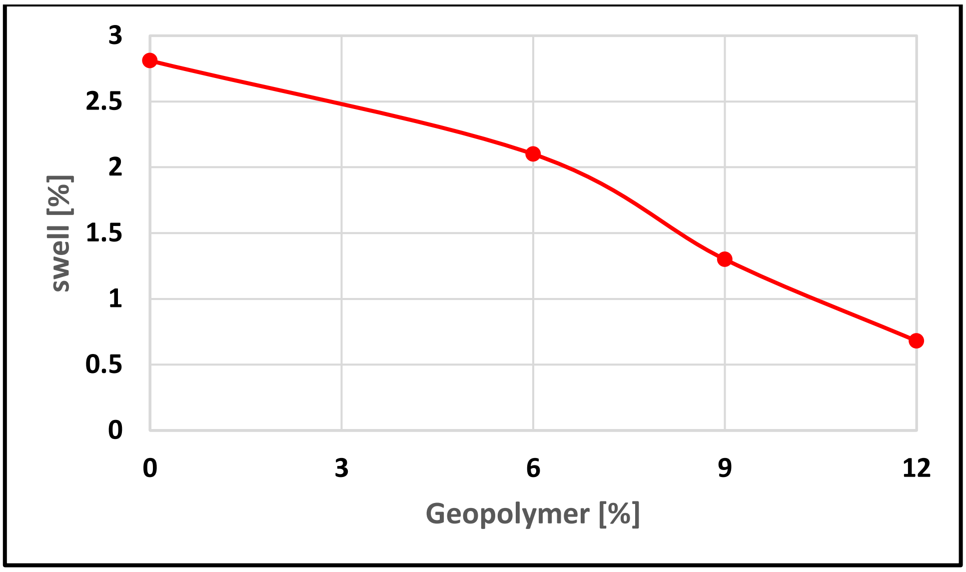

Fig. 10: The influence of adding gypsum-lime mixture with geopolymer on the free swell.

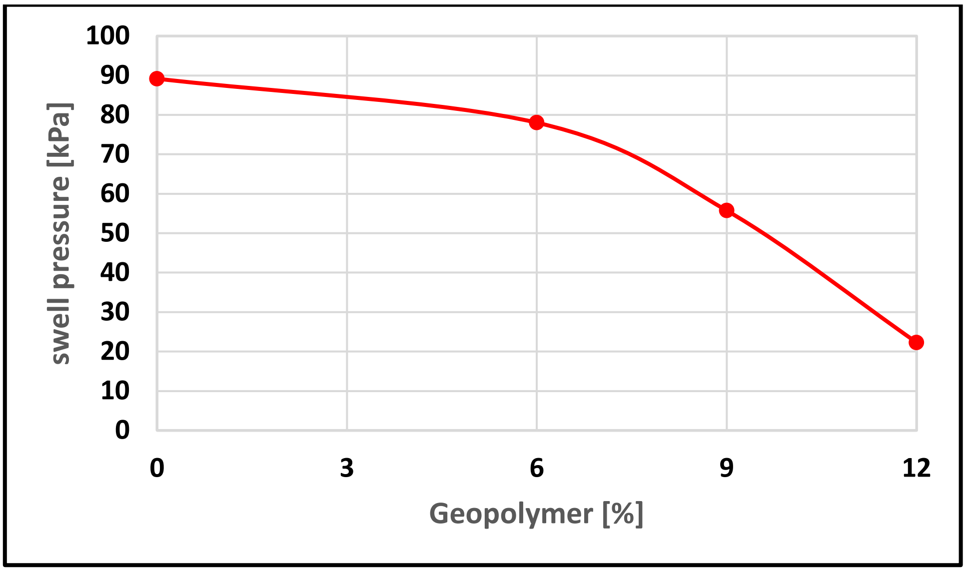

Fig. 11: The influence of adding gypsum-lime mixture with geopolymer on the swelling pressure.

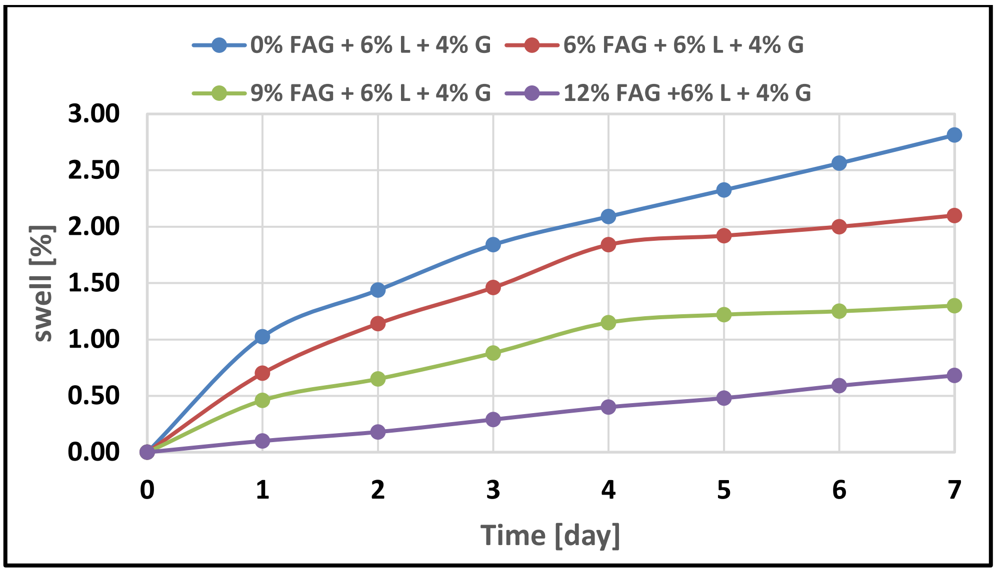

Fig. 12: The influence of adding gypsum-lime mixture with geopolymer on the swell%-time relationship.

5.4 California bearing ratio

The influence of adding fly ash geopolymer and (4% G + 6% L) to the California bearing ratio value for prepared soil is investigated as shown in Table 15 and Fig. 13. It can be seen that the California bearing ratio value increased with increasing fly ash geopolymer addition, and the maximum value of the California bearing ratio is obtained when adding (6% L + 4% G + 12% FAG). Adding (4% G + 6% L) alone led to increases in the value of the California bearing ratio from 12.13% to 16.17%, with a percentage improvement of about 33.3 %. While adding (6% L + 4% G + 12% FAG) increased the California bearing ratio value to 23.66% from 12.13%, with a percentage improvement of about 95.1%.

Table 15: The influence of adding gypsum-lime mixture with geopolymer on the California bearing ratio.

Sample	CBR [%]	CBR increasing [%]
Prepared Soil + 6% L + 4% G	16.17	33.3
Prepared Soil + 6% L + 4% G + 6% FAG	18.42	51.9
Prepared Soil + 6% L + 4% G + 9% FAG	20.59	69.7
Prepared Soil + 6% L + 4% G + 12% FAG	23.66	95.1

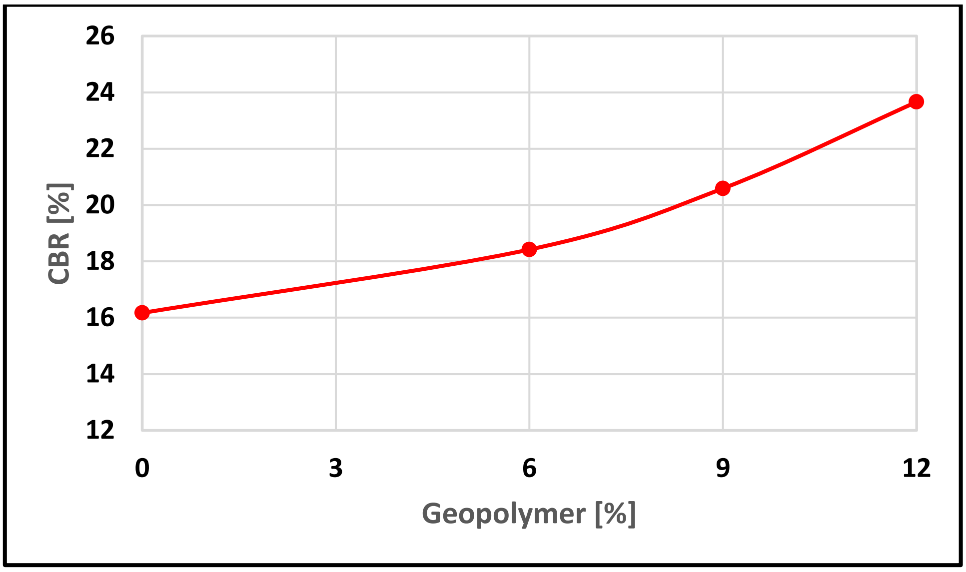

Fig. 13: The influence of adding gypsum-lime mixture with geopolymer on the California bearing ratio.

5.5 Unconfined compressive strength

The influence of adding various percentages of fly ash geopolymer on the unconfined compressive strength (UCS) for prepared soil without a curing period and with a curing period of 7 and 14 days are listed in Table 16 and are plotted in Fig. 14. It can be concluded that the UCS value improved with the increasing addition of fly ash geopolymer and curing period. The higher increase in unconfined compressive strength is obtained when (6% L + 4% G + 12% FAG) is added, and its value increases from 211.946 kPa to 554.770 kPa without curing and to 872.871 kPa and 1484.602 kPa for 7 and 14 days of curing period respectively. Physical and chemical bonds formed over time by soil particles and geopolymer are responsible for increasing strength over time. So, the reason for the increase in UCS in the curing period is attributed to aluminum and silicon reacting in the presence of an alkaline solution and generating a geopolymer binder [28]. Also, the results show increasing in the unconfined compressive strength value up to 492.131 kPa, 736.318 kPa, and 828.590 kPa by adding (6% L + 4% G) for the curing periods of (0,7 and 14 days) respectively.

Table 16: The influence of adding gypsum-lime mixture with geopolymer on the unconfined compressive strength.

Sample	UCS, without curing [kPa]	UCS, 7 days curing [kPa]	UCS, 14 days curing [kPa]
Prepared Soil + 6% L + 4% G	492.131	736.318	828.590
Prepared Soil + 6% L + 4% G + 6% FAG	514.450	775.466	1081.699
Prepared Soil + 6% L + 4% G + 9% FAG	531.299	820.936	1231.015
Prepared Soil + 6% L + 4% G + 12% FAG	554.770	872.871	1484.602

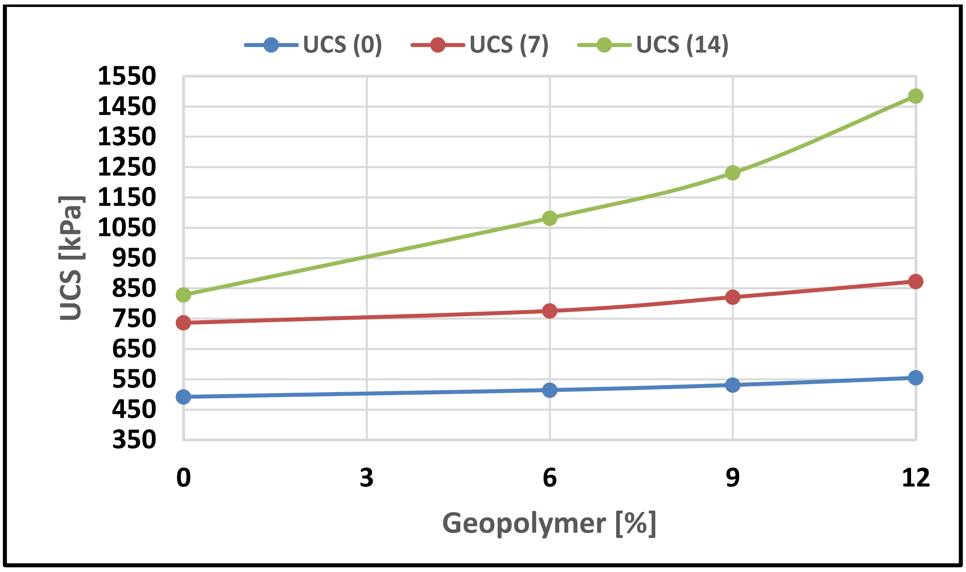

Fig. 14: The influence of adding gypsum-lime mixture with geopolymer on the unconfined compressive strength.

6 Conclusion

1) Adding fly ash geopolymer to the soil with a gypsum-lime mixture results in a decreasing plasticity index with increasing geopolymer content. Adding (6% L + 4% G + 12% FAG) reduced the plasticity index for prepared soil to 19%.

2) The addition of fly ash geopolymer to soil mixtures caused increasing in maximum dry density up to 1.516 g/cm^3 and reduced the optimum moisture content up to 18%.

3) Adding (6% L + 4% G + 12% FAG) to the prepared soil reduced the free swell and swelling pressure by about 96.4% and 96.9%, respectively.

4) The California bearing ratio increased with increasing Fly ash geopolymer content. The highest increase in CBR value was 95.1% at (6% L + 4% G + 12% FAG).

5) Increasing the curing period and geopolymer content up to 12% increased the unconfined compressive strength. Using (6% L + 4% G + 12% FAG) with a curing period of 14 days increased the UCS to be estimated at 1484.602 kPa.

6) Overall, the use of a gypsum-lime mixture with geopolymer for soil stabilization offers a sustainable and more effective solution for different construction and environmental projects such as road and highway construction, building foundations, embankments and slopes, etc.

References

[1] NELSON, J. D. – MILLER, D. J.: Expansive soils: problems and practice in foundation and pavement engineering. John Wiley & Sons, 1992.
[2] AMETA, N. – PUROHIT, D. – WAYAL, A. – SANDEEP, D.: Economics of stabilizing bentonite soil with lime-gypsum, Electronic Journal of Geotechnical Engineering, Vol. 12, Iss. 1, 2007, pp. 1–8.
[3] TILAK, V. – DUTTA, R. K. – MOHANTY, B.: Engineering properties of bentonite modified with lime and gypsum, Jordan Journal of Civil Engineering, Vol. 8, Iss. 2, 2014, pp. 199–215.
[4] KILIÇ, R. – KÜÇÜKALI, Ö. – ULAMIS, K.: Stabilization of high plasticity clay with lime and gypsum (ankara, turkey), Bulletin of Engineering Geology and The Environment, Vol. 75, 2015, doi: 10.1007/s10064-015-0757-2.

[5] MOHAMMED SHAFIQU, Q.: Effect of adding polyacrylamide polymer with lime and cement kiln dust on the properties of expansive clayey soils, International Journal of Geomate, Vol. 15, Iss. 51, 2018, pp. 233–239, doi: https://doi.org/10.21660/2018.51.19491.
[6] MOHAMMED SHAFIQU, Q. S. – ABASS, R. I.: Enhancement of Expansive Soil Properties Using Cement Kiln Dust Mixed with Lime, In Recent Advancements on Expansive Soils, Eds., Cham: Springer International Publishing, 2019, pp. 45–55, doi: https://doi.org/10.1007/978-3-030-01914-3_4.
[7] KHADKA, S. D. – JAYAWICKRAMA, P. W. – SENADHEERA, S. – SEGVIC, B.: Stabilization of highly expansive soils containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum, Transportation Geotechnics, Vol. 23, 2020, p. 100327, doi: 10.1016/j.trgeo.2020.100327.
[8] AL-JEZNAWI, D. – SHAFIQU, Q. S. M. – SA'UR, R. H.: Properties of swelling soil improved using mixture of polyethylene with silica fume and cement kiln dust, presented at the AIP Conference Proceedings, AIP Publishing, 2020, doi: https://doi.org/10.1063/5.0000224.
[9] AL-JEZNAWI, D. – JASIM, T. N. – MOHAMMED SHAFIQU, Q. S.: Evaluating the Use of Polypropylene Polymer in Enhancing the Properties of Swelling Clayey Soil, presented at the IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2021, p. 012015, doi: https://doi.org/10.1088/1755-1315/856/1/012015.
[10] ASTM D2487-11: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System), West Conshohocken, PA: ASTM International, 2011.
[11] ROESYANTO – ISKANDAR, R. – HASTUTY, I. – DIANTY, W.: Clay stabilization by using gypsum and paddy husk ash with reference to UCT and CBR value, presented at the IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018, p. 012026, doi: https://doi.org/10.1088/1757-899x/309/1/012026.
[12] DUXSON, P. – FERNÁNDEZ-JIMÉNEZ, A. – PROVIS, J. L. – LUKEY, G. C. – PALOMO, A. – VAN DEVENTER, J. S. J.: Geopolymer technology: the current state of the art, Journal of Materials Science, Vol. 42, Iss. 9, 2007, pp. 2917–2933, doi: 10.1007/s10853-006-0637-z.
[13] GUO, H. - SHI, X. - WEI, X.: Pore properties, inner chemical environment, and microstructure of nano-modified CFA-WBP (class C fly ash-waste brick powder) based geopolymers, Cement and Concrete Composites, Vol. 79, 2017, pp. 53–61, doi: 10.1016/j.cemconcomp.2017.01.007.
[14] TEMUUJIN, J. - SURENJAV, E. - RUESCHER, C. H. - VAHLBRUCH, J.: Processing and uses of fly ash addressing radioactivity (critical review), Chemosphere, Vol. 216, 2019, pp. 866–882, doi: 10.1016/j.chemosphere.2018.10.112.
[15] RASHAD, A. M.: A brief on high-volume class F fly ash as cement replacement – A Guide for Civil Engineer, International Journal of Sustainable Built Environment, Vol. 4, Iss. 2, 2015, pp. 278–306, doi: 10.1016/j.ijsbe.2015.10.002.
[16] GUPTA, R. - BHARDWAJ, P. - MISHRA, D. - PRASAD, M. - AMRITPHALE, S. S.: Formulation of Mechanochemically Evolved Fly Ash Based Hybrid Inorganic–Organic Geopolymers with Multilevel Characterization, Journal of Inorganic and Organometallic Polymers and Materials, Vol. 27, Iss. 2, 2017, pp. 385–398, doi: 10.1007/s10904-016-0461-0.
[17] SCHMÜCKER, M. - MACKENZIE, K. J. D.: Microstructure of sodium polysialate siloxo geopolymer, Ceramics International, Vol. 31, Iss. 3, 2005, pp. 433–437, doi: 10.1016/j.ceramint.2004.06.006.
[18] DEBANATH, O. - RAHMAN, M. - FAROOQ, S.: Use of fly ash based geopolymer for stabilization of expansive soil, presented at the 9th International Conference on Geotechnique, Construction Materials and Environment, Tokyo, Japan: GEOMATE, 2019, pp. 344–347.
[19] MAHROUS, M. A. - ŠEGVIĆ, B. - ZANONI, G. - KHADKA, S. D. - SENADHEERA, S. - JAYAWICKRAMA, P. W.: The Role of Clay Swelling and Mineral Neoformation in the Stabilization of High Plasticity Soils Treated with the Fly Ash and Metakaolin-Based Geopolymers, Minerals, Vol. 8, Iss. 4, 2018, doi: 10.3390/min8040146.
[20] ASTM D698-12: Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 KN-m/m^3)), West Conshohocken, PA: ASTM International, 2012, p. 1-13.
[21] ASTM D4318-10: Standard test methods for liquid limit, plastic limit, and plasticity index of soils, West Conshohocken, PA: ASTM International, 2014, p. 1-16.
[22] ASTM D4546-96: Standard test methods for one-dimensional swell or settlement potential of cohesive soils, West Conshohocken, PA: ASTM International, 1996.
[23] ASTM D1883-87. Standard test method for California Bearing Ratio (CBR) of laboratory-compacted soils. West Conshohocken, PA: ASTM International, 1987. p. 1-8.
[24] ASTM D2166-13: Standard test method for unconfined compressive strength of cohesive soil, In: Annual Book of ASTM Standards, West Conshohocken, PA: ASTM International, 2013. p. 1-7.

[25] SIVAPULLAIAH, P. - JHA, A. K.: Gypsum induced strength behaviour of fly ash-lime stabilized expansive soil, Geotechnical and Geological Engineering, Vol. 32, 2014, pp. 1261–1273.
[26] ELLEBOUDY, A.: Characterization of Chemical Compaction Aids for Fine-Grained Soils, PhD THESIS, Iowa State University, 1977.
[27] SANTOS, F. - LI, L. - LI, Y. - AMINI, F.: Geotechnical properties of fly ash and soil mixtures for use in highway embankments, presented at the World of Coal Ash (WOCA) Conference, USA, 2011.
[28] SOMNA, K. - JATURAPITAKKUL, C. - KAJITVICHYANUKUL, P. - CHINDAPRASIRT, P.: NAOH-activated ground fly ash geopolymer cured at ambient temperature, Fuel, Vol. 90, Iss. 6, 2011, pp. 2118–2124.