Geomechanics and Engineering, *Vol. 18, No. 5 (2019) 471-480*
DOI: https://doi.org/10.12989/gae.2019.18.5.471

Delayed compaction effect on the strength and dynamic properties of clay treated with lime

Murat Türköz*

Eskisehir Osmangazi University, Civil Engineering Department, 26480, Turkey

(Received March 20, 2019, Revised May 24, 2019, Accepted July 15, 2019)

Abstract. The constructions of engineering structures such as airports, highways and railway on clayey soils may create many problems. The economic losses and damages caused by these soils have led researchers to do many studies using different chemical additives for the stabilization of them. Lime is a popular additive used to stabilize the clayey soils. When the base course is stabilized by mixing with an additive, inevitable delays may occur during compaction due to reasons like insufficient workers, breakdown of compaction equipment, etc. The main purpose of this study is to research the effect of compaction delay time (7 days) on the strength, compaction, and dynamic properties of a clay soil stabilized with lime content of 0, 3, 6, 9, 12 and 15% by dry weight of soil. Compaction characteristics of these mixes were determined immediately after mixing, and after 7 days from the end of mixing process. Within this context, unconfined compressive strength (UCS) under the various curing periods (uncured, 7 and 28 days) and dynamic triaxial tests were performed on the compacted specimens. The results of UCS and dynamic triaxial tests showed that delayed compaction on the strength of the lime-stabilized clay soil were significantly effective. Especially with the lime content of 9%, the increase in the shear modulus (G) and UCS of 28 days curing were more prominent after 7 days mellowing period. Because of the complex forms of hysteresis loops caused by the lime additive, the damping ratio (D) values differed from the trends presented in the literature and showed a scattered relationship.

Keywords: lime; stabilization; delayed compaction; strength; dynamic properties

1. Introduction

Most engineering structures like airports, highways and railways are built on the weak soils that would affect greatly to the superstructures on them. The most problematic soils are clayey soils with low bearing capacity. These soils generally exhibit high compressibility, shrinkage and swelling properties (Sakr *et al.* 2009, Sas *et al.* 2017, Lu *et al.* 2019, Mebarki *et al.* 2019). For these reasons, the base courses containing clay is excavated at a certain depth and then the foundation bed is improved by compacting a layer of the crushed stone filling material brought from the quarries. More importantly, in these practices, the excavation of the poor subbase soil and the filling material which was prepared by breaking on the quarry and bringing it to the construction site caused economic losses. These processes destroy the environment, increase the exhaust gas emissions due to the use of more machinery and trucks and generate excessive traffic on the roads. Various methods have been adopted to solve such problems (Canakci *et al.* 2015, Angın and İkizler 2018, Chavali and Reddy 2018, Kim *et al.* 2018, Yilmaz *et al.* 2018). Among these methods, lime stabilization is the most popular since it is both economic and ecological. (Asgari *et al.* 2015, Ali and Mohamed 2017, Escolano *et al.* 2018, Moayyeri *et al.* 2019). Lime stabilization has long been used successfully in different engineering applications such as road construction, railway and airport construction, and is still a widely applied technique (Anon 1985, 1990, Al-Mukhtar *et al.* 2012, Al-Mukhtar *et al.* 2014, Calik and Sadoglu 2014, Yilmaz and Fidan 2018). Numerous researches and explanations have been made for the mechanisms responsible for the engineering properties of the lime-stabilized soil. These mechanisms include cation exchange, flocculation of clay and pozzolanic reactions (Bell, 1996).

Extensive studies have been performed on the engineering behavior of lime stabilized clay (Basma and Tuncer 1991, Bell 1996, Rao and Shivananda 2005, Sakr *et al.* 2009, Kavak and Akyarlı 2007, Ghobadi *et al.* 2014). As a result of lime stabilization, it has been stated that the liquid limit has decreased in the clayey soils and the plastic limit has increased and the plasticity index has decreased sharply (Sherwood 1993, Parsons*et al.* 2001, Al-Rawas *et al.* 2005, Millogo *et al.* 2012). In addition, the maximum dry unit density of the soil decreases, the optimum water content increases and the compaction curve is flattened and gain more independent compressibility properties than water (Mallela *et al.* 2004, Garzón *et al.* 2016, Sharma *et al.* 2018). The literature study has shown that the efficiency of lime stabilization depends on many factors (Bozbey and Garaisayev 2010). However, literature on effects of delayed compaction on properties of lime treated soils is scarce. When the base course is stabilized by mixing with an additive, inevitable delays may occur during compaction due to reasons like insufficient workers, breakdown of compaction equipment, etc. Although there is less attention, some studies have been performed to scientifically identify such compaction delay results (Mitchell and Hooper 1961,

*Corresponding author, Associate Professor
E-mail: mturkoz@ogu.edu.tr

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

Sweeney *et al.* 1988, Osinubi 1998, Gallage *et al.* 2012, Di Sante *et al.* 2015). Delayed compaction is generally referred to as the elapsed time between the addition of lime and water to the soil and the compaction of the mixture. This term has also been referred to as rotting period, amelioration period, aging period or mellowing period (Sweeney, 1988).

In the study by Mitchell and Hooper (1961), the effect of aging on expansive clay treated with 4% dolomitic hydrated lime was investigated. It was found that aging was detrimental in terms of density, unconfined compressive strength, and swell characteristics for specimens prepared using a constant compactive effort. Osinubi (1998) investigated the influence of compactive effort as well as compaction delays up to 3 hours on the compaction and strength characteristics of lateritic soil treated with lime. The compaction and strength properties of the lime stabilized soil decreased with increases in compaction delays. Di Sante *et al.* (2015) also studied the effect of delayed compaction (after 48 hrs) on the compressibility and hydraulic conductivity of the clayey soil treated with 5% hydrated lime. A comprehensive experimental study was performed by Ali and Mohamed (2017) to investigate the delayed compaction and temperature effects of on the different geotechnical characteristics of lime treated Wyoming Sodium Bentonite powder as expansive clay. As a result of the study, it was stated that the compaction delay of the first 12 hours caused a significant decrease in dry density and the increased compaction delay did not cause a significant change in dry density.

The performance of the stabilization with the lime additive is mostly evaluated in terms of the strength characteristics in the static state. Dynamic properties are important to determine the engineering behavior of stabilized clay soils subjected to cycling loading. The dynamic properties of sand (Seed and Idriss 1970) and clay (Vucetic and Dobry 1991, Fahoum *et al.* 1996, Hoyos *et al.* 2004) were studied by various researchers. On the other hand, the studies evaluating the dynamic properties of lime treated soils are quite limited. In addition, most of the studies on this subject were carried out at low deformation levels to determine the maximum shear modulus (Akoto and Singh 1986, Fahoum *et al.* 1996, Wang *et al.* 2012).

When the presented technical literature is considered as a whole, it is understood that the effect of compaction delay is mostly investigated on high plasticity clays and the compaction delay time is evaluated in the limited time intervals as 1 hour, 3 hours, 12 hours and 48 hours. Although there are few studies investigating the effect of lime additive on the dynamic behavior of clay soils, there is no study to evaluate the effect of compaction delay on the dynamic behavior of clay soils. The main purpose of this study is to investigate the effect of longer compaction delay time (7 days) on the strength, compaction and dynamic properties of low plasticity clay soil stabilized with different percentages of lime.

2. Materials

2.1 Soil

The soil sample was taken from a soil pit excavated at a depth of 0.5 m to 1 m from highway subsoil. To define the soil sample, grain size analysis, hydrometer analysis, Atterberg limits and specific gravity tests were performed in accordance with ASTM D 422-63, ASTM D 4318-00 and ASTM D 854-00 standards, respectively. The particle size distribution for the studied soil is presented in Fig. 1.

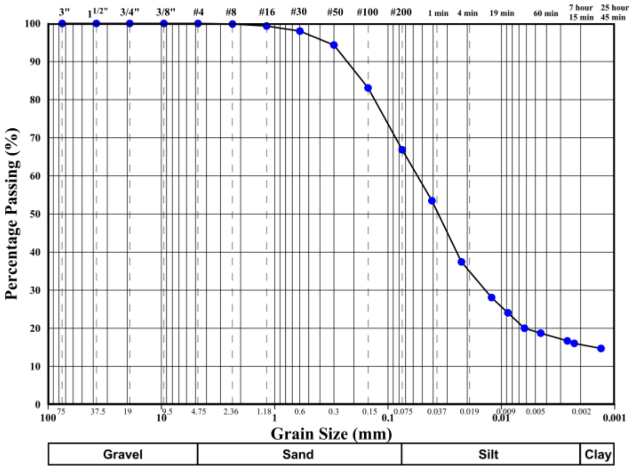


Fig. 1 The grain size distribution for the soil sample used in the study

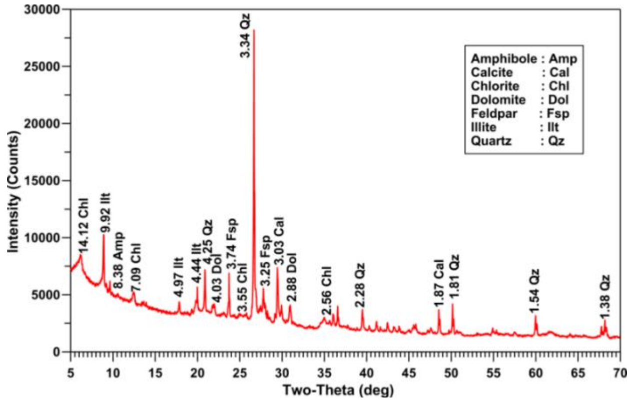


Fig. 2 XRD pattern of the soil sample

Table 1 Geotechnical properties of the soil used in the study

Property	Soil
Grain size	
Gravel (%)	-
Sand (%)	33
Silt (%)	51
Clay (%)	16
Atterberg limits	
Liquid limit (%)	32
Plastic limit (%)	20
Plasticity index (%)	12
Specific gravity, Gs	2.69
Classification (USCS)	CL
Activity, A	0.75
Maximum dry density (Mg/m^3)	1.562
Optimum water content (%)	20.8

Table 2 Chemical compositions of the soil and hydrated lime

Property	Soil (%)	Hydrated Lime (%)
SiO2	55.15	6.00
Al_2O_3	12.67	1.70
Fe_2O_3	4.58	0.70
CaO	7.62	86.90
MgO	3.68	0.70
Na_2O	1.34	0.06
K_2O	2.89	0.18
Loss of ignition	10.83	6 (max)

The particle size distribution of the soil exhibited 0% gravel, 33% sand, 51% silt and 16% clay. The Atterberg limits of the soil were obtained as follows; liquid limit (LL) of 32%, plastic limit (PL) of 20%, and plasticity index (PI) of 12%. From the identification test results, the soil is classified as low plasticity clay soil (CL) according to ASTM D 2487-00 standard.

Compaction test was performed according to ASTM D 698-00 standard. The geotechnical properties of the soil are shown in Table 1. The chemical compositions of the soil sample are given in Table 2. The chemical analysis indicated that the soil is principally composed of silica (55.15%) and aluminum oxide (12.67%). Based on the X-ray diffraction pattern of the soil (Fig. 2), the clay involves mainly illite mineral, furthermore small amount of chlorite and non-clay minerals e.g., quartz, calcite, dolomite, amphibole and feldspar.

2.2 Lime

In this study, hydrated lime obtained from standard manufacturers was used. The chemical properties of the lime are presented in Table 2. Table 2 shows a significantly high content of CaO (86.90%) the main components of cement in lime, with small amounts of alumina, iron, and alkali oxides.

3. Methods

3.1 Sample preparation

The soil sample was dried for 24 h at 105 °C in an oven and after that, it was grounded and passed through a No. 4 sieve to obtain a uniform distribution. The soil was mixed with a required amount of water and different amounts of lime as 0, 3, 6, 9, 12 and 15% by dry weight of the soil. The compaction tests on the prepared mixture were carried out in 2 stages to determine the compaction characteristics which will be used in the preparation of the specimens. In the first stage, standard proctor tests (ASTM D 698) were performed immediately after mixing and in the second stage 7 days after the mixing process was completed. The blended mixtures were stored in desiccator for 7 days and then compaction tests were performed to evaluate delayed compaction effects on compaction characteristics. The optimum water content (OWC) and maximum dry density (MDD) values needed to prepare the specimens for unconfined compressive strength and dynamic triaxial tests were determined from the compaction tests performed both immediately after the mixing and 7 days after the mixing in each lime additive percentage.

Table 3 Experimental program

Lime content (%)	Compaction tests		Unconfined compressive tests						Dynamic triaxial tests	
			MP* 0-day			MP 7-day				
			Curing days			Curing days				
	MP 0-day	MP 7-day	0	7	28	0	7	28	MP 0-day	MP 7-day
0	x	x	x	x	x	x	x	x	x	x
3	x	x	x	x	x	x	x	x	x	x
6	x	x	x	x	x	x	x	x	x	x
9	x	x	x	x	x	x	x	x	x	x
12	x	x	x	x	x	x	x	x	x	x
15	x	x	x	x	x	x	x	x	x	x

*MP = Mellowing Period (referred to as the elapsed time between the addition of lime and water to the soil and the compaction of the mixture)

3.2 Experimental study

The experimental studies focused on investigation the impact of the lime content and delayed compaction on the i) compaction characteristic including optimum water content (OWC) and maximum dry density (MDD), ii) unconfined compressive strength, (iii) dynamic properties of the soil. The experimental program is demonstrated in Table 3. ASTM (1994) standard was followed in the preparation, sampling and testing of the experiment samples.

3.3 Compaction tests

In order to evaluate the effects of delayed compaction on the development of the compaction properties of lime stabilized samples as shown in Table 3, compaction tests were carried out at a standard energy level of 600 kN-m/m^3 as specified in ASTM D 698-00. Before the experiment, lime and soil were mixed homogeneously in dry condition. The required amount of water was added to the mixture and the first step compaction test was performed. After extraction from the compaction mold and taking the sample for the water content, it was crushed and the compaction tests were performed in the increasing water contents.

3.4 Unconfined compressive strength tests

Unconfined compressive strength (UCS) tests on compacted specimens were performed according to the ASTM D2166-00 standard. As shown in Table 3, two series of experiments were performed on specimens. In the first series, the soil specimens prepared in the compaction characteristics obtained from the compaction test results immediately after mixing were compressed in a stainless steel tube for UCS tests. In the second series, the soil specimens prepared in the compaction characteristics obtained from the compaction test results after 7 days of mixing were compressed in a stainless steel tube for UCS tests after 7 days. All specimens subjected to the UCS test were prepared at their compaction characteristics. The specimens were prepared in stainless steel tube with a ratio of height to diameter 2 (100-mm height and 50-mm diameter). The specimens were extracted from the tubes and warped by plastic film and then, cured for 7 and 28 days in vacuum desiccators. This procedure allowed the effects of both the additive contents and the curing time on the specimens' strength to be determined (Türköz *et al.* 2014). UCS tests were performed with an automatic loading machine which applied 1 mm deformation per minute.

3.5 Dynamic triaxial tests

Dynamic triaxial tests were performed in the Soil Mechanics Laboratory at the Eskisehir Osmangazi University to determine the shear modulus, G, and the damping ratio, D, of soils (Fig. 3). The tests conducted for the evaluation of these characteristics are chosen as the strain-controlled approach. A servo-system is used to apply cycles of controlled deformation. The testing system is capable of performing stress or strain controlled loading tests. The maximum cell pressure capacity of the system is 1000 kPa and the maximum axial load that can be applied to the sample is 1961.33 N. In laboratory experiments, generally traffic loads can be conducted as harmonic loadings to excite the soil sample for simplicity.

Fig. 3 Laboratory position of the dynamic triaxial testing equipment used in this study

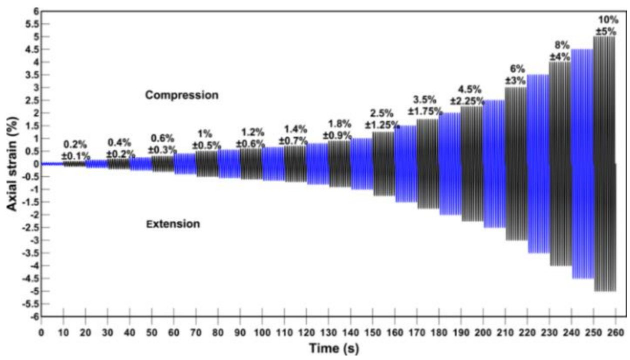


Fig. 4 Applied axial strain levels (double amplitude) during dynamic triaxial test

In this study, cyclic loading in the form of sinusoidal waves was conducted at a frequency of 1 Hz on soil specimens using a servo-controlled pneumatic triaxial apparatus by Wykehamm Farance. All specimens tested were prepared at their compaction characteristics as in the UCS tests. The specimens were prepared in stainless steel tube with a ratio of 2 heights to diameter (140-mm height and 70-mm diameter). The prepared specimens were not subjected to a curing time. As seen in Fig. 4, in the dynamic experiments, strain controlled cyclic triaxial tests were performed on the prepared specimens up to 10% of desired axial strain level (double amplitude) with 10 cycles at each strain level (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.1, 1.2, 1.3, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5, 6, 7, 8, 9 and 10%). Because the stabilization was to be done at shallow depths, lime treated specimens were isotropically consolidated under the confining pressure of 20 kPa.

4. Results and discussion

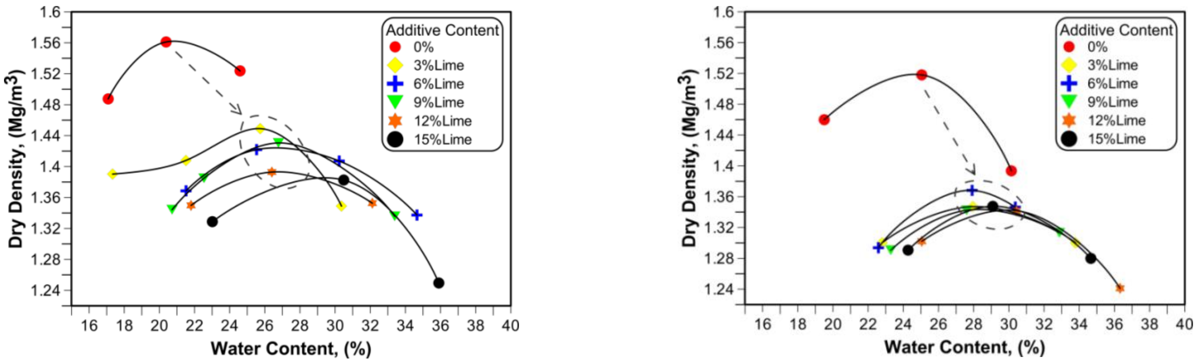
4.1 Compaction tests

Compaction curves obtained as a result of the compaction experiments, immediately after mixing and after 7 days from the end of mixing process (mellowing period) is given in Fig. 5(a) and Fig. 5(b), respectively. The values of MDD and OWC determined from these curves are given in Table 4. As shown in Fig. 5(a), the MDD values have decreased while the OWC values have increased with increasing percentage of lime. A similar trend was observed by Cheng and Huang (2019). MDD value of 1.562 Mg/m^3 without lime has reduced to 1.393 Mg/m^3 at 12% lime content and it has not changed significantly at 15% lime. There was a 12.13% decrease in the maximum dry density value. As stated by Ali and Mohamed (2017), the cause of this reduction can be attributed to the flocculation caused by the cation exchange of lime stabilized clay and the fast growing cement compounds to the bonding of very fine particles.

The compaction delay of mixtures resulted in an additional drop in the MDD (Fig. 5(b)). As seen in Fig. 5(b), there was a sudden decrease in dry density at 3% of the lime additive and no significant change in dry density was observed at the increased additive level. The change in compaction characteristics remained limited. This decrease in dry density can be clarified by the formation of

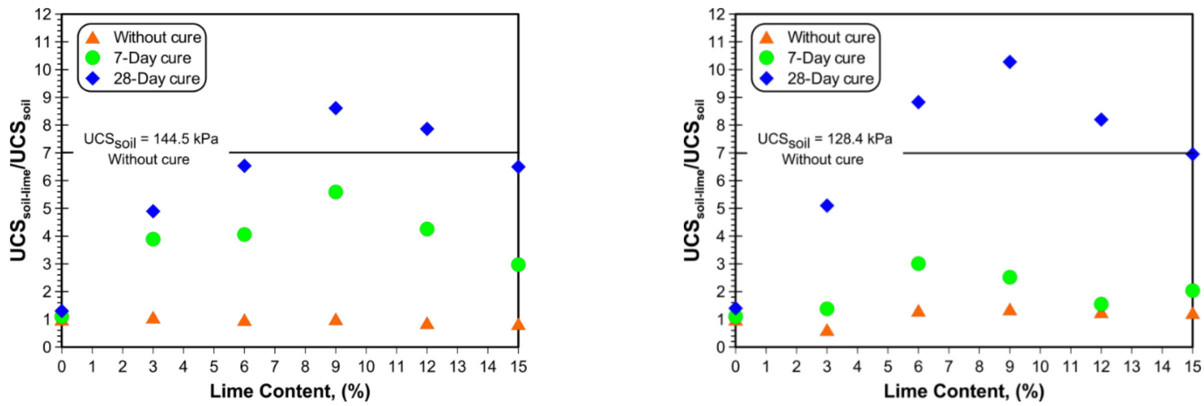
Table 4 Compaction characteristics at different lime contents and mellowing periods

Lime content (%)	MP (0-day)		MP (7-day)	
	MDD (Mg/m^3)	OWC (%)	MDD (Mg/m^3)	OWC (%)
0	20.80	1.562	24.60	1.520
3	25.30	1.451	28.00	1.347
6	26.70	1.424	28.50	1.370
9	26.20	1.432	28.00	1.343
12	26.40	1.393	29.80	1.343
15	29.80	1.385	29.08	1.348



(a) Without mellowing (b) With 7 days mellowing

Fig. 5 Compaction curves of specimens mixed with different percentages of lime



(a) Without mellowing (b) With 7 days mellowing

Fig. 6 Effects of lime content and curing time on UCS

cementitious compounds which are resistant to compression developing 7 days after the mixture in a loose state. In other words, the delay in the compaction process led to increased clay agglomeration and tightening between the clay particles to cause tighter bonding. The water molecules or other ions present in the soil are replaced by calcium ions as a result of which decrease in the diffuse double layer of water. This causes particles come close to each other and the soil structure becomes flocculated and offers more resistance to the applied load. In addition, due to flocculation large antiparticle void spaces are created and water molecules gets trapped in voids between spaces. This increases the OWC of lime added soils and reduce the density of soil. Added lime goes into the pore spaces of the soil (Sahoo *et al.*, 2017). For these reasons, irrespective of lime content, MDD of soils decreased rapidly and thereafter no significant change in the MDD was observed.

4.2 Unconfined compressive strength tests

The tests were conducted to investigate the effects of the mellowing period on the UCS of the lime stabilized soil as well as to assess the change in strength during the curing time. The effect of the lime content and mellowing period on unconfined compressive strength results is shown in Fig. 6(a) and Fig. 6(b). The test results are illustrated in terms of the ratio of strength value of reference soil without curing in the non-additive state to be able to understand the impact of the lime content and mellowing on the unconfined compressive strength.

As can be seen in Fig. 6(a), there was no significant change in UCS values of specimens in the uncured state. Significant increases were observed in strength with increasing curing time. From the UCS tests results, by increasing the lime content from 3 to 9%, UCS values of specimens with lime increased from 561.8 to 707 kPa and from 807.3 to 1244.1 kPa for 7 and 28 curing days, respectively. Similar results were observed in studies conducted by Jahandari *et al.* (2019) and Tebaldi *et al.* (2016). Especially in the 9% lime additive level, the UCS values increased 5.59 and 8.61 times for the 7 and 28 days cure respectively. The increase in the short-term (7 days cure) strength was higher than the increase in long-term strength (28 days cure). More than 9% lime additive has led to a decrease in strength values. In other words, the clearly developed strength is influenced by the amount of cement-based gel produced and thus the consumed lime amount (Bell 1996). Considering that the clay content of the soil is low, more than 9% lime could not react with clay in soil sufficiently.

The effects of the mellowing period (7 days) on the UCS of the lime stabilized soil are presented in Fig. 6(b). As seen in Fig. 6(b), the UCS values of specimens with lime found in 28 curing days were found to be much higher than those found in uncured and 7 days curing conditions. While the UCS values of the uncured and 7 days cure conditions have reached the highest values in 6% lime content, it has reached its maximum value in 9% lime content in 28 days cure condition. From the data in Fig.

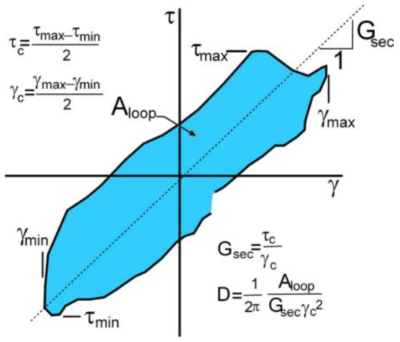


Fig. 7 An example of stress-strain loop and quantities used for evaluation of secant modulus G_{sec} and damping D

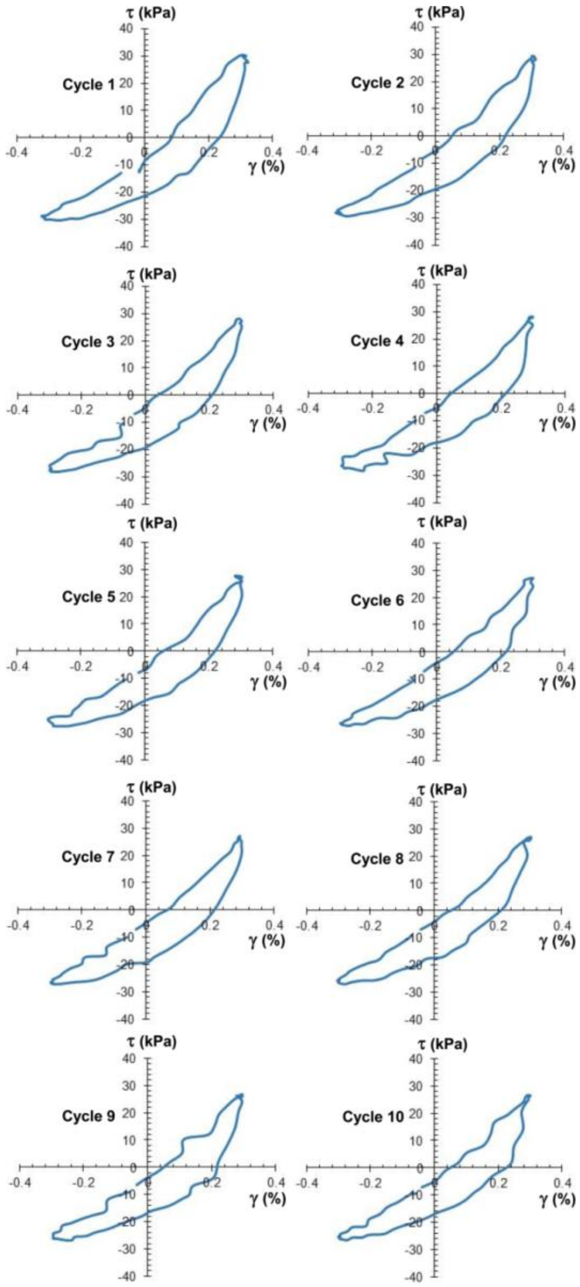
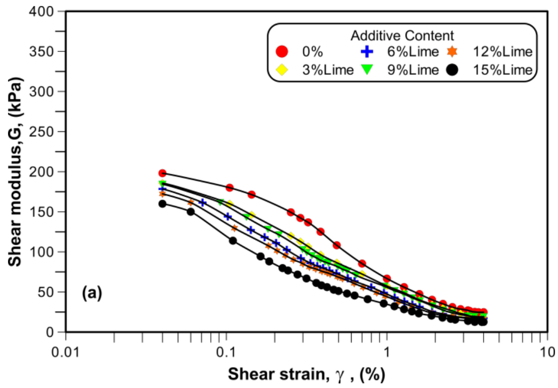
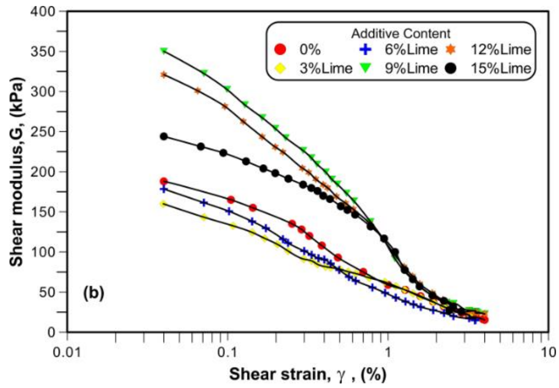


Fig. 8 Shear stress-shear strain hysteresis loops for the case of 3%lime at the 7 days mellowing period at 0.3% shear strain level

6(b), at the lime content of 9%, UCS values of specimens increased from 363.9 to 1485.3 kPa for 7 and 28 curing days, respectively. In other words, the effect of delayed compaction on UCS values was much more pronounced in



(a) Without mellowing



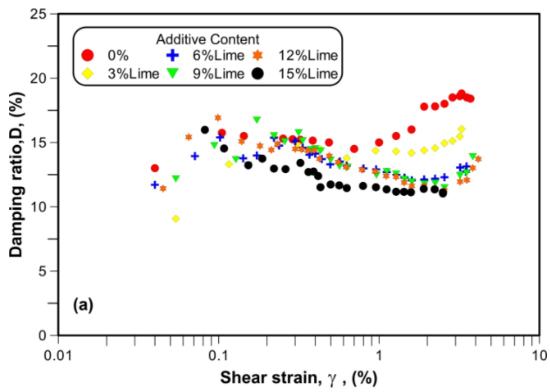
(b) With 7 days mellowing

Fig. 9 Shear modulus and shear strain relationship depending on the lime content

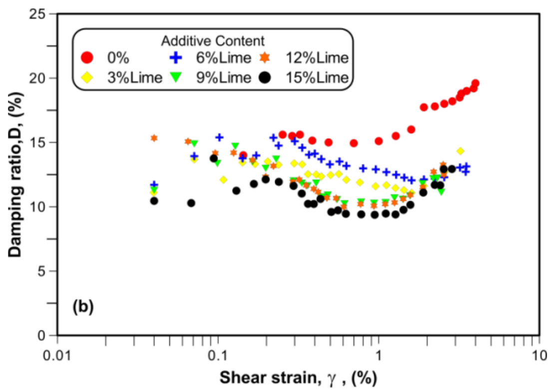
(a) Immediately after the mixture

(b) After 7 days mellowing period

Fig. 10 Photos of dynamic test results performed at the 9% lime additive level



(a) Without mellowing



(b) With 7 days mellowing period

Fig. 11 Damping ratio and shear strain relationship depending on the lime content

specimens left cure for 28 days.

4.3 Dynamic triaxial tests

The data obtained from the cyclic loading for each case were recorded. In the data set, main points were considered as the behavior of the axial stress with time and the behavior of the axial strain with time. Shear stress-shear strain behavior was calculated from these recorded values and evaluated together in order to understand the shape of the modulus reduction curve at different shear strain levels. Based on the schematic stress-strain loop in Fig. 7, secant shear modulus G_{sec} and damping D were calculated. The area of each loop needed to obtain D was computed using trapezoidal integration as stated by Afacan *et al.* (2014).

The hysteresis loops from the shear stress-shear strain data were extracted at different strain levels. An example set of loops is shown in Fig. 8. This example was taken from data observed for the case of 3% lime at the 7 days mellowing period at 0.3% shear strain level.

As seen in the Fig.8, the shapes of the hysteresis loops look similar. The shear modulus for each cycle, the slope of the loop, was calculated and similar values were observed. However, the damping values due to change in the shape of the loop were came up to be different. Therefore, the damping ratios for 10 different cycles at the same shear strain level were calculated and the average of these values was reported as the damping ratio at that specific shear strain level.

The shear modulus and damping values for different shear strains are presented in Fig. 9(a) and Fig. 9(b), respectively. Fig. 9(a) shows the changes in the shear modulus with the increasing lime content without mellowing period. As can be seen from Fig. 9(a), the shear modulus values decreased in a narrow range with the increased lime content. As the test was carried out immediately after the mixture, the chemical reaction between the lime and the soil could not be realized and the shear modulus decreased in the increasing lime content. However, the effect of mellowing period as in Fig. 9(b) has provided a positive effect on shear modulus. Although the curing was not applied after the preparation of the specimens, the cementation occurred during the release of the mixture in the loose state for 7 days caused an increase in the strength. Especially with lime content of 9%, the increase in the shear modulus was more prominent.

Photographs of the test results performed immediately after the mixture and 7 days after the mixture at the 9% lime additive level are presented in Fig. 10(a) and Fig. 10(b), respectively. As can be seen from Fig. 10(b), a remarkable shear surface has been formed as a result of cementation depending on the mellowing period before the compaction.

Regarding the damping data, they are scattered all over for both cases. The red points, the samples without lime, follow the same path and they are not so different compared to each other. However, increasing lime content for Fig. 11(a) and Fig. 11(b) did not give a general idea about the damping behavior. The damping data recorded in the laboratory is generally higher than the ones reported in the literature which is an obvious point can be made from this figure. The damping values were calculated from 9% to 20% for a shear range of 0.04% to 5%. Afacan *et al.* (2014) recorded damping ratios of 8% to almost 40% in their study. Although their study was on centrifuge testing, similar damping behavior were observed with the dynamic triaxial data.

5. Conclusions

A study of delayed compaction of lime treated clay soil on the compaction, unconfined compressive strength and dynamic properties has been investigated. Based on the findings of experimental investigation the following conclusions are drawn:

• From the compaction test results immediately after the mixture, the maximum dry density (MDD) increased and the optimum water content (OWC) decreased as the additive content increased up to 12%. In the 15% lime content, no significant change was observed in compaction characteristics. The compaction delay of mixtures resulted in an additional increase in the MDD and decrease in the OWC at 3% of the lime. The variation in compaction characteristics at the increasing lime additive levels was very limited.

• Unconfined compressive strength of lime treated soil was found to increase up to 9% lime with delay of compaction and dependent on period of curing. The effect of delayed compaction on UCS values was much more pronounced in specimens left cure for 28 days. Delayed compaction has shown its effect especially in long-term strength for studied soil.

• Dynamic properties are important to determine the engineering behavior of lime stabilized clay soils subjected to cycling loading. The effect of mellowing period (7 days) has provided a positive effect on the shear modulus (G). Although the curing was not applied after the preparation of the specimens, the cementation occurred during the release of the mixture in the loose state for 7 days caused an increase in the strength. Because of the complex forms of hysteresis loops caused by the lime additive, the damping ratio (D) values differed from the trends presented in the literature and showed a scattered relationship.

References

Afacan, K.B, Brandenberg, S.J. and Stewart, J.P. (2014), “Centrifuge modeling studies of site response in soft clay over wide strain range”, *J. Geotech. Geoenviron. Eng.*, **140**(2), 04013003. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001014.

Akoto, B.K.A. and Singh, G. (1986), “Behavior of lime-stabilized laterite under repeated loading”, *Australian Road Res.*, **16**(4), 259-267.

Ali, H. and Mohamed, M. (2017), “The effects of compaction delay and environmental temperature on the mechanical and hydraulic properties of lime-stabilized extremely high plastic clays”, *Appl. Clay Sci.*, **150**, 333-341. https://doi.org/10.1016/j.clay.2017.09.019.

Al-Mukhtar, M., Khattab, S. and Alcover, J.F. (2012). “Microstructure and geotechnical properties of lime-treated expansive clayey soil”, *Eng. Geol.*, **139-140**, 17-27. https://doi.org/10.1016/j.enggeo.2012.04.004.

Al-Mukhtar, M., Lasledj, A. and Alcover, J.F. (2014), “Lime consumption of different clayey soils”, *Appl. Clay Sci.*, **95**, 133-145. https://doi.org/10.1016/j.clay.2014.03.024.

Al-Rawas, A.A., Hago, A. and Al-Sarmi, H. (2005), “Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman”, *Build. Environ.*, **40**(5), 681-687. https://doi.org/10.1016/j.buildenv.2004.08.028.

Angın, Z. and İkizler, S.B. (2018), “Assessment of swelling pressure of stabilized Bentonite”, *Geomech. Eng.*, **15**(6), 1219-1225. https://doi.org/10.12989/gae.2018.15.6.1219.

Anon. (1985), *Lime Stabilization Construction Manual*, National Lime Association, Arlington, Virginia, U.S.A.

Anon. (1990), *Lime Stabilization Manual*, British Aggregate Construction Materials Industry, London, U.K.

Asgari, M.R., Baghebanzadeh Dezfuli, A. and Bayat, M. (2015), “Experimental study on stabilization of a low plasticity clayey soil with cement/lime”, *Arab. J. Geosci.*, **8**(3), 1439-1452. https://doi.org/10.1007/s12517-013-1173-1.

ASTM (1994), *Annual Book of ASTM Standards: Soil and Rock*, American Society for Testing and Materials, Philadelphia, U.S.A.

Basma, A.A. and Tuncer, E.R. (1991), “Effect of lime on volume change and compressibility of expansive clays”, *Transport. Res. Rec.*, **1296**, 54-61.

Bell, F.G. (1996), “Lime stabilization of clay minerals and soils”, *Eng. Geol.*, **42**(4), 223-237. https://doi.org/10.1016/0013-7952(96)00028-2.

Bozbey, I. and Garaisayev, S. (2010), “Effects of soil pulverization quality on lime stabilization of an expansive clay", *Environ. Earth Sci*., **60(**6), 1137-1151. https://doi.org/10.1007/s12665-009-0256-5.

Calik, U. and Sadoglu, E. (2014), "Engineering properties of expansive clayey soil stabilized with lime and perlite", *Geomech. Eng*., **6**(4), 403-418. http://dx.doi.org/10.12989/gae.2014.6.4.403.

Canakci, H., Aziz, A. and Celik, F. (2015), "Soil stabilization of clay with lignin, rice husk powder and ash", *Geomech. Eng*., **8**(1), 67-79. http://dx.doi.org/10.12989/gae.2015.8.1.067.

Chavali, R.V.P. and Reddy, P.H.P. (2018), "Control of phosphoric acid induced volume change in clays using fly ash", *Geomech. Eng*., **15**(6), 1135-1141. https://doi.org/10.12989/gae.2018.15.6.1135.

Cheng, Y. and Huang, X. (2019), "Effect of mineral additives on the behavior of an expansive soil for use in highway subgrade soils", *Appl. Sci*., **9**(1), 30. https://doi.org/10.3390/app9010030.

Di Sante, M., Fratalocchi, E., Mazzieri, F. and Brianzoni, V. (2015), "Influence of delayed compaction on the compressibility and hydraulic conductivity of soil-lime mixtures", *Eng. Geol*., **185**, 131-138. https://doi.org/10.1016/j.enggeo.2014.12.005.

Escolano, F., Sánchez, J.R., Pacheco-Torres, R. and Cerro-Prada, E. (2018), "Strategies on reuse of clayey expansive soils as embankment material in urban development areas: A case study in new urbanized zones", *Appl. Sci*., **8**(5), 764. https://doi.org/10.3390/app8050764.

Fahoum, K., Aggour, M.S. and Amini, F. (1996), "Dynamic properties of cohesive soils treated with lime", *J. Geotech. Eng*., **122**(5), 382-389. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:5(382).

Gallage, C., Cochrane, M. and Ramanujam, J. (2012), "Effects of lime content and amelioration period in double lime application on the strength of lime treated expansive sub-grade soils", *Proceedings of the 2nd International Conference on Transportation Geotechniques*, Hokkaido, Japan, September.

Garzón, E., Cano, M., O`Kelly, B.C. and Sánchez-Soto, P.J. (2016), "Effect of lime on stabilization of phyllite clays", *Appl. Clay Sci*., **123**, 329-334. https://doi.org/10.1016/j.clay.2016.01.042.

Ghobadi, M.H., Abdilor, Y. and Babazadeh, R. (2014), "Stabilization of clay soils using lime and effect of pH variations on shear strength parameters", *Bull. Eng. Geol. Environ*., **73**(2), 611-619. https://doi.org/10.1007/s10064-013-0563-7.

Hoyos, L.R., Puppala, A.J. and Chainuwat, P. (2004), "Dynamic properties of chemically stabilized sulfate rich clay", *J. Geotech. Geoenviron. Eng*., **130**(2), 153-162. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:2(153).

Jahandari, S., Saberian, M., Zivari, F., Li, J., Ghasemi, M. and Vali, R. (2019), "Experimental study of the effects of curing time on geotechnical properties of stabilized clay with lime and geogrid", *Int. J. Geotech. Eng*., **13**(2), 172-183. https://doi.org/10.1080/19386362.2017.1329259.

Kavak, A. and Akyarlı, A. (2007), "A field application for lime stabilization", *Environ. Geol*., **51**(6), 987-997. https://doi.org/10.1007/s00254-006-0368-0.

Kim, Y., Dang, M.Q. and Lee, J.K. (2018), "Soil stabilization by ground bottom ash and red mud", *Geomech. Eng*., **16**(1), 105-112. https://doi.org/10.12989/gae.2018.16.1.105.

Lu, W., Miao, L., Zhang, J., Zhang, Y. and Li, J. (2019), "Characteristics of deformation and damping of cement treated and expanded polystyrene mixed lightweight subgrade fill under cyclic load", *Appl. Sci*., **9**(1), 167. https://doi.org/10.3390/app9010167.

Mallela, J., Harold Von Quintus, P., Smith, K.L. and Consultants, E. (2004), *Consideration of Lime Stabilized Layers in Mechanistic-Empirical Pavement Design*, The National Lime Association, Arlington, Virginia, U.S.A.

Mebarki, M., Kareche, T., Derfouf, F.E.M., Taibi, S. and Abou-bekr, N. (2019), "Hydromechanical behavior of a natural swelling soil of Boumagueur region (east of Algeria)", *Geomech. Eng*., **17**(1), 69-79. https://doi.org/10.12989/gae.2019.17.1.069.

Millogo, Y., Morel, J.C., Traoré, K. and Ouedraogo, R. (2012), "Microstructure, geotechnical and mechanical characteristics of quicklime-lateritic gravels mixtures used in road construction", *Constr. Build. Mater*., **26**(1), 663-669. https://doi.org/10.1016/j.conbuildmat.2011.06.069.

Mitchell, J.K. and Hooper, D.R. (1961), "Influence of time between mixing and compaction on properties of a lime-stabilized expansive clay", *Highway Res. Board Bull*., **304**, 14-31.

Moayyeri, N., Oulapour, M. and Haghighi, A. (2019), "Study of geotechnical properties of a gypsiferous soil treated with lime and silica fume", *Geomech. Eng*., **17**(2), 195-206. https://doi.org/10.12989/gae.2019.17.2.195.

Osinubi, K.J. (1998), "Influence of compactive efforts and compaction delays on lime-treated soil", *J. Transport. Eng*., **124**(2), 149-155. https://doi.org/10.1061/(ASCE)0733-947X(1998)124:2(149).

Parsons, R.L., Johnson, C.P. and Cross, S.A. (2001), "Evaluation of soil modification mixing procedures", *Proceedings of the 80th Annual Meeting*, Transportation Research Board, National Research Council, Washington, D.C., U.S.A.

Rao, S.M., Shivananda, P. (2005), "Compressibility behavior of lime-stabilized clay", *Geotech. Geol. Eng*., **23**, 309-319. https://doi.org/10.1007/s10706-004-1608-2.

Sahoo, S.P., Singh, S.P. and Das, R. (2017), "Effects of delay time on plasticity and compaction characteristics of lime modified expansive soil", *Proceedings of the Indian Geotechnical Conference GeoNEst*, Guwahati, India, December.

Sakr, M.A., Shahin, M.A. and Metwally, Y.M. (2009), "Utilization of lime for stabilization soft clay soil of high organic content", *Geotech. Geol. Eng*., **27**, 105-113. https://doi.org/10.1007/s10706-008-9215-2.

Sas, W., Głuchowski, A., Gabryś, K., Soból, E. and Szymański, A. (2017), "Resilient modulus characterization of compacted cohesive subgrade soil", *Appl. Sci*., **7**(4), 370. https://doi.org/10.3390/app7040370.

Seed, H.B. and Idriss, I.M. (1970), "Soil moduli and damping factors for dynamic response analyses", Report EERC70-10, Earthquake Engineering Research Center, University of California, Berkeley, California, U.S.A.

Sharma, L.K., Sirdesai, N.N., Sharma, K.M. and Singh, T.N. (2018), "Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study", *Appl. Clay Sci*., **152**, 183-195. https://doi.org/10.1016/j.clay.2017.11.012.

Sherwood, P.T. (1993), *Soil Stabilization with Cement and Lime*, in *State of Art Review*, HMSO, London, U.K.

Sweeney, D.A., Wong, D.K.H. and Fredlund, D.G. (1988), "Effect of lime on highly plastic clay with special emphasis on aging", *Transport. Res. Rec*., **1190**, 13-23.

Tebaldi, G., Orazi, M. and Orazi, U.S. (2016), "Effect of freeze–thaw cycles on mechanical behavior of lime-stabilized soil", *J. Mater. Civ. Eng*., **28**(6), 06016002. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001509.

Türköz, M., Savaş, H., Acaz, A. and Tosun, H. (2014), "The Effect of magnesium chloride solution on the engineering properties of clay soil with expansive and dispersive characteristics", *Appl. Clay Sci*., **101**, 1-9. https://doi.org/10.1016/j.clay.2014.08.007.

Vucetic, M. and Dobry, R. (1991), "Effect of soil plasticity on cyclic response", *J. Geotech. Eng*., **117**(1), 89-107. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:1(89).

Yilmaz, Y., Eun, J. and Goren, A. (2018), "Individual and combined effect of Portland cement and chemical agents on unconfined compressive strength for high plasticity clayey soils", *Geomech*. *Eng*., **16**(4), 375-384. https://doi.org/10.12989/gae.2018.16.4.375.

Yilmaz, F. and Fidan, D. (2018), "Influence of freeze-thaw on strength of clayey soil stabilized with lime and perlite", *Geomech*. *Eng*., **14**(3), 301-306. https://doi.org/10.12989/gae.2018.14.3.301.

Wang, M., Kong, L., Zhao, C. and Zang, M. (2012), "Dynamic characteristics of lime-treated expansive soil under cyclic loading", *J. Rock Mech*. *Geotech*. *Eng*., **4**(4), 352-359. https://doi.org/10.3724/SP.J.1235.2012.00352.

GC