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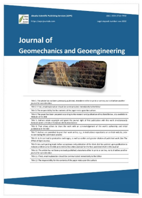

Effect of lime on the stabilization of an expansive clay soil in Algeria

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Abstract: This paper presents the influence of lime addition on the geotechnical properties of an expansive Algerian clayey soil. The studied soil was classified as a fat clay (CH) with high plasticity according to the unified soil classification system (USCS). 2, 4 and 6% lime was added to the clay soil in order to studied their effect on the physical and mechanical properties of the studied soil. The pH variation, consistency limits, compaction, swell, unconfined compressive strength, mineralogical and microstructural analysis are particularly investigated. For the purpose of studying the effect of curing time on soil strength, treated specimens were cured for 1, 7 and 28 days. Tests results indicate that the pH of the studied soil was significantly increased after their treatment with lime, which indicates the beginning of chemical reactions between lime and clay soil. After lime treatment the studied soil become more friable and easier to work with a higher unconfined compressive strength (UCS) due to the flocculation of the soil structure and the production of new cementation products such as CSH and CAH.

1. Introduction

Clay minerals are very fine particles with very high electrochemical activity produced by the interaction between electrically charged particles (Davis, 1955). The presence of low clay mineral content in natural soils significantly alters their engineering properties (Holtz and Kovacs 1981). Clay soils have a large specific surface area and high ion exchange capacity which produce high plasticity, high volume change capacity such as swelling and shrinkage, high compressibility and low bearing capacity (Davis, 1955). Due to these poor properties, clay soils are considered to be a big problem for civil engineers.

Engineers have observed several problems in the treatment of clay soils due to their poor geotechnical properties which do not meet the requirements imposed for the realization of construction projects. Therefore, many techniques have been developed by geotechnical engineers to improve the geotechnical characteristics and mechanical properties of unstable soils. Among these stabilization techniques, there are mechanical, hydromechanical, thermal and chemical methods. Some of these methods are very old, such as woodpiles, others are more recent, such as injection and freezing methods.

The usual method of stabilizing clay soils is to replace it with a more resistant material that meets the requirements of the project. The very high cost of performing this method has led researchers to look for alternative methods. In this context, numerous research and experimental studies have been carried out on the chemical stabilization of soils which is based on the use of chemical and / or cementitious additives to improve certain geotechnical properties of soils. Extensive studies have been carried out on soil stabilization using various additives such as lime (Bell, 1989; Driss et al., 2018, 2019-a, 2021), cement (Osula, 1996; Ouhadi et al., 2014), fly ash (Sezer et al., 2006; Mir et al., 2014), natural pozzolana

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(Harichane et al., 2018; Driss et al., 2021-b) and slag (Cokca et al., 2009; Mccarthy et al., 2014).

Lime stabilization of cohesive soils is one of the most useful chemical methods due to the low cost of lime and their effectiveness in the field of soil treatment and improvement (Al- Mukhtar et al., 2012; Driss et al. 2021-a,b). Lime stabilization of clay soils usually results in decreased plasticity and volume change, increased particle size, permeability and soil strength. Generally, lime stabilization based on two principal reactions causing immediate and long-term changes in clay soils. Adding lime to clay soil immediately increases soil pH due to the dissociation of calcium hydroxide particles (Vitale et al., 2017). The short-term reaction based on cation exchange, when the exchangeable monovalent ions in the clay particles are replaced by the calcium ions which lead to a reduction in the thickness of the diffused double layer (DDL). The ion exchange causes flocculation of clay particles which improve the workability of the soil by forming an open soil fabric which decreases its plasticity and increases its hydraulic conductivity. The relatively high pH of the pore water facilitates the formation of pozzolanic reaction bases to produce new cementation gels (Calcium Silicates Hydrates (CSH) and Calcium Aluminates Hydrates (CAH)) which harden over time and lead to a considerable strength gain.

In this context, an experimental study was carried out to assess the geotechnical and microscopic properties of lime stabilized a hight plasticity Algerian clay soil. On the geotechnical level, pH, Atterberg limits, compaction characteristics, swell and Unconfined compressive strength were determined before and after lime treatment. The microstructural and the mineralogical behavior of the studied soil were investigated with the scanning electron microscopy (SEM) and the X-Ray Diffraction (XRD). The results of these study provide a deeper understanding of the influence of lime on the clayey soils.

2 Experimental Program

2.1 Materials Used

In the present study, a gray clay soil was used, it was extracted at a varying depth between 7 and 17 meters from a project of resumption of landslide at the Pole University 2000 Educational places in Mansourah–Tlemcen. For a better understanding of the behavior of the soil studied, identification tests were carried out in the laboratory according to American standards. The physico-mechanical properties of clay soil are presented in Table 1.

The soil is composed of 14% sand, 36% silt and 50% clay, as shown in the grain size distribution curve shown in Fig.1. Fig. 2 shows the location of the soil in the Casagrande plasticity chart, it has been classified as a fat clay (CH) according to USCS (ASTM D2487-06). The mineralogical

Table 1 Basic properties of the studied clay soil.

Geotechnical Parameters			Values
Color			Grey
Depth (m)			7 - 17
Natural water content (%)			12 - 14
Specific gravity of soil solids			2.67
Bulk density (g/cm³)			1.17
Passing 80 µm sieve (%)			86.68
Atterberg Limits	LL	(%)	52.64
	PL	(%)	21.18
	PI	(%)	31.47
Classification (USCS)			CH
Compaction PROCTOR	Optimum water content (%)		19.55
	Maximum dry density (kN/m³)		16.57
Organics matter content (%)			2.42
Content of calcium carbonate (%)			24.33

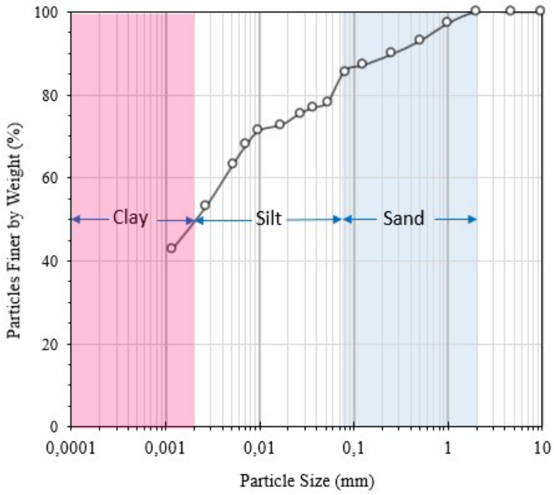

Fig. 1 Particle size distribution of the clay soil.

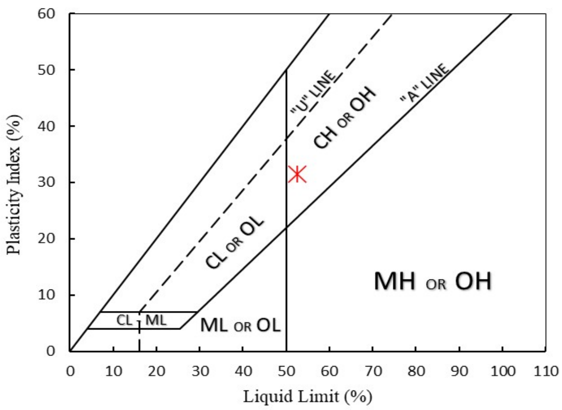

Fig. 2 Classification of the studied soil according to the Casagrande plasticity chart.

Table 2 Physical and chemical properties of the lime used.

Physical and chemical properties			Values
Colour			White
Specific gravity		(g/cm^3)	2.24
Bulk density		(g/cm^3)	0.72
The specific surface -blaine-		(cm^2/g)	11663
Particle fineness less than 45 µm		(%)	64.87
Normal consistency -vicat E/L		(%)	69.5
Set time -vicat- (min)	Initial		80
	Final		40
Calcium oxide [CaO]		(%)	> 83.3
Magnesium oxide [MgO]		(%)	< 0.5
Iron oxide [Fe_2O_3]		(%)	< 2
Alumina [Al_2O_3]		(%)	< 1.5
Silica [SiO_2]		(%)	< 2.5
Sulfite [SO_3]		(%)	< 0.5
Sodium oxide [Na_2O]		(%)	0.4 – 0.5
Carbon dioxide [CO_2]		(%)	< 5
Calcite [$CaCO_3$]		(%)	< 10

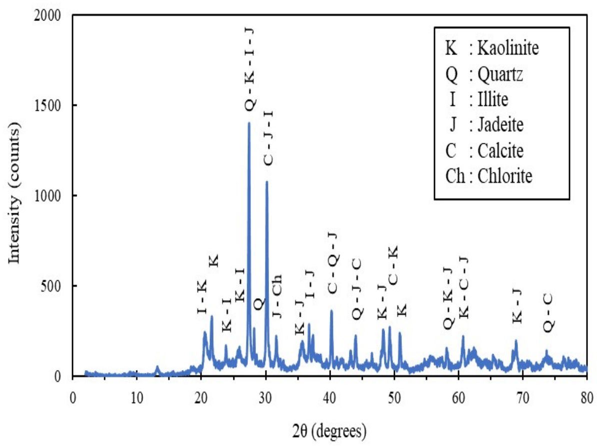

Fig. 3 X-ray diffraction of the studied clay soil.

composition of the clay soil was determined by X-ray diffraction (XRD). As shown in Fig. 3, the XRD analysis indicated that kaolinite, illite, jadeite and chlorites were the major clay minerals in untreated soil sediments, other non-clay minerals were also detected in soil samples, including quartz and calcite.

The lime (L) used in this study is a hydrated lime produced by the company SARL-BSM located in the city of Saïda (south-west of the Algerian national territory), the chemical and physical properties of the lime are presented in Table 2.

2.2 Sample Preparation and Test Procedure

The main objective of this research is to study the effect of lime addition on the geotechnical properties of an expansive clay soil. Several laboratory tests were performed such as pH, Atterberg limits, compaction, swell, UCS, x-ray diffraction and scanning electron microscopy in order to justify and relate the results of the experiments to the mineralogical and microstructural changes resulting from the treatment of soil. The lime contents used in this study to treat clay soil were 0, 2, 4 and 6. Table 3 present the combinations used for the soil treatment.

In this study, a pH meter was used for the purpose of determining the acidity or alkalinity of soil materials suspended in water. Two pH determination procedures were used to determine the pH value of untreated and treated clay soil. For the case of the natural clay soil, the standard test method for soil pH was used as described in ASTM D4972 (2001). In order to study the variation of the pH value and the estimation of the lowest lime content needed for soil stabilization, the standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization was used in accordance with ASTM D6276 (1999). This test method is based on the determination of the lime content favouring the increase of the pH to a minimum value greater than or equal to 12.4. According to Eades and Grim (1966), this pH value is necessary to activate both immediate lime-soil reactions and long-term pozzolanic reactions.

The consistency parameters such as plastic limit (PL), liquid limit (LL) and plasticity index (PI) for treated and untreated clay soil were determined according to Atterberg limit tests (ASTM D4318-17). This method can only be performed on soil particles smaller than 425 µm (N° 40 sieve). The studied soil was firstly dried in the open air before being thoroughly mixed with 0,2,4 and 6 lime. After adding distilled water to the mixtures, the paste was left in an airtight container for about 16 hours before testing.

The standard Proctor compaction test in accordance with ASTM D698 was used to determine compaction parameters such as optimum water content (OMC) and maximum dry density (MDD) for the various studied combinations. The soil-lime mixtures have been carefully mixed with different water contents and leave for 2 hours before starting tests, this period is equal to the lime setting time (time that lime needs to react or fully hydrate with water).

Table 3 Combinations used for stabilization.

Combination	L0	L2	L4	L6
Lime (%)	0	2	4	6
Clay soil (%)	100	98	96	94
Lime (%)	0	2	4	6

One-dimensional free swelling tests were carried out on natural soil samples before and after stabilization according to method A mentioned in standard ASTM D4546-03, and under a constant overpressure of 1 kPa by means of a series of conventional oedometric devices. First, the sample is prepared at the optimum water content and the maximum dry density determined according to the normal Proctor compaction test. The samples were placed in the oedometers and were flooded with water. The axial deformation or swelling was then recorded during various swelling stages (0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0 and 30.0 min and 1, 2, 4, 8, 24, 48 and 72 h) up to a point where axial swelling has reached an equilibrium value defined as swelling potential or free swelling percentage. When the soil expansion reaches its maximum value, the applied vertical load is increased to maintain the original position. This process is continued until there is no more swelling (its volume returns to their initial value), The corresponding stress representing the swelling pressure.

Unconfined compressive strength (UCS) tests were carried out on samples that compacted with their optimum compaction characteristics in accordance with ASTM D2166 (2016). Cylindrical specimens with 38 mm diameter and 80 mm height were compacted by the static compaction method. The masses of samples were determined immediately after preparation and then kept in plastic bags to prevent the moisture change, thus hardened during the different curing periods such as 1, 7 and 28 days, after curing and before carrying out tests, the mass and dimensions of samples were recorded. The strength of specimens was recorded during the UCS test until the sample fail.

In order to study the effect of lime treatment on the microstructure and mineralogical behaviour of clay soil, scanning electron microscopy (SEM) and X-ray diffraction (XRD) tests were carried out with a MiniFlex 600 type XRD diffractometer and a JEOL JSM-6060lv Scanning Electron Microscope.

3 Results and Discussion

3.1 pH variation

Fig. 4 shows the variation in the pH value of the clay soil studied before and after treatment with different contents of lime. The studied clay soil is a moderately alkaline soil with a pH value of 8.3.

The clay soil is very reactive to lime. As shown in Fig. 4, a considerable increase in pH was observed after the treatment of clay soil with lime. Adding 6% lime to the clay soil raised its pH from 8.3 to 12.7. This significant increase in the pH value is explained by the short-term reaction of lime-clay soil. As known, the addition of lime to clay soils

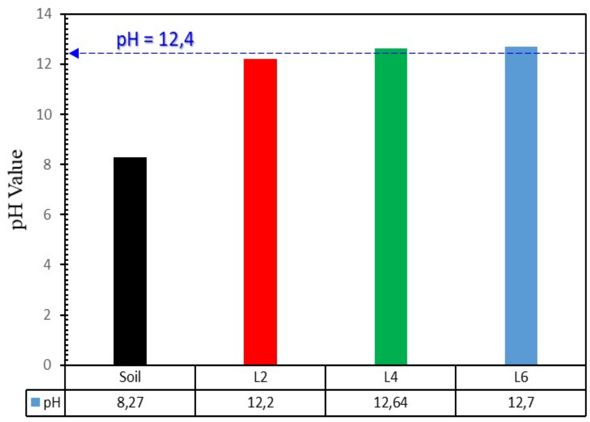

Fig. 4 Influence of the addition of lime on the variation of the pH.

produces a highly alkaline environment, due to OH- anions from the hydration of lime, which leads to slow dissolution of silica and alumina from the particles of clay. The same behaviour was observed by Driss et al. 2021-b when studied the effect of natural pozzolana on microstructural behavior and hydraulic conductivity of lime-stabilized clayey soil

3.2 Atterberg limits

Fig. 5 represent the effect of lime stabilization on the variation of the Atterberg limits of clay soil. It can be observed that the addition of lime increases both the liquid limit (LL) and the plastic limit (PL). But the rate of increase of LL is lower than that of PL, resulting in a decrease in the plasticity index (PI).

The liquid limit of the clay soil equal to 52.64%, this value up to 62% after the addition of 2% lime, beyond this content, the LL has remained almost constant at 4% lime (62.37%) before dropping slightly at 6%. The plastic limit increased from 21.18% to 39.41% with the addition of 4% lime, after this percentage, the plastic limit remains almost

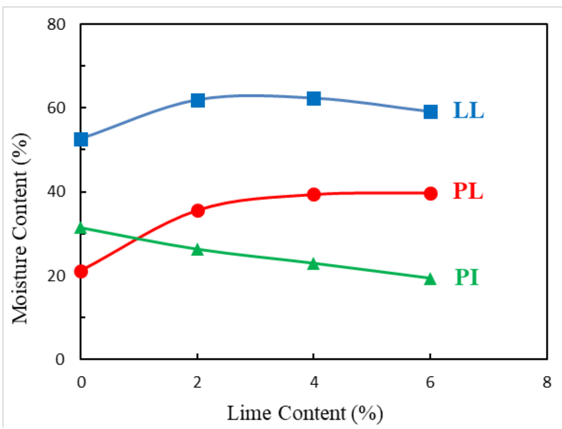

Fig. 5 Influence of lime content on the Atterberg limits

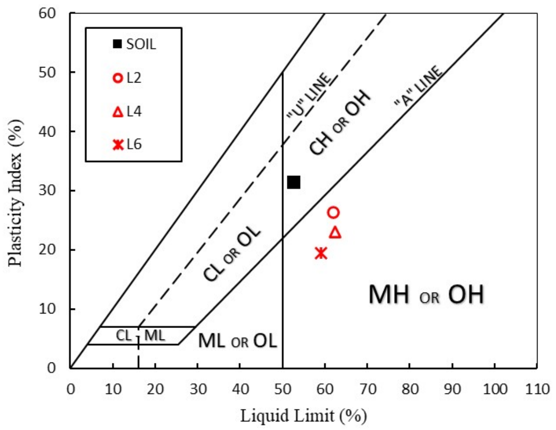

Fig. 6 Effect of adding lime on soil classification.

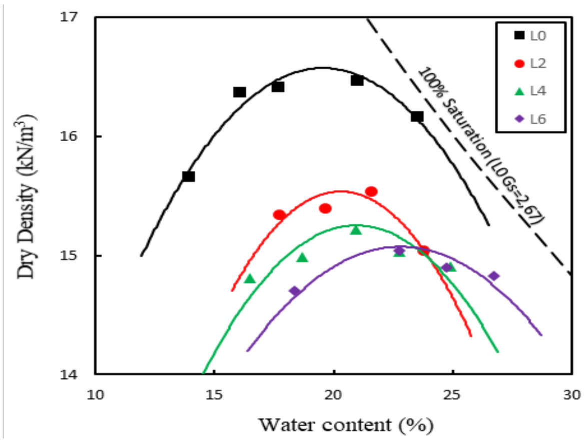

Fig. 7 Variation of compaction curves.

constant. The same behavior has been observed by Kinuthia et al. (1999). For liquid limit and plastic limit, it was found that the LL of pure kaolinite increases considerably after the addition of 3% lime. Above this content, the LL remained constant even at high percentages of lime before decreasing slightly at 20%. The PL also increased significantly with the addition of lime and remains constant at a lime content varying between 3% and 14%. The increase in LL and PL after lime treatment can be explained by the short-term reactions (cation exchange and agglomeration), which make the soil more granular and friable. Changes in the structure from relatively dispersed to flocculated soil particles cause development of shear strength at the particle level which increases both of LL and PL.

The results of the consistency limit tests were plotted on the Casagrande plasticity chart to determine the classification of the treated soils according to the unified classification system of soils (USCS) (Fig. 6). As noted, the studied clay soil is classified as high plasticity clay soil (CH). After the treatment with the different lime contents, their class was transformed to high plasticity silt class (MH). These changes in soil classification are due to the flocculation of clay particles based on the cation exchange between lime and clay particles. The same results were observed by Harichane et al. (2018).

3.3 Compaction

Compaction tests were carried out to determine the effect of lime on the compaction characteristics (optimum moisture content and maximum dry density) of the treated soil.

The soil compaction curves before and after treatment, with 2, 4 and 6% lime are represented in Fig. 7. The studied clay soil has a single peak compaction curve with a maximum dry density (MDD) of 16.57 kN/m^3 and an optimal moisture content (OMC) of 19.55% close to its plastic limit (21%), these results are consistent with the model proposed by Gurtug and Sridharan (2004), when the authors report that there is a good correlation between OMC and the plastic limit of the cohesive soils (the optimal moisture content almost equal to 92% of the plastic limit with a correlation coefficient of 0.95). The compaction curves of the lime treated clay soil retain their shape (single peak) with a right pull-down, which means that the MDD has decreased and the OMC has increased

Fig. 8 indicated that adding lime to the clay soil decreases their MDD and increases the OMC. When the lime content increased from 0 to 6%, the MDD decreased by 8.6% and the OMC increased by 16%. As reported by Bell (1989), the design of lime stabilized soil is proportional to the amount of lime added (more lime, lower MDD and higher OMC).

According to the literature, the decrease in dry density can be explained by the low-density value of lime and the flocculation of soil particles with immediate formation of gelatinous compounds (Vitale et al., 2017; Kinuthia et al.,

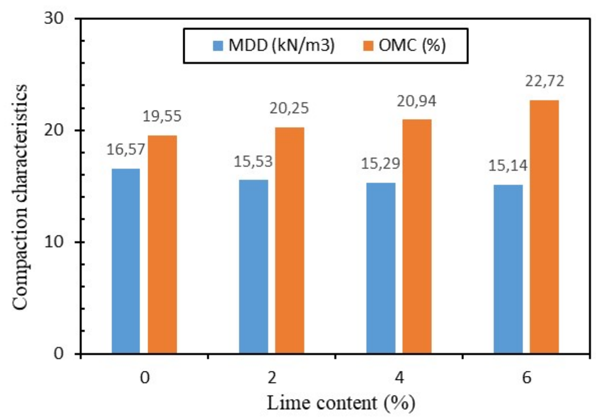

Fig. 8 Compaction characteristics of lime-treated clay soil.

1999). The increase in OMC may be due to the increase in the water holding capacity to supply the amount of water necessary for pozzolanic reactions produced between clay particles and the added lime.

3.4 swelling potential and pressure

The swell-time curves for natural soils and samples stabilized with various percentages of lime cured for 1 and 28 days, are shown in Fig. 9. It can be clearly seen from Fig. 9 that the addition of lime to the clayey soil accelerates the swelling procedure, especially during the early stages of this phenomenon (up to about 120 min). on the other hand, lower swelling potential was recorded for almost all samples stabilized with lime compared to natural soil. Simply put, it can be concluded that it takes less time for lime-treated samples to approach their maximum swelling potential.

Fig. 10 shows the variation in swelling potential and swelling pressure of soil samples mixed with lime content varying between 2% and 6%. It is observed that the untreated clay sample reaches the maximum swelling potential (10%). The use of 2% lime in the expansive clay leads to a significant decrease in swelling potential and pressure.

The effect of lime on the swelling behavior of the clayey soil can be explained by a series of chemical reactions that take place in the presence of water between the lime and the clay minerals. These chemical reactions can be divided into three broad categories, namely cation exchange, flocculation-agglomeration and pozzolanic reaction. During the cation exchange process, the cations common to the clay surface, notably sodium (Na^+) and potassium (K^+) are replaced by more charged cations, especially calcium (Ca^{2+}) and in some cases magnesium (Mg^{2+}). This

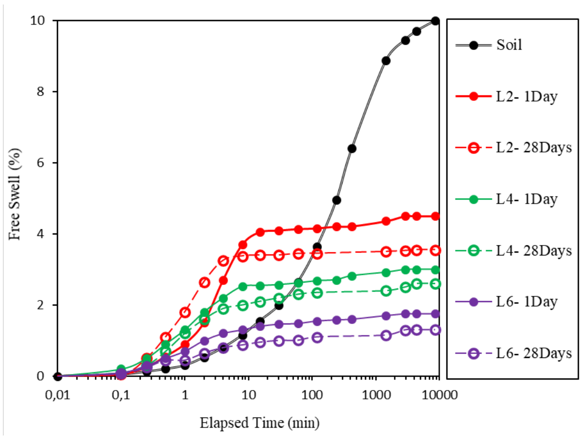

Fig. 9 Free swell as a function of time for treated and untreated clay soil.

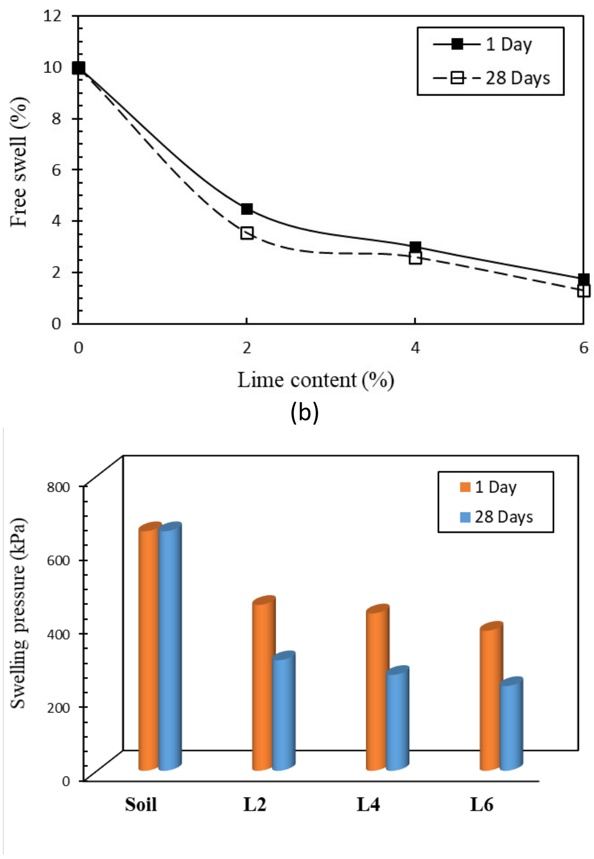

Fig. 10 Variation of swelling potential and swelling pressure as a function of lime content.

process leads to the formation of attractive forces between the clay particles, which promotes flocculation of the particles and the formation of coarse aggregates. Then, the clay content is reduced which decreases the swelling potential. After the completion of the cation exchange and agglomeration, a process called pozzolanic reactions occurs. This process is strongly dependent on time. During the pozzolanic reactions, the calcium cations react with alumina and silica resulting new cementing materials (CSH, CAH) which promotes solidification of soil caused a considerable reducing in swelling potential and swelling pressure. Schanz and Elsawy (2017) found the same variation in volume change when they investigated the effect of 5% and 10% lime addition on the free swelling of expansive clay soil.

3.5 Unconfined Compressive Strength

Fig. 11 shows the effect of the addition of lime on the stress-strain relationships of the studied soil. The first type of curves, which has an asymptotic appearance without peak, represents the curves of the clayey soil alone. The second type represents the curves of soil treated with lime, containing peaks expressing their maximum stress

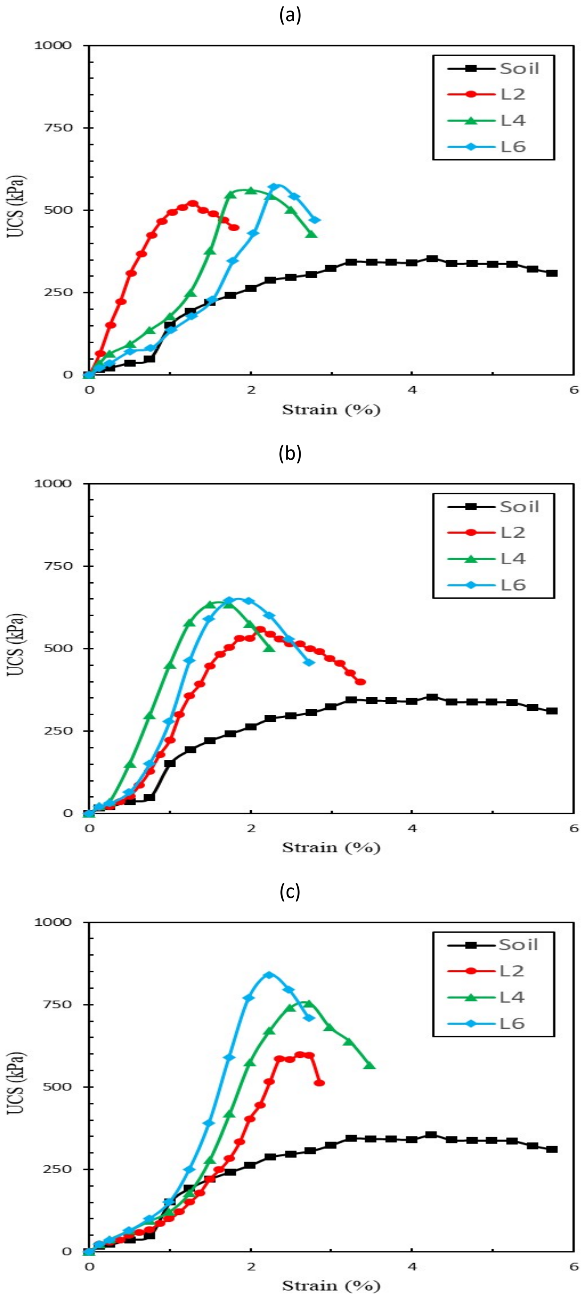

Fig. 11 Stress-strain curves of clay soil treated with different lime contents and different hardening times (a) 1 day, (b) 7 days, (c) 28 days.

value followed by a reduction in stress (residual stress) until the sample failure. So, it can be noted that the clay soil behaves as a ductile material with a plastic deformation in their natural state. In the other side, when treated the clay soil with lime their behaviour was transforming from ductile to brittle. The same behaviour was observed by Yıldız and Soğancı (2012) and Kavak and Baykal (2012).

Fig. 12 represents the variation in the UCS of the studied clay soil treated with 2, 4 and 6% lime at 1, 7 and 28 curing days. Adding lime to the clay soil produced considerable

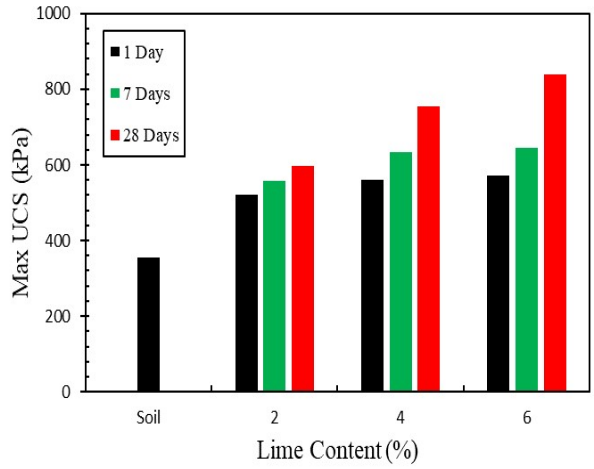

Fig. 12 Variation of the unconfined compressive strength of lime treated clay soil at different curing times 1, 7 and 28 days.

stress gain, when the UCS of the studied soil increased from 354 kPa to 572 kPa when treated with 6% lime after 1 curing day. A further increase was produced with the curing time, the UCS of the 6% treated soil increased by 13% and 47% after 7 and 8 days of cure compared to 1 day. These improvement in the compressive strength based on two principal factors; short-term reactions such as cation exchange and the flocculation or agglomeration of soil particles which make the soil more granular and brittle (Al-Mukhtar et al., 2012). On the other hand, there is a significant increase in the UCS after 28 days of hardening compared to the untreated soil and the treated soils at short curing times (1day and 7 days), this increase is attributed to the pozzolanic reaction of lime with the particles of clay soil which produced new cementing compounds, thus binding the soil particles together.

3.6 Mineralogical and microstructural analysis

Fig. 13 and 14 represent the effect of lime treatment on the microstructure (SEM) and the mineralogical composition (XRD) of the studied soil at 1 and 28 curing days. As shown in Fig. 13 (a, b) the compacted clay soil has an evident massive close packing structure with a dispersed arrangement. The same microstructural structure was observed by Rosone et al. (2018) when treated a similar class of clay soil (CH) with lime. The microstructure of the studied soil was changed immediately after the addition of lime. As reported in Fig. 13 (c, d) in the short term, a modification of the clay particles arrangement was observed with formation of larger aggregates compared to not treated soil (particles soil flocculation) without any evidence of new hydrated phases (Fig. 14).

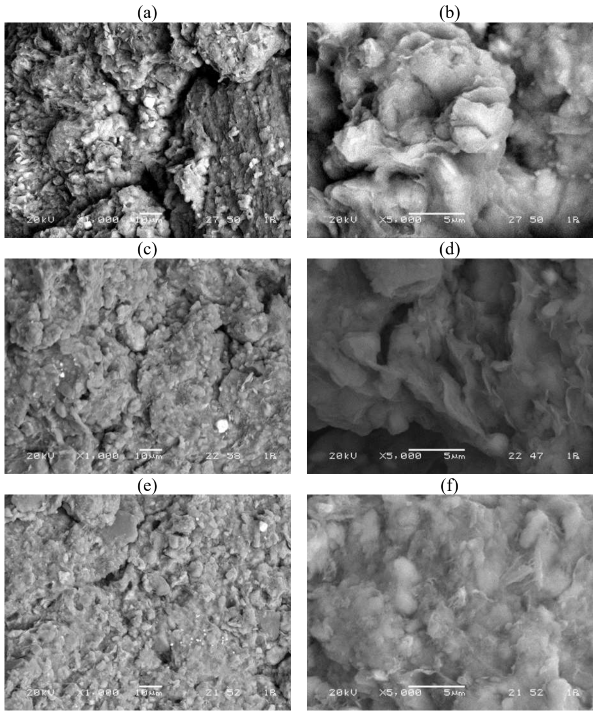

Fig. 13 SEM microphotographs of samples of clay before and after treated with lime. (a) and (b) clay soil, (c) and (d) lime treated soil at 1day of hardening, (e) and (f) lime treated soil at 28 days of hardening.

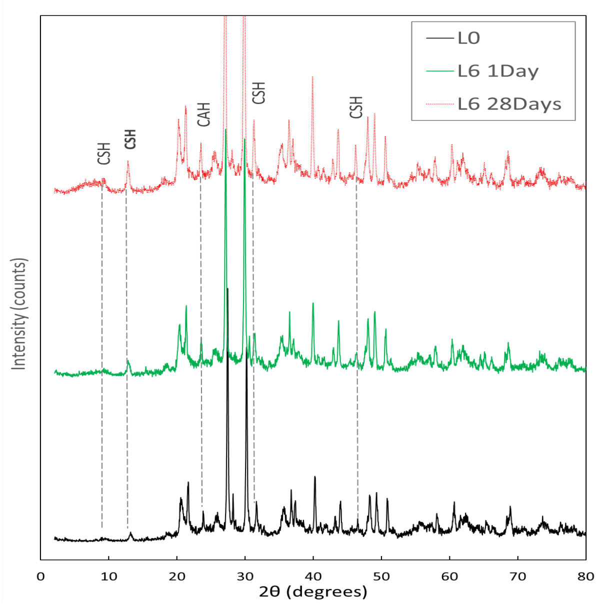

Fig. 14 X-ray diffraction patterns of soil treated and untreated with lime at 1 day and 28 days of hardening.

After 28 curing days (Fig. 13 (e, f)), the flocculated clay particles were covered by a white hydrated gel, which means the formation of new cementitious compounds such as C-S-H and C-A-H (Fig. 14). The short- and long-term reactions have caused the considerable change in the behaviour of the clay soil when the soil changes from ductile to brittle with higher compressive strength.

4. Conclusions

An experimental investigation was conducted to study the effect of lime addition on pH variation, Atterberg limits, compaction parameters, swell and unconfined compressive strength of an expansive clay soil. In light of the test results, the following conclusions were drawn:

The increase in lime content for stabilized clay soil changes its moderately alkaline pH to a high alkaline pH value, this increase in pH is a sign of the start of chemical reactions between the soil and lime.

Addition of lime to clay soil increased both LL and PL, causing a considerable decrease in PI due to the change in the structure of soil particles, which changes the behaviour of the soil from dispersed to flocculated.

The design of the lime stabilized soil corresponds to the added lime content; more lime led to a decrease in MDD and an increase in the OMC.

A significant reduction in swelling parameters was noted for the lime-treated samples with further improvement upon increasing curing time.

The unconfined compressive strength of the treated clay soil increased with the increase in both lime content and hardening time, this behaviour can be explained by the considerable modification of the soil structure caused by the short- and long-term reactions.

The mineralogical and microstructural analyses confirmed that the addition of lime to the clay soil produced an important change in their microstructure when the soil become more friable. In the same time, showed that at 28 curing days new cementitious phases was produced (pozzolanic reactions) which induced significant improvements in the engineering properties of the clayey soil such as their workability, compaction and compressive strength.

Disclosures

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References

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2010). Behaviour and mineralogy changes in lime-treated expansive soil at 20°C. Applied Clay Science, 50(2), 191–198.

Al-Mukhtar, M., Khattab, S., & Alcover, J.-F. (2012). Microstructure and geotechnical properties of lime-treated expansive clayey soil. Engineering Geology, 139-140, 17–27.

ASTM D2166 / D2166M-16. (2016). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM International, West Conshohocken, PA.

ASTM D2487 (2017), Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International, West Conshohocken, PA.

ASTM D4318-05. (2005). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA.

ASTM D4546-03 (2003), Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils, ASTM International, West Conshohocken, PA, www.astm.org

ASTM D4972-01 (2001) Standard Test Method for pH of Soils, ASTM International, West Conshohocken. www.astm.org

ASTM D6276-19 (2019) Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization. ASTM International, West Conshohocken. www.astm.org

ASTM D698-12e2. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International, West Conshohocken, PA.

Attoh-Okine, N. O. (1995). Lime treatment of laterite soils and gravels — revisited. Construction and Building Materials, 9(5), 283–287.

Bell FG (1989) Lime stabilization of clay soils. Bulletin of the International Association of Engineering Geology 39:67-74.

Cokca, E., Yazici, V., & Ozaydin, V. (2008). Stabilization of Expansive Clays Using Granulated Blast Furnace Slag (GBFS) and GBFS-Cement. Geotechnical and Geological Engineering, 27(4), 489–499.

Davis LE (1955) Electrochemical Properties of Clays. Clays and Clay Minerals, 1(1): 47–53.

Driss, A. A. E., Harichane, K., & Ghrici, M. (2018) Effet de la chaux sur la stabilisation des proprietes geotechniques d'un sol argileux. In 8th International Symposium on construction in seismic zone (SICZS 2018), Chlef on (Vol. 10).

Driss, A. A. E., Harichane, K., Ghrici, M., Gadouri, H., & GOUFI, A. (2019) Stabilization of expansive clay soil based on initial consumption of lime. In 1st International Congress on Advances in Geotechnical Engineering and Construction Management ICAGECM'19 (p. 285).

Driss, A. A. E., Harichane, K., Ghrici, M., & Gadouri, H. (2021-a). Assessing the effect of moulding water content on the behaviour of lime-stabilised an expansive soil. Geomechanics and Geoengineering, 1-13.

Driss, A. A. E., Harichane, K., & Ghrici, M. (2021-b). Effect of natural pozzolana on microstructural behavior and hydraulic conductivity of lime-stabilized clayey soil. Innovative Infrastructure Solutions, 6(4), 1-17.

Eades JL, Grim RE (1966) A quick test to determine lime requirements for lime stabilization. Highway Research Record n°139.

Garzón, E., Cano, M., O`Kelly, B. C., & Sánchez-Soto, P. J. (2016). Effect of lime on stabilization of phyllite clays. Applied Clay Science, 123, 329–334.

Gurtug, Y., & Sridharan, A. (2004). Compaction Behaviour and Prediction of its Characteristics of Fine Grained Soils with Particular Reference to Compaction Energy. Soils and Foundations,44(5),27–36.

Harichane, K., Ghrici, M., & Kenai, S. (2018). Stabilization of Algerian Clayey Soils with Natural Pozzolana and Lime. Periodica Polytechnica Civil Engineering. 62(1), 1-10.

Harichane, K., Ghrici, M., Kenai, S., & Grine, K. (2011). Use of Natural Pozzolana and Lime for Stabilization of Cohesive Soils. Geotechnical and Geological Engineering, 29(5), 759–769.

Hossain, K. M. A., Lachemi, M., & Easa, S. (2007). Stabilized soils for construction applications incorporating natural resources of Papua new Guinea. Resources, Conservation and Recycling, 51(4), 711–731.

Jha, A. K., & Sivapullaiah, P. V. (2015). Mechanism of improvement in the strength and volume change behavior of lime stabilized soil. Engineering Geology, 198, 53–64.

Kavak, A., & Baykal, G. (2012). Long-term behavior of lime-stabilized kaolinite clay. Environmental Earth Sciences, 66(7), 1943–1955.

Kinuthia, J., Wild, S., & Jones, G. (1999). Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilised kaolinite. Applied Clay Science, 14: 27–45.

Manasseh, J., & Olufemi, A. I. (2008). Effect of lime on some geotechnical properties of Igumale shale. Electronic Journal of Geotechnical Engineering, 13(5), 1-9.

McCarthy, M. J., Csetenyi, L. J., Sachdeva, A., & Dhir, R. K. (2014). Engineering and durability properties of fly ash treated lime-stabilised sulphate-bearing soils. Engineering Geology, 174, 139–148.

Mir, B. A., & Sridharan, A. (2013). Physical and Compaction Behaviour of Clay Soil–Fly Ash Mixtures. Geotechnical and Geological Engineering, 31(4), 1059–1072.

Osula, D. O. A. (1996). A comparative evaluation of cement and lime modification of laterite. Engineering Geology, 42(1), 71–81.

Ouhadi, V. R., Yong, R. N., Amiri, M., & Ouhadi, M. H. (2014). Pozzolanic consolidation of stabilized soft clays. Applied Clay Science, 95, 111–118.

Rao, S. M., & Shivananda, P. (2005). Compressibility behaviour of lime-stabilized clay. Geotechnical and Geological Engineering, 23(3), 309–319.

Rosone, M., Celauro, C., & Ferrari, A. (2018). Microstructure and shear strength evolution of a lime-treated clay for use in road construction. International Journal of Pavement Engineering, 1–12.

Schanz, T., & Elsawy, M. B. (2017). Stabilisation of highly swelling clay using lime–sand mixtures. Proceedings of the Institution of Civil Engineers-Ground Improvement, 170(4), 218-230.

Sezer, A., İnan, G., Yılmaz, H. R., & Ramyar, K. (2006). Utilization of a very high lime fly ash for improvement of Izmir clay. Building and Environment, 41(2), 150–155.

Stoltz, G., Cuisinier, O., & Masrouri, F. (2012). Multi-scale analysis of the swelling and shrinkage of a lime-treated expansive clayey soil. Applied Clay Science, 61, 44–51.

Vitale, E., Deneele, D., Paris, M., & Russo, G. (2017). Multi-scale analysis and time evolution of pozzolanic activity of lime treated clays. Applied Clay Science, 141, 36–45.

Yıldız, M., & Soğancı, A. S. (2012). Effect of freezing and thawing on strength and permeability of lime-stabilized clays. Scientia Iranica, 19(4), 1013–1017.

Yong, R., & Ouhadi, V. (2007). Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils. Applied Clay Science, 35(3-4), 238– -249.