

RESEARCH PAPER

Deep Improvement of Fine-Grained Soil Using Lime Piles

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ABSTRACT:

In the present study, the effects of lime piles on the geotechnical properties of fine-grained soil have been investigated in details, where the lime piles are used as sustainable deep improvement technique for the shear strength and compressibility of fine-grain textured soil. The sustainable development required using environmentally friendly materials and of low cost. Soil samples are obtained from the north of Babylon governorate and improved by lime piles, where a small-scale physical model prepared for this purpose. A suitable mesh, diameter, and depth of lime piles are suggested to measure the improvement in shear strength and compressibility of soil. Lime piles are prepared by mixing 15% of lime with dry soil and poured into the holes of 20 mm diameter and 500 mm length, and then lime piles left for 30 days as suggested curing period to allow the chemical reactions between soil and lime compounds. The results of tests detected that lime piles technique has significant effects on the chemical and engineering properties of silty clay soil samples. Also, the deep improvement of the soil causes increasing the undrained shear strength of soil by 23% and increasing the static and dynamic subgrade reaction of soil by 16 and 20% than that of natural soil sample respectively.

KEY WORDS: Lime pile, soil improvement, Geotechnical properties, Clayey soil, Cyclic subgrade reaction.

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1. INTRODUCTION

The lime pile technique is one of the most methods used to improve the geotechnical properties of fine ground soil. It is developed before 3 decades in Europe and Japan and can be considered as sustainable development technique because of using environmentally friendly materials. The major strength gained by lime improved soil is mainly categorized into three reactions known lime hydration, ion exchange, and pozzolanic reactions. In addition, carbonation causes minor strength which increases with increasing of carbonic acid. Carbonic acid is resulted from the reaction of CO₂ of air with H₂O of pores water, or from any organic contaminant existed in the soil mass.

Pozzolanic reactions are essentially cementation (CaSiO₂.2H₂O or CaAlO₃.2H₂O) and carbonation matters (Bergado et al., 1997). Broms (2000) simulated the reduction of soil moisture content is attributed to the slaking of quicklime and evaporation which are resulted in increasing the ground temperature. The decreasing of soil moisture content causes increasing the shear strength and decreasing the compressibility of soil. The increasing of soil strength by cement columns is achieved after 30 days of curing, while the increase of the soil strength by lime piles continues for more than one year (Broms, 1999). Furthermore, the clay fraction and then the clay minerals present in the soil have a significant impact on the undrained shear strength. The required lime content increases with increasing of the specific surface area of the clay minerals such as the montmorillonite.

Bergado et al. (1997) explained the lime behavior during insertion lime piles into the soil layers where the generated heat and expansion of

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the lime will affect the behavior of soil. From the hydration of quicklime or when using calcium hydroxide as stabilizer will lead to increase of the pH value and dissolving of SiO_2 and AlO_3 presented in the clay particles. This process leads to ion exchangeable, flocculation, and pozzolanic reactions. Moseley and Kirsch (2004) concluded that the shear strength of soil is mainly obtained after 28 days of installation of lime piles. The shear strength of improved soil is increased by increasing the curing time due to achieving the soil strength of the long-term after 28 days of mixing. Therefore, the appropriate design of lime piles must be depended on the estimated shearing strength after three months.

In the soil improved by lime piles, the construction load is carried by the lime piles and the surrounding soil between the piles together. Settlement of lime piles and the surrounding soil can be computed according to the analytical approach of the Swedish Geotechnical Society (Carlsten, and Ekstrom, 1997). The settlement of the composite ground is determined by the soil profile into a property of layers, this calculation method is similar to conventional settlement calculation methods which use the average stiffness value of the composite ground. The finite element method is useful for these calculations (Kempfert, 2003).

Ashok and Reddy (2016) studied the effect of the lime pile technique on the properties of clay soil. The lime causes increasing the average of particle size and decreasing the clay content due to flocculation of fine particles. Also, lime piles caused high increase in the plastic limit and slight increase in the liquid limit. In addition, increasing the curing periods of lime piles leads to decreasing of optimum moisture content (OMC) due to increasing the desired water by the clay mineral particles undergoes to hydration reaction. The increasing of soil shear strength with lime (CaO_2) is achieved due to decreasing of soil moisture content by hydration and evaporation during the slaking of lime and ion exchange and pozzolanic reactions.

2. SUSTAINABLE IMPROVEMENT OF SOIL

Soil improvement is often considered to be a sustainable practice as it allows the use and development of inappropriate land. However, the most soil improvement methods involve a wide

range of activities that result in environmental, social and economic impacts. The largest, most obvious impacts (particularly cost and duration) will usually be taken into consideration when selecting an appropriate technology to be used. However, potentially significant impacts can be observed such as dioxide emissions and consumption of raw materials. There are several technologies of soil improvement can be contributed to achieving a sustainable design. In this work, soil improvement of clay soil by using lime piles techniques is described as the main aspect and vital, so the principle of sustainability will be applied to this aspect. Several indicators that will be taken into consideration to reduce the environmental and economic impacts and which are included:

- 1) Use an environmentally friendly material to improve soft soil rather than other alternative techniques.
- 2) Deep soft soil improvement contributes to sustainable development instead of using deep foundation, to reduce the environmental and economic impacts.
- 3) Using materials of low energy like lime leads to reduce carbon emission.
- 4) Using a contaminated site rather than of leaving it and using an alternate site.

The essential factors which control hardening properties of lime-improved soil are the type of lime where the quicklime is more effective than hydrated lime; lime content where the strength increases with increasing of lime content and curing time. Also, the type of soil is an important factor, where the normally consolidated clay is highly affected by improving with lime. For successful lime treatment, the clay fraction should not be less than 20% and the plasticity index should be more than 10%. Pozzolanic reaction and ion exchange are based on the clay mineral, where the clay minerals (kaolinite, illite, and montmorillonite) react with lime to give greater strength. Furthermore, the effectiveness of lime based on the pH value of soil where ion exchange is lowered with $\text{pH} < 7$, and the pozzolanic reaction is increased with $\text{pH} > 7$. The long-term pozzolanic reactions have increased with increasing of pH value of soil, because the reactions are accelerated due to increasing of the solubility of SiO_2 and AlO_3 of soil particles (Bergado et al., 1997).

The activity of pozzolanic reactions increased by increasing the curing temperature, which causes increasing the soil strength. The rising of curing temperature up to 45°C leads to a significant increase in the solubility of SiO₂ and AlO₃ of soil particles and then increasing the pozzolanic reaction (Broms, 1999). Ion exchange and flocculation occurred immediately after some hours of mixing, where the calcium hydroxide is transformed again due to the presence of carbonic acid in the soil block (from the reaction of CO₂ of air with soil porewater). The reaction of lime with clay minerals causes exchangeable ions between calcium Ca⁺² and ions of clay minerals. Consequently, this leads to increasing the electrical surface force of clay minerals, and transformation of soil structure which causes the flocculation and coagulation of clay particles into large spaces. The shear strength increased gradually by pozzolanic reactions due to reactions of calcium hydroxide with SiO₂ and AlO₃ present in clay particles resulting cementing materials or hydrated gel around soil particles such as (gel of calcium silicate hydrates and calcium aluminates). The stability of the pozzolanic reaction depends on the pH value of soil water and soil temperature (Bergado et al., 1996).

3. BEARING CAPACITY OF LIME PILES

Bergado et al. (1997) detected the bearing capacity of the single lime pile is either governed by the surrounding soil strength (soil failure) or by the lime column strength (column failure). In lime piles group, the ultimate bearing capacity is depended on both the shear strength of the surrounding soil (soil failure) and the strength of the lime column (column failure), but failure is governed by the bearing capacity of the block failure or by the local bearing capacity of the block along the edge when the spacing between columns is large. The short-term ultimate bearing capacity of a single column in the clayey soil which depends on the soil failure can be determined by the following equation:

$$Q_{ult,soil} = (\pi dH + 2.25\pi d^2) c_u \quad (1)$$

where H and d are the length and diameter of the lime pile, and c_u is the undrained shear strength of the surrounding soil. The short-term ultimate bearing capacity of single lime pile which depends

on the column failure can be determined by the following equation:

$$Q_{ult,col.} = A_{col.} (3.5 c_{col.} + 3\sigma_h) \quad (2)$$

where A_{col.} and c_{col.} are the surface area and the cohesion of the lime pile, and σ_h is the horizontal stress acting on the lime column. The ultimate capacity of long-term is less than the short term by 65-85% due to creep of the column. The ultimate capacity of the lime piles group associated with the block failure is:

$$Q_{ult,g} = 2 c_u H(B + L) + (6 \text{ to } 9)c_u BL \quad (3)$$

where B, L, and H are the width, length, and height of block failure of composite soil. The factor 6 is used for rectangular foundation L>B but factor 9 is used for the square foundation. The ultimate capacity of the lime piles group associated with local failure along the lime pile shaft is:

$$q_{ulti.} = 5.5 c_{av.} (1 + 0.2 \frac{b}{l}) \quad (4)$$

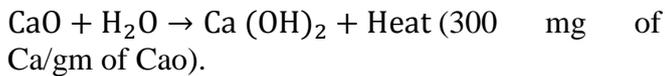
where b and l are the width and the length of locally loaded area, and c_{av.} is the average shear strength of improved area which affected by the relative area of the lime column.

4. SOIL SAMPLING AND MATERIALS

The soil specimens are obtained from the north of Babylon governorate (UTM: 33N515276, 44E28102). The disturbed and undisturbed intact soil specimens are obtained from 4 m below the ground surface. The water table encountered 2.5 to 3 m below the existing ground surface. An open pit of 10 m length and 5 m width was drilled at the site to get the soil samples. Then, the disturbed soil samples are placed in tight plastic containers and labeled, and transported to the laboratory to be used in the physical and chemical tests of the soil. The undisturbed soil samples extracted by Shelby tubes covered with wax and labeled to be used in testing the mechanical properties of soil samples.

The field unit weight is 19.3 kN/m³ (ASTM D2937-00) and the natural water content is 32% (ASTM D2216). Lime is a binder and transformed

into calcium hydroxide after mixing with water, and later is reacted with SiO_2 and AlO_3 existed in soil particles to produce hydrated silicate gel and hydrated aluminates gel. Those cementation gels lead to cover the clay particles and cementation the particles into close up together, which causes increasing the cohesion of lime-soil mixture (Bergado et al., 1997).



5. LABORATORY WORK

In a present study, the impacts of soil improvement on geotechnical soil properties are investigated. The designations of tested soil samples are natural soil sample (Co) and improved soil sample C1o. Also, the remolded natural soil samples Cro to investigate the sensitivity of clay on the geotechnical properties of soil.

5.1. Deep Improvement Using Lime Piles

Deep soil mixing technique is used to install the lime piles by mixing the hardening binder of lime with the surrounding soil. Lime pile mechanism characterized by dry mixing and wet mixing. The dry mixing method involves the penetration of the hand auger to the required depth and then injection of the dry lime binder into the soft soil using compressed air. The dry lime is then mixed with the surrounding soil. In the dry method, no water is added therefore the natural moisture content soil should be at least 20%. The wet mixing method involves adding lime slurry to the soil mechanically, the mixing of lime slurry with the surrounding soil is easier than dry mixing method, especially when the soil moisture content is low and the initial shear strength of the soil is high (Kempfert, 2003).

Lime piles are used in the present study to increase the stability and strength of soil. Also, lime piles used to improve of clay soil samples. Soil samples firstly remolded in the container of physical model by tamping process according to the field unit weight and natural water content. Then holes are bored of 20 mm diameter (d) and spacing ratio 3d with depth 500 mm as shown in Figure 1. Lime is mixed with 15% of dry soil have been poured into the holes and mixed to ensure filling. Then, soil treated with lime piles left for

30 days for curing. The soil container was covered with two layers of polyethylene sheet and 10 cm of saturated sand to keep the moisture content of the soil and reduce the slaking and hydration reactions.



Figure 1: Lime pile installation process.

5.2. Chemical Tests

In the present study, the following chemical properties of soil samples are tested to measure the impacts of lime piles on the chemical composition of soil samples. The chemical properties tested according to ASTM (2003) are SO_3 (ASTM D516), SO_4 (ASTM D516), gypsum, Ca^{+2} (ASTM D511), Cl^{-1} (ASTM D512 A), pH value (ASTM D4972), TPH (atomic absorption spectrometer, AAS), TDS ASTM (D5907), Ec (ASTM D1125), CaCO_3 (ASTM D4373), and Mg^{+1} (ASTM D511).

5.3. Physical Tests

Routine soil tests were carried out to characterize the physical properties of soil. The tests are the particle size distribution (ASTM D422), specific gravity (BS:1377, 1976, Test 6B), Atterberg's limits (ASTM D4318), and standard Proctor compaction test (ASTM D698).

5.4. Mechanical Tests Results

The tests included determining the shear strength parameters, modulus of elasticity, the coefficient of consolidation, and modulus of subgrade reaction. Two types of soil samples, undisturbed and remolded are used to investigate the compressibility characteristics of the natural soil, while remolded soil samples used to measure these characteristics of improved soil samples by

an oedometer test according to ASTM (D2435). The shear strength of soil samples is measured by conducting unconfined compression test (UCT, ASTM D2166), direct shear test (DST, ASTM D3080), and unconsolidated undrained tests (UUT, ASTM D2850) on undisturbed and remolded soil samples before and after the improvement.

A comparison between static and cyclic modulus of subgrade reaction (K_s) due to deep improvement impacts are investigated by conducting static and cyclic plate loading tests. The tests are performed in a steel cube box of side 700 mm. The rigidity of steel box has been guaranteed by using rigid steel plates of 4 mm thickness. The loading is applied on a square steel plate of dimensions 125×125×10 mm. In the present study, K_s is determined according to ASTM (D1196). For verification the modulus of subgrade soil reaction under repeated loading test conditions (loading, unloading, reloading schedule) as per standard practice (Rao, 2011). Repeated loads are induced on plates with two cycles per second and number of cycles that applied at each load is equal to five hundred cycles to investigate the behavior of soil under cyclic loads. The model of cyclic plate loading test is shown in Figure 2.



Figure 2: Cyclic plate loading model.

6. RESULTS AND DISCUSSION

The results of chemical tests are given in Table 1. The pH values of the improved soil

specimen (CIo) increased slightly than that of Co, because lime is considered an alkaline medium. Three sulfate ions (SO_3), gypsum, four sulfate ions (SO_4), and chloride content (Cl^{-1}) are increased rapidly in the improved soil sample (CIo). This increase may be attributed to the chemical composition of lime which involves these compounds. The content of total hydrocarbon increased slightly in the soil sample CIo, where the chemical reactions of lime will produce carbonic acid resulted from the reaction of CO_2 of air and H_2O of pores water as an assistance factor in its reaction. The content of calcium carbonate ($CaCO_3$), calcium ion (Ca^{+2}), and magnesium ion (Mg^{+1}) increased in improved soil CIo because lime has high concentrations of calcium carbonate. Finally, the electrical conductivity (Ec) and total dissolved salts (TDS) are highly increased in the improved soil sample due to the low value of salts in natural soil while the high content of salts such as sulfate compounds, chloride ions, calcium ion, and magnesium ion in lime.

Table (1) Chemical analysis of soil samples.

Compound/Property	Soil Sample	
	Co	CIo
SO_3 (%)	0.1015	1.37
SO_4 (%)	0.065	0.70
Gypsum (%)	0.21	2.95
Ca^{+2} (ppm)	680	820
Cl^{-1} (%)	0.07	0.10
pH value	7.2	7.42
Total Hydrocarbon (%)	0.095	0.732
TDS (ppm)	3742	200000
Ec (ms/cm)	8.730	800
$CaCO_3$ (ppm)	1700	2050
Mg^{+1} (ppm)	413	498

The impacts of deep soil improvement on the physical properties of soil are presented in terms of different physical indexes of soil. The results of physical properties of soil samples are given in Table 2. In addition, the particle size distribution curves and compaction test results are given in Figures 3 and 4.

Table (2) Results of Atterberg's limits and specific gravity.

Soil sample	LL %	PL %	PI %	Gs	$\gamma_{d,max}$ kN/m^3	ω_{opt} %
Co	53	23	30	2.72	17	20
CIo	55	30	25	2.7	17.5	18

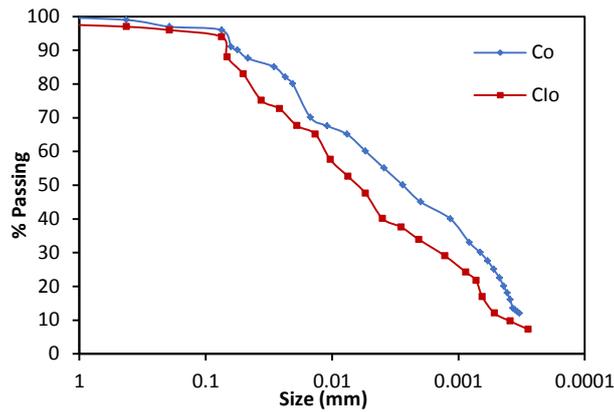


Figure 3: Particle size distribution curves.

The results of particle size distribution tests showed that the percentage of particles of size less than 0.005 mm in intact soil is 55%, but in the improved soil sample (Clo) is 40%, due to the flocculation of clay particles with lime, so the clay fraction is reduced. Also, the particle size of insoluble salts found within lime compounds are greater than that in the clay particles, therefore the soil condenses more quickly in a hydrometer test. Atterberg's limits are increased in the soil sample improved with lime piles. The plastic limit increased significantly due to cation exchange capacity (CEC). The cation exchange capacity led to abundant cations around clay particles, so it needs more water to obtain plastic properties while increasing of liquid limit is generally less than that of plastic limit. The non-absorbed water by clay minerals moved into the free water, and the quantity of this water is small, so increasing the liquid limit value is small.

In soil sample improved with lime piles, the specific gravity decreased slightly, because the lime has less density than that of soil. Also, the maximum dry unit weight is increased and the optimum water content is decreased. The reduction of soil moisture content is caused by evaporation and rising of soil temperature resulted from the chemical reactions between the lime and soil and dehydration affects the maximum dry unit weight. The second reason of decreasing the optimum water content is attributed to increasing demand for water cations and the clay mineral particles undergo to hydration reaction (Ashok and Reddy, 2016, Karkush et al., 2018). The dehydration, agglomeration, and flocculation of the clay particles led to an increase in the maximum dry unit weight as shown in Figure 4.

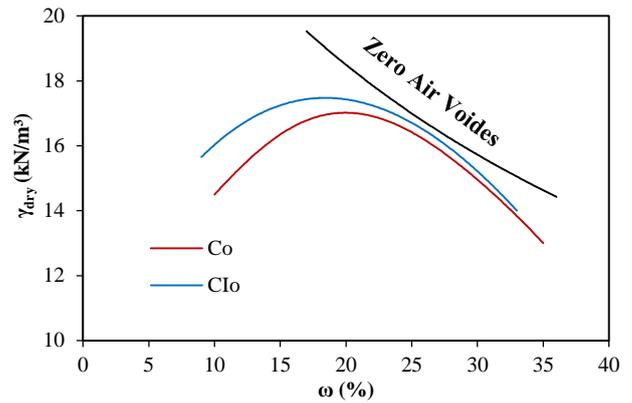


Figure 4: Results of standard Proctor tests.

From the results of oedometer tests, it's observed that the coefficient of consolidation (c_v) increased by 5%, the coefficient of permeability (k) increased by 13%, the compression index increased by 3%, but the constrained modulus (D) decreased by 6% for remolded soil sample (Cro) than that of natural undisturbed soil sample Co. This increase in the compressibility indexes is attributed to the loss of strength resulting from the destruction of molecular attraction forces between the clay particles which depends on the sensitivity of clay. In soil sample improved with lime piles, the coefficient of consolidation, the permeability, and compression index decreased by 16, 40, and 8% respectively than that of Co. Also, the constrained modulus (D) increased by 6% compared with the soil sample (Co). The lime will be flocculated the clay particles and causes a good compacted state of the soil. The permeability of the soil improved with lime has been as low as 1.4 times the permeability of the sample Co; this result is compatible with the result obtained by Ahnberg *et al.* (1994). The summary of oedometer test results is given in Table 3 and Figure 5.

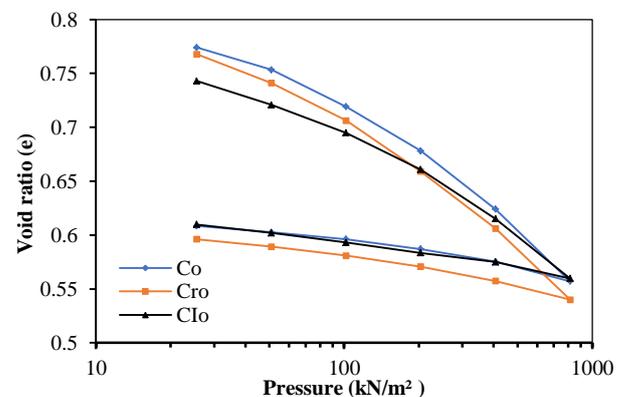


Figure 5: Results of 1-D consolidation tests.

Table (3) Results of 1-D consolidation tests.

Soil Sample	$c_v \times 10^{-3}$ cm ² /sec	$k \times 10^{-9}$ cm /sec	e_o	e_f	Cc	Cs	D MPa
Co	1.31	6.08	0.8	0.61	0.145	0.034	21.02
Cro	1.38	6.92	0.8	0.6	0.149	0.035	19.54
CIo	1.11	4.3	0.81	0.65	0.134	0.033	25.47

The results unconfined compression test (UCT) and unconsolidated undrained test (UUT) showed that the undrained shear strength and the modulus of elasticity of remolded soil sample (Cro) are decreased by 7-8% than that of the undisturbed soil sample because of the soil disturbance that leads to the destruction of soil structure. The sensitivity of soil is about 1.075 and the soil sample can be classified as slightly or low sensitive clays (Skempton and Northey, 1952; Rosenqvist, 1953). A significant regain of strength occurred with elapsed time, where regain of soil strength in long-term phenomena depends on the sensitivity of clay. Consequently, the strength will usually increase because of the thixotropic regain of undrained shear strength as structural bonds destroyed by remolding. Improvement of soil by lime piles causes increasing the shear strength and modulus of elasticity of soil which may be attributed to the decreasing of soil moisture content by slaking and dehydration and partly by a reduction of plasticity index. Therefore; lime can play an important role to obtain certain shear strength with increasing of the specific surface area of clay minerals.

The results of DST indicated decreasing the shear strength of remolded soil sample (Cro) by 6 % and the angle of internal friction by 9% than that of the undisturbed soil sample due to soil disturbance and destruction of structural bonds by remolding of soil sample, while the cohesion and angle of internal friction of improved soil sample (CIo) increased by 14 and 5% respectively due to decreasing the moisture content by lime slaking and dehydration. Also, the soil-lime reactions produced cementation compounds such as calcium silicate gel which lead to increase the strength of soil. The agglomeration and flocculation of the clay particles make it come into a closer packing and then increasing the friction between particles. Thus, soil strength will usually increase due to the thixotropic regain of undrained shear strength as structural bonds destroy by remolding (Poulos and Davis, 1980). The results of UCT, DST, and UUT are given in

Table 5. Also, the variations of stress with an axial strain of tested soil samples are given in Figures 6 and 7.

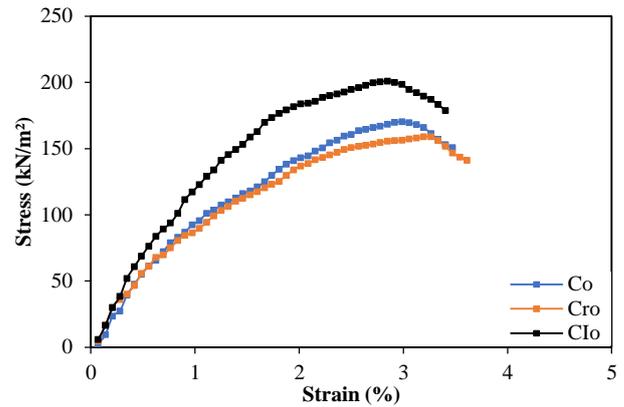
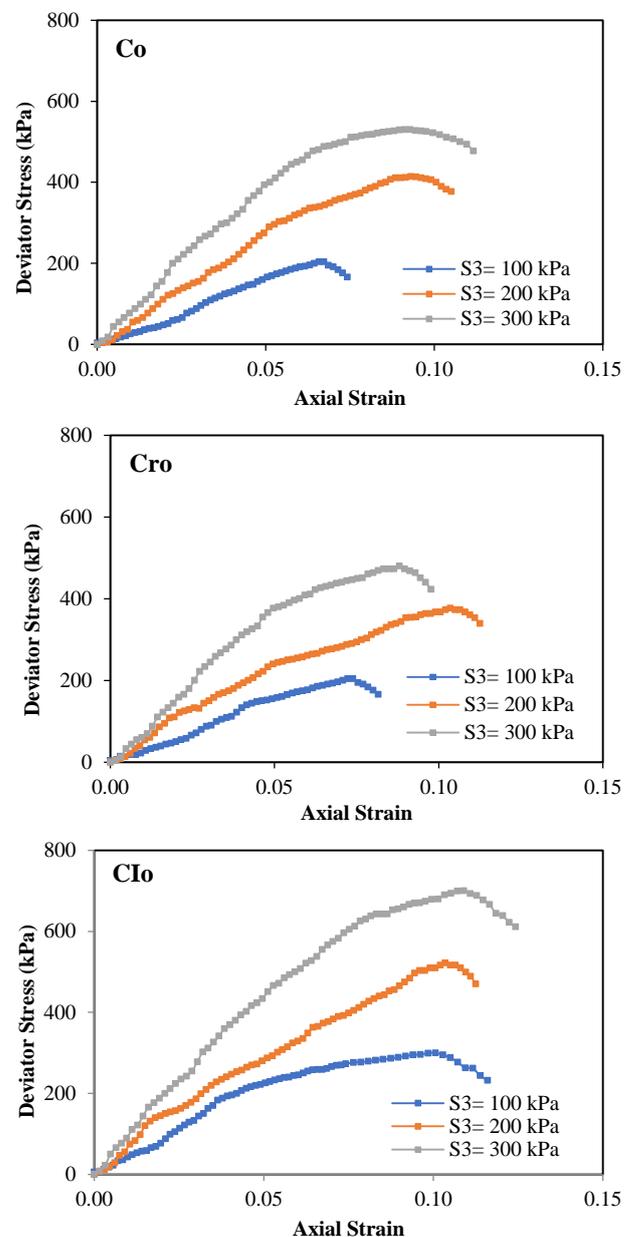
**Figure 6:** Stress versus axial strain from UCT.**Figure 7:** Stress versus axial strain from UUT.

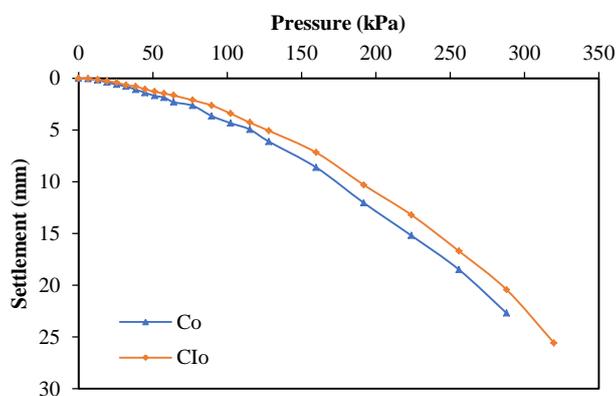
Table (5) Results of shear strength tests.

Soil Sample	UCT		DST		UUT	
	c_u kPa	E MPa	c_u kPa	ϕ degree	c_u kPa	E_{50} MPa
Co	85	12	74	22	102	6.0
Cro	79	11	70	20	94	5.6
CIo	105	12.0	84	23	130	7.5

The results of the plate loading test indicated increasing the modulus of subgrade reaction $K_{s_{static}}$ and $K_{s_{dynamic}}$ of soil samples (CIo) by 16 and 20% respectively in comparison with soil sample Co due to increasing the strength of soil and decreasing the compressibility of soil resulted from the reactions of lime which produce cementation matter among the soil particles. Thus, the microfabric of soil will be changed to allow the water-insoluble gel of calcium silicate coating the soil particles, which bring the soil particles closer together. Consequently, the stability of soil structure has resulted due to increasing the stiffness of the soil sample, as well as a modulus of subgrade reaction. In addition, the reaction of lime hydroxide with soil silicate and aluminates to produce a cementation substance around the soil particle consequently increases the soil strength and stiffness. The static and cyclic modulus of subgrade reaction resulted from loading a square plate of 125 mm side are listed in Table 6. The results of the static plate loading test are given in Figure 8.

Table (6) Results of static and cyclic plate loading test.

Soil Sample	$K_{s_{static}}$	$K_{s_{dynamic}}$	% Reduction
	MN/m ³	MN/m ³	$K_{s_{dynamic}}/K_{s_{static}}$
Co	34.40	25.25	73
CIo	39.750	30.3	76

**Figure 8:** Results of the static plate loading test.

7. CONCLUSIONS

Lime piles are considered a newly developed application for deep improvement of fine grain textured soils. Lime piles are mainly used for increasing the strength and stability of soil which is significantly affected by the chemical reactions between lime and minerals of soil and confinement of soil provided by lime piles. The conclusion drawn from this study can be summarized as follows:

- 1) The pH value, three sulfate ions (SO_3), gypsum, four sulfate ions (SO_4), chloride content; calcium carbonate ($CaCO_3$), calcium ion (Ca^{+2}) and TDS are increased slightly in improved soil (CIo) as compared with Co.
- 2) PL and LL are increased in the improved soil, but increasing of PL is more than that of LL. In addition, the specific gravity and optimum water content decrease in stabilized soil by lime piles, but the maximum unit weight is increased in CIo.
- 3) The compressibility and permeability are decreased in the improved soil sample since lime will be flocculated clay particles and causes good compaction. In addition, the constrained modulus (D) increased by 6% in the improved soil samples.
- 4) The undrained shear strength and the modulus of elasticity of remolded soil sample (Cro) decreased by 7% due to disturbance of the soil sample, where the soil sample classified as slightly sensitive.
- 5) The undrained shear strength and modulus of elasticity of the improved soil sample (CIo) are increased by 23 and 27% respectively in comparison with the natural soil sample (Co).
- 6) The direct shear test proved that the undrained shear strength and angle of internal friction have been increased significantly in soil samples improved by using lime piles.
- 7) Deep improvement of the soil leads to increasing the static and dynamic subgrade reaction of soil by 16 and 20% than that of natural soil sample respectively.
- 8) The cyclic modulus of subgrade reaction is less than the static modulus of subgrade reaction, due to the response of soil to cyclic loading.

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Conflict of Interest

This paper is a part of Ph.D. thesis conducted at the Department of Civil Engineering/University of Baghdad to deep improvement the geotechnical properties of cohesive soil by using lime piles and subjected to static. The project funded by the authors.

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