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Relatively Large-Scale Experimental Study on Behavior of Compacted Lime Mortar (CLM) Columns: Influence of Moisture Content

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ABSTRACT: Various materials have been utilized for ground improvement techniques based on geoenvironmental compatibility. The application of lime mortar in soil has been catching the attention of researchers and engineers. However, there is a lack of research on the variation of moisture content in soil affecting the mechanical behavior of lime mortar. In this study, large-scale laboratory tests were conducted on approximately thirty specimens to evaluate the size effect on stiffness and load bearing capacity of compacted lime mortar (CLM) columns and clayey soil under different saturation conditions. In addition, approximately forty small-scale laboratory tests were carried out on dry clay, dry CLM column and lime mortar specimens to evaluate the unconfined compressive strength (UCS). According to results, UCS of CLM column under small-scale condition was higher than that of the large-scale. Moreover, high moisture content had a significant influence on the stiffness of improved ground and the bearing capacity of CLM columns. Finally, validation of results indicated that numerical model predictions are in agreement with experimental results.

Keywords: Bearing Capacity, Lime Mortar, Soft Soil, Stone Column, Unconfined Compressive Strength.

INTRODUCTION

Stone columns are extensively used for ground improvement in order to improve the strength and stiffness characteristics in-situ and decrease shallow foundation settlement. Stone columns are constructed by replacing the poor soils with a compacted sand or gravel. This concept was proposed by Hughes and Withers (1974), Priebe (1976), Baumann and Bauer (1974) and Aboshi et al. (1979) and they consider different failure modes for stone column under compressive loads, such as bulging, general shear failure and sliding. Bulging failure is more likely to be associated with using the stone column in soft soil due

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to insufficient lateral confinement. The deep mixing method is a process of mixing stabilizer into the ground with mixing tools. This method included the cement-soil column and lime mortar column for improving lateral confinement of soft soil.

Many of the researchers have investigated the influence of the cement-soil column on the behavior of improved ground (Horpibulsuk et al., 2011; Farouk et al., 2013; Yapage et al., 2014). The main advantage of using cement column in soil is its high shear strength and stabilization of organic soil (Broms et al., 1999). The cement-soil columns constructed by replacement of existing soil by cement-soil mixture. There are several methods for in situ construction of cement-soil columns, such as methods of slurry double mixing, dry and wet jet mixing (Chai et al., 2005). The effect of cement-soil mixing on the engineering properties of soil related to water/cement ratio, mixing speed and installation method (Horpibulsuk et al., 2011; Mousavi and Wong, 2016). Utilizing another chemical admixture is a significant concept with respect to some problems of incompatibility of cement soil such as low permeability, rigidity, susceptible to frost and causing greenhouse effect (Romeo et al., 2011; Sukontasukkul and Jamsawang, 2012).

Lime is older than other chemical stabilizer employed in soil stabilization (Mallela et al., 2004). The lime-soil chemical reaction induced short-term and long-term treatment (Nalbantoglu and Gucbilmez, 2002; Abdi and Parsa Pajouh, 2009). By adding lime to the soil, the plasticity and moisture of soil decreased immediately and shear strength, durability and compressibility of the soil increased after long-term treatment (Wilkinson et al., 2004; Tang et al., 2011; Harichane et al., 2011; Dash and Hussain, 2011). The effective soil-lime treatment depended on lime content, curing time and temperature and soil mineralogy (Mitchell and Hooper, 1961; Farzaneh and Mosadegh, 2011; Jawad et al., 2014; Di Sante et al., 2014; Jha and Sivapullaiah, 2016). The behavior of using the lime column in clayey soil investigated by many researchers through experimental tests (Broms et al., 1999; Larsson et al., 2009; Al-Naqshabandy et al., 2012; Chong and Kassim, 2014). Abiodun and Nalbantoglu (2014) recommended the electrical conductivity test for monitoring lime diffusion in lime column through field application. Several studies have been reported on the application of mixing lime and well-graded soil (lime mortar) in soft soils by compaction. The strength of compacted lime mortar (CLM) column is related to the lime mortar homogeneity ratio and lime-clay chemical reaction (Malekpoor and Toufigh, 2010). Malekpoor and Toufigh (2010) performed series small-scale laboratory tests on CLM columns under soaking condition. The results demonstrated that: i) the strength of CLM columns depended on water content and ii) the strength of soft clay soils increased by using 20% lime and 22% clay in CLM columns. Malekpoor and Poorebrahim (2014) presented the large-scale laboratory tests and numerical analysis to evaluate the effect of different diameter, slenderness ratio, area ratio and the shear strength of the surrounding soil on the behavior of CLM columns. They observed a significant decrease in load bearing capacity by increasing the size of specimens.

There have been few studies of the effect of soil moisture content on the behavior of lime mortar in CLM columns. The CLM column has been physically modeled as floating column in the present study. The general objective of this research was investigating the behavior of large-scale CLM columns under different moisture condition. To achieve an appropriate lime mortar, the basic properties of soil was determined and the effect of different parameters such as lime content, curing time and temperature on strength of lime were evaluated. In addition, the laboratory tests were performed to evaluate the stiffness and load bearing capacity of small and large-scale specimens (clayey and CLM column). Then, the effect of using CLM column on the ground was determined by employing a different loading mechanism. Moreover, the friction and continuity of clay-lime mortar column interface were investigated under saturated condition. Finally, numerical analyses performed to validate experimental results under dry and saturated condition.

MATERIALS AND METHODS

Experimental Program

The experimental setup consists of two parts: preliminary tests and main tests as illustrated in Figure 1. The preliminary tests were divided into two test groups to determine: 1) the physical properties of the soil material according to ASTM standards and 2) the optimum percentage of clay, mortar and water for making lime mortar. The main tests were separated into two test groups. The first test group was determined the bearing capacity and stiffness of three types of large-scale specimens under dry, partially saturated and saturated condition for evaluating the effect of moisture on the behavior of improved ground compared with clay and CLM column. The dimensions of these specimens were 25 cm in diameter and 50 cm in height. The second test group was included as three types of small-scale specimens. The clay and CLM column specimens were tested under dry condition. The objective of using small-scale specimens was to characterize: 1) the effect of specimen size on compressive strength of clay and CLM column under dry condition and 2) the influence of lime content, curing time and curing temperature on the compressive strength of lime mortar. The dimensions of small-scale specimens are 10 cm in diameter and 20 cm in height.

In this study, the laboratory apparatus was simplified based on unit cell concept for evaluation of an interior column behavior in a large group of columns. The interior column with its tributary soil around it in an infinitely large group was considered as a unit cell.

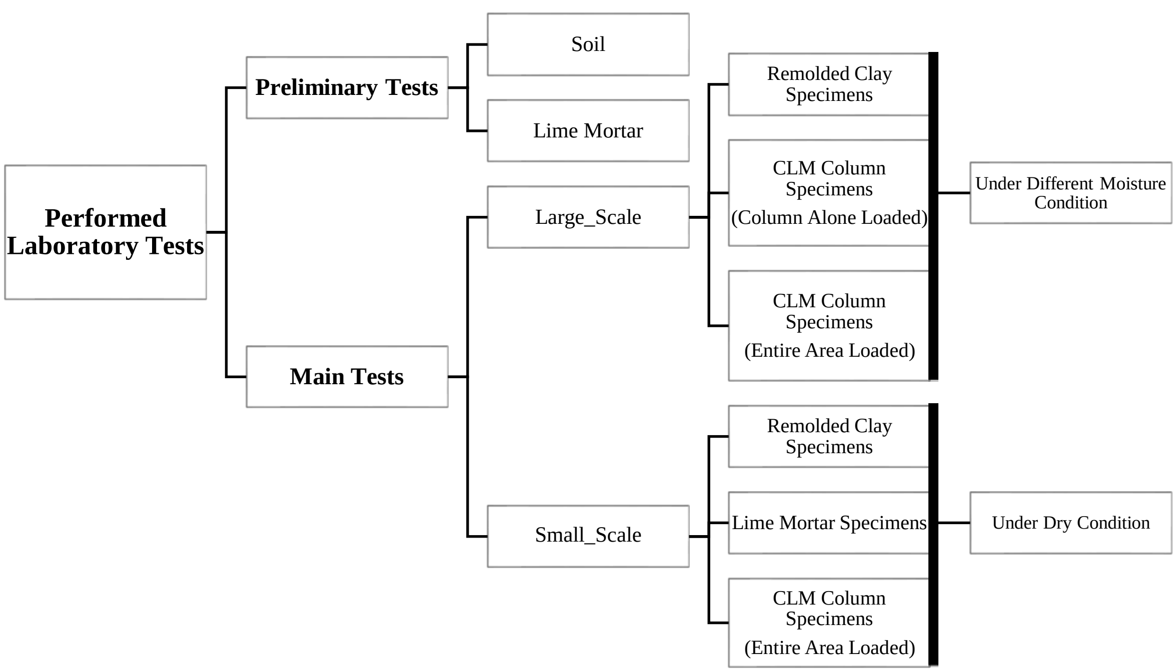


Fig. 1. Overview of performed laboratory tests

In this concept, a uniform loading applied on top of the columns simultaneously and the behavior of soil around a column was depending on column spacing (Indraratna et al., 2012; Ng and Tan, 2015). Since the lateral deformations of soil across the boundaries of the unit cell were assumed to approach zero (Barksdale and Bachus, 1983), the boundary of the unit cell can be simulated in the laboratory by using a rigid exterior wall around the column. The columns were assumed in a triangular pattern and the diameter of the equivalent unit cell (using circular tributary area instead of hexagon tributary area) was obtained from Eq. (1).

$$D_C = 1.05S \tag{1}$$

where *S*: is the spacing between columns and *Dc*: is the diameter of the equivalent unit cell (Balaam and Booker, 1981). The space between columns was 250 cm in the field and 25 cm (scale 1:10) in the laboratory. The area ratio was derived as the stone column area divided by the area being improved by the column. Since the stiffness of CLM column was higher than the typical stone column, the area ratio was considered constant and equal to 16%, in this study. Therefore, the diameter of the unit cell and lime mortar was 25 cm and 10 cm, respectively.

The dry specimens were kept in the oven for 7 days at 45 ºC and partially saturated specimens were prepared by adding moisture for simulation of field soil. The capillary behavior of clay was used for saturating the specimens. Thus, the mold was perforated in the range of 17 cm (about one-third of pipe length) from the bottom with a diameter of 0.4 cm. The specimens were floated in the water container (about 20 cm) for 5 days as shown in Figures 2 and 3. The partially saturated and saturated specimens were kept in plastic to prevent moisture loss for testing.

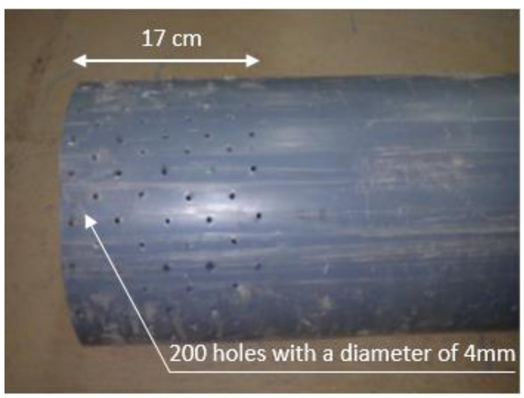


Fig. 2. Perforated polyethylene pipe

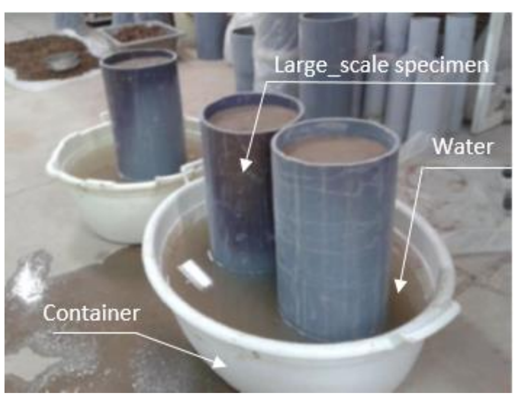


Fig. 3. Capillary process for saturating the specimens

Materials Properties

Soil

In this study, the lean clay was collected from Kerman city in Kerman province, Iran. The physical properties of lean clay are given in Table 1. The specific gravity of the soil (Gs), liquid limit (LL), plastic limit (PL), moisture content (ω) and dry unit weight of the soil (γ_d) were determined based on ASTM C127-15, ASTM D4318-17, ASTM D2216-10 and ASTM D7263-09.

Lime Mortar

The optimum percentage of clay, mortar and water for making lime mortar was 22% of the weight of well-graded soil, 20% of total weight of soil and 35% of the weight of soil and lime together, respectively. The grain size distribution of well-graded soil is shown in Figure 4. As can be seen, the soil chosen is classified as well graded sand (SW), according to the unified soil classification system (ASTM D422-63). Since the existing soil had 5% of clay, 17% clay was added to the well-graded sand. The hydrated lime which was passed through the sieve (#40) has been used in this study.

Specimen Preparation

Lime Specimens

The inner surface of mold wall was covered with a thin coat of grease for ease of removal of lime mortar from the mold after curing for 3 days. The lime mortar was poured into the mold and kept in laboratory For estimating the optimum curing time, more than 15 specimens were prepared and cured for 28, 48, 60, 78 and 120 days at 15 ºC. To study the effect of curing temperature on the compressive strength of lime mortar, three specimens were made and cured in an oven for 7 days at 45 ºC. In addition, 15 specimens were fabricated for different percentages of hydrated lime content (5%, 10%, 15% and 20%) to study the effect of lime content on compressive strength of lime mortar.

Clay Specimens

For separating the hunks of fine and coarse particles, the clay was passed through a 0.85 mm sieve (#20). The clay was compacted to reach a density of 1747.2 kg/m^3 in ten-layer of 5 cm thick with 16.5% water content to simulate the field soil. The clay water content was determined and calculated for moisture adding amounts on each layer. More than 9 large-scale and 9 small-scale specimens were prepared and compacted in the laboratory using standard Proctor method according to ASTM D698-12.

CLM Column Specimens

Similar to clay specimens, CLM column specimens were prepared in two different sizes. Here, eighteen large-scale CLM column specimens were made using the lime mortar with the diameter of 10 cm and height of 40 cm at the center of clay. The height of stone column was selected with regard to "float" columns. The punching failure occurred at floating pile tip in soft soils. The critical radial distance from the circumstance of the pile in order to avoid a punching failure was about 1.5 times of pile diameter (Meyerhof and Sastry, 1978). Since the stiffness of pile is higher than the stone column, the critical distance was assumed to be approximately equal to stone column diameter. In this study, the thickness of the soil beneath the CLM column was chosen to be 10 cm for the large-scale specimens and 4 cm for the small-scale specimens. Here, ten-layer of 5 cm thick clay was compacted with natural moisture content and field density. For replacing the soil with lime mortar column, a hole was placed in the central part with a pipe as illustrated in Figure 5a and 5b. Then, the pipe was removed at the end of the soil compaction and the lime mortar was placed (Figure 5c). In addition, four small-scale CLM column specimens were prepared by using the lime mortar with the diameter of 4 cm and height of 16 cm at the center of clay under dry condition.

Test Procedure

The Universal Testing Machine (UTM) and unconfined compression tests were employed for large and small-scale specimens, respectively. For small-scale specimens, the failure load was applied to the total area section of the specimen. Two mechanisms were conducted for loading the large-scale CLM column specimens after making and curing processes. The first mechanism was based on applying vertical load only on CLM column using a rigid steel piston with a diameter of 10 cm and height of 5 cm (Figure 6a). Settlements and loads were monitored at regular displacement intervals up to failure by universal test machine.

Table 1. Soil properties

	Gs	**LL**	**PL**	**ω (%)**	$\gamma_d \left(\frac{kN}{m^3}\right)$
Lean Clay	2.72	30.60	22.59	16.5	17.14

Note: Gs, specific gravity; LL, liquid limit; PL, plastic limit; ω(%), moisture content; γ_d, dry unit weight.

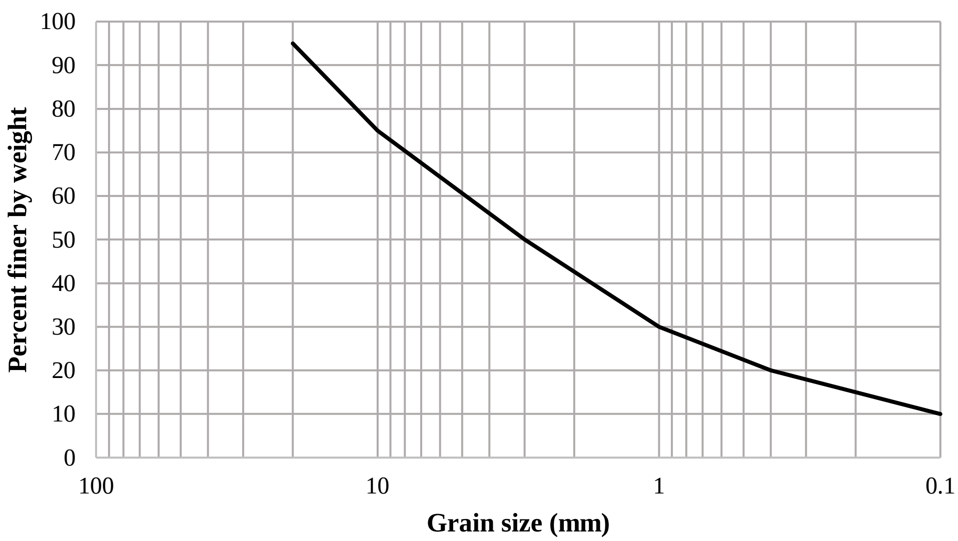


Fig. 4. Grain size distribution of well-graded sand

(a) Compacted soil layer and pipe on the second layer

(b) Removing pipe after completing the soil compaction

(c) Placing lime mortar in the central part of the mold

Fig. 5. Preparing CLM column specimens

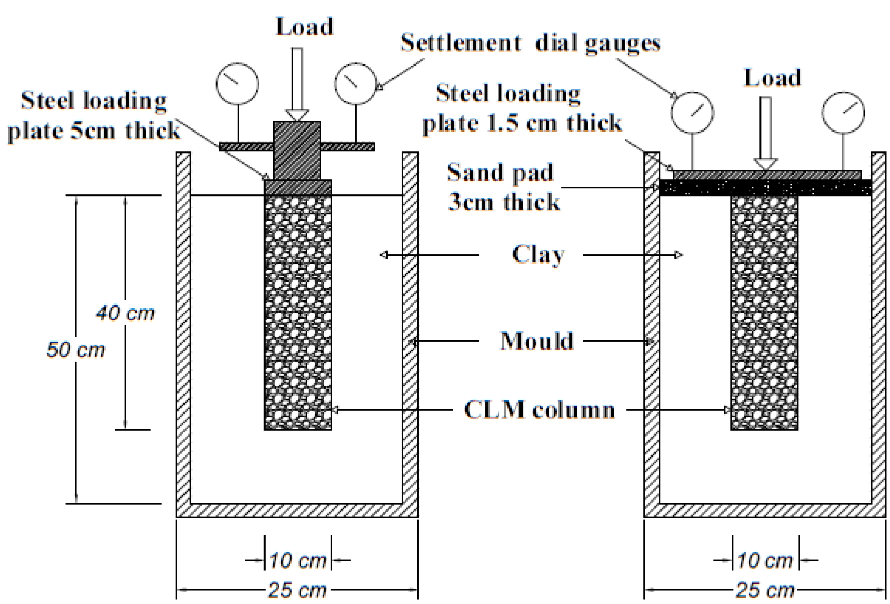
The specimens were loaded under displacement control (cross-head speed, 0.5 mm/min) for measuring the load-displacement behavior of CLM columns. For the second mechanism, a 3 cm thick sand pad placed on top of the specimens and the load was applied through a 1.5 cm thick steel plate with a diameter of 24 cm (Figure 6b). The well-graded sand with aggregates varying from 4.7 to 0.075 mm particles size and relative density of 70% was used to form the sand pad. This mechanism was conducted to observe the load-deformation behavior of the improved ground. Note, nine of the total large-scale CLM column specimens were tested using the second mechanism.

RESULTS AND DISCUSSION

Lime Specimens

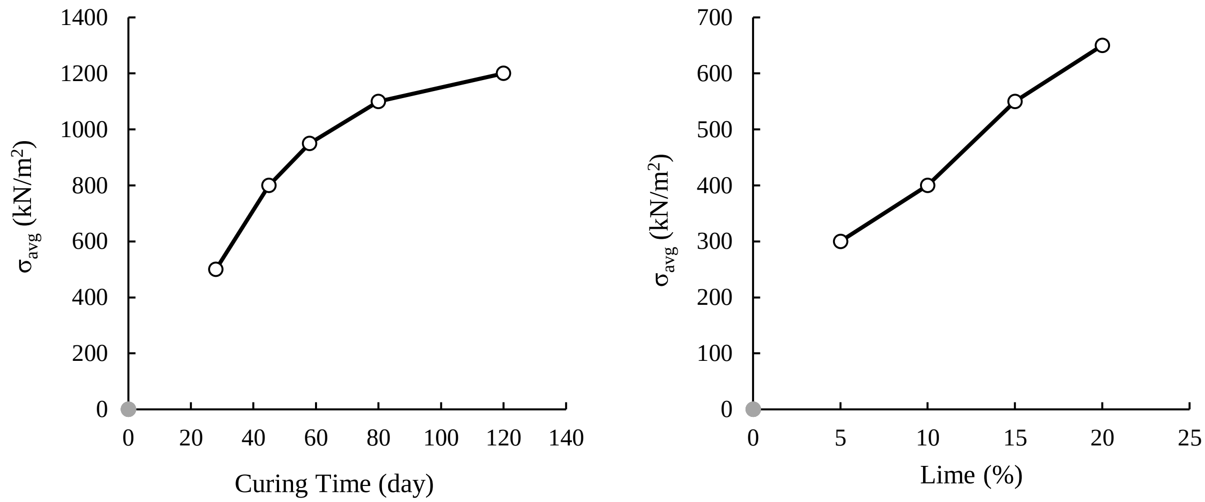
Unconfined compressive strength values of the lime mortar specimens versus the curing time are shown in Figure 7a. The strength of lime mortar increased rapidly at curing for 30 to 78 days and after curing for 78 days, the rate of increase in compressive strength reduced. This phenomenon caused by chemical reactions between clay and lime mortar with respect to the pozzolanic reaction, flocculation agglomeration and lime carbonation. Also, the activation energy was reduced by decreasing the hydration process. Therefore, 90 days compressive strength of the lime mortar was approximately equal to its ultimate strength.

As illustrated in Figure 7b, for 22% clay, the strength ratio of lime was increased by adding lime content; however, using lime content more than 20% was not economical. The influence of temperature on curing time was also investigated in this study. The strength of lime mortar increased by increasing temperature as illustrated in figure 8.This could arise because the acceleration of lime soil reactions and pozzolanic activity increased due to the higher curing temperature. The compressive strength of lime mortar which is kept in an oven at 45 ºC for 7 days was approximately equal to the compressive strength after 28 days at 15 ºC. According to this figure, the 28 days strength of lime mortar was almost equal to half of the ultimate lime mortar strength.



(a) CLM column Specimen (Column alone loaded) **(b)** CLM column specimen (Entire area loaded)

Fig. 6. Test arrangement of large-scale CLM column specimens



a) Relationship between compressive strength of lime mortar and curing time

b) Relationship between compressive strength of lime mortar and lime content

Fig. 7. Effect of curing time and lime content on compressive strength of lime mortar

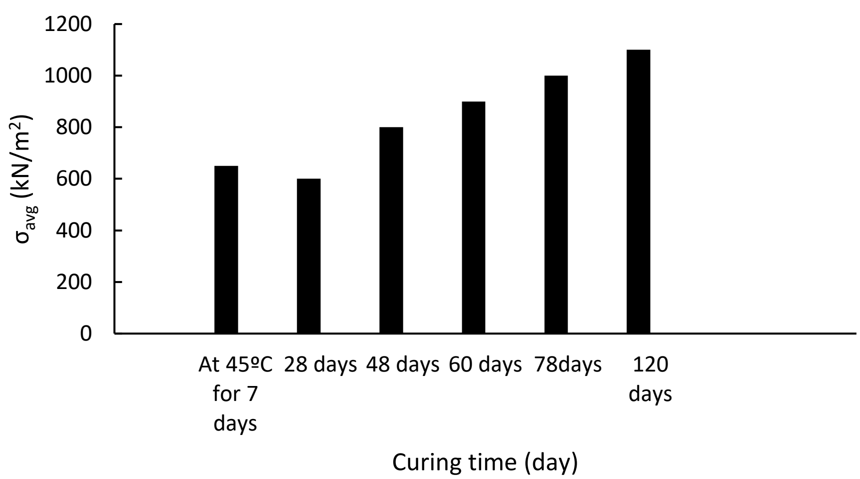


Fig. 8. Influence of temperature on curing time

Clay Specimens

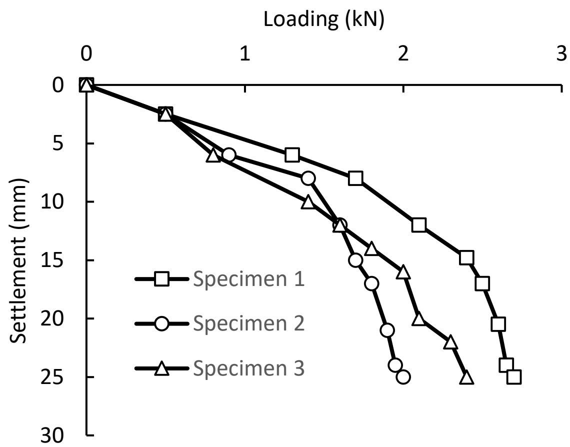
The uniaxial compression strength of four small clayey specimens was approximately 800 kN/m^2. The typical load-deformation behavior of large-scale clay specimen under different conditions is presented in Figure 9. According to the results, the bearing capacity of clay specimen decreased significantly under saturated condition. For investigating the effect of moisture content on bearing capacity, a specimen was selected randomly from each group and the water content was determined. The moisture content has been played an important role in increasing the strength of soil according to Figure 10. As can be seen, the soil strength is decreased approximately 80% under saturated condition.

CLM Column Specimens (Column Alone Loaded)

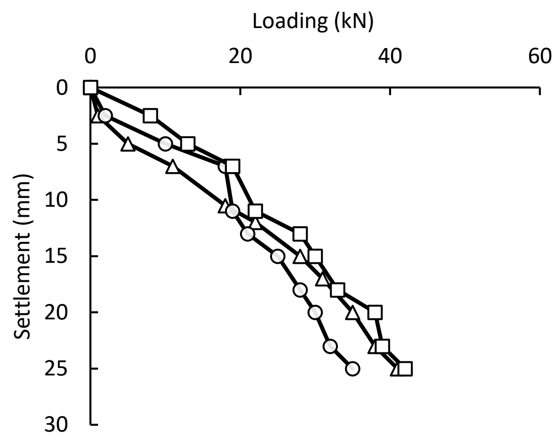
The typical load-deformation behavior of large-scale CLM column specimen under different conditions is illustrated in Figure 11. The axial stress of CLM column decreased substantially under saturated condition. For investigating the influence of moisture content on bearing capacity of CLM column specimens, a specimen was selected randomly from each group and the water content of lime mortar was measured. Figure 12 shows the relationship between the load bearing capacity of CLM column and water content of lime mortar.

CLM Column Specimens (Entire Area Loaded)

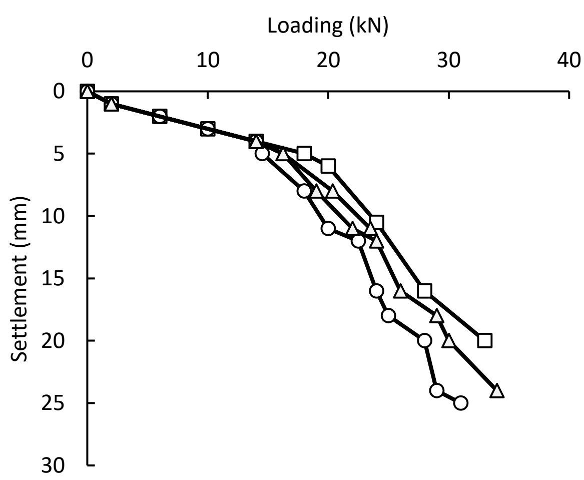
The uniaxial compressive strength of four small-scale CLM column specimens was approximately 1100 kN/m^2. As illustrated in Figure 13, the bearing capacity of CLM column specimens are decreased by increasing the moisture content. It appears that increasing in moisture content decreases the shear strength of clay.



(a) Saturated condition



(b) Dried condition



(c) Partially saturated condition

Fig. 9. Load-settlement behavior of untreated layered soils

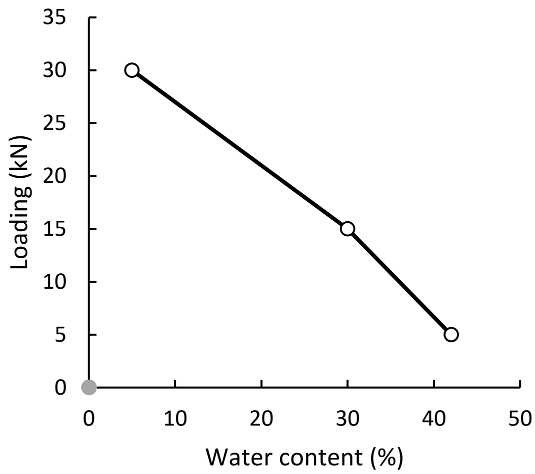
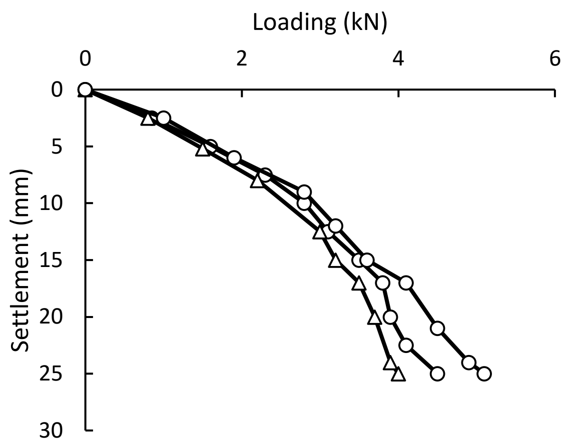
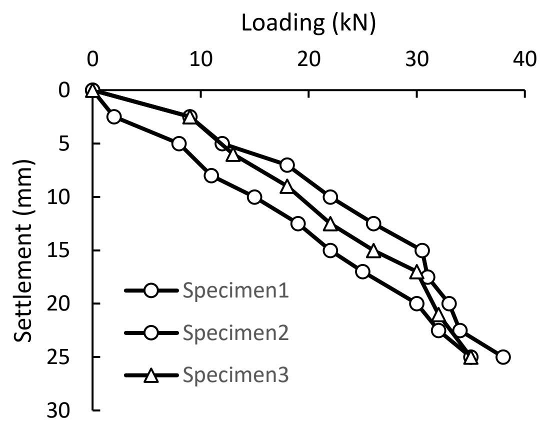


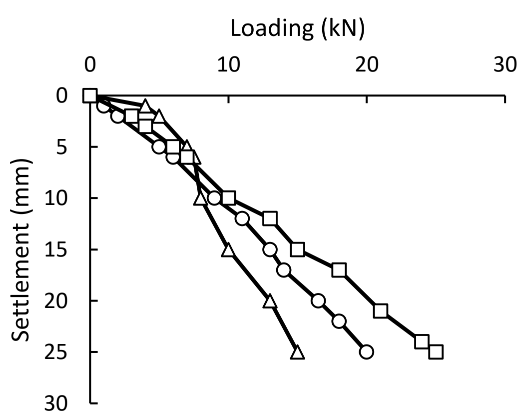
Fig. 10. The effect of percentage of moisture on clayey specimen's strength



(a) Saturated condition



(b) Dried condition



(c) Partially saturated condition

Fig. 11. Load-settlement behavior of CLM column (column alone loaded) specimens

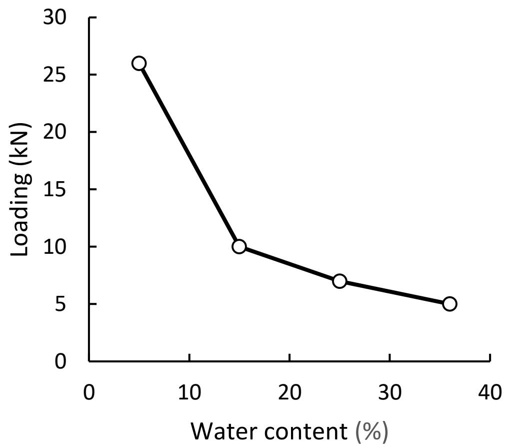
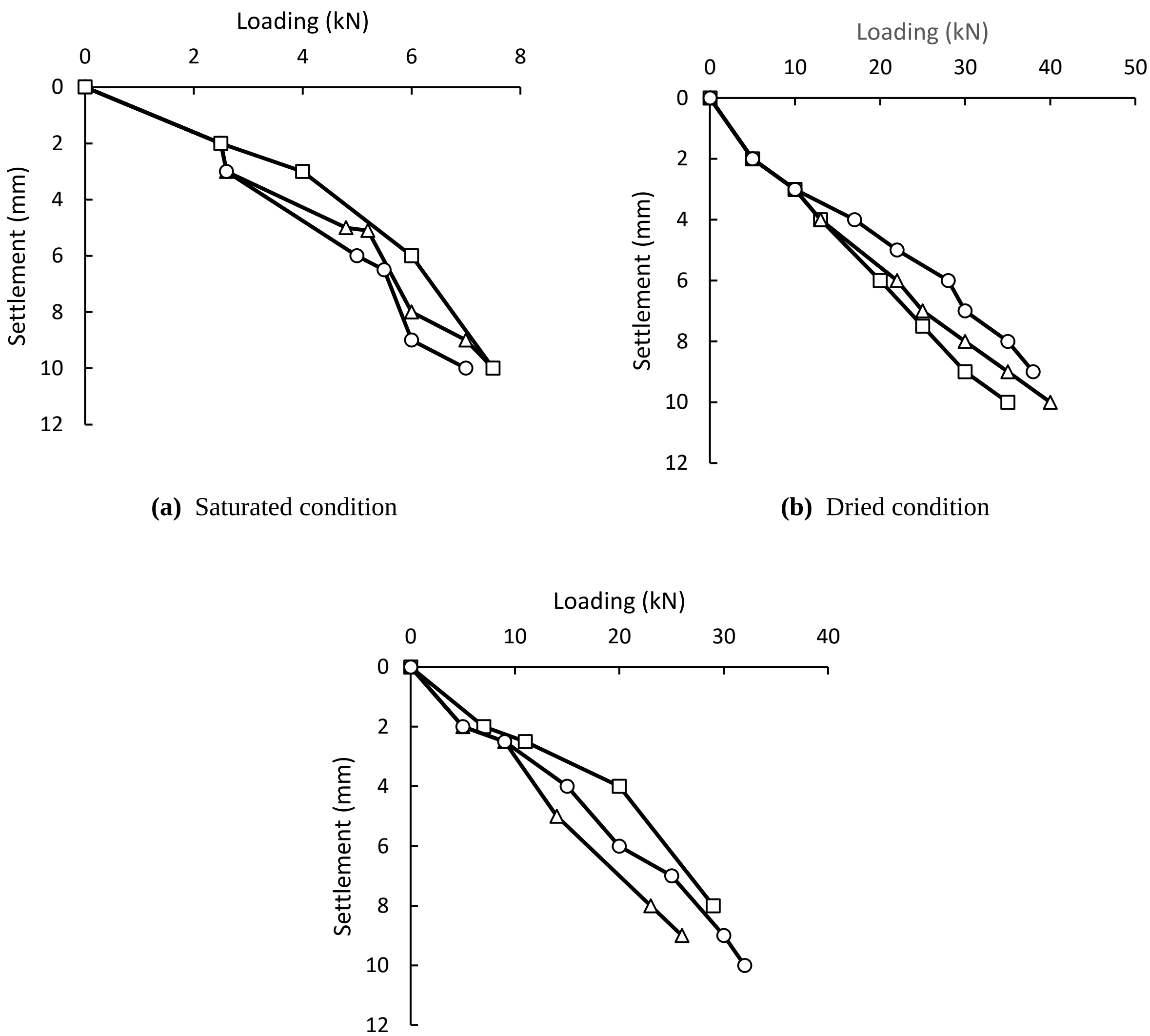


Fig. 12. The effect of percentage of lime mortar moisture on strength of CLM column specimens



(a) Saturated condition

(b) Dried condition

(c) Partially saturated condition

Fig. 13. Load-settlement behavior of CLM column specimen (entire area loaded)

Friction and Continuity of Clay-Lime Mortar Column Interface

In this section, a group of large-scale specimens was tested to indicate the friction and continuity of clay-column interface. This group consisted of one clay specimen, a 14-day CLM column (column alone loaded) specimen, two of 90-day CLM column (column alone loaded) specimens and a compacted clay column. The compacted clay column specimen was performed by replacing compacted clay as compacted lime mortar. These specimens were made under partially saturated condition. Figures 14 and 15 show the load-settlement curves for clay specimens and CLM columns, respectively. The behavior of clay specimens and compacted clay column specimen were illustrated in Figure 16.

As illustrated in Figure 15, the load bearing capacity of 90-days CLM column specimen was 1.5 times higher than 14-days CLM column specimen. According to Figure 16, the load bearing capacity of clay specimen was approximately equal to compacted clay column specimen for 25 mm settlement. Since the clay behaved the same as compacted clay column under the partially saturated condition, the friction and continuity of clay-column interface were successfully acceptable.

NUMERICAL MODELING

Three types of large-scale specimens in homogeneous clay were performed for numerical modeling. The details of the geometry and material properties are given in Figure 6 and Table 2, respectively. Two-dimensional axisymmetric finite element analysis was implemented by PLAXIS program (Brinkgreve and Vermeer, 2010) using elastic-perfectly plastic Mohr-Coulomb failure criterion for the soft clay and isotropic linear elastic behavior for lime mortar column (Figure 17). Drained materials were used to simulate the behavior of clay specimens and compacted clay column specimens under saturated and dry conditions. The load-settlement curve obtained based on numerical modeling is compared with experimental load-settlement curves in Figures 18 and 19. The results show reasonable agreement between the model test and numerical analysis.

The regression was conducted on data to gain a significantly better comprehension of behavior of large-scale specimens (R^2 values of the regressions never fall below 0.8). Figures 18 and 19 show the behavior of large-scale specimens under different moisture conditions. According to these Figures, the increasing moisture had negative effects on load-bearing capacity of specimens. As expected, the load-bearing capacity of CLM column (column alone loaded) specimens was higher than clay specimens under saturated condition. However, a decrease in soil moisture caused a well-behaved increase in clay specimens. As previously mentioned, the shear strength of clay increased with decreasing moisture content. The bearing capacity of clay specimens was higher than CLM column (column alone loaded) under partially saturated condition (Figures 18 and 19a). This phenomenon caused by decreasing skin friction of CLM column under partially saturated condition. The stiffness of improved ground (by using a sand pad) was performed approximately 7 times and 4 times higher bearing capacity compared with clay and CLM column (column alone loaded) specimens under the saturated condition, respectively as shown in Figure 19b. The comparison of the results from the Figures 18 and 19 indicated that, under dry and partially saturated conditions, the stiffness of improved ground was approximately 2.5 times higher than clay specimen. In addition, the behavior of partially saturated CLM column (entire area loaded) was slightly less than similar type under dry condition. As these figures show, the CLM column (column alone loaded) was ineffective for improvement of bearing capacity of clay under dry and partially saturated conditions.

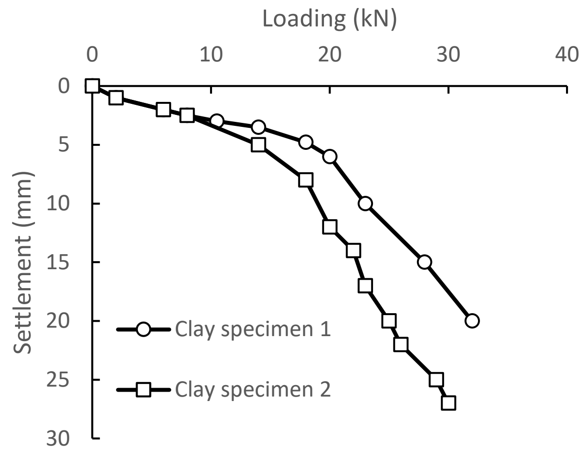


Fig. 14. Load-settlement behavior of clay specimens

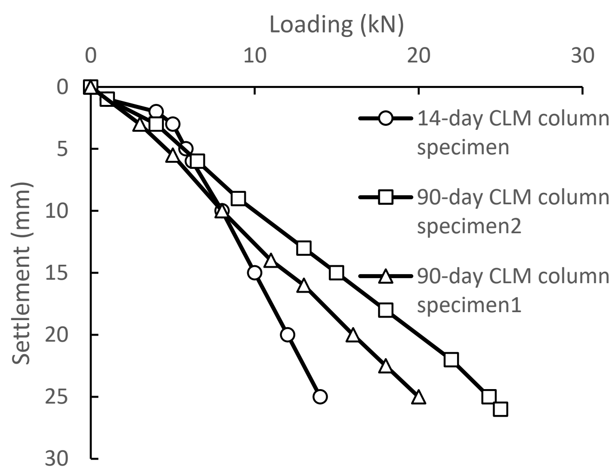


Fig. 15. Load-settlement behavior of CLM column (column alone loaded) specimens

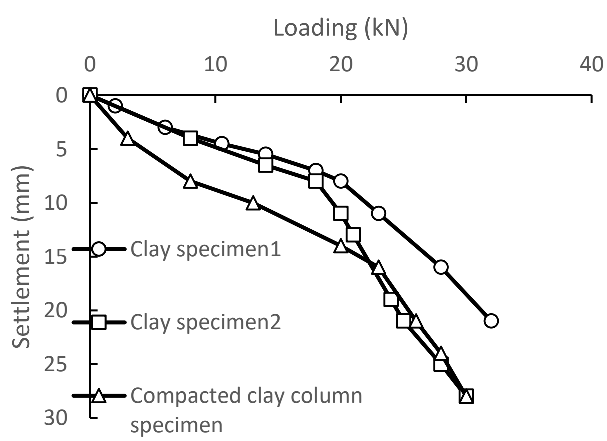


Fig. 16. Load-settlement behavior of compacted clay column (column alone loaded) specimen and clay specimens

Table 2. Material properties

	E (kPa)	ν	C (kPa)	ϕ	$\gamma_d\left(\frac{kN}{m^3}\right)$
Dried clay	15000	0.33	55	20	17.14
Saturated clay	1000	0.35	10	20	17.14
Lime mortar	200000	0.21	-	-	21.2

Note: E, modulus of elasticity; ν, Poisson's ratio; C, cohesive; ϕ, friction angle; γ_d, dry unit weight.

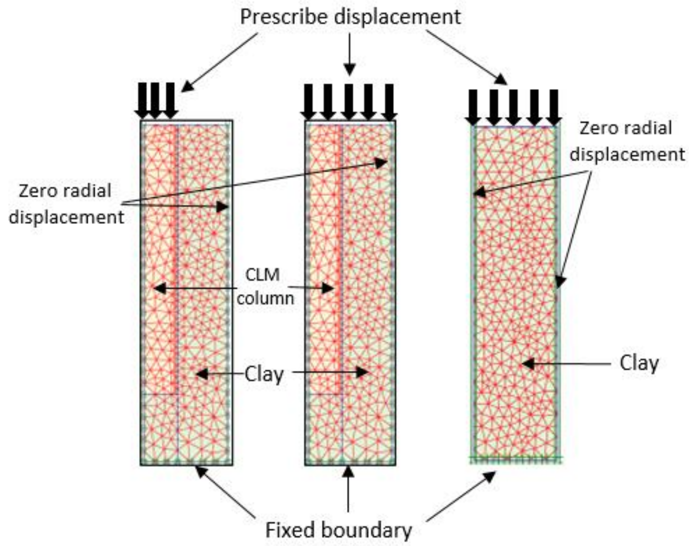


Fig. 17. Load-settlement curves for clay specimens

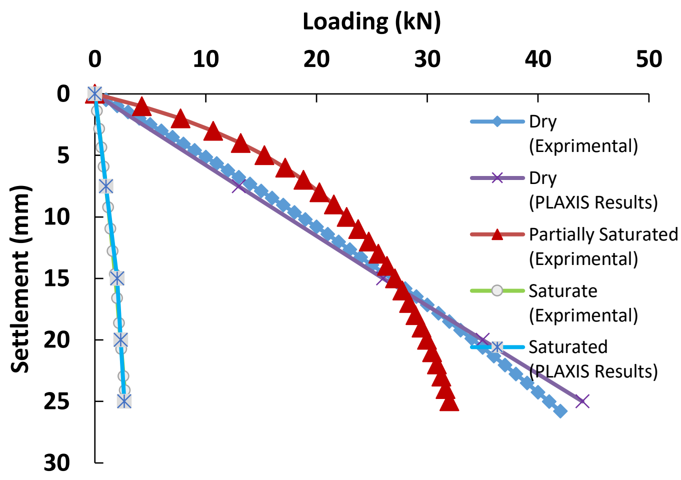
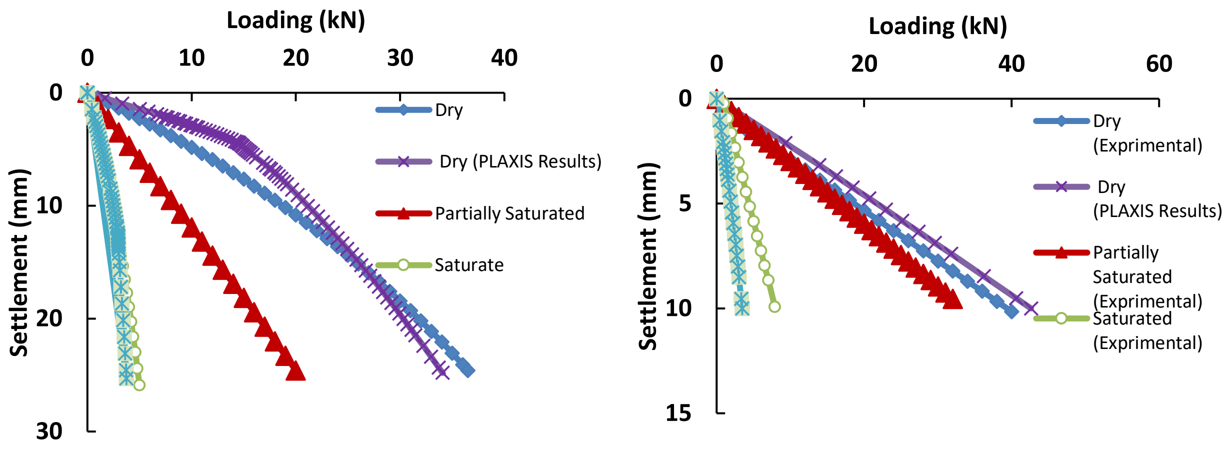


Fig. 18. Load-settlement curves for clay specimens

CONCLUSIONS

In this research, a series of compressive tests were conducted in order to study the behavior of CLM column in clay under different moisture conditions. Then, the load-settlement curves were plotted after data regressions and the additional tests were performed after analysis of CLM column behavior under saturated condition. The following conclusions can be drawn:



(a) Column alone loaded **(b)** Entire area loaded

Fig. 19. Load-settlement curves for CLM column specimens

1- The behavior of lime mortar depended on lime content, curing temperature and curing time.
2- The unconfined compression test for CLM column in the small-scale was higher than that of large-scale.
3- The results of small-scale tests indicated that bearing capacity of CLM column specimen was higher than bearing capacity of clay specimen under dry condition. However, the large-scale tests indicated that CLM column (column alone loaded) was ineffective for increasing bearing capacity of the clay under dry and partially saturated condition.
4- The CLM column needed a long time to reach its ultimate strength under partially saturated condition.
5- A significant settlement was observed in CLM column (column loaded alone) due to the compressibility behavior of lime mortar and lack of participation by the surrounding soil.
6- Using sand pad improved the stiffness of ground under different moisture conditions.
7- Compaction of the column was effective in performing the required friction and continuity of clay-lime mortar column interface.

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