*Turkish Journal of Civil Engineering, 2023 135-152, Paper 720, **Research Article***

The Investigation of the Addition of Sodium Lignosulfonate to Lime Column Used For Improving the Expansive Soils

İlyas ÖZKAN[1]
Erdal ÇOKÇA[2]

ABSTRACT

The lime column (LC) technique has been commonly used for the improvement of expansive soils. The achievement of this technique depends on the lime diffusion into the expansive soils, but lime diffusion into the expansive soil is generally a slow process due to the low permeability of these soils. In this study, sodium lignosulfonate, which is used as a superplasticizer in the concrete industry, was added to lime columns to accelerate the diffusion of lime particles. First, treated expansive clay specimens with thirty-seven 4.5 mm diameter columns were prepared in an oedometer ring. These columns were filled with two different mixtures: water-lime and water-lime-sodium lignosulphonate to investigate the effect of the addition of sodium lignosulphonate. Free swell tests were done on these treated expansive clay specimens that were subjected to different curing periods, it was observed that the treated specimens with sodium lignosulphonate lime columns (NaLS-LC) are more effective than the treated specimens with lime columns (LC). A treated expansive clay specimen (in a 30cmx30cm mold) with seven pieces of 45 mm diameter sodium lignosulphonate lime columns were prepared to observe the alteration of engineering properties of untreated expansive clay specimen (US) located between the columns. Free swell and unconfined compressive strength tests were done on the undisturbed expansive clay specimens taken from the mold between the columns. SEM-EDX analyses were made to investigate whether the ettringite mineral, which leads to swelling of the expansive soil during lime stabilization, forms or not. While the ettringite mineral formed during the curing period in the lime column stabilization method, the addition of sodium lignosulphonate to lime columns blocked the formation of the ettringite mineral. It can be stated that sodium lignosulphonate lime columns (NaLS-LC) show better performance than lime columns (LC), in the treatment of expansive clays.

Note:

- This paper was received on April 21, 2022 and accepted for publication by the Editorial Board on October 10, 2022.
- Discussions on this paper will be accepted by March 31, 2022.

• https://doi.org/10.18400/tjce.1209185

1 Middle East Technical University, Department of Civil Engineering, Ankara, Türkiye
ozkan.ilyas@hotmail.com - https://orcid.org/0000-0001-9660-8229

2 Middle East Technical University, Department of Civil Engineering, Ankara, Türkiye
ecokca@metu.edu.tr - https://orcid.org/0000-0001-8367-2539

Keywords: Sodium lignosulphonate, expansive soil, lime column, stabilization, swelling potential.

1. INTRODUCTION

Expansive soils cause damage to lightweight structures such as one or two-story buildings, pavements, etc. Expansive clays can be found in semi-arid and arid regions [1]. As the volume change of expansive soils depends on the water contents, their volumes are affected by both arid and wet weather conditions, these soils shrink due to the loss of water and their volumes increase due to the absorption of water. Although these alterations of their volumes do not result in the loss of life, they can cause great economic loss [2].

The improvement methods for these soils have been developed in the last decades. Chemical stabilization, one of these improvement methods, is commonly applied to stabilize these soils. Lime is a more preferable additive for the chemical stabilization of expansive soils. Treated specimens with lime, gain higher strength and durability properties during the stabilization process. Lime stabilization of expansive soils can be done by two different methods that are chemical additive technique and the lime column technique. Lime column techniques have been applied for many purposes such as slope stability, improving the properties of soft soil, etc. [3-4-5].

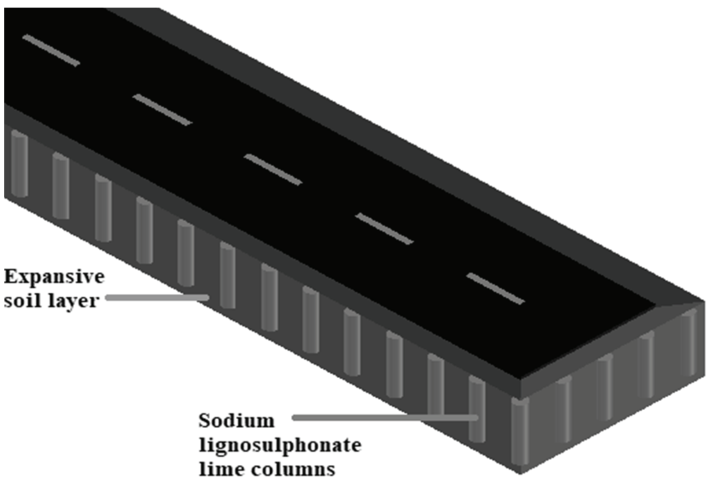


Figure 1 - Sodium lignosulphonate lime columns under the pavement and embankment load

Lime stabilization of expansive soil consists of three steps that are cation exchange, flocculation and agglomeration, and pozzolanic reaction. At the cation exchange step, calcium ions presented from lime particles are exchanged with monovalent ions presented from clay particles. After this exchange process, clay particles get closer to each other and the thickness of diffused double layer reduces. Then, the structure of clay particles, which are generally flat and parallel, convert to a more random edge-to-face orientation after the flocculation process. The first two steps that are cation exchange and flocculation and agglomeration occur in the first 72 hours after the applications. The final step of this stabilization is the pozzolanic reaction which both depends on time and consists of the reaction between the calcium ions and clay particles. The strength of the treated specimen gradually enhanced with this reaction process [6-7-8].

The lime column technique is a commonly applicable method in the field. However, the lime column, which contains sodium lignosulphonate, has not been studied until now. The main objective of this study is to investigate the influence of the addition of sodium lignosulphonate to the lime column technique. Figure 1 illustrates an example of sodium lignosulphonate lime columns in an expansive soil subgrade in the field.

Lignosulphonate is a waste material obtained from the paper industry that is produced by 50 million tons per year. This material is classified into different groups according to calcium, sodium, magnesium, and potassium in it, which depends on both type of the wood and the chemical processes. Although this waste material is an inexpensive and extensive chemical, a very small amount of this production is used as an additive such as concrete superplasticizer, agricultural chemical, and industrial binder [9-10].

Some studies related to the application of lignosulphonate on soils have been done over the past decade.

Electrostatic interactions, hydrogen bonding, covalent bonding, and cation exchange occur during the reactions between the calcium lignosulphonate and clay minerals. Then, expansive clay particles covered with this material absorb less amount of water [11].

Vinod et al. (2010) studied the physicochemical and microstructural changes of silty clay soil due to lignosulphonate addition. First, lignosulphonate was added to the water, after the hydrolysis, hydrogen (H^+) and hydroxyl (OH^-) ions were disintegrated and caused the protonation of the lignosulphonate. The protonated lignosulphonate releases water and forms a positively charged lignosulphonate. The positively charged lignosulphonate neutralizes the negative charges of clay minerals due to electrostatic attraction which leads to the reduction of the double-layer thickness and subsequent binding of the soil particles together to form a flocculated structure and the engineering properties of the soil were improved [12].

Vakili et. al. (2018) stated that the attractive forces between the clay particles increase while the repulsion forces decrease during the lignosulphonate stabilization [13]. Indraratna et al. (2010) used lignosulphonate for the improvement of erodible soils and the strengths of these soils were enhanced after this stabilization process [14]. Tingle and Santoni (2003) used lignosulphonate for the treatment of a low plasticity clay (CL). The unconfined compressive strength (UCS) of CL soil was measured as 1379 kPa, when %5 lignosulphonate was added to CL soil and cured in the humid room for 28 days, UCS concerning the untreated condition [15]. A study related to the deformation behavior of sandy silt under cyclic loading was done by Chen and Indraratna in 2015. According to this study, the resilient modulus of the treated specimen with lignosulphonate was significantly greater than the resilient modulus of the untreated soil specimen [16].

In this study, the efficiency of the addition of sodium lignosulphonate to the lime column is studied by carrying out scanning electron microscope (SEM) and energy dispersive x-ray diffraction (EDX) analysis on both untreated and treated specimens. Methylene blue value MBV test results were used to determine the change in specific surface area (SSA) and cation exchange capacity (CEC) of both untreated and treated samples. The curing effect on the swelling potential and unconfined compressive strength tests of both lime column and sodium lignosulphonate lime column specimens were also studied. The sodium lignosulphonate lime columns show better performance than lime columns, in the treatment of expansive clays.

2. EXPERIMENTAL WORK

An expansive soil specimen consisting of 85% kaolinite and 15% bentonite in terms of dry weight was prepared to obtain a homogenous specimen. Both kaolinite and bentonite were oven-dried for one day. They were passed through the No.40 sieve. They were mixed with a trowel in the cup. They were sieved two times through the No.20 sieve to obtain a homogeneous sample. The test specimens were compacted at maximum dry density. The water content of this specimen was %15. This expansive soil specimen is called specimen US.

Lime, which is a calcium-slaked lime, is sieved from the No. 200 sieve to accelerate the diffusion process.

Sodium lignosulphonate utilized in this study was in pulverized form and was sieved from the No. 200 sieve.

2.1. Properties of the Untreated Specimen US

The expansive soil specimen prepared in the laboratory is a high plasticity clay according to USCS. The properties of this specimen such as specific gravity, Atterberg limits, PSD, compaction, and swelling potential are determined according to ASTM standards (D422 (2007), D4318 (2017), D854 (2014), D4546 (2014)) respectively [17-18-19-20]. These properties are presented in Table 1.

Table 1 - Physical properties of the untreated specimen US from laboratory testing

*Properties, (Unit)	Value
Specific gravity	2.56
Liquid limit (%)	95.2
Plastic limit (%)	23.2
Plasticity index (%)	72.3
Clay content (%)	57
Activity	1.27
Water content (%)	15
Dry unit weight (kN/m^3)	1.495

Table 1 - Physical properties of the untreated specimen US from laboratory testing (continue)

*Properties, (Unit)	Value
Swelling potential under 7 kPa (%)	43.95
Swelling potential under 25 kPa (%)	29.47
Swelling pressure (kPa)	265

*(ASTM Standard D854, (2014), ASTM Standard D4318, (2017), ASTM Standard D422, (2007), ASTM D698-12, (2012), ASTM Standard D4546, (2014) respectively)

The swelling potential of untreated specimen US under 7 kPa surcharge pressure is approximately 44%. Thus, this specimen is classified as "very high" expansive according to the classification proposed by Seed et al. (1962) [21].

The chemical characteristics of the untreated specimen were determined in the form of major oxides in the Middle East Technical University Central Laboratory, using the X-ray fluorescence (XRF) technique. The chemical composition of untreated specimen US is provided in Table 2. Elementary sulfur can be analyzed but SO_3 (SO_4) can not be determined in the XRF technique.

Table 2 - Chemical composition of untreated specimen US

Chemical Composition	Expansive soil specimen (%)
SiO_2	51.6
Al_2O_3	41.3
Fe_2O_3	1.22
CaO	0.51
SO_3 (SO_4)	-
CO_2	3.46
K_2O	0.5
Na_2O	0.17
MgO	0.15
P_2O_5	0.06
SrO	0.02
ZrO_2	0.02

2.2 Treated Specimens with Lime Columns (LC)

The treated specimen with lime columns, which have 63.5 mm diameter and 19 mm height, consists of 37 pieces of lime columns that have 4.5 mm diameter and 19 mm height is presented in Figure 2. The lime columns were placed in a circular orbit due to the shape of the oedometer ring. The distance between the lime columns is 4.05 mm.

Water was added to lime columns to increase the lime diffusion. In addition to this, the water content of lime columns should be greater than the water content of expansive soil specimens. Thus the columns were filled with a mixture that consists of 70% lime and 30% water by weight. This mixture was in a plastic state. When the water content of this mixture was greater than 30%, this mixture was not workable material due to its sticky structure, the treated specimen was called LC.

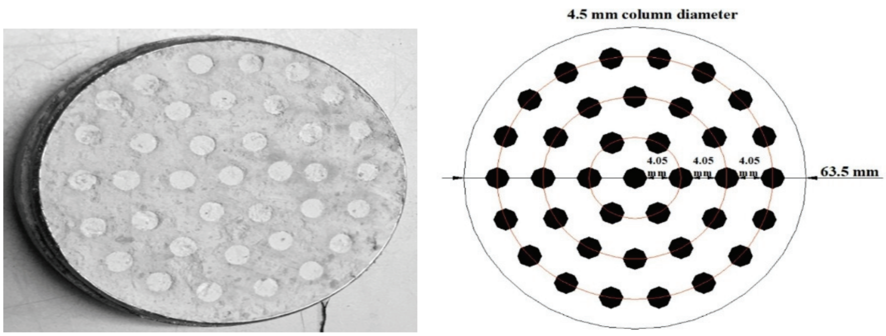


Figure 2 - Model of the treated specimen with lime columns (LC)

The properties of lime columns installed in an oedometer ring are presented in Table 3.

Table 3 - The properties of lime columns installed in the oedometer ring

Specimen Diameter (cm)	Specimen Area (cm^2)	Borehole Diameter (cm)	Borehole Area (cm^2)	Total Column Volume (cm^3)	Total Columns Surrounding Area (cm^2)	Area Ratio (%)
6.35	31.67	0.45	5.88	11.18	99.4	18.58

2.3. Treated Specimens with Sodium Lignosulphonate Lime Columns (NaLS-LC)

Sodium lignosulphonate is used as a superplasticizer in the concrete industry and was selected as an additive material in this study to accelerate the diffusion of lime particles into the expansive soil.

The sodium lignosulphonate lime columns are composed of lime, water, and sodium lignosulphonate. Since sodium lignosulphonate is a water-soluble material, first water, and sodium lignosulphonate were mixed, then lime was added to this mixture. The weight percentage of the mixture prepared in this step of the study is given in Table 4.

Table 4 - The weight percentage of the mixture consists of a water-sodium lignosulphonate-lime mixture

Percentage by weight (%)	Water	Sodium lignosulphonate	Lime
	30%	3.75%	66.25%

The optimum amount of sodium lignosulphonate is determined as 12.5% of water weight. When the amount of sodium lignosulfonate is greater than this value, lignosulfonate particles could not dissolve in water.

In this study, sodium lignosulphonate lime columns were prepared in an oedometer ring and a 30cm*30 cm mold as follows:

2.3.1. Treated Specimens in Oedometer Ring

The number and arrangement of columns in treated specimens with **sodium lignosulphonate lime columns (NaLS-LC)** are the same as in treated specimens with lime columns (LC). These treated specimens have been tested only for free swell tests to observe the change in their swelling potential of them.

*2.3.2. Treated Specimens (BG-36 and BG-50) between the Sodium Lignosulphonate Lime Columns in a 30cm*30 cm Mold*

The untreated specimen US was compacted in a mold that has 30 cm*30 cm*18 cm dimensions. Then seven boreholes were opened for the sodium lignosulphonate lime column (NaLS-LC) which has a 45 mm diameter. These boreholes were filled with sodium lignosulphonate-lime mixture, and the specimens were put into plastic bag and put into moisture room with 70% moisture and 22°C temperature for 7 days, 28 days, and 90 days curing. After the curing periods of 7 days, 28 days, and 90 days, two different diameter, undisturbed specimens were obtained from treated soil (Figure 3).

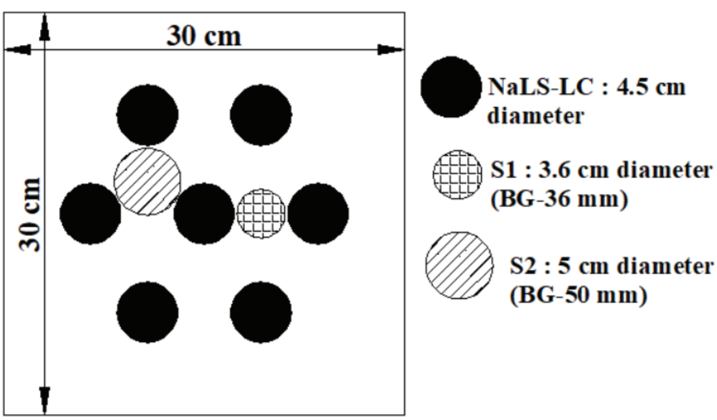


Figure 3 - Locations of undisturbed soil sampling

The specimen that has a 50 mm diameter, was tested to determine the swelling potential and permeability coefficient of treated expansive clay placed between the sodium lignosulphonate lime columns. The undisturbed specimen is called BG-50mm. The specimen which has a 36 mm diameter and was tested to measure the unconfined compressive strength of treated expansive clay placed between the sodium lignosulphonate lime columns. The undisturbed specimen is called BG-36mm. The undisturbed specimen sampling tubes were pushed into the compacted soil with a hydraulic jack (Figure 4).

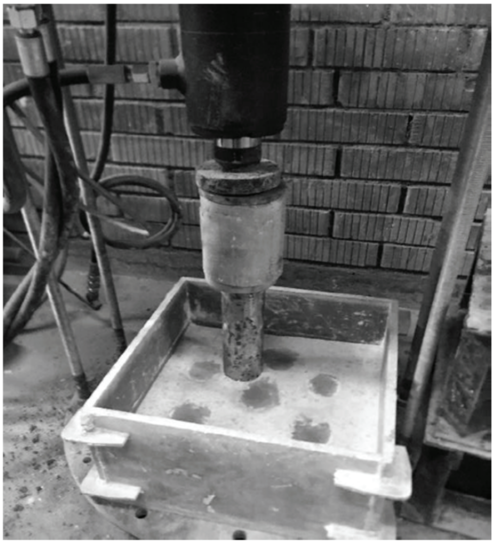


Figure 4 - The pushing process

2.4. Laboratory Tests

Free swell test, unconfined compressive strength test, and SEM-EDX analysis were done on both Specimen US and the treated specimens.

2.4.1. Free Swell Test

Untreated specimen US and treated specimens were prepared at the same dry density (1.495 g/cm^3) and water content (15%). While the densities of these specimens were selected as the maximum dry density of untreated specimen US, the water contents were lower than the optimum water content of untreated specimen US (26%) to see the effect of sodium lignosulphonate lime column stabilization better.

The volume of the soil specimen changes only in a vertical direction during the free swell test. The swelling potential is a ratio between the volume change and the initial volume of the specimen.

The swelling potential (SP) of a soil specimen is calculated as a function of the height of the soil specimen (Eqn. 1).

$$SP(\%) = \frac{(h_f - h_i)}{h_i} \times 100\% \quad (1)$$

Where h_f is the final height of the specimen and h_i is the initial height of the specimen.

Free swell tests were done to determine the swelling potentials of the treated specimens in the oedometer ring which had 6.35 cm in diameter and 1.9 cm in height and on the treated expansive clay specimens taken from the 30 cm*30 cm mold, in between the sodium lignosulphonate lime columns.

Two surcharge pressures, which are 7 kPa and 25 kPa, were applied to the specimens. The 7 kPa surcharge pressure represents a very lightweight structure such as a sidewalk, the 25 kPa surcharge pressure represents a lightweight structure such as pavement and embankment fill loading or one-two storey house loading.

7 days, 28 days, 90 days, and 180 days curing periods were applied on the treated expansive clay specimens in oedometer rings with both lime columns and sodium lignosulphonate lime columns. 7 days, 28 days, and 90 days curing periods were applied to treated expansive clay specimens taken from the 30 cm*30 cm mold, in between the sodium lignosulphonate lime columns.

Swelling potentials of untreated specimen US under 7 kPa and 25 kPa were determined as 43.95% and 29.47% respectively. These two values are reference points for the results of the other swell tests in this study.

2.4.2. Unconfined Compressive Strength (UCS) Test

Untreated specimen US (36 mm diameter and 72 mm height) for the UCS test has a water content of 15%, the dry density was 1.495g/cm^3, the degree of saturation was 53.9% and the unconfined compressive strength (ASTM D2166) was measured as 385 kPa [22]. Three curing periods of 7 days, 28 days, and 90 days were applied to treated specimens prepared to investigate the curing effect.

2.4.3. SEM-EDX Analysis

SEM-EDX analyses were done at METU Central Laboratory to examine the change in the chemical composition and structure of the expansive soil specimen during the stabilization process. The selection of the specimens for this analysis was determined according to the results of free swell tests.

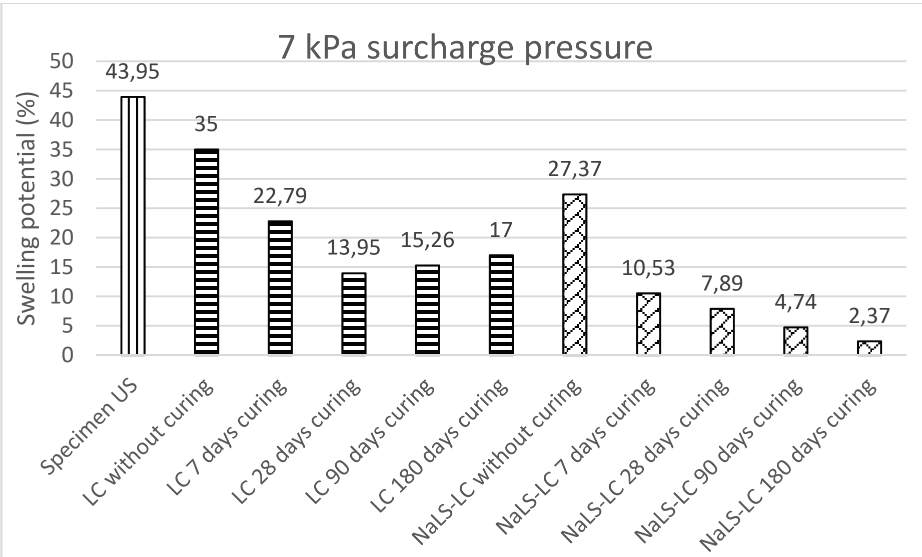
2.4.4. Methylene Blue Tests

Methylene Blue Test (MBT) was done according to NF P 94-068 standard to determine the cation exchange capacity and specific surface area of treated samples [23]. The samples for MBT were taken between the NaLS lime columns and the test samples were cured in a humid room for 90 days.

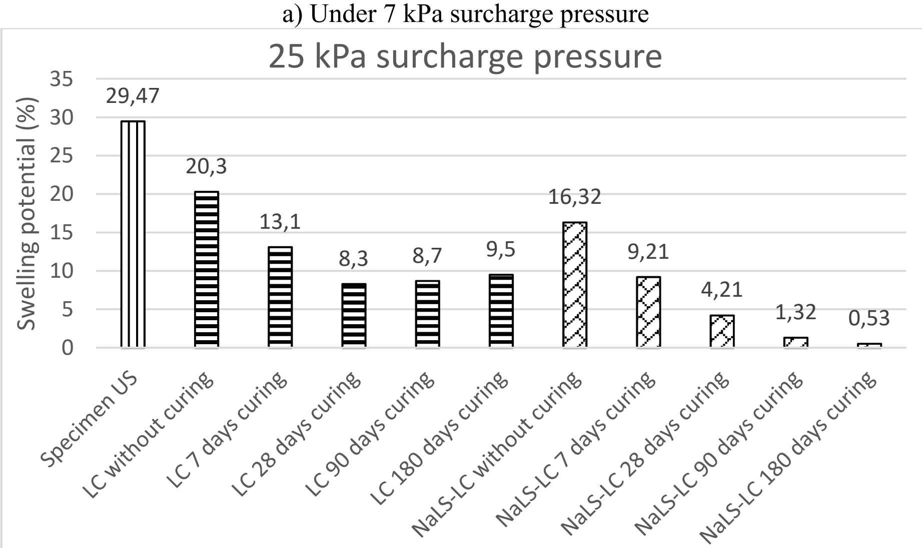
3. TEST RESULTS AND DISCUSSION

3.1. The Swelling Potentials of Treated Specimens

The swelling potentials of treated specimens under 7kPa and 25kPa (the treated specimen with lime columns, which has 63.5 mm diameter and 19 mm height (i.e. in oedometer ring), consists of 37 pieces of lime columns which have 4.5 mm diameter and 19 mm height) are presented in Figure 5.



a) Under 7 kPa surcharge pressure



b) Under 25 kPa surcharge pressure

Figure 5 - The swelling potentials of treated specimens consist of 37 columns (LC and NaLS-LC)

The swelling potentials of treated specimens including 37 columns (LC and NaLS-LC) are lower than the swelling potentials of untreated specimen US under both surcharge pressures. An optimum curing period, which was 28 days, was applied for treated specimens including 37 lime columns. After 28 days period, the swelling potentials of the treated specimens increase. The reason for this increment can be the formation of ettringite minerals during the stabilization process, which was investigated by SEM-EDX analysis. The swelling potentials of treated specimens including sodium lignosulphonate lime columns gradually decrease with the curing period. Thus, the specimens used for SEM-EDX analysis were selected as untreated specimen US and treated specimens with a 180-day curing period according to the test results of the free swell tests.

The swelling potentials of treated specimens placed between the sodium lignosulfonate lime columns in the big mold (30cmx30cm) were determined. The swelling potentials of treated specimens in this group are presented in Figure 6.

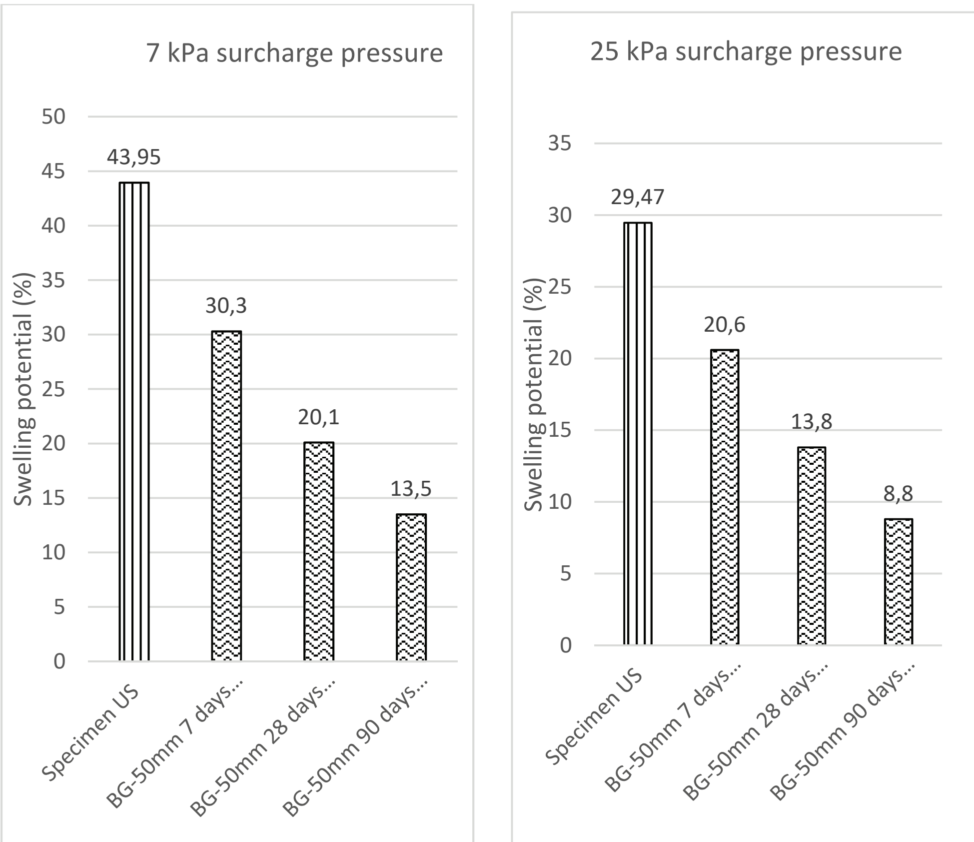


Figure 6 - The swelling potentials of treated specimens (BG-50) placed between the sodium lignosulphonate lime columns

For each surcharge pressure, the swelling potentials of treated specimens decrease with the curing period applied.

3.2. The UCS Values of Treated Specimens

The UCS values of treated specimens obtained from big mold (30cmx30cm) are presented in Figure 7. The UCS values of treated specimens are greater than the UCS of specimen US and improved with curing periods. For example, the UCS value of treated specimens called BG-3 is approximately 533 kPa after a 90-day curing period. While Specimen US behaves as a ductile material, treated specimens are converted to a brittle material with a curing period. This behavior can be explained by the formation of a flocculated structure due to the addition of lignosulphonate to the clay soil (Vinod et al., 2010).

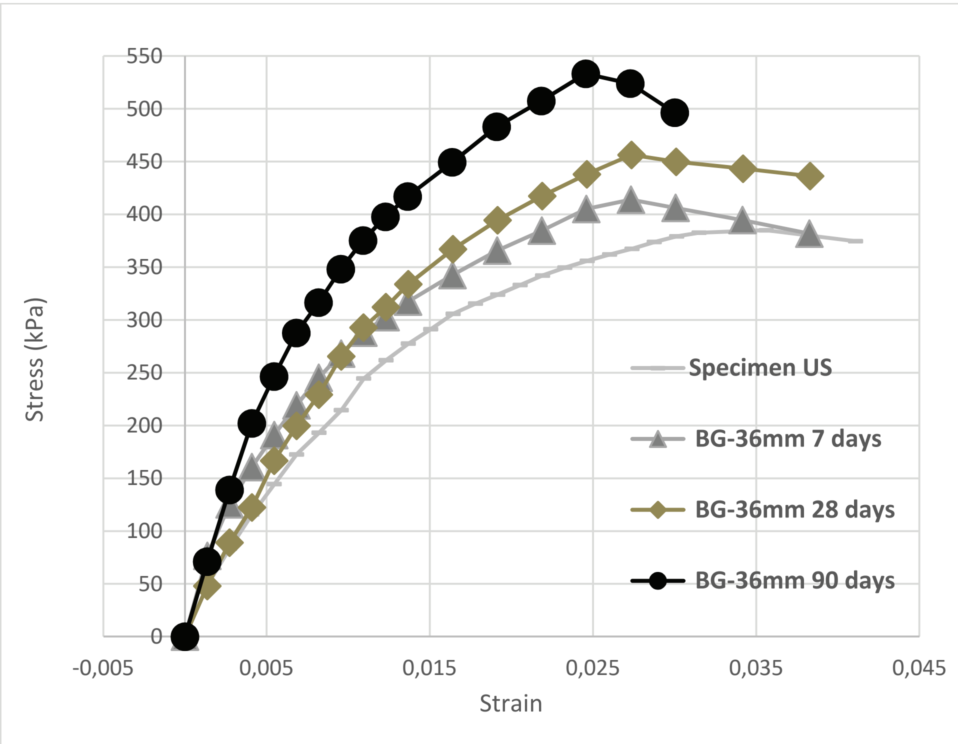


Figure 7 - Unconfined compressive strength test graphs (BG-36 specimens)

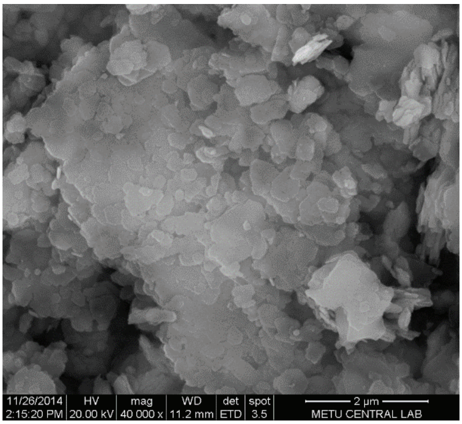
3.3. The Results of the SEM-EDX Analysis

The untreated sample US and treated samples which are named LC and NaLS-LC, with a 180-day curing period were tested. The samples for SEM-EDX analysis were taken from the midpoint of the two columns. The microstructural change of the untreated sample during the stabilization process was searched by SEM analysis. In addition to this, an Energy Dispersive

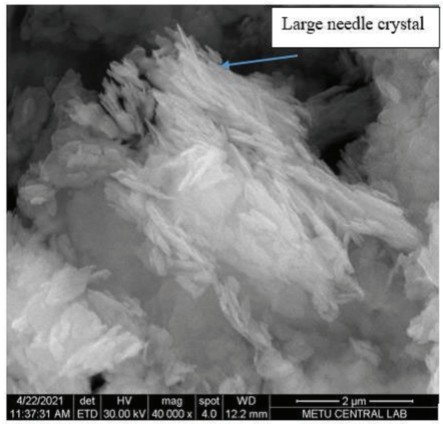
X-Ray (EDX) analysis (for 180 days of curing) was performed to get information about the chemical characterization of both untreated samples and treated samples in SEM analysis.

QUANTA 400F Field Emission Scanning Microscope was used for SEM analysis at METU Central Laboratory. First, untreated sample US was dried at 45°C and pulverized. Then, the specimens were coated with gold and palladium for SEM Analysis.

The alteration of microstructural properties of particles was investigated (Figures 8a, 8b, 8c). The magnification factor of the SEM images is x40000.

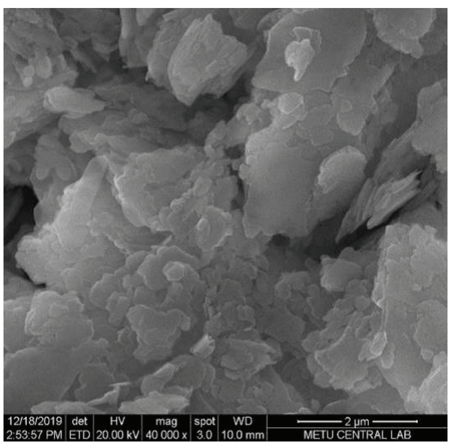


is



a) Untreated Specimen US

b) Treated specimen with Lime Columns (LC) (180 days curing)



c) Treated specimen with NaLS-Lime Columns (180 days curing)

Figure 8 - The SEM images of test specimens

The main mineral of untreated sample US is kaolinite which has plate-shaped particles in Fig 8a. According to the outputs of the free swell tests, the swelling potentials of treated specimens with lime columns increased after the 28day curing period, this might be due to the formation of ettringite mineral. When the SEM image of the treated specimen with the lime column, which was cured for 180 days, was studied (Fig. 8b), the formation of ettringite mineral was observed, ettringite formation needs sulfate ions, it is thought that the sulfate in the specimens is due to the presence of sulfate SO_4 in lime (0.79%) and/or in water (167mg/L). The major oxides of the untreated specimen were determined in the X-ray fluorescence (XRF) technique, but SO_3 (SO_4) can not be determined in the XRF technique.

To block the formation of ettringite mineral, sodium lignosulphonate was added to the lime column and the problem was solved (Fig 8c) the swelling potentials of treated specimens decreased with the curing period.

Energy Dispersive X-Ray (EDX) analysis was performed to take information about the chemical characterization of specimens during SEM analysis. Table 5 shows the microchemical compositions of test specimens obtained from EDX analysis.

Table 5 - The microchemical compositions of test specimens obtained from EDX analysis

Elements	**Untreated sample US**	LC 180 days curing	NaLS-LC 180 days curing
Al	15.57	18.25	16.91
Si	19.39	25.02	27.59
O	48.68	51.70	45.95
Ca	0.39	1.60	1.81
Na	-	0.25	0.94

Essential elements of the untreated specimen US that is aluminum, silica, and oxygen form the major part of this specimen. The change of percentages of their weight was sought during the stabilization process.

The elements listed in Table 5, which are calcium and sodium, are crucial for this stabilization process. The calcium ion of lime is an identifier element that shows the diffusion of lime particles during the stabilization process. Sodium lignosulphonate was used for the acceleration of diffusion of lime particles. For two stabilization methods, the weight percentages of both sodium ion and calcium ion increase after the 180-day curing period. However, the weight percentages of both calcium ion and sodium ion in the treated specimens with NaLS-LC are greater than in the treated specimens with the lime column, and this output verifies the beneficial effect of the sodium lignosulphonate addition on the acceleration of lime diffusion into the clay.

3.4 The Results of the Methylene Blue Test

The methylene blue value of the samples, taken between the sodium lignosulphonate lime columns, was found to investigate the change of cation exchange capacity and specific surface area of treated expansive clay specimens.

Cation exchange capacity and specific surface area of both untreated specimen US and NaLS-LC treated specimen for 90 days curing are presented in Table 6.

Table 6 - MBV, cation exchange capacity, and specific surface area of untreated expansive soil specimen the US and NaLS lime column treated specimen for 90 days curing

Specimens	Final reading (cc)	Methylene Blue value (g/100g)	Cation exchange capacity (CEC) (meq/100g)	Specific surface Area (SSA) (m^2/g)
Untreated Specimen US	180	6	18.75	146.73
NaLS-LC 90Days	125	4.167	13.02	101.89

Cation exchange capacity and specific surface area are determinant properties of the activity of expansive soils. In this stabilization process, the values of CEC and SSA decrease with the curing period. Therefore, the treated expansive clay specimens with the sodium lignosulphonate lime columns are less active soils than untreated expansive clay specimens.

4. CONCLUSIONS

This study aimed to study the effect of the addition of sodium lignosulphonate to lime columns for the stabilization of expansive clay. The swelling potential and unconfined compressive strength of untreated expansive clay specimen, treated expansive clay specimen with lime columns, and treated expansive clay specimen with sodium lignosulphonate lime columns were measured and compared.

Under 25 kPa surcharge pressure, the swelling potential of NaLS-LC specimens with 180 days of curing was measured as 0.53%. This value is smaller than both untreated expansive clay specimens (29.5%) and the LC-treated expansive clay specimens (9.5%) after 180 days of curing.

The formation of ettringite mineral during the lime column stabilization method occurred after 180 days curing period. To solve this problem, sodium lignosulphonate was added to the lime column and the formation of ettringite mineral was prevented.

The treated expansive clay specimens placed between the sodium lignosulphonate lime columns have higher unconfined compressive strength than untreated expansive clay specimens. The unconfined compressive strength of the treated specimens was measured as 533 kPa after 90 days curing period.

According to the result of the EDX analysis, the amount of both Ca^{+2} and Na^{+1} ions diffused through the expansive clay specimen during the sodium lignosulphonate lime stabilization method.

The treated expansive clay specimens with sodium lignosulphonate lime columns have lower cation exchange capacity and a specific surface area than untreated specimen US.

The swelling percent and unconfined compressive strength of the treated soils improved with the curing period due to the reactions between both the clay–lime and clay-NaLS.

In conclusion, it can be stated that the addition of sodium lignosulphonate to lime columns shows better performance than lime columns for the treatment of expansive clays.

Acknowledgments

The authors would like to express their thankfulness and a deep sense of gratitude to the Department of Civil Engineering, Middle East Technical University for providing the laboratory facilities and equipment to conduct and accomplish this study.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

[1] Masia, M. J., Totoev Y. Z., Kleeman P. W., Modeling Expansive Soil Movements Beneath Structures. Journal of Geotechnical and Geoenvironmental Engineering, 130(6), 572–579, 2004. doi:10.1061/(ASCE)1090-0241(2004)130:6(572)

[2] Parhi, P.S., Garanayak, L., Mahamaya, M., Das, S.K., Stabilization of expansive soil using alkali-activated fly ash based geopolymer. In Advances in Characterization and Analysis of Expansive Soils and Rocks; Hoyos, L., McCartney, J., Eds.; Springer: New York, NY, USA; pp. 36–50, 2017.

[3] Rogers, C. D., Glendinning, S., Improvement of clay soils in situ using lime piles in the UK. Engineering Geology, 47(3), 243–257, 1997.

[4] Goud, G.N., Hyma, A.; Chandra, V.S., Rani, R.S., Expansive soil stabilization with coir waste and lime for flexible pavement subgrade. In Proceedings of the International Conference on Recent Advances in Materials, Mechanical and Civil Engineering, Hyderabad, India, 1–2 June 2017; IOP Publishing: Bristol, UK, 2018; Volume 330, p. 012130.

[5] Shaqour, F, Ismeik, M., Esaifan, M., Alkali activation of natural clay using a $Ca(OH)_2/Na_2CO_3$ alkaline mixture. Clay Minerals, 52(04), 485–496, 2017.

[6] Rajasekaran, G., Narasimha Rao, S., Sulphate attack in lime-treated marine clay. Marine Georesources & Geotechnology, 23(1-2), 93–116, 2005.

[7] Prusinski, J., Bhattacharja, S., Effectiveness of Portland cement and lime in stabilizing clay soils. Transportation Research Record: Journal of the Transportation Research Board, 1652, 215–227, 1999.

[8] Muntohar, A. S., The influence of molding water content and lime content on the strength of stabilized soil with lime and rice husk ash. Civil Engineering Dimension, 7(1), Pp. 1-5, 2005.

[9] Yang D, Qiu X, Zhou M, Lou H, Properties of sodium lignosulfonate as a dispersant of coal water slurry. Energy Conversion and Management, 48(9), 2433–2438, 2007. doi:10.1016/j.enconman.2007.04.00

[10] Ekinci C. E., Ay S., Baykuş N., Ay. A., (2016), Examination of the impact of lignin sulfonate-based structure chemicals on fresh and hardened concrete. Pamukkale Univ Muh Bilim Derg., 22(6): 478-485, 2016.

[11] Alazigha, D P, Indraratna, B, Vinod, J S, Heitor A, Mechanisms of stabilization of expansive soil with lignosulphonate admixture. Transportation Geotechnics, 14 81-92., 2018 //doi.org/10.1016/j.trgeo.2017.11.001

[12] Vinod J S, Indraratna B, Mahamud M A A, Stabilization of an erodible soil using a chemical admixture, Journal of Ground Improvement, Vol. 163: 43 – 51, 2010. //doi.org/10.1680/grim.2010.163.1.43

[13] Vakili A H, Kaedi M, Mokhberi M, Selamat M R, Salimi M, Treatment of highly dispersive clay by lignosulphonate addition and electroosmosis application. Applied Clay Science. 152, 1–8, 2018. //doi.org/10.1016/j.clay.2017.11.039

[14] Indraratna, B., Mahamud, M., Vinod, J.S., and Wijeyakulasuriya, V., Stabilization of an erodible soil using chemical admixtures, in Bouassida, M, Hamdi, E & Said, I (eds), ICGE'10: Proceedings, 2nd International Conference on Geotechnical Engineering: 45-54, 2010.

[15] Tingle, J. S., and Santoni R. L., Stabilization of Clay Soils with Nontraditional Additives. In Transportation Research Record: Journal of the Transportation Research Board, No. 1819, Vol. 2, Transportation Research Board of the National Academies, Washington, D.C., pp. 72–84, 2003.

[16] Chen, Q., and Indraratna, B., Shear behavior of sandy silt treated with lignosulfonate. Canadian Geotechnical Journal, 52(8), 1180–1185, 2015.

[17] ASTM Standard D422, Standard Test Method for Particle-Size Analysis of Soils. ASTM International, West Conshohocken, PA, 2007.

[18] ASTM Standard D4318, Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, 2017.

[19] ASTM Standard D854, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International, West Conshohocken, PA, 2014.

[20] ASTM Standard D4546, Standard Test Methods for One- Dimensional Swell or Collapse of Soils. ASTM International, West Conshohocken, PA, 2014.

[21] Seed, H. B., Woodward, R. J., Jr. and Lundgren, R., Prediction of swelling potential for compacted clays: J. ASCE, Soil Mechanics, and Foundation Division, Vol. 88, No. SM-3, Part 1, pp. 53–87, 1962.

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

[23] NF P 94-068., Soils: Investigation and testing—Measuring of the methylene blue adsorption capacity of a rock soil—Determination of the methylene blue of soil using the stain test. Paris: Association Française de Normalisation, 1998.