*Research Article*

# Effect of Sand and Sand-Lime Piles on the Behavior of Expansive Clay Soil

**Mohamed Hussein** [ID]

*Civil Engineering Department, Faculty of Engineering, Sohag University, Sohag, Egypt*

Correspondence should be addressed to Mohamed Hussein; mohamed.ma_2000@yahoo.com

Expansive clay soil causes serious problems to many structures due to its swelling and shrinkage during wet and dry seasons. With the existence of expansive soil in Ahkmim new city, Sohag governorate, Egypt, some light buildings, road pavements, and buried pipelines have shown some damage. To avoid such damage, prior to construction, expansive clay soils should be stabilized. Different methods are available to improve the engineering properties of these soils such as densification, chemical stabilization, reinforcement, and techniques of pore water pressure reduction. The chemical stabilization of clay using lime is one of the widespread methods that can be used to improve the behavior of expansive clay soil. This study aims to investigate the effect of both sand and sand-lime piles on the behavior of expansive clay soil. A series of laboratory tests were carried out using the conventional Oedometer apparatus. Sand piles with different replacement area ratios (RARs) (4.68%, 10.16%, 24.6%, 35.84%, and 56.9%) were used. Also, sand piles stabilized with different percentages of lime (3%, 6%, 9%, 12%, 15%, and 20%) and with a replacement area ratio of 35.84% were used. The experimental results showed there is a significant improvement in reducing the swelling potential of expansive clay soil reinforced with sand or sand-lime piles. This improvement increases with the increase of both replacement area ratio and lime content.

## 1. Introduction

Expansive clay soils are normally accompanied by volumetric changes when subjected to changes in water content due to seasonal water variations. These soils have a good bearing capacity and low settlement in dry conditions. As soon as the water reaches it, it loses these properties, in addition to its swelling, which causes severe damage to the civil engineering structures built on it, by it, or in it. This implies that two main problems are accompanying expansive clay soil when water reaches it, differential heave and low bearing capacity.

Several methods have been suggested by different researchers to overcome the problems arising from these soils. There were some suggested methods to overcome its swelling and others to increase its bearing capacity. There are a few methods that have been suggested to reduce swelling and increase the bearing capacity of these soils at the same time.

Among the methods used to overcome the swelling are the chemical and mechanical treatments. Many additives such as lime, cement, lime-cement, lime-fly ash, lime–rice husk-cement–fly ash, gypsum, enzymes, cement dust, marble dust, granite dust, and other chemicals were used as chemical stabilizers for expansive soils [1–7]. Mechanical stabilization of soil (without altering chemical properties) includes controlling compaction [8], prewetting [9], mixing with sand [10], removing and replacing it by nonswelling soil [11], expanded polystyrene (EPS) geofoam [12], reinforcing the soil using geosynthetics [13, 14], and using polypropylene fiber [15] that have been used successfully in the treatment of expansive soils. Furthermore, some special foundation techniques like underreamed piles, belled piers, drilled piers, helical piles, micro-piles, granular pile anchors, geopile-anchor gravel piles, and sand piles have also been suggested to mitigate the swelling result from the expansive clay soils [9, 14, 16–23].

The technique of pile type, lime pile, or sand pile has been successfully applied in recent years to improve the physical and mechanical properties of the problematic soils. These techniques increase soil bearing capacity and reduce both soil settlement and swelling owing to the improvement of soil stiffness and strength [24–35].

Recently, Kumar and Jain [36] have verified that the concept of the granular pile, which is common in improving the weak marine clays, could be applied to improve the load-carrying capacity of soft expansive soils too. In the granular pile, also known as the stone column technique, about 10 to 35% weak soil is removed and replaced with granular material in the form of piles. Kumar [37] executed model tests in the laboratory on granular piles of sand constructed in soft expansive soil of different unconfined compressive strength values. End-bearing granular piles were casted in the soil, and the load test was carried out. The test results indicated that the load-carrying capacity of a footing resting on a granular pile was significantly more than the corresponding value for the footing placed directly on the soft soil bed. The increase in load-carrying capacity was observed for all soil consistencies of the expansive soil. It was concluded from this study that the loss in strength and excessive settlement of the expansive soil due to wetting could be diminished to a large extent by the installation of granular piles in the soil.

Hussein [20] carried out model tests in the laboratory on expansive clay soil reinforced with sand compaction piles with different replacement area ratios. The model was subjected to a pressure equal to $120 \, kN/m^2$, and water was added to it. It was concluded from this study that the swelling potential of the model decreases significantly with the increase of replacement area ratio (i.e., pile diameter), and at RAR equal to about 57%, the swelling potential value reached a very small value, which can be neglected. Moreover, the effect of externally applied pressure (120, 140, 160, and 180 kPa) was studied, and the results showed that as the applied pressure increases, the swelling potential decreases.

Now, there are several efforts to increase the stiffness of sand piles or sand columns with different additives. The effect of both cement and lime additives on the stiffness and strength characteristics of sand was studied by Abbawi and AL-Soudany [38]. Abbawi and AL-Soudany performed an experimental program that includes (32) sand specimens stabilized with lime. Lime was added to the sand with 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10% by weight and cured for 7 and 28 days. The results showed that there was an almost a linear increase in the strength of stabilized sand and cured for 7 days with increasing lime content; at 3% lime, the unconfined compressive strength increased to $4.99 \, kN/m^2$, and at 10% lime, it increased to $41.48 \, kN/m^2$. Although there was a gradual nonlinear increase in the strength of stabilized sand cured for 28 days as increasing lime content, at 3% lime, the unconfined compressive strength increased to $24.88 \, kN/m^2$, and at 10% lime, it increased to $93.25 \, kN/m^2$.

Al-Gharbawi [39] studied the performance of sand columns and sand columns stabilized with different percentages of lime (1, 3, 5, 7, 9, and 11%) and cured for 7 and 28 days. Three types of lime were used to stabilize the stone columns (Iranian lime, Turkish lime, and Turkish lime exposed to heat 512°C). The study considered two types of columns, floating and end-bearing. The results indicated that sand columns stabilized with 11% lime type III (floating type) provided the highest degree of bearing improvement ratio of 2.91 after seven-day curing and 4.1 after twenty-eight-day curing, and the lowest degree of settlement reduction ratio of 0.09 after seven- and twenty-eight-day curing. Sand columns stabilized with 11% lime type III (end-bearing type) provided a bearing improvement ratio of 3.33 and a settlement reduction ratio of 0.086 after seven-day curing. Thus, it is advisable to use lime type III to improve the performance of both floating and end-bearing sand columns.

Al-Saoudi et al. [40] studied the behavior of isolated sand columns stabilized with lime and embedded in a bed of soft soil of undrained shear strength $C_u$ between 16 and 19 kPa. Columns with 50 mm in diameter and 300 mm in depth were excavated in a bed of soft soil and backfilled with sand mixed with various percentages of lime and cured for 7 days. A rigid circular footing with a diameter of 64.6 mm was placed on each column and loaded up to failure. The results of the tests showed that there are good improvements in the load-carrying capacity of the columns and a significant decrease in the settlement over the traditional sand columns without lime.

The use of this technique for improving expansive clay soils has not received enough attention. Most of the previous studies were concerned with using this technique (Sand-lime piles) for improving soft soils. There are few studies that investigated the effect of sand-lime piles for stabilizing expansive clay soils [41–48].

Premalatha and Sabarishri [49] studied the stabilization of expansive soil using sand-lime piles in situ. The soil profile at this site consists of a layered system. The first layer is an earth fill and has a thickness range between 0.45 m and 1.5 m. The second layer is silty clay with thickness ranges between 0.5 m and 2.5 m followed by silty sand. The fourth layer is gravelly sand followed by weathered rock. The classification of filled-up earth in this site is nonplastic silty sand. The silty clay layer has high plasticity, which will undergo volume change due to absorbing water. This clay was black in color and has a presence of organic content range between 20 and 30%. Thus, it was dangerous to execute flexible pavement directly on this soil. Therefore, this layer requires stabilization. The authors recommended using sand-lime piles for this site because of its proven performance, constructability, durability, and low cost. The stabilization using sand-lime piles was achieved systematically. After removing the top fill soil until reaching the silty clay soil layer, a hole was made with a diameter of 30 cm, and the depth of the hole was up to the top of the underlying silty sand/gravelly sand layer. The spacing between the holes was 150 cm. Pulverized lime powder $(Ca (OH)_2)$ was mixed with sand in 1 : 1 ratio. This mix was poured in layers, with a thickness of 25 cm each inside the hole, and compacted to attain the maximum density. The holes were watered after filling it. The site was left for curing for about 30 days to allow the lime to react with the surrounding soil. After curing, the

value of design field California bearing ratio (CBR) was determined to be equal to 15%, and the flexible pavement was designed and constructed on the prepared ground.

This research aims to take the advantage of lime to reduce the swelling of expansive clay soils as proven from different previous studies and improve the stiffness of sand piles as well. The improvement in swelling potential is due to the migration of lime to the surrounding expansive clay soil when the water reaches the expansive clay soil.

The size of the sand pile and increasing its stiffness by mixing it with hydrated lime play an important role in changing the behavior of expansive clay soil. Hence, these two aspects are varied in the present work, and the influence of the sand pile diameter, which is presented here by replacement area ratio (RAR), and the lime content on the swelling of expansive clay soil was studied. The details of the experimental program, the results of the tests, and the conclusions drawn from the study are described below.

## 2. Experimental Program

To study the effectiveness of sand piles and sand piles stabilized with hydrated lime on the behavior of expansive clay soil, laboratory tests were conducted. The parameters varied during tests, the diameter of sand piles or replacement area ratio (RAR (%)) and lime content (Lc (%)). The complete laboratory program is demonstrated in Table 1.

## 3. Material Properties

The basic materials used in this study are expansive clay soil representing the soil to be reinforced with a sand piles or sand-lime piles and sand soil for forming sand piles. Additionally, hydrated lime was used for stabilizing sand piles. The properties of these materials are as follows.

### 3.1. Clay.
The expansive clay soil used in this study was collected from a depth of 2.0 m below the ground surface in Ahkmim new city, Sohag, Egypt. The main properties of used expansive clay soil were determined by [20] and are presented in Table 2.

The highly liquid limit associated with a high plasticity index indicates a high-volume change potential of the soil. Besides, a free swell index of 177% shows that the soil has a high degree of expansiveness.

### 3.2. Sand.
The properties of used sand for forming sand piles (SPs) were determined by [20] and are presented in Table 3.

### 3.3. Lime.
Hydrated lime was used in this investigation. The chemical properties of lime are shown in Table 4.

### 3.4. Water.
Tap water was used for the preparation of expansive clay samples as well as in the soaking process.

## 4. Tests Setup and Procedure

### 4.1. Preparation of Unreinforced Expansive Clay Soil.
The direct measurement of the volume change that happens when expansive clay soil is exposed to heave is usually obtained using the conventional one-dimensional Oedometer test. Consolidation-swelling test according to ASTM D4546-08 (method C) was used, in which the sample is inundated with water and allowed to swell under the nominal pressure of 6.9 kPa [50].

Untreated expansive clay soil (UECS) was prepared first to take its results as a reference for comparison with the expansive clay soil reinforced with sand piles (SPs) and sand-lime piles (SLPs). To prepare an unreinforced expansive clay soil model with a natural dry unit weight (20.21 kN/m$^3$) and natural moisture content (8.69%), an expansive clay soil sample with a weight of 1.0 kg was crushed employing a rubber hammer and sieved through sieve No. 8 (2.36 mm). The passing soil was dried in an oven at 105°C for 24 hours. The desired amount of dry expansive soil to fill the Oedometer ring with the target dry unit weight (20.21 kN/m$^3$) was weighted. The Oedometer ring was 63.5 mm in diameter and 19 mm in height. The dry expansive soil was then mixed thoroughly with a predetermined amount of water to achieve the desired natural moisture content (8.69%). The mixture of expansive clay soil and water was preserved in the airtight container for 24 hours to allow for a uniform distribution of water. The inner wall surfaces of the Oedometer ring were greased with a lubricant material to reduce the sidewall friction resulting from soil expansion upon clay wetting. A porous stone plate was placed at the underside of the ring, and then, a filter paper was placed on it; afterward, the specified weight of the mixture (expansive clay soil and water) to fill the Oedometer was determined. The soil sample was compacted statically in the Oedometer ring to the specified dry unit weight (20.21 kN/m$^3$) with a water content of 8.69% using a hydraulic Jack.

The whole assembly was weighted to check if the desired amount of density was reached and mounted within the consolidation cell and was placed on the Oedometer frame under a surcharge pressure of 6.9 kPa. The vertical movement of the expansive clay sample was measured by a dial gauge with a sensitivity of 0.01 mm and a travel of 25 mm. The vertical displacement was monitored continuously by taking the dial gauge reading at regular interval times. The swelling experiment was terminated when two consecutive readings for the dial gauge are of the same value.

### 4.2. Preparation of Expansive Clay Soil Reinforced with Sand Piles.
Conventional one-dimensional Oedometer apparatus was also used in the experimental tests. Sand piles with various diameters (13.74, 20.24, 25.31, 31.47, 38.00, and 47.92 mm) and height 19 mm were prepared in the center of the expansive clay soil sample. These diameters give replacement area ratios equal to 4.7%, 10.16%, 15.88%, 25.47%, 35.84%, and 56.94%, respectively, where these values of replacement area ratios were carried out in the previous

TABLE 1: Laboratory study program.

| Test | Sand pile diameter (mm) | RAR (%) | Lime content (Lc) (%) |
|---|---|---|---|
| Clay only | 0 | 0 | 0 |
| | 13.74 | 4.7 | 0 |
| | 20.24 | 10.16 | 0 |
| Clay reinforced with SP | 25.31 | 15.88 | 0 |
| | 31.47 | 25.47 | 0 |
| | 38.00 | 35.84 | 0 |
| | 47.92 | 56.94 | 0 |
| Clay reinforced with SLP | 38.00 | 35.84 | 3, 6, 9, 12, 15, 20 |

TABLE 2: Properties of used expansive clay soil [20].

| Properties | Values |
|---|---|
| Sand | 2% |
| Silt | 22% |
| Clay | 76% |
| Liquid limit (%) | 85 |
| Plastic limit (%) | 32 |
| Plasticity index (%) | 53 |
| Free swell index (%) | 177 |
| Natural dry unit weight ($kN//m^3$) | 20.21 |
| Natural moisture content (%) | 8.69 |
| USCS and IS classification | CH |

TABLE 4: Chemical composition of hydrated lime.

| Constituents | (%) |
|---|---|
| $SiO_2$ | 0.0 |
| $Al_2O_3$ | 0.13 |
| $Fe_2O_3$ | 0.08 |
| CaO | 59.03 |
| MgO | 0.25 |
| $Na_2O$ | 0.05 |
| $K_2O$ | 0.03 |
| MnO | 0.004 |
| $P_2O_5$ | 0.00 |
| $H_2O$ | 0.04 |
| Loss of ignition | 2.05 |

TABLE 3: Properties of used sand [20].

| Properties | Values |
|---|---|
| Specific gravity | 2.76 |
| Maximum dry unit weight ($kN/m^3$) | 20.5 |
| Optimum moisture content (%) | 6.4 |
| USCS and IS classification | SP |

study by Hussein [20] using a modified Proctor mold with dimensions 152 mm in diameter and 168 mm in height.

Teflon piles (TPs) were manufactured from Polytetra-fluoroethylene material (which is known commercially as Teflon) with the same diameters of sand piles. Each Teflon pile has one steel hand to help in pulling it out from the SP hole. In addition, circular hollow Teflon plates (CHTPs) with a constant outer diameter of 62.5 mm and with various inner diameters equal to 14.74, 21.24, 26.31, 32.47, 39, and 48.92 mm and with a thickness of 5 mm were used temporarily for centralizing the Teflon pile in the center of Oedometer cell. Each CHTP has two steel hands to help in pulling it out of the Oedometer cell. These components are shown in Figure 1. A steel hand was fixed at the top of each Teflon pile for its easy handling for making a hole in the clay bed.

The amount of dry expansive clay soil required for filling the space between the TP and the Oedometer ring to give the required natural dry unit weight ($20.21 \, kN/m^3$) was determined from the same used soil. The amount of water to give the natural moisture content (8.69%) was determined. Water and dry expansive clay soil were mixed carefully to have a homogenous mixture. The amount of dry sand required for filling the hollow of the sand pile at maximum dry unit weight ($20.5 \, kN/m^3$) and the corresponding optimum water
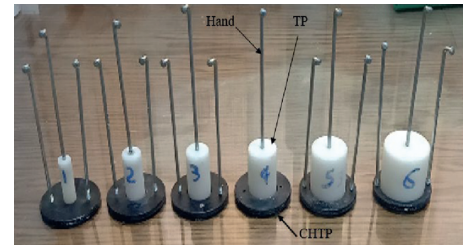


FIGURE 1: Teflon piles and circular hollow Teflon plates with steel hands.

content (6.4%) were determined and mixed carefully. Each kind of mixture (dry expansive soil/water) and (dry sand/water) was kept in airtight containers for twenty-four hours to permit uniform distribution of moisture.

For preparing the first clay layer in Oedometer cell, TP was placed in the center of the Oedometer cell and adjusted in the center by using CHTP as shown in Figure 2(a). CHTP was extracted and the required amount of expansive soil/water mixture for the first layer was placed around the TP, and the top surface was leveled, and CHTP is repositioned. The compaction of the first clay layer was carried by knocking on CHTP using a steel rod with diameter 10 mm until the thickness of first clay layer reaching nearly the third height of Oedometer cell as shown in Figure 2(b). CHTP was extracted, and the second clay layer was placed around TP, and the same previous procedures were repeated for finishing the second clay layer and reaching nearly the two-thirds of Oedometer cell height. The same procedures were repeated for third clay layer.

Next, the TP was withdrawn completely, leaving a hole behind. The amount of dry sand/water mixture was placed carefully in the hole and compacted slowly by the steel rod until reaching the same level of the around expansive clay soil.

After that, the Oedometer cell was placed under the hydraulic Jack to completely compact the sand pile and the surrounding expansive clay soil until both reaching the required height of 19 mm. After the compaction had been completed, the final surface of the expansive soil/SP model was leveled off in the Oedometer cell, and a filter paper followed by a porous stone plate was placed over the expansive soil/SP model. These steps are illustrated in detail in Figure 2.

The entire assembly was positioned in the loading frame under a surcharge pressure of 6.9 kPa, and the same procedure for adding water and recording the dial gauge readings was followed as explained in the previous section.

*4.3. Preparation of Expansive Clay Soil Reinforced with Sand-Lime Pile.* The same procedures used in the previous section were followed here. The only difference is that the expansive clay soil bed was reinforced with a sand-lime pile (SLP) with a diameter of 38.0 mm instead of a sand pile only. Various percentages of lime 3%, 6%, 9%, 12%, 15%, and 20% by dry weight were mixed carefully with the required dry sand for forming sand-lime piles.

# 5. Results and Discussion

*5.1. Effect of SP on Expansive Clay Soil Behavior.* The variation of vertical swelling ratio (VSR) with respect to the time for unreinforced and reinforced expansive clay soil with sand piles (SPs) is shown in Figure 3. The vertical swelling ratio is defined as the following equation:

$$\text{VSR}(\%) = \frac{\Delta H}{H_o} \times 100, \qquad (1)$$

where $\Delta H$ = increase in specimen height at a given time interval and $H$ = initial height of the compacted specimen.

From Figure 3, it can be generally noticed that there is a significant effect on the mitigation of expansive clay soil swelling when reinforcing it with sand piles. The swelling reached the equilibrium state after about 25 hours, beyond which there is not a significant change in swelling. Moreover, it is obvious that as the replacement area ratio increases, the swelling potential decreases significantly. This result is in good agreement with the results obtained by [20, 41].

*5.2. Effect of SP on the Swelling Potential of Expansive Soil.* To illustrate the effect of sand piles on the swelling potential of expansive clay soil, the relationship between the replacement area ratio (RAR) and swelling potential (SPO) is plotted as shown in Figure 4. From this figure, it is found that as the RAR increases, the swelling potential decreases. The swelling potential decreases from 28.52% to 10.68% when RAR is increased from zero to 56.94%. The reason for such behavior is due to the replacement of swelling particles of

expansive clay soil with nonswelling particles of the sand pile.

Moreover, these results have been compared with those results obtained by Hussein [20]. Hussein carried out laboratory model tests on expansive clay soils having the same properties and stabilized with SP with the same RAR values and sand with the same properties. Laboratory tests were carried out on a large-scale soil model using a modified Proctor mold (MPM) measuring 168 mm in height and 152 mm in diameter. The applied overburden pressure is equal to 120 kPa. The obtained results are presented on the same figure with those obtained from this study as shown in Figure 4. This figure indicates that the behavior trend of swelling potential with RAR for the results obtained from this study is in good agreement with that obtained by Hussein [20].

The prediction model has been developed for the change in swelling potential with different RAR for both Oedometer (OED) model and modified Proctor model (MPM) results. The model is predicted as shown in the following equation:

$$\text{SPO}_R = \text{SPO}_U \, e^{n.\text{RAR}}, \qquad (2)$$

where $\text{SPO}_R$ is the maximum vertical swelling ratio (swelling potential) for reinforced expansive soil with SP. $\text{SPO}_U$ is the maximum vertical swelling ratio for unreinforced expansive soil. RAR is the replacement area ratio. $n$ = a coefficient = −0.15 ($R^2$ = 0.997 for OED and $R^2$ = 0.981 for MPM).

The verification of the proposed equation (2) was done using the experimental test results by Hergül [51]. Hergül carried out an experimental study using a conventional Oedometer apparatus, and the expansive clay soil was reinforced with sand piles. Sand piles with diameters that satisfy the replacement area ratios of 5%, 10%, and 20% were used. The sand was placed inside the holes of the pile in a loose to medium dense state with a relative density of 40%. Free swell tests with 7, 25, 50, 100, and 150 kPa seating pressures were used during the experimental tests. The obtained results for different seating pressures were compared with those predicted from the proposed equation (2) as shown in Table 5. From Table 5, it can be seen that there is a good agreement between the results of Oedometer test results under different seating pressures and those predicted from the proposed equation. In addition, to increase the emphasis on the accuracy and conformity of the laboratory results with the results obtained from the proposed equation, the correlation index or coefficient of determination ($R^2$) was calculated for each seating pressure using nonlinear regression analysis for experimental data as proposed by [52]. It was found that it equals 0.9997, 0.9951, 0.9956, 0.9845, and 0.3632 for seating pressures 7 kPa, 25 kPa, 50 kPa, 100 kPa, and 150 kPa, respectively. From the obtained $R^2$ value, it can be seen that the proposed equation (2) is in good agreement with the experimental data except for the seating pressure 150 kPa. It can be said with confidence that the proposed equation (2) can be used to obtain the swelling potential for any expansive clay soil reinforced with sand piles at any replacement area ratio.
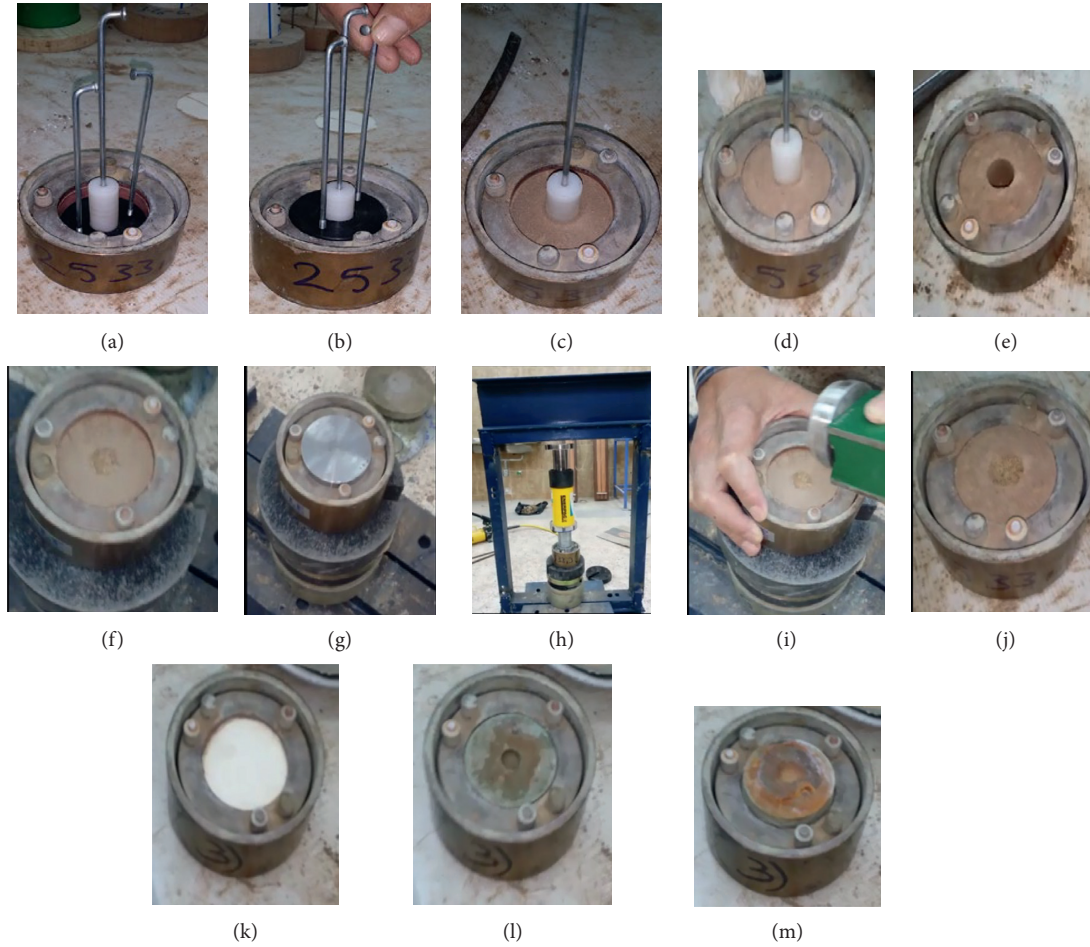
FIGURE 2: Used steps for preparing the expansive clay soil model reinforced with SP. (a) Placement of the TP and CHTP in the center of the Oedometer cell. (b) Removal of the CHTP and place the first clay layer around TP, then reposition of the CHTP over the first clay layer, and its slight compaction. (c) Removal of the CHTP and placement of the second clay layer around TP, then reposition of the CHTP over the second clay layer, and its slight compaction. (d) Removal of the CHTP and placement of the third clay layer around TP, then reposition of the CHTP over the third clay layer, and its slight compaction. (e) Extraction of the TF leaving a hole. (f) The hole was filled with sand/water mixture and compacted forming a sand pile. (g) Placement of the steel guide compaction plate. (h) Placement of the model under the hydraulic Jack to final compaction of the model. (k) Removal of the guide compaction plate. (i) The model was completed. (m) Filter paper was placed. (n) Upper porous stone was placed. (o) Loading cap was placed.

### 5.3. Effect of SP on the Swelling Potential Reduction Factor.

The relationship between the swelling potential reduction factor (SPRF) and RAR for unreinforced and reinforced expansive clay soil with sand piles is shown in Figure 5.

$$\text{SPRF}(\%) = \frac{\text{SPO}_U - \text{SPO}_R}{\text{SPO}_U} \times 100, \qquad (3)$$

where SPRF (%) = swelling potential reduction factor.

From this figure, it can be seen that there is a significant reduction in swelling potential when reinforcing the expansive clay soil with SP. Furthermore, the swelling reduction factor increases significantly with the increase of RAR, where it reaches 8.3%, 17.026%, 25.898%, 33.657%, 43.57%, and 61.06% with RAR being equal to 4.68%, 10.16%, 15.9%, 24.6%, 35.84%, and 56.94%, respectively. The prediction model has been developed for the change in swelling

potential reduction factor with various RARs. The model is predicted as follows:

$$\text{SPRF}(\%) = 1.181\text{RAR}(\%),$$
$$R^2 = 0.9841. \qquad (4)$$

The results obtained by Hussein [20] are plotted in Figure 5. This figure indicates that there is a good agreement between the obtained results from OED and MPM, and the relation can also be expressed as a linear relationship with the following equation:

$$\text{SPRF}(\%) = 1.1027\text{RAR}(\%),$$
$$R^2 = 0.964. \qquad (5)$$

From equations (4) and (5), it appears that the values of constants for the two equations are nearly the same, and if
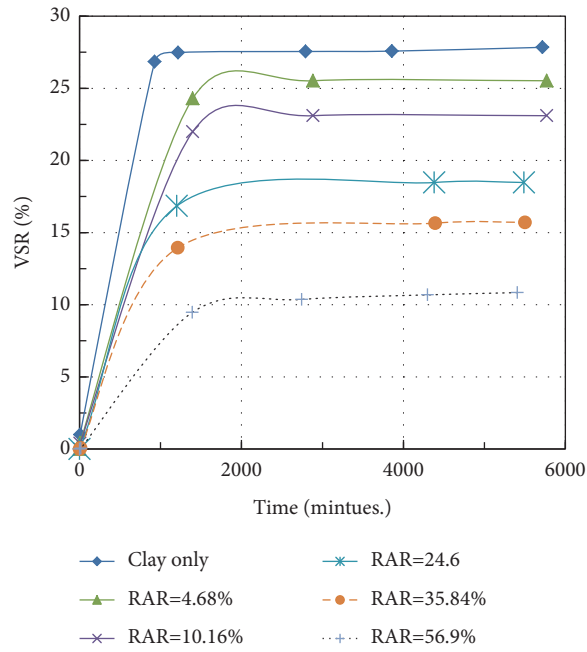
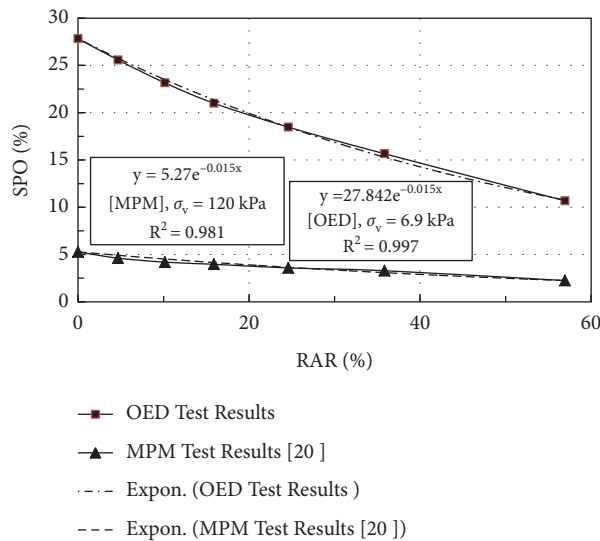FIGURE 3: Variations of VSR with time for unreinforced and reinforced expansive clay soil with SP.



FIGURE 4: Variations of SPO with RAR for OED and MPM.

TABLE 5: Comparison of SPO (%) obtained from equation (3) with that from Hergül [51].

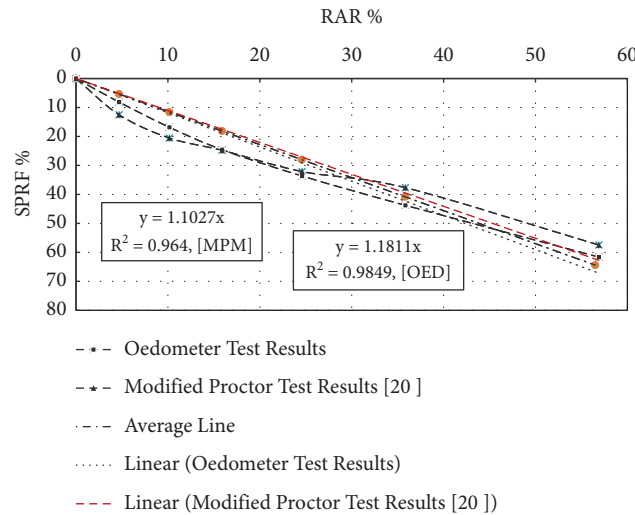| RAR (%) | Experimental values obtained by [50] | | | | | Predicted values from equation (2) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 7 kPa | 25 kPa | 50 kPa | 100 kPa | 150 kPa | 7 kPa | 25 kPa | 50 kPa | 100 kPa | 150 kPa |
| 0 | 34 | 13.7 | 8.9 | 4.5 | 3.8 | 34 | 13.7 | 8.9 | 4.5 | 3.8 |
| 5 | 31.5 | 12.8 | 8 | 4 | 3.2 | 31.543 | 11.875 | 7.4219 | 3.711 | 2.9688 |
| 10 | 29.2 | 13.1 | 7.8 | 4.1 | 3 | 29.264 | 11.275 | 6.7135 | 3.5289 | 2.5821 |
| 20 | 26.1 | 9.9 | 7.2 | 3.3 | 1.6 | 25.188 | 7.3341 | 5.3339 | 2.4447 | 1.1853 |
| $R^2$ | | | | | | 0.9997 | 0.9951 | 0.9956 | o.9845 | 0.3632 |

Figure 5: Variations of SPRF with RAR for both OED and MPM.

Table 6: Comparison of SPRF (%) obtained from equation (6) with that from Hergül [51].

| RAR (%) | Experimental values obtained by [50] | | | | | Predicted values from equation (6) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 7 kPa | 25 kPa | 50 kPa | 100 kPa | 150 kPa | 7 kPa | 25 kPa | 50 kPa | 100 kPa | 150 kPa |
| 0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 7.35 | 6.57 | 10.11 | 11.11 | 15.79 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| 10 | 14.12 | 4.38 | 12.36 | 8.89 | 21.059 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| 20 | 23.24 | 27.74 | 19.10 | 26.67 | 57.899 | 22.8 | 22.8 | 22.8 | 22.8 | 22.8 |
| | | | | | $R^2$ | 0.966 | 0.793 | 0.893 | 0.854 | 0.421 |

the average value is taken equal to 1.14, the proposed equation becomes as follows:

$$\text{SPRF} (\%) = 1.14 \text{RAR} (\%). \tag{6}$$

The coefficient of determination, $R^2$, was recalculated for both the Oedometer model and modified Proctor model results. It was found that it is strong and equals 0.961 and 0.924, respectively.

The proposed equation (6) has been verified with the results obtained by Hergül [51] as shown in Table 6. This table shows that the proposed equation for predicting the swelling potential reduction factor for expansive clay soils reinforced with sand piles can be applied confidently.

*5.4. Effect of Sand-Lime Piles (SLPs) on VSR.* The effect of sand piles stabilized with various percentages of hydrated lime by weight on the behavior of expansive clay soil was studied. The variation of vertical swelling ratio with time for various lime percentages used in stabilizing the sand piles embedded in expansive clay soil is presented in Figure 6. It can be demonstrated that, by adding lime as a stabilizing agent to the sand piles, there is a significant decrease in VSR of expansive clay soil. Moreover, it can be seen from the magnified part from the beginning of Figure 6 that as the lime content increases up to 15% or greater, some settlement occurs in the soil sample at the beginning, and after that, the soil sample starts to heave. The time required for the soil
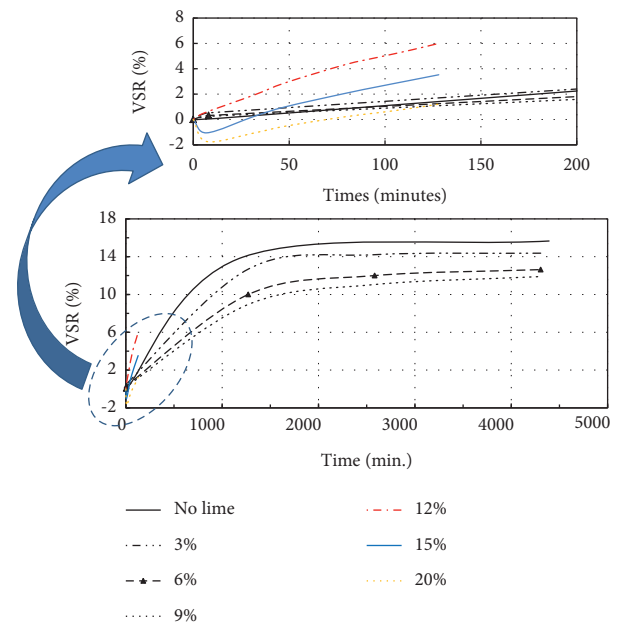


Figure 6: Variations of VSR with time for different percentages of lime content in the sand pile (RAR = 35.84%).

sample to start heaving increases with the increase of lime content. Additionally, it is obvious that when the percentage of lime in the sand pile reaches 20%, there is no significant
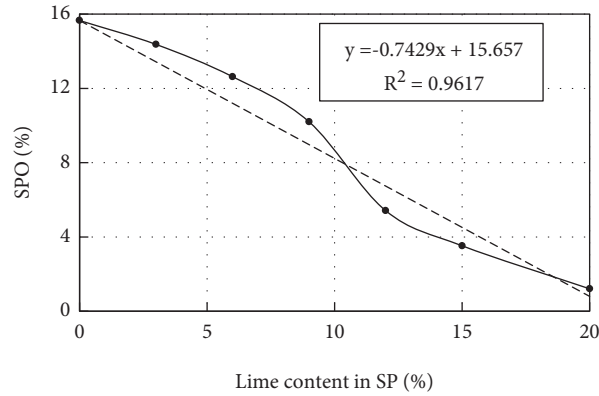
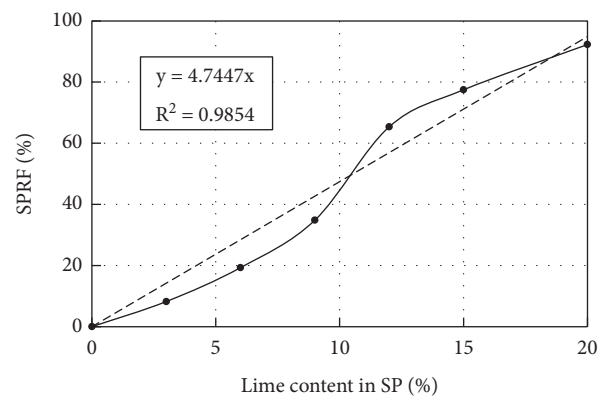FIGURE 7: Swelling potential versus lime content in SP (RAR = 35.84%).



FIGURE 8: Swelling potential reduction factor versus lime content in SP (RAR = 35.84%).

swelling occurred in the expansive clay soil sample. This result shows clearly that adding lime to sand piles gave a significant improvement in reducing the swelling of expansive soil compared to not adding lime, and this improvement is attributed to the migration of $Ca^{+2}$ ion to the surrounding soil when adding water, which causes dehydration, agglomeration, and flocculation of the clay particles, then reduces the plasticity property of the clay, and thus reduces the swelling behavior.

*5.5. Effect of Lime Content in SP on SPRF.* Figure 7 demonstrates the relationship between the swelling potential for unreinforced and reinforced expansive clay soil reinforced with sand piles stabilized by hydrated lime, where different percentages of lime 0%, 3%, 6%, 9%, 12%, 15%, and 20% by dry weight of sand were added. From this figure, it can be observed that as the lime content increases in the sand pile, the swelling potential decreases drastically, and this relationship is linear as shown in

$$\text{SPO}(\%) = 0.7431 L_c (\%) + S_u,$$
$$R^2 = 0.96. \tag{7}$$

*5.6. Effect of Lime Content in SP on SPRF.* Figure 8 shows the relationship between the swelling potential reduction factors

of unreinforced and reinforced expansive clay soil with sand piles stabilized by different percentages of lime. From this figure, it can be observed that as the lime content increases in the sand pile, the swelling potential reduction factor decreases significantly and reaches 92.27% at lime content 20%. The relationship is linear as shown in the following equation:

$$\text{SPRF}(\%) = 4.7447 L_c (\%),$$
$$R^2 = 0.9854. \tag{8}$$

## 6. Conclusions

Based on the results obtained from the experimental tests and through the analysis of these results, the main conclusions can be summarized as follows:

(1) Installation of sand piles in expansive clay soils plays an effective role in reducing its swelling, and this role increases with stabilized sand piles by lime.

(2) The replacement area ratio plays a major role in the treatment level of expansive clay, where the swelling potential decreases dramatically with the increase of RAR.

(3) Further reduction in the swelling potential of expansive clay soil is noticed with the increasing lime content in stabilizing sand piles.

(4) The swelling potential of expansive clay soil decreases from 28.52% to 10.68% with increasing RAR from zero to about 57%.

(5) The swelling reduction ratio increases significantly with the increase of RAR, where it reaches 8.3%, 17.026%, 25.898%, 33.657%, 43.57%, and 61.06% with RAR being equal to 4.68%, 10.16%, 15.9%, 24.6%, 35.84%, and 56.94%, respectively, and this relationship is linear.

(6) The efficacy of sand piles in reducing the swelling potential of expansive soil can be improved by stabilizing sand piles by lime. The maximum of about (92.27%) reduction in the swelling potential is observed when the sand piles stabilized with lime content 20% at a replacement area ratio of 35.84%.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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