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Swelling Behavior Evaluation of a Lime-Treated Expansive Soil through Centrifuge Test

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Abstract: The main objectives of this research are to investigate the effect of hydrated lime (HL) treatment on the swelling behavior of a natural expansive soil, Eagle Ford clay from Texas, through centrifuge testing. So far, no studies have been performed using the centrifuge to analyze the swelling reduction in expansive soils by stabilization treatments. Also, no studies have measured the improvement of lime treatment efficiency due to variables controlled during preparation of lime-soil mixtures, such as compaction moisture content, compaction dry density, and the applied effective stress. From the analysis of the swelling versus time curves, three values were defined to examine the swelling behavior: the swelling potential (Sp), the primary swelling slope (PSS), and the secondary swelling slope (SSS). Assessment of the lime treatment efficiency, as quantified by the swelling potential reduction ratio (SPR) indicates that lime dosage requirements can be decreased by increasing the compaction moisture content and/or reducing the compaction dry density. Also the hydrated lime dosage needed to prevent swelling depends on the applied g-level (i.e., applied stress). **DOI: 10.1061/(ASCE)MT.1943-5533.0002090.** © *2017 American Society of Civil Engineers.*

Author keywords: Expansive soil; Swelling potential; Lime treatment; Centrifuge.

Introduction

Expansive soils typically involve highly plastic clays found around the world that undergo volumetric changes, in terms of swelling or shrinkage, due to changes in moisture content. The swelling of these soils is triggered by changes in environmental conditions either due to natural causes, such as heavy rains, or by construction-related issues, such as inadequate drainage of surface water from the structure or leaks in water or sewer lines.

Expansive soils originate from a combination of geological processes and diagenetic conditions that result in the formation of clay minerals susceptible to volumetric changes with moisture variations. The swelling potential of a soil mass depends on the fraction and type of clay minerals existent in the soil. The natural soil selected for this study was a clayey soil named Eagle Ford, which is abundant in Texas. The Eagle Ford soil is a yellowish/tan highly plastic clay weathered from fossiliferous clayey shale with sandy shale lenses (Lin and Cerato 2014). Lin (2012) reported that Eagle Ford clay includes montmorillonite (28%), illite (27%), and kaolinite (11%) as the main mineral components. As one of the main components of Eagle Ford clay, the montmorillonite is responsible for swelling behavior of this soil, because when this mineral comes into contact with water, the weak bonds are prone to break when any polar cationic fluid, such as water, penetrates between structural sheets (Mitchell and Soga 2005). The volumetric changes undergone by expansive soils have been responsible for significant damages on transportation infrastructure, shallow foundations and lightweight constructions, such as pavements, canals and reservoir linings, retaining walls, and single-story buildings.

The centrifuge test adopted in this study to evaluate the swelling behavior of expansive soils is a new technique developed at The University of Texas at Austin. This technique allows the testing of multiple specimens simultaneously, with a testing time that is significantly reduced in relation to that required from conventional free swell test. The rotation within the centrifuge imposes a gravitational field across the specimen, accelerating the water flow through the specimen and facilitating full water permeation and, consequently, entering into the microporous structure of the soil. The centrifuge facility used in this study also allows measurement in an expeditious way using an in-flight data acquisition system (Zornberg et al. 2009). The testing programs conducted using the newly developed device aim at expediting the determination of soil properties that would otherwise take a significant time to obtain. This is different than many other projects involving geotechnical centrifuges where the objective is to obtain in a reduced-scale model the response and state of stresses corresponding to a full-scale prototype structure. Nonetheless, evaluation of the scaling laws for centrifuge conditions leading to unsaturated flow under an approximately uniform acceleration field indicate that the discharge velocity is properly scaled by $1/N$ and time by N^2, where N is the average acceleration ratio between model and prototype (DellAvanzi et al. 2004). So far, a number of studies have confirmed the capability of this centrifuge test to measure accurately and quickly the expansion of natural soils (Plaisted 2009; Kuhn 2010; Walker 2012; Armstrong 2014; Das 2014; Snyder 2015). However, no studies have been performed using this centrifuge technology to analyze the swelling reduction in expansive soils by stabilization treatments.

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Note. This manuscript was submitted on December 4, 2016; approved on May 31, 2017; published online on October 4, 2017. Discussion period open until March 4, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561.

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Soil stabilization is the most common technique adopted to overcome issues related with problematic soils, such as expansive clays, around the world. In locations without availability of good aggregates or appropriate soils, the stabilization of available soils, in order to improve the geotechnical properties, is an effective solution. Among the techniques used to stabilize expansive soil in order to mitigate its swelling behavior, lime addition has been the most common technique due to the comparatively low cost of lime and its availability. A number of studies have documented that lime treatment may reduce the swelling potential of expansive soils (Holt et al. 2000; Al-Rawas et al. 2005; Panjaitan 2014; Schanz and Elsawy 2015; Nalbantoglu and Tuncer 2001). For instance, Schanz and Elsawy (2015) concluded that the swelling potential (i.e., the ratio between the height increase due to wetting in relation to the initial height) of an expansive soil was reduced from 34.5% to about 26.5% in specimens mixed with 10% of limestone, and from 34.5% to about 1% in specimens with 10% of hydrated lime (HL). Also, Nalbantoglu and Tuncer (2001) found that the swelling potential was drastically reduced from 20% for the untreated specimen to 1.5% when treated with a lime dosage of 2% with no curing time.

Even though the effect of lime addition on the swelling potential (Sp) of expansive soils has been well characterized, no studies have been identified that thoroughly address the effect of lime on the swelling mechanisms. Only a few studies have been identified regarding the swelling mechanisms in natural expansive soils, such as the research carried out by Sivapullaiah et al. (1996), who concluded that the size, shape, type, and amount of the nonclay fraction play significant roles in governing the swelling behavior. Das (2014) conducted a series of centrifuge tests on natural expansive soils, concluding that the secondary swelling increased with the increase in compaction moisture content and compaction dry density, and reduced with increasing gravitational gradient. Also, this study concluded that clays with flocculated structure (compacted dry of optimum) develop rapid primary swelling but less secondary swelling, as compared to clays with a disperse structure (compacted wet of optimum).

Several studies have only reported the Sp reduction obtained with a certain amount of lime, leaving aside the analysis of the effect of lime treatment on the expansion process. In other words, no studies have investigated the swelling behavior by measuring the improvement of lime treatment efficiency due to variables controlled during preparation of lime-soil mixtures (e.g., moisture content, density, applied effective stresses by increased g-level).

Thus, the main purposes of this research are to investigate the modification of swelling behavior due to lime treatment, and to measure the efficiency of lime treatment on swelling reduction due to different specimen preparation conditions. The modification of swelling behavior due to variations in lime-soil mixtures preparation is studied by analyzing the swelling versus time curves obtained from centrifuge tests carried out in the expansive soil of Eagle Ford clay. The analysis of these curves was made considering three important values: the primary swelling slope (PSS), the secondary swelling slope (SSS) and the swelling potential (Sp). The PSS provides insight into the water flow rate in the specimen that generates the most relevant fraction of the total swelling. The primary swelling occurs at a comparatively fast rate and it develops when the voids are not able to accommodate swelling clay particles. The Sp is the inflection point of the curve and usually represents around 80–90% of total swelling potential. The secondary swelling occurs at a lower rate, after the swelling potential has been reached and it allows predicting long-term swelling.

Based on the Sp values obtained for untreated and lime-treated Eagle Ford clay specimens prepared at different conditions, the parameter designated as swelling potential reduction ratio (SPR) was introduced to estimate the efficiency of lime treatment on swelling mitigation. The SPR corresponds to the ratio between the swelling potential of untreated Eagle Ford clay and that of lime-treated Eagle Ford clay.

Experimental Program

The expansive soil used in this study was Eagle Ford clay, which is abundant in Texas. Hydrated high-calcium lime, henceforth called *hydrated lime* (HL) was used because this type of lime enables the control of the moisture content of the lime-soil mixtures easier than quicklime. The chemical composition of the HL used in this study contains 94% of $Ca(OH)_2$.

Testing for this study was performed on remolded samples. Prior to testing, the soil was air-dried in room temperature until the soil was dry enough to be crushed. Then, the air-dried soil was processed using a mechanical soil crusher to break the large clods. After crushing, the soil was passed through the No. 10 sieve (aperture size 2 mm) and stored in sealed buckets until further use.

Lime-soil mixtures were prepared with dosage rates based on the dry weight of soil to be treated. Lime was added to the air-dried soil and mixed for approximately 5 min, before water addition, enabling the lime to be evenly distributed throughout the mix. Distilled water was added to the lime-soil mixture to achieve the desired moisture content. Then the lime-soil mixtures and water were hand mixed with the spatula for approximately 5 min more and finally compacted in order to run the tests.

Physical characterization tests were carried out using the natural and lime-treated expansive soil for determining the index properties of expansive soil. Table 1 summarizes the physical characterization results. As indicated by the results in Table 1, the Plasticity Index was significantly affected by lime addition, so the swelling properties of Eagle Ford clay were also expected to change with the presence of lime. The grain size distribution was evaluated by hydrometer tests conducted using a sample of untreated Eagle Ford clay (0% HL) and two lime-treated samples (2 and 4% HL) in order to determine the effect of lime treatment on the grain size distribution (Fig. 1). It can be observed that the addition of hydrated lime leads to a reduction in the percent of smaller particles. The flocculation process occurs after lime addition and particle aggregates are formed. The grain size distribution curve of fine-grains moved downward due to the increase in particle sizes. Compaction test results showed that the maximum dry density of the untreated Eagle Ford clay was 14.8 kN/m^3 obtained at an optimum moisture content of 24%, and a lime addition of 4% produced a decrease in the maximum dry density (14.0 kN/m^3), which corresponded to an optimum moisture content of 25%.

The Sp tests were carried out using the centrifuge equipment to evaluate the effect of compaction moisture content, compaction dry density (or relative compaction, RC %), and effective stress

Table 1. Physical Characterization of Natural and Lime-Treated Eagle Ford Clay

Hydrated lime (%)	CEC (meq/100 g)	pH	Gs	Atterberg limits LL	PL	PI
0	34.8	8.4	2.74	91.8	32.5	59.3
1	20.1	11.8	2.71	66.5	48.6	17.9
2	16.1	12.3	2.69	56.7	44.6	12.1
3	14.7	12.4	2.68	58.1	45.6	12.5
4	13.4	12.4	2.66	57.8	43.5	14.3

J. Mater. Civ. Eng., 2017, 29(12): 04017240

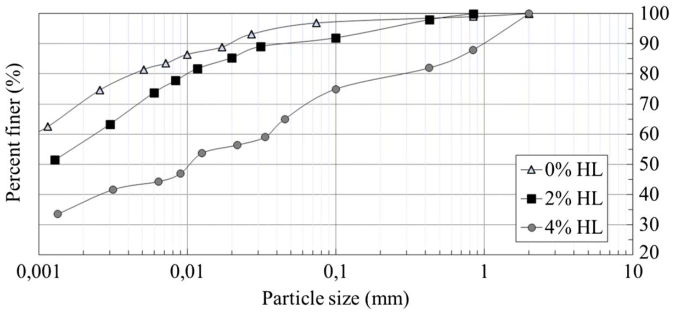

Fig. 1. Grain size distribution measured by hydrometer tests

(by g-level) on swelling behavior of the expansive soil treated with lime.

The centrifuge testing device and testing protocols used in this study to evaluate swelling behavior of expansive soils is a technique recently developed at The University of Texas at Austin (Zornberg et al. 2009). The centrifuge allows testing up to six soil specimens simultaneously, which facilitates the repeatability of results among identical specimens in order to obtain more reliable results. The rotation of the specimen within the centrifuge imposes a gravitational gradient across it by accelerating the water flow. Thus, the centrifuge testing approach takes comparatively short periods of time to permeate water into the specimen, which enters the microporous structure of the soil.

The centrifuge setup involves a Damon IEC CRU-5000 drum-centrifuge with a Model 259 rotor, with a diameter of 50 cm, data acquisition system (DAS), six centrifuge cups, and a control board. The equipment is located in the Geotechnical Laboratories at the University of Texas at Austin. Fig. 2 shows a view of the centrifuge testing environment. The centrifuge control board allows control of the angular speed and temperature. The centrifuge's rotor allows hanging metal cup holders that contain the soil specimens, which then spin along a radial direction, perpendicular to the axis of rotation of the centrifuge. The specimens are subjected to an increased gravitational field induced by the rotation within the centrifuge that is able to reach g-levels up to 200-g.

Fig. 3 shows the data acquisition system (DAS) components. The DAS includes a battery supply, an accelerometer, an analog-to-digital converter, and a linear position sensor (LPS). The LPS is attached at the lid of the centrifuge cup and is used for monitoring the vertical deformations of the soil specimens. The DAS is able to transmit wirelessly the sensor's data to a computer, which records voltage values over time from the LPS and accelerometer.

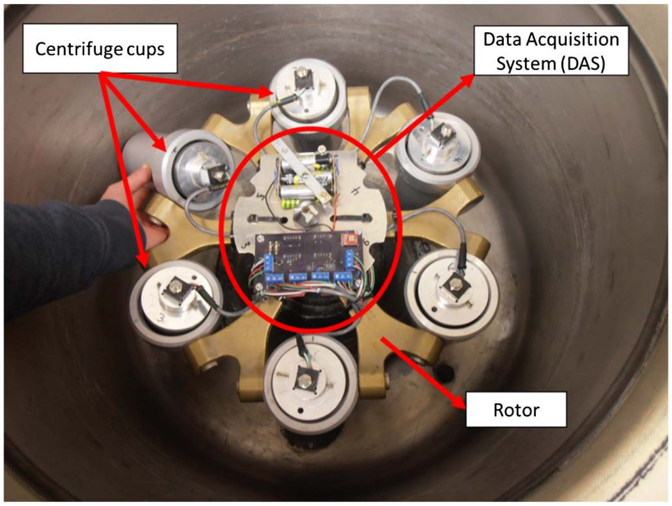

Fig. 2. Internal view of Damon IEC CRU-5000 centrifuge

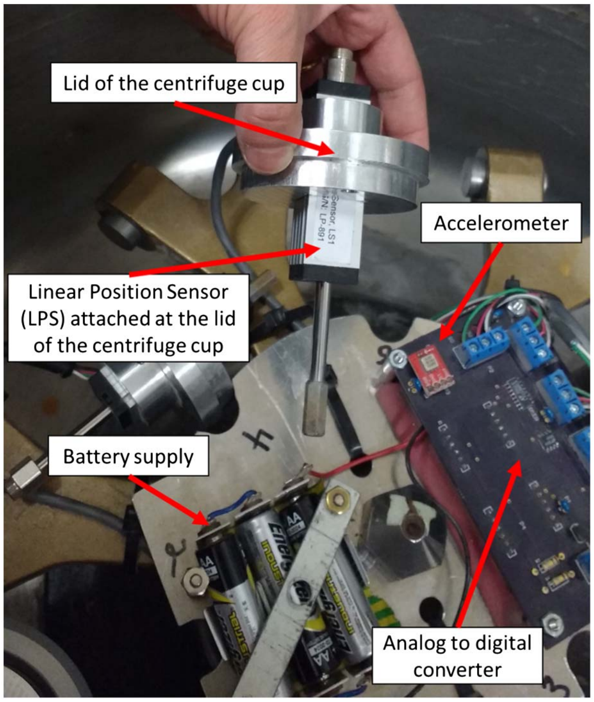

Fig. 3. Data acquisition system (DAS) components

In order to conduct the centrifuge test, compaction procedures were carried out to achieve the target density. The metal ring was prepared applying vacuum grease to reduce the friction between the specimen and ring walls during testing. Afterward, the ring was assembled with a brass porous disk and a filter paper, and the soil was poured into the ring using a funnel. The soil mass required to achieve the desired dry density was controlled with a scale. The specimens were prepared with dimensions of 1 cm in height and 5 cm in diameter using a rubber mallet and a cylindrical compactor. The specimen height was continuously monitored across the specimen surface using a caliper. Once the target specimen height was reached, the remaining soil on the ring wall was removed using a scratcher. Finally, the specimen preparation was completed by placing a second filter paper and brass porous disk on the top of the specimen. These brass porous disks were used to increase the applied effective stress and the filter papers to avoid the soil migration.

After specimen compaction, each ring was placed into a permeameter cup, which allows water infiltration from both sides, i.e., the top and base side of the specimen. Thus, the permeameter cup was inserted into the centrifuge cup in order to be hung on the centrifuge arms rotor. The lid of the centrifuge cup was placed close to the permeameter cup in order to finalize the testing assembly. Subsequently, the centrifuge was turned on and a *LabView* program was started to acquire the LPS and accelerometer data. Details about this program can be found in Walker (2012).

The specimens were spun into the centrifuge applying g-levels of 2–3-g in order to apply a seating load during 5 min. After the seating load cycle was completed, the g-level was adjusted for the desired g-level testing. At the desired g-level, the specimen underwent a compression for approximately an hour, or until the compression reached the original height specimen. After the

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compression cycle was completed, the centrifuge was stopped and around 80 g of distilled water were added to the specimen, using a syringe, through a little hole on the lid of the cups. After that, the centrifuge was restarted and allowed to spin for approximately 24 h. During this time, the water was infiltrated into the specimen generating the soil expansion.

When the centrifuge test was finalized, the centrifuge cups were removed to record the final weights of the total assembly and permeameter cups. The water in the cup was poured out and the metal ring with the specimen was taken out. The porous disks were removed and the solid dry mass was determined by placing the metal ring, wet specimen, and filter papers into the oven at 110°C.

Test Results and Analysis

Swelling was defined as the vertical strains in the specimen; that is, the ratio between the increase in height to the original specimen height, expressed as a percentage, and as shown in Eq. (1)

$$\text{Swelling}(\%) = \frac{h_t - h_0}{h_0} \times 100 \qquad (1)$$

where h_t = specimen height at time t and h_0 = specimen height at the beginning of the swelling potential test.

A typical swelling percent versus log time curve is shown in Fig. 4. It can be seen that the increase in swelling is comparatively fast during the initial phase of the test and then it decreases, ultimately reaching an asymptotic level. If tangent lines are constructed about the point of inflection, it is possible to define three important values from this curve: the PSS, the SSS, and the Sp, which is considered to be the inflection point of the curve.

These three values are important to describe the swelling mechanism of natural or lime-treated soils. The PSS provides an idea of the rate of flow into the specimen that generates the most representative percentage of the total swelling. The primary swelling occurs at a faster rate and it develops when the voids are not able to accommodate further swelling clay particles. The primary swelling typically represented 80–90% of the total swelling. The secondary swelling occurs at a lower rate, after the swelling potential is reached. The slope of the secondary swelling portion of the test allows prediction of long-term swelling.

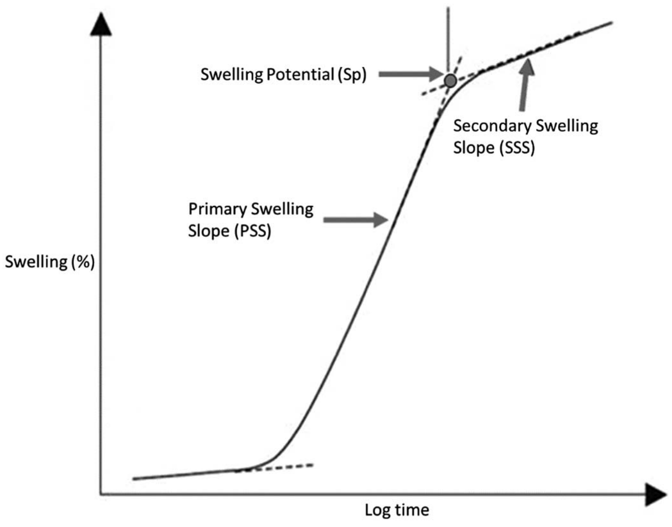

Fig. 4. Typical swelling percent versus log-time curve

In order to analyze the efficiency of lime dosage on the reduction of swelling potential, a parameter defined as the SPR, was introduced. SPR measures the reduction on Sp produced by HL additions, at different specimen preparation conditions, regarding the swelling potential in natural soil. SPR is defined by Eq. (2)

$$\text{SPR} = 1 - \frac{Sp_{(n\%HL)}}{Sp_{(0\%HL)}} \qquad (2)$$

where $Sp_{(0\%HL)}$ = swelling potential in untreated Eagle Ford clay and $Sp_{(n\%HL)}$ = swelling potential at particular hydrate lime dosage (n% HL). SPR value ranges from zero to 1. SPR will be zero for untreated Eagle Ford clay because there is no reduction of swelling potential, since there is no lime addition. And SPR will be equal to 1 when the addition of lime produces 100% of reduction of swelling potential compared with swelling potential in untreated Eagle Ford clay. Therefore, higher SPR corresponds to a more efficient lime treatment.

Evaluation of Compaction Moisture Content Effect on Swelling Behavior

Although several researchers have demonstrated that the swelling potential in expansive soils can be reduced with compaction at high moisture contents (Walker 2012; Armstrong 2014; Snyder 2015), no studies have been conducted on the effect of moisture content on the Sp of lime-treated soils. In order to examine the combined effect of lime addition with compaction moisture content variations on swelling behavior, the specimens with different HL dosages were compacted at three different moisture conditions, designated as dry of optimum (DOP), optimum (OPT), and wet of optimum (WOP).

The DOP condition was established at a moisture content of 21%, the OPT condition corresponded to 24%, and the WOP condition corresponded to 27%. A variation of ±1% in the moisture content was deemed acceptable. The dry density was kept constant at 14.8 kN/m^3 with acceptable variation of $\pm 1\ \text{kN/m}^3$. This series of experiments was carried out using the centrifuge technology where it was kept constant at the applied g-level of 5-g.

The swelling versus log-time curves obtained by a centrifuge test of untreated and lime-treated Eagle Ford clay, with lime dosages ranging between 0 and 4%, and prepared at different compaction moisture content are depicted in Figs. 5–7. It can be noted

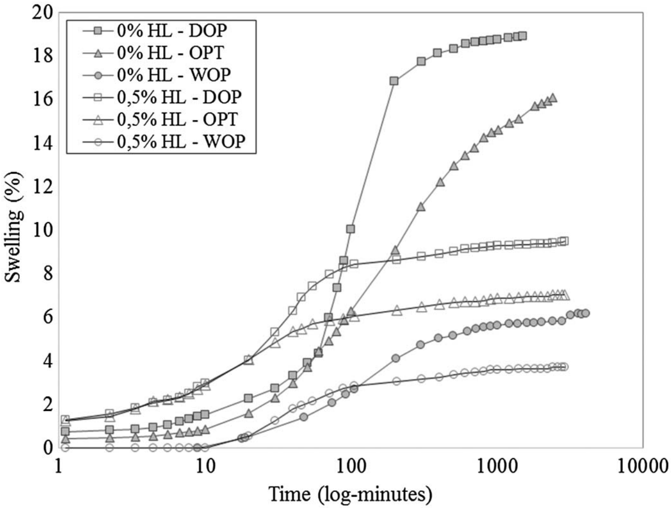

Fig. 5. Semi-log plot of centrifuge test results from specimens with 0 and 0.5% of hydrated lime compacted at different moisture conditions

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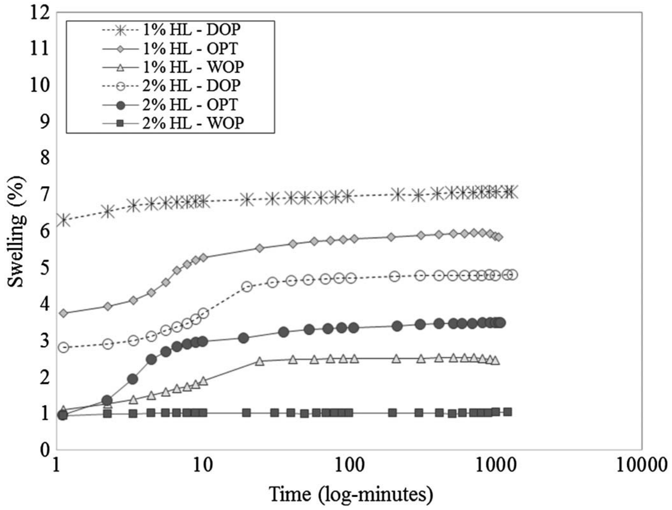


Fig. 6. Semi-log plot of centrifuge test results from specimens with 1 and 2% of hydrated lime compacted at different moisture conditions

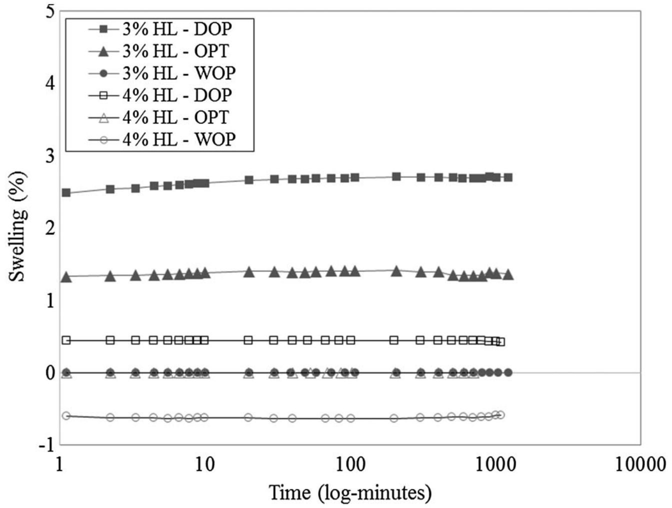
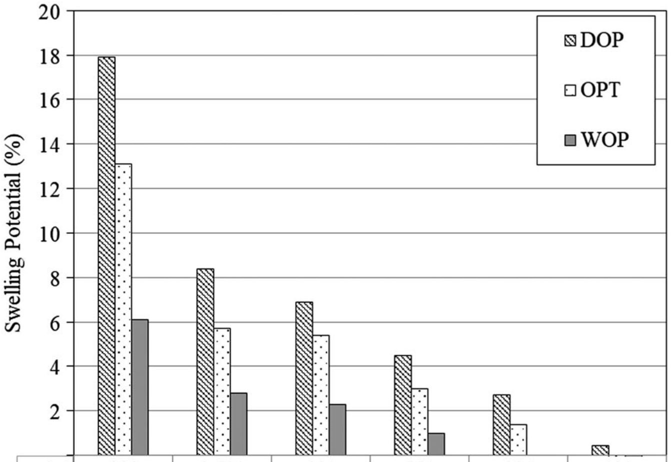


Fig. 7. Semi-log plot of centrifuge test results from specimens with 3 and 4% of hydrated lime compacted at different moisture conditions

that the centrifuge test exhibited changes in the swelling versus time curves when HL was added to the expansive soil, Eagle Ford clay. The lime-treated specimens reached the final of primary swelling faster than the untreated Eagle Ford clay (0% HL), regardless of the compaction moisture condition (DOP, OPT, or WOP). Also, it can be seen that the secondary swelling increased less after lime addition, because after the Sp was reached, i.e., when the curve passed the inflexion point, the second part of the curve becomes almost horizontal.

Bin et al. (2007), working on a clayey soil microstructure with nitrogen adsorption and desorption test, found that the addition of lime leads to an increase in the amount of pores related to the flocculation process. This may explain why lime-treated Eagle Ford clay reached its total swelling faster than the untreated Eagle Ford clay. The entrance of water into the lime-treated specimen may be facilitated by the presence of big pores of the flocculated structure. On the other hand, the entrance of water into natural Eagle Ford clay may be difficult, because of its small pores, making the development of the total swelling slower.



HL (%)	0%	0.5%	1%	2%	3%	4%
DOP	17.9	8.4	6.9	4.5	2.7	0.4
OPT	13.1	5.7	5.4	3.0	1.4	-0.3
WOP	6.1	2.8	2.3	1.0	0.0	-0.6

Fig. 8. Compaction moisture condition effect on swelling potential for different hydrated lime percentages

In Fig. 7, it can be noticed that the swelling potential obtained for specimens treated with 4% of HL and compacted at moistures conditions OPT and WOP resulted in small negative values. From the physical point of view, these values might be interpreted as small compressions undergone by the specimens, however, since the aim of this research is the expansion evaluation, they will be taken as zero swelling.

The effect of compaction moisture content on Sp for different HL dosages is depicted in Fig. 8. It can be observed that when the compaction moisture condition changed from OPT to WOP in the untreated specimens (0% HL), the Sp was similar to those reached from specimens with 0.5 and 1.0% of HL and compacted at OPT moisture condition. This suggests that the increase in moisture content is able to somehow substitute the lime addition in order to reduce the swelling potential. However, in field applications, if the moisture content is too high, the clayey soil might become so sticky and plastic that the equipment cannot handle the soil properly, and besides that, the soil can lose significant bearing capacity. Thus, the use of high moisture contents to reduce the swelling potential could not be applicable or recommendable in many cases of natural expansive soils.

Comparing the swelling potential obtained at DOP and WOP compaction conditions, a reduction of 66% of Sp in untreated Eagle Ford clay, from DOP to WOP can be observed. Making the same comparison for lime-treated specimens, it can be seen that the increase of compaction moisture content, from DOP to WOP condition, can reduce up to 100% of swelling potential, as shown in Fig. 8 for specimens with 3 and 4% of hydrated lime.

The moisture content variation makes a change in the soil microstructure. Lambe (1958) considered the microstructure of soil specimens compacted on the dry side of the compaction curve as soil particles that are typically configured in face-to-face and edge-to-face contacts that allow the development of soil swelling. The rearrangement of particles on the wet side of the compaction curve, instead, comes out in a more regular configuration, with only face-to-face contacts that make the entrance of water and the swelling behavior more difficult.

In order to estimate the SPR, defined by Eq. (2), the baseline swelling potential was established as the Sp obtained using the

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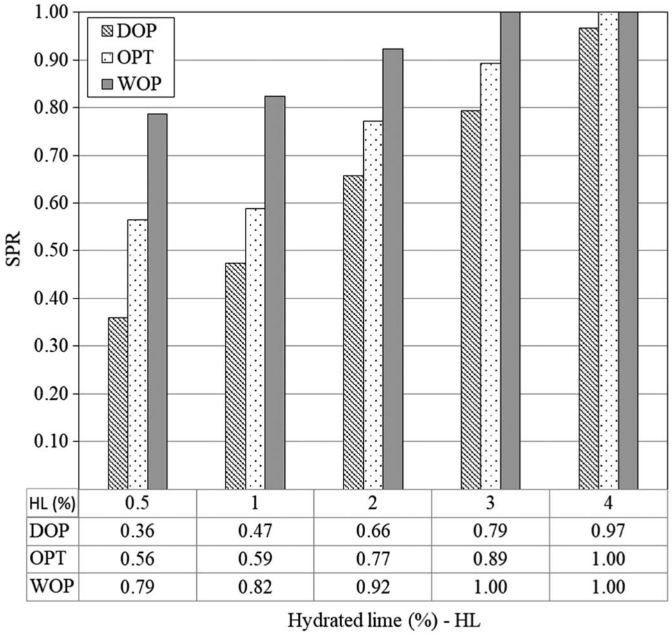
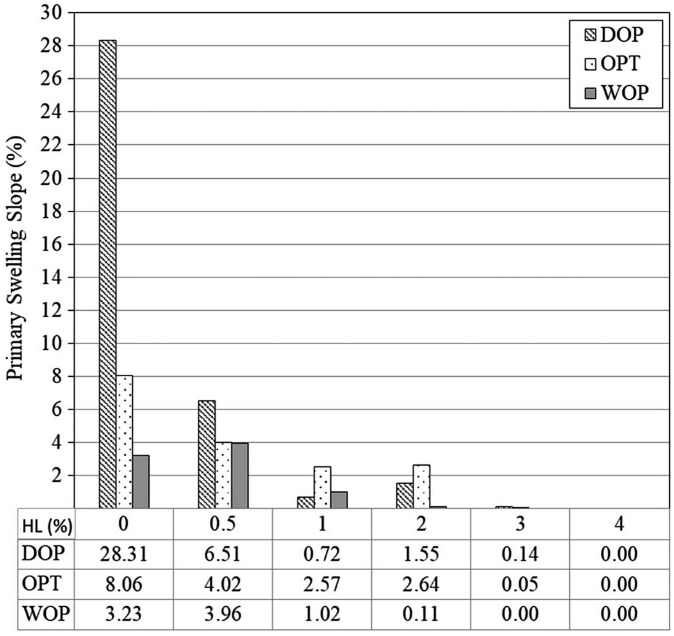


HL (%)	0.5	1	2	3	4
DOP	0.36	0.47	0.66	0.79	0.97
OPT	0.56	0.59	0.77	0.89	1.00
WOP	0.79	0.82	0.92	1.00	1.00

Fig. 9. Swelling potential reduction ratio (SPR) at different compaction moisture conditions



HL (%)	0	0.5	1	2	3	4
DOP	28.31	6.51	0.72	1.55	0.14	0.00
OPT	8.06	4.02	2.57	2.64	0.05	0.00
WOP	3.23	3.96	1.02	0.11	0.00	0.00

Fig. 10. Compaction moisture condition effect on primary swelling slope

centrifuge test for untreated Eagle Ford clay at OPT moisture condition, i.e., $Sp_{(0\%HL)} = 13.1\%$. The SPR at different compaction moisture contents and HL dosages is illustrated in Fig. 9.

Based on the patterns exposed in Fig. 9, the WOP condition produced the highest SPR values for all HL dosages. Furthermore, it can be noted that while the HL dosage is increased, the difference between the SPR at the three compaction moisture conditions DOP, OPT, and WOP seems to be reduced.

Also, the increment of compaction moisture content, e.g., from OPT to WOP condition, might reduce the amount of HL needed to avoid swelling behavior. For instance, in Fig. 9, it was observed that a slightly higher SPR value for the specimen treated with 1% HL and compacted at WOP than the SPR value obtained from the specimen treated with 2% HL and compacted at OPT condition. Therefore, an increase of 3% in compaction moisture content (i.e., from OPT = 24% to WOP = 27%) might result in almost the same swelling reduction produced by an additional of 1% of HL into the mixture. Since the lime addition also reduces the clay plasticity, problems related with workability are not to be expected with increasing compaction moisture content, as could be expected in the case of natural expansive soils compacted at high moisture contents.

Conversely, the DOP condition exhibited an adverse effect on swelling reduction. As can be observed in Fig. 9, the SPR value obtained in the specimen treated with 3% HL and compacted at DOP condition was similar to the one obtained with 2% HL and compacted at OPT condition. Since the DOP moisture condition may result in higher swelling potential, regardless of the HL dosage, the lime-treated soil moisture should be checked before compaction in construction processes in order to ensure that this soil had not lost too much water. In the cases of the lime-treated expansive soils that are found very dry, additional hydration must be necessary in order to reach the intended swelling potential reduction.

In order to examine the combined effect of lime addition with compaction moisture content variation on the swelling mechanism, the PSS and SSS were analyzed as follows.

The effect of compaction moisture content on the PSS is depicted in Fig. 10. The untreated Eagle Ford specimens (0% HL) showed an abrupt decrease in the PSS when the compaction moisture content was increased. The suction-induced infiltration occurred very fast under DOP condition, where the PSS was very high, due to the fact that in the DOP there were many available air voids being filled by water. When the compaction moisture condition changes from DOP to OPT or DOP to WOP, the void volume filled with water increases while the void volume filled with air decreases, thus it is expected in this case that a slower infiltration process occurs during the primary phase of swelling.

There is no clear pattern for slopes of primary swelling due to the combined effect of compaction moisture content with lime addition. However, it can be seen that there is some decrease of PSS when the compaction moisture condition changes from OPT to WOP in lime-treated Eagle Ford specimens. This behavior was also observed for the untreated Eagle Ford clay specimens.

On the other hand, no clear trend can be seen with respect to the DOP moisture condition in lime-treated specimens, because for 0.5 and 3% of HL, the PSS of DOP was higher than OPT and WOP, whereas for 1 and 2% of hydrated lime, the PSS of DOP was lower than OPT condition. The scattered behavior of PSS in DOP specimens may be attributed to a possible uneven water distribution into these specimens causing an uneven lime reaction through them.

In addition, it can be identified that the primary swelling slope observed in treated Eagle Ford specimens with 3 and 4% of HL was almost null for the three compaction moisture conditions (DOP, OPT, and WOP). This is because of the insignificant Sp reached for these HL dosages.

The effect of compaction moisture content on SSS was depicted in Fig. 11. It can be seen that the untreated Eagle Ford specimens (0% HL) also exhibited a decrease in the SSS when the compaction moisture condition was increased from DOP to OPT and DOP to WOP conditions. This is understandable because specimens with a higher compaction moisture content contain particles nearer to the

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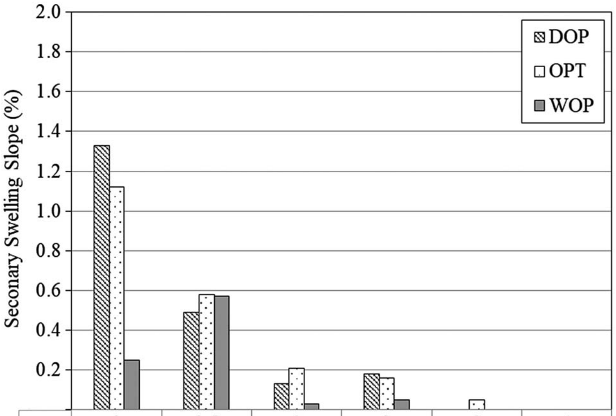


HL (%)	0	0.5	1	2	3	4
DOP	1.33	0.49	0.13	0.18	0.00	0.00
OPT	1.12	0.58	0.21	0.16	0.05	0.00
WOP	0.25	0.57	0.03	0.05	0.00	0.00

Fig. 11. Compaction moisture condition effect on secondary swelling slope

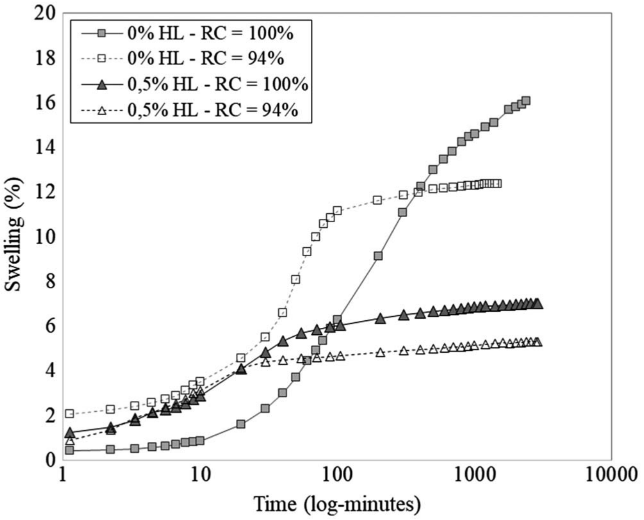


Fig. 12. Semi-log plot of centrifuge test results of specimens with 0 and 0.5% of hydrated lime and compacted at 94 and 100% relative compaction (RC)

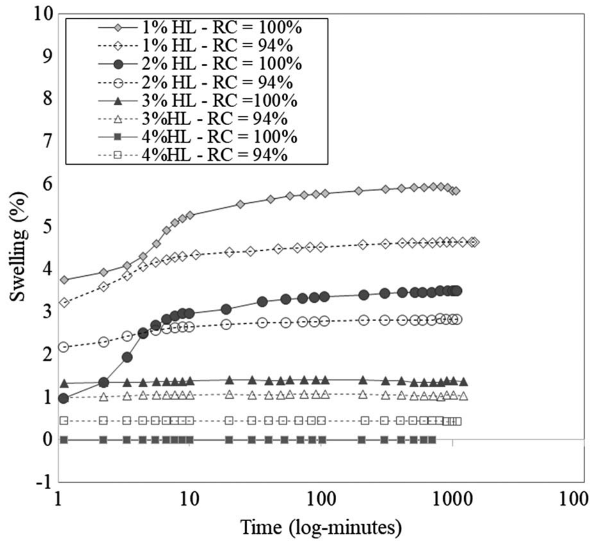


Fig. 13. Semi-log plot of centrifuge test results of specimens with 1, 2, 3, and 4% of hydrated lime and compacted at 94 and 100% relative compaction (RC)

total hydration. Thus, the secondary swelling, which is driven by the hydration process, is expected to decrease with an increase of compaction moisture content.

When HL was added, a high scatter pattern on the secondary swelling slope along with the compaction moisture condition can be observed. Despite the scattering behavior on the secondary swelling data, it can be noted that the lime addition produced very small SSS (<0.6%), so that the secondary swelling does not represent a significant portion over the total swelling in lime-treated Eagle Ford clay specimens.

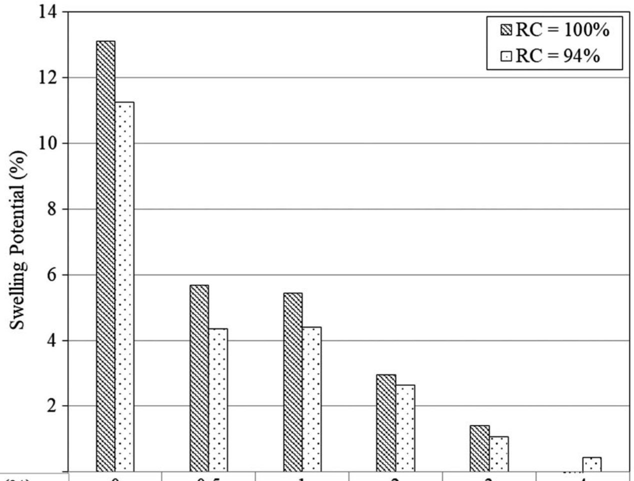
Evaluation of Compaction Dry Density Effect on Swelling Behavior

In order to quantify the combined effect of lime addition with compaction dry density variations on swelling behavior, the specimens were compacted at 94 and 100% of relative compaction (RC). According to the results of a standard Proctor compaction test carried out in untreated Eagle Ford clay, the maximum dry density was 14.8 $\mathrm{kN/m^3}$. Thus, the specimens with RC = 100% were compacted as close as possible to this dry density, whereas specimens with RC = 94% were compacted with dry density equivalent to 13.9 $\mathrm{kN/m^3}$. In this set of experiments, the specimens were spun at 5-g into the centrifuge. The moisture content was kept constant and close to the OPT condition of 24%.

The swelling versus log-time curves obtained by centrifuge testing of untreated and lime-treated Eagle Ford clay specimens that were compacted at RC = 100% and RC = 94% are shown in Figs. 12 and 13. By observing these figures, the general trend noted is a higher swelling in specimens compacted at RC = 100% than specimens compacted at RC = 94%, except for the specimens with a lime dosage of 4%, because with this dosage the swelling behavior trends to zero, regardless of the compaction dry density. Moreover, it was observed that while the lime dosage increases, the difference between the swelling developed by specimens at RC = 94% tends to become the same to the swelling developed by specimens at RC = 100%.

The swelling potential obtained in specimens compacted at RC = 100% and at RC = 94%, with different lime dosage, are depicted in Fig. 14. The untreated and lime-treated Eagle Ford specimens with lime dosages of 0.5, 1, 2, and 3%, reduced their swelling potential ranging from 13 to 25% for the same lime dosage, when RC was decreased from 100 to 94%. Contrariwise, the lime-soil mixture with a lime dosage of 4% showed a slight increase in swelling potential when RC was decreased from 100 to 94%. As stated earlier, the negative value of swelling potential should be interpreted as null swelling potential in this study.

Pedarla et al. (2016) analyzed specimens of natural expansive soils using a conventional consolidometer setup for measuring 1D swell. The specimens compacted at lower dry density experienced lower swell strains than the more compact specimens. They reported that this was expected for two reasons: the reduction in swell particles for a given volume of soils, and a larger void ratio at low dry density. These conditions allowed the void space to accommodate a partial amount of swelling in the soil specimen.



HL (%)	0	0.5	1	2	3	4
RC = 100%	13.1	5.7	5.4	3.0	1.4	-0.3
RC = 94%	11.3	4.3	4.4	2.6	1.1	0.4

Fig. 14. Relative compaction effect on swelling potential for different hydrated lime percentages

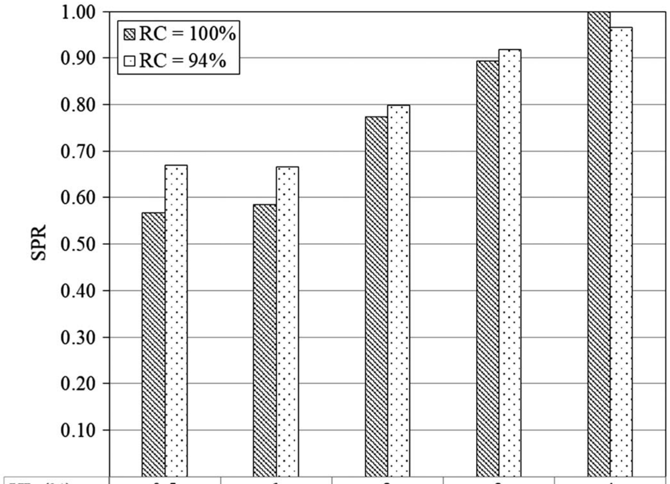
Likos and Lu (2006) analyzed the axial strain of Na and Ca smectite specimens compacted to different initial void ratios and hydrated within the crystalline swelling regimen. Their results also showed that denser specimens swelled more than initially loose specimens. They indicated that loosely compacted specimens exhibit more inefficient translation from particle-scale swelling to bulk-scale swelling because the interlayer volume changes occurring on the particle scale are internally adsorbed by the larger scale pores. Conversely, densely compacted specimens exhibit more efficient translation from particle-scale swelling to bulk-scale swelling because the interlayer volume changes are less well accommodated by the internal pores.

The combined effect of relative compaction reduction with lime addition on swelling potential was estimated by the SPR value, as defined by Eq. (2). The baseline swelling potential was established as the Sp obtained from untreated Eagle Ford clay compacted at OPT moisture condition and RC = 100%, i.e., $Sp_{(0\%HL)} = 13.1\%$. Therefore, the SPR values were calculated using the swelling potential obtained with different HL dosages; both relative compaction of RC = 100% and RC = 94% and the results are reported in Fig. 15.

The results suggest that when the hydrated lime dosage was increased, the SPR difference between specimens with RC = 94% and 100% was reduced. Also, it can be observed that the SPR for all HL dosages was greater in specimens compacted at RC = 94% than those compacted at RC = 100%, except for a lime dosage of 4%. Thus, the reduction in dry density (or RC) leads to the increase of lime addition efficiency on swelling reduction. However, unlike that observed for variations of compaction moisture content, the dry density variation could not offset the effect of a greater lime dosage.

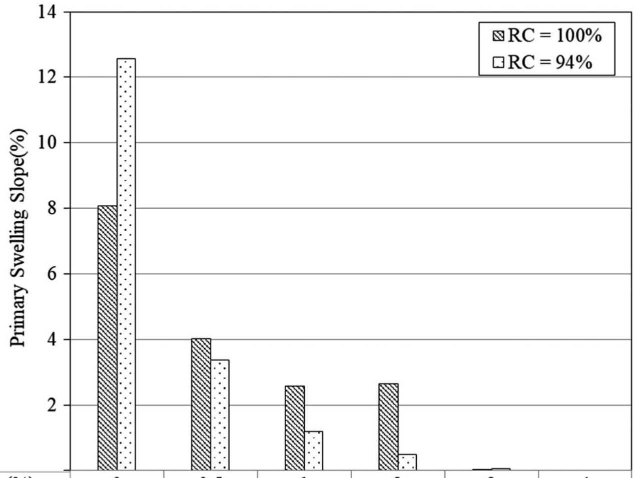
The PSS obtained in specimens compacted at RC = 100% and at RC = 94%, with different lime dosages, are shown in Fig. 16. It can be observed that the PSS in the untreated Eagle Ford specimen compacted at RC = 94% was higher than the specimen compacted at RC = 100%. Conversely, the lime-treated Eagle Ford specimen presented smaller PSS compacted at RC = 94% than those compacted at RC = 100%. Therefore, for untreated Eagle Ford specimens, a faster primary swelling development was observed in a loose specimen than in a denser one, whereas in lime-treated Eagle Ford clay, the primary swelling occurred faster in specimens compacted at higher dry density. The PSS changes its behavior from untreated to lime-treated Eagle Ford clay because the generation of cemented compounds, due to lime addition, may modify the process of water absorption by the capillarity process responsible for the primary swelling.

On the other hand, the SSS obtained in specimens compacted at RC = 100% and at RC = 94%, with different lime dosages, are shown in Fig. 17. It can be noted that both untreated and lime-treated Eagle Ford specimens compacted at RC = 94% presented SSSs smaller than those compacted at RC = 100%. Furthermore, it can be seen that lime-treated Eagle Ford clay for lime dosages of 3 and 4% presented negligible PSS and SSS values due to null (or almost null) swelling. From these results, it is possible to conclude that the hydration process, responsible for development of secondary swelling, depends on the compaction dry density in both



HL (%)	0.5	1	2	3	4
RC = 100%	0.57	0.59	0.77	0.89	1.00
RC = 94%	0.67	0.67	0.80	0.92	0.97

Fig. 15. Relative compaction effect on swelling potential reduction ratio (SPR) for different hydrated lime percentages



HL (%)	0	0.5	1	2	3	4
RC = 100%	8.06	4.02	2.57	2.64	0.05	0.00
RC = 94%	12.57	3.38	1.20	0.50	0.07	0.00

Fig. 16. Relative compaction effect on primary swelling slope

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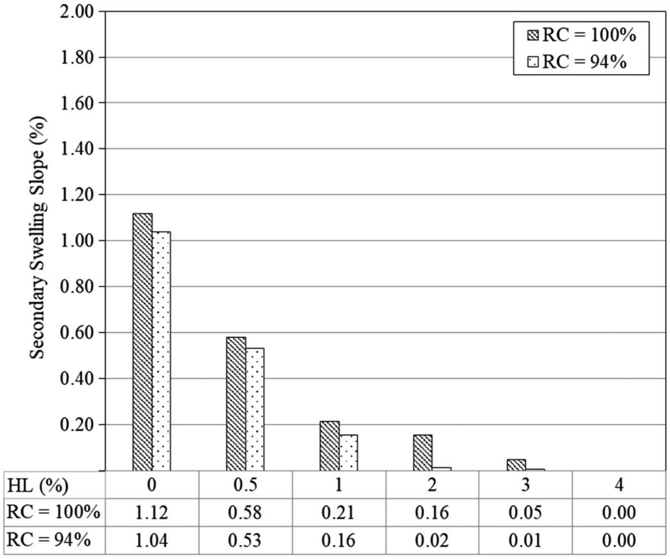

HL (%)	0	0.5	1	2	3	4
RC = 100%	1.12	0.58	0.21	0.16	0.05	0.00
RC = 94%	1.04	0.53	0.16	0.02	0.01	0.00

Fig. 17. Relative compaction effect on secondary swelling slope

untreated and lime-treated Eagle Ford clay. The behavior of secondary swelling is in accordance with the observations reported by Walker (2012) and Das (2014), for untreated expansive soils.

Evaluation of G-Level (Effective Stress) Effect on Swelling Behavior

The g-level within the soil specimens was controlled through regulating the rotational velocity of the centrifuge. In this set of experiments, the untreated and lime-treated Eagle Ford clay with lime dosages of 1 and 2% were subjected to g-levels of 5, 50, and 200-g. Untreated and lime-treated Eagle Ford specimens, regardless of the HL dosage, were compacted at the same dry density of 14.8 $\mathrm{kN/m^3}$ (with acceptable variation of $\pm 1\ \mathrm{kN/m^3}$) and at the same initial moisture content of 24% (with acceptable variation of ±1%). Since a constant water height of 2 cm was added on top of the soil specimen, the total stress applied over the specimen varied only with the g-level. For these tests, the effective stress varied between approximately 5 and 61 kPa.

The swelling versus log-time curves obtained by centrifuge testing for untreated and lime-treated Eagle Ford clay specimens subjected at different g-levels are shown in Figs. 18 and 19. It can be seen that less swelling was developed when the g-level was increased. This is because the increase in g-level results in an increase of effective stress applied on the specimens. This swelling behavior is corroborated with experimental results reported in the literature, such as Al-Mhaidib and Al-Shamrani (1996), Villar and Lloret (2008), and Komine (2004). Al-Mhaidib and Al-Shamrani (1996) conducted odometer tests on specimens treated with different lime dosages and subjected to different vertical pressures. According to their results, the increase in overburden pressure causes a reduction in the swell percentage. Villar and Lloret (2008) performed swelling deformation tests on a compacted bentonite. They concluded that the swelling develops more rapidly in the samples subjected to lower loads, because these samples are able to expand more, causing a greater increase in pore size and, therefore, in permeability.

The swelling potential variation with g-level is depicted in Fig. 20. It can be seen that the relationship between Sp and g-level, in a centrifuge test, fits trend lines described by natural logarithmic

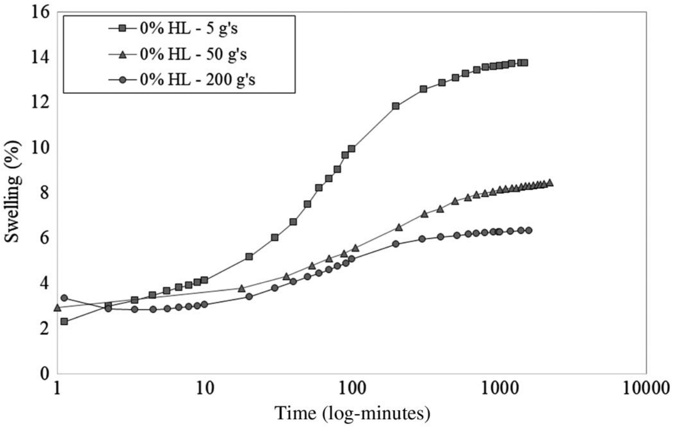

Fig. 18. Semi-log plot of centrifuge test results of untreated Eagle Ford clay specimens subjected to different g-levels

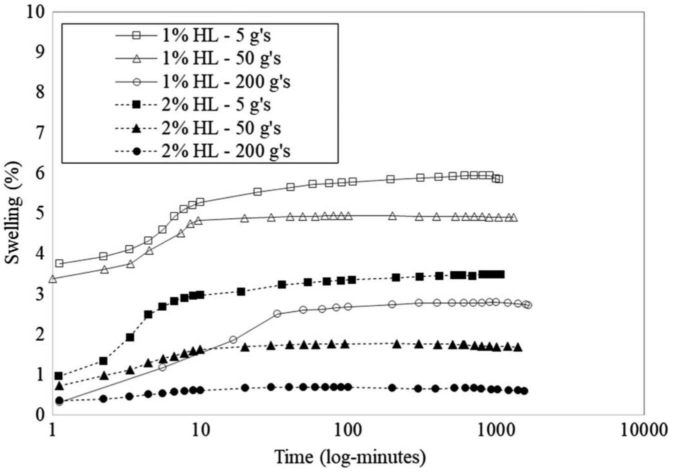

Fig. 19. Semi-log plot of centrifuge test results at different g-levels for lime-treated soils with 1 and 2% of hydrated lime

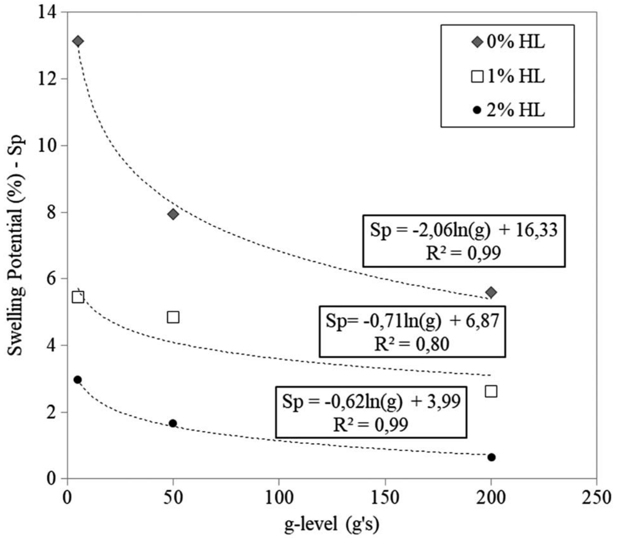

Fig. 20. Relationship between g-level and swelling potential in centrifuge tests of specimens with different percentage of hydrated lime

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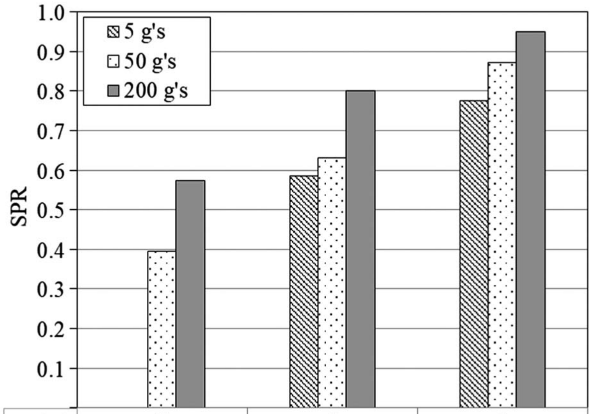
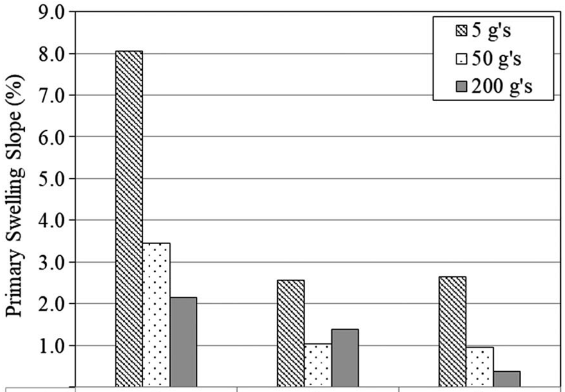


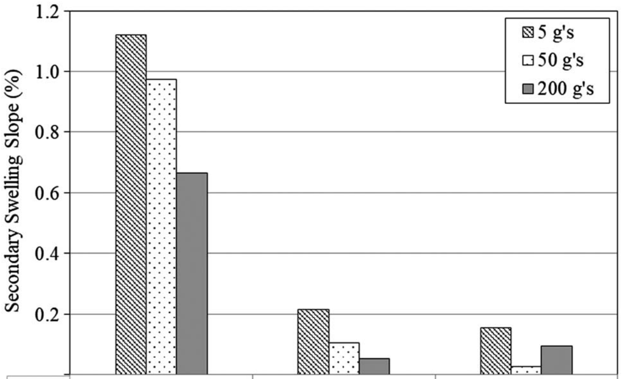
HL (%)	0	1	2
5 g's	0.00	0.59	0.77
50 g's	0.39	0.63	0.87
200 g's	0.57	0.80	0.95

Fig. 21. G-level effect on swelling potential reduction ratio (SPR) for different hydrated lime percentages



HL (%)	0	1	2
5 g's	8.06	2.57	2.64
50 g's	3.46	1.04	0.96
200 g's	2.14	1.38	0.37

Fig. 22. G-level effect on primary swelling slope



HL (%)	0	1	2
5 g's	1.12	0.21	0.16
50 g's	0.97	0.11	0.03
200 g's	0.67	0.05	0.09

Fig. 23. G-level effect on secondary swelling slope

functions for untreated and lime-treated Eagle Ford clay. If the Sp is estimated by using these natural logarithmic functions for a g-level equal to 1, then the Sp results will be 16.33% for 0% HL, 6.87% for 1% HL, and 3.99% for 2% HL. A significant drop in swelling potential occurred when the g-level was increased from 5 to 50-g. For instance, in untreated and lime-treated Eagle Ford clay specimens with a lime dosage of 2%, there was approximately a 40% reduction in Sp from 5 to 50-g. However, once the specimen was subjected to stresses related to 50 and 200-g, the swelling potential showed a less significant change.

The combined effect of effective stress (produced by variations of g-level) with lime addition on swelling potential was estimated by the SPR value, as defined by Eq. (2). The baseline Sp was established as the swelling potential obtained from untreated Eagle Ford clay compacted at OPT moisture condition, RC = 100%, and subjected to 5-g, i.e., $Sp_{(0\%HL)} = 13.1\%$. Therefore, the SPR values were calculated using the swelling potential obtained with different HL dosages and g-level variations. The results are plotted in Fig. 21.

The SPR results suggest that when the g-level (i.e., applied effective stress) increases, the SPR values also increase. Thus, the increase of effective stress leads to the increase of lime addition efficiency on swelling reduction. Also, the increment of the g-level might reduce the amount of HL needed to avoid the swelling behavior. So that the lime dosage needed to prevent the swelling behavior depends on the applied vertical stress generated by the structure projected on the expansive soil. Since the artificial g-levels are correlated with effective stress applied on the specimen, the amount of lime needed to prevent the swelling behavior also depends on the vertical stress that will be applied by the weight of the structure projected on the expansive soil.

The effect of g-level on the primary and secondary swelling slopes for 0, 1, and 2% of HL is depicted in Figs. 22 and 23. There is an evident decrease in primary and secondary swelling between results obtained at 5-g and those results at 200-g, independently of the HL dosage. Das (2014) reported a decrease in the SSS upon increasing the g-level for four types of untreated expansive soils (Eagle Ford, Tan Taylor, Houston Black, and Black Taylor), which are in accordance with the SSS results found here. The higher values of primary and secondary swelling in the specimens subjected to low g-levels are in accordance with the expected behavior due to the low effective stress applied on the specimens.

Concluding Remarks

In this study, the capability of centrifuge technology to assess the swelling reduction in expansive soils by stabilization treatments, such as lime treatment, was successfully verified. So far, only swelling measurements of natural soils had been done with this technology. However, the present results demonstrate that this technology can also facilitate the evaluation of solutions to mitigate soil expansion.

The swelling behavior of untreated and lime-treated Eagle Ford clay was found to be highly sensitive to variations in compaction moisture content. Varying the moisture content at the time of compaction changed from DOP (dry of optimum) to WOP (wet of optimum), and led to a reduction of 66% in the swelling of untreated Eagle Ford clay. Similarly, for the case of lime-treated specimens, reductions of up to 100% in the swelling was observed for similar

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variations in compaction moisture condition. Furthermore, it was found that the increase of compaction moisture content, e.g., from OPT to WOP conditions, resulted in a decrease in the dosage of HL needed to reduce the swelling potential of Eagle Ford clay. Since the lime addition also reduces the clay plasticity, problems associated with workability are not expected after increasing the moisture content during compaction, as it would be the case for natural expansive soils compacted at high moisture content values.

The compaction moisture condition DOP was found to have an adverse effect on the efficiency of the lime-treatment for swelling reduction. This moisture condition resulted in higher swelling potentials than those found for OPT or WOP conditions. Accordingly, lime treatment operations during construction should check the moisture of the lime-soil mixture in order to ensure that it is not in the DOP condition.

The compaction moisture content was found to affect the mechanism of swelling in untreated and lime-treated Eagle Ford clay. A decreasing primary swelling slope was identified for increasing compaction moisture content. Specifically, suction-induced infiltration occurred very fast under DOP conditions. Conversely, a slower infiltration process was found to develop for compaction moisture condition OPT and WOP.

Evaluation of the impact of the compaction dry density on the swelling behavior of untreated and lime-treated Eagle Ford clay showed that the Sp decreases slightly with decreasing relative compaction. This behavior was attributed to the fact that loosely compacted specimens exhibit a more inefficient transition from particle-scale swelling to bulk-scale swelling because the interlayer volume changes occurring on the particle scale are internally adsorbed by the larger scale pores. Conversely, densely compacted specimens exhibit a more efficient transition from particle-scale swelling to bulk-scale swelling because the interlayer volume changes are less well accommodated by the internal pores.

The efficiency of lime addition can be increased by reducing the compacted dry density. However, unlike what was observed by varying the compaction moisture content, reducing the compacted dry density did not offset the effect of a greater HL dosage required to mitigate swelling.

Simultaneous changes in compacted dry density and lime dosage resulted in different swelling mechanisms of untreated and lime-treated Eagle Ford clay. While for untreated Eagle Ford specimens, a faster primary swelling was observed to develop in comparatively looser specimens than in denser ones, in the case of tests involving lime-treated Eagle Ford clay, the primary swelling was found to be faster in specimens compacted at comparatively higher dry density values. The change in the primary swelling slope from untreated to lime-treated Eagle Ford clay was attributed to the generation of cemented compounds, due to lime addition, which is able to modify the water absorption that develops during primary swelling. Conversely, the hydration process responsible for the development of secondary swelling was found to depend only on the compacted dry density because its behavior showed the same trend for untreated and lime-treated specimens. The final hydration process occurred in a faster manner in specimens with high dry density.

The combined effect of lime addition and stress changes on the swelling behavior of untreated and lime-treated soils was evaluated by varying the g-level of centrifuge tests. A decreasing natural logarithmic function was found to describe the relationship between swelling potential and g-level. Considering that the artificial g-level correlates with the effective stress applied on the specimen, it was observed that the lime dosage needed to eliminate swelling also depends on the applied vertical stress to be applied by the founded structure on the expansive soil. Water infiltration was faster in specimens subjected to 5-g than in those subjected to 200-g, which was reflected in the higher values of primary and secondary swelling in the specimens subjected to 5-g.

Acknowledgments

The authors are grateful for the financial support from the Brazilian government: (1) National Council for Scientific and Technological Development (CNPq), for the scholarships (Doctorate and Research Productivity), and Universal Research Project and (2) Coordination for the Improvement of Higher Level or Education Personnel (CAPES), for the sandwich doctorate scholarship to develop this study. Support received by the Texas Department of Transportation and the National Science Foundation is also gratefully acknowledged.

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