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Swelling Potential Behavior of Expansive Soils Treated with Hydrated Lime

Ingrid Reyes Martinez Belchior
PUC-Rio, Rio de Janeiro - RJ, Brazil, ingridreyes@aluno.puc-rio.br

Michele Dal Toe Casagrande
PUC-Rio, Rio de Janeiro - RJ, Brazil, michele_casagrande@puc-rio.br

Jorge Zornberg
UT at Austin, Austin - TX, United States of America, zornberg@mail.utexas.edu

SUMMARY: This paper presents the results of an experimental program developed to investigate the effect of lime treatment on the reduction of swelling potential of an expansive soil. The swelling properties were determined using the new geotechnical centrifuge developed by The University of Texas at Austin. This new technology allows the infiltration water into the soil in shorter time than the conventional free-swell testing because of the high g-level acceleration applied in the specimens. The expansive clayey soil used in this study was Eagle Ford clay that was treated with different percentages of hydrated lime by weight of soil (between 0% and 4%). The compaction density of the specimens was varied between 94% and 100% of the maximum dry density, and the compaction moisture was varied between dry of optimum, optimum and wet of optimum moisture content. The centrifuge tests were carried out at three different g-levels acceleration in order to apply different vertical stresses during the swelling tests. The test results demonstrated that the effect of compaction density on the swelling potential is more significant when the specimens are compacted with low moisture content (dry of optimum) than specimens prepared at the optimum moisture content. However, most of the cases, higher potential swelling was observed in specimens prepared with densities near to the maximum than the specimens with lower density compaction. The results also allowed to conclude that the hydrate lime percentage required to avoid completely the swelling depends on the moisture condition and the effective stress. Samples compacted with wet of optimum moisture content required only 2% of lime to prevent the swelling behavior, whereas samples compacted at dry of optimum moisture content needed 4% of lime to avoid significant expansion at the same effective stress. The strong influence of the compaction moisture on swelling showed the same trend observed in untreated soils, where high potential swelling is produced when the specimens were compacted at dry of optimum moisture content than the compacted at optimum or wet of optimum moisture content. Higher compaction moisture than the optimum can be recommended for lime treated soils in order to allow the pozzolanic reactions taking place into the treated soil and to achieve the total elimination of swelling potential of expansive soils.

KEYWORDS: Expansive soil, swelling, lime treatment, centrifuge.

1 INTRODUCTION

The expansion of clayey soils has been considered an important challenge in the geotechnical engineering because of the potential and unpredictable damage associated with the heave movements of structure founded on such soils. Chen (2012) reported that the expansive soil damages can exceed the combined average annual damages from floods, hurricanes, earthquakes, and tornados in the United States.

Special relevance must be attributed to study the potential swelling behavior of soils used as subgrade for pavements since they are lightly loaded and this can facilitate the development of volume changes. This can result in instability of the road, uneven pavement surface, cracking and premature road deterioration. Among the solutions to the problems due to expansive soils are the replacing of clay with select fill material, the increasing of base thickness layer and the chemical treatment of the in situ clay. In many cases, the most economical alternative to reduce the swelling of expansive soils is the chemical treatment and lime has been the most popular chemical used for this purpose.

Numerous researchers have shown that two main processes occur when lime is added in soil in the presence of water: modification and stabilization (Boardman et al., 2001). During the modification process, the cation exchange begins to take place and the calcium ions from hydrated lime migrate to the surface of clay particles and substitute water and other ions. This changes the density of the electrical charge around the clay particles and attracts them closer to each other to form flocs (flocculation and agglomeration). In addition, improvements occur immediately in soil plasticity, workability, swelling and shrinkage properties, and permeability. On the other hand, the stabilization process indicates the presence of pozzolanic reactions. These reactions take place over a long period of time and are temperature dependent (Al-Mukhtar et al., 2010). During this process, the highly alkaline environment is produced by the addition of lime and induces the silica and alumina dissolution in clay minerals, which are combined with calcium to produce new cementitious compounds, such as, calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH) and calcium aluminum-silicate hydrates (CASH) (Al-Mukhtar et al., 2010).

The amount of lime required for the treatment of expansive soils is dictated by the ultimate objective of the treatment. If the objective is the soil modification, then strength and durability are not criteria at this dosage level. When the objective is soil stabilization, higher dosage of lime is required. According to Bell (1996), the optimum addition of lime needed for maximum modification of the soil is normally between 1% and 3% lime by weight, because further additions of lime do not bring changes in the plastic limit. Beyond this point, lime is available to increase the strength of the soil by pozzolanic reactions.

In this study, the lime dosage will be studied with focus on the modification process. We will assess the influence of dry density and moisture content on the lime treatment because these parameters usually are very heterogeneous in roads and railways embankments. Also the centrifuge tests were carried out at three different g-levels acceleration in order to apply different vertical stresses during the swelling tests. So far, the influence of water content and dry density on swelling potential of natural soils has been reported for many authors (Seed et al., 1962; Komine & Ogata, 1994; Al-Shayea, 2001; Mishra et al., 2008), however there are no studies about the effect of these parameters on the swelling behavior of lime-treated expansive soils.

2 METHODS AND MATERIALS

2.1 Centrifuge test method

Past works have demonstrated that the centrifuge set-up developed by The University of Texas at Austin is capable to measure the swelling potential of different expansive soils (Plaisted, 2009; Kuhn, 2011; Walker, 2012; Zornberg et al., 2013 and Armstrong, 2014). A briefly description of the equipment and the procedure test are summarized as follows.

The centrifuge set-up is composed of a Damon IEC CRU-5000 centrifuge with a Model 259 rotor, a Data Acquisition System (DAS), six centrifuge cups and a control board (Figure 1) The centrifuge's rotor allows hanging the metal buckets that contain the specimen cups letting them spin perpendicular to axis of rotation of the centrifuge. The specimens are subjected to an increased gravitational field induced by the rotation within the centrifuge that allows to reach G-levels up to 200g's.

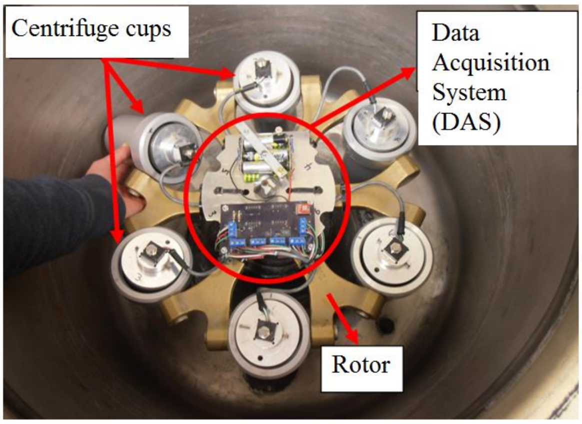

Figure 1. View within the centrifuge.

Figure 2 shows the Data Acquisition System (DAS) components, which are the Linear Position Sensors (LPS) for monitoring the vertical deformations of the soil specimens, battery supply, an accelerometer and an analog-to-digital converter. The DAS wirelessly transmits sensor data to a computer, which records the values over time. More details about DAS can be found in Walker (2012).

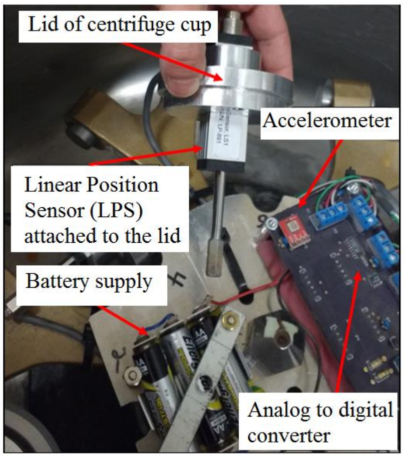

Figure 2. Data Acquisition System (DAS) components

The specimens are compacted to 1 cm height and 5 cm diameter into a metal ring, with control of the mass of soil required to achieve the desired dry density. Porous disks machined out of brass are placed on the top and under the base of the specimen to increase the applied effective stress, and filter papers are placed in between the soil specimen and each of the two porous disks to avoid the migration of soil and provide separation between the porous disks and soil. Each ring is placed into a permeameter cup that allows infiltration at both the top and base of the specimen.

The permeameter cups are inserted into the centrifuge cups and placed into the centrifuge (Figure 3 – A and B). The specimens are spun into the centrifuge where it is applied a G-level between 2 and 3 g's for seating load during 5 minutes. The seating load is necessary to guarantee the full contact between the porous disk, filter paper, and soil specimen. After the seating load cycle has been completed, the G-level is adjusted for the desired testing G-level, allowing the compression soil for approximately an hour. For this study, the G-level was maintained constant at 28g's for all the tests. After the compression cycle is completed, the centrifuge is stopped and around 80 grams of distilled water is added to the specimens through a little hole on the lid of the cups, using a syringe (Figure 3- C).

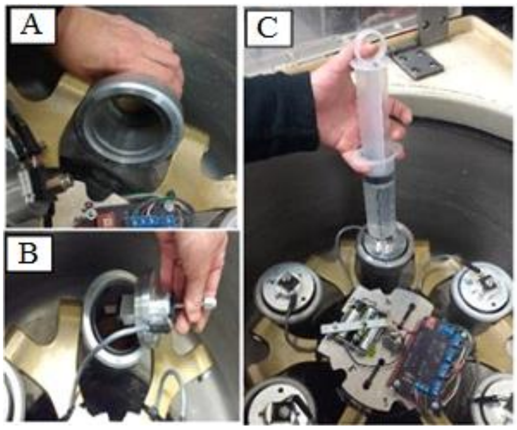

Figure 3. Placement of centrifuge cups into the centrifuge and (A and B) and water addition into the permeameter cups (C).

Therefore, the centrifuge is started and allowed to spin for approximately 24 hours until primary swelling is completed. After that, the specimens are removed from the centrifuge and placed in an oven at temperature of 110°C in order to verify the actual dry density of the specimens.

2.1 Materials

2.1.1 Expansive soil

The expansive soil selected for study was a highly clayey soil named Eagle Ford predominant in Texas, United States. This soil is a yellowish tan clay that contains minerals, such as montmorillonite/vermiculite, kaolinite, illite, and traces of palygorskite. The main geotechnical properties of Eagle Ford clay are listed in Table 1 and were determined in general accordance with American Society of Testing and Materials (ASTM) Standards.

Table 1. Geotechnical properties of Eagle Ford clay.

Property	Value
Liquid Limit, LL (%)	92
Plastic Limit, PL (%)	32
Plastic Index, PI (%)	59
Optimum moisture content, OMC (%)	22
Maximum dry density, MDD (kN/m3)	14.8
Specific gravity	2.74

Atterberg limits were performed following the procedures outlined in ASTM D4318-10. The values obtained suggest that Eagle Ford soil can be classified as clay of high plasticity (CH) in accordance with the Unified Soil Classification System (USCS). Standard Proctor compaction tests were performed in accordance with ASTM D698-12 in order to determine the relationship between moisture content compaction and dry density for Eagle Ford clay. The optimum moisture content determined by Standard Proctor compaction was 22% with a corresponding maximum dry density of 14.8 kN/m^3.The specific gravity was determined in accordance with ASTM D854-14 using the fraction of soil passing the No. 4 sieve. The average value of specific gravity of Eagle Ford clay was 2.74.

2.1.2 Lime

Lime is produced in various forms, however for stabilization applications, the most typically used are: hydrated high-calcium lime [Ca $(OH)_2$] and quicklime (CaO). In this study, we used hydrated high-calcium lime because this type of lime enables to control the moisture content of the soil-lime mixtures easier than quicklime. Quicklime needs to consume a considerable amount of water when it hydrates in an exothermic reaction before reacting with the soil particles. The chemical composition of the hydrated lime was provided by Austin White Lime Company[1] and is listed in Table 2.

Table 2. Chemical analysis of hydrated lime (Austin White Lime Company).

Chemical analysis	(%)
Ca(OH)2	94
Free CaO	0.1
Free H_2O	0.4
Inerts	3.5
LOI	24.16
$CaCO_3$	2.0

2.1.3 Specimens preparation

The lime-treated soil was prepared by adding various percentages of lime ranging from 0% to 4% by dry weight of soil. Figure 4 shows that the liquid limit (LL) decreases with the added lime percentage up to 2% while plastic limit (PL) increases up to 1%. Lime additions higher than 2% showed almost constant values for both LL and PL, and consequently the plastic index (PI) becomes also almost constant between 2% and 4% of lime. According to Bell (1996), when lime is added to a clayey soil, it must first satisfy the affinity of the soil for lime. Thus, ions are absorbed by clay minerals and are not available for pozzolanic reactions until this affinity is satisfied. The amount of lime that satisfies this affinity corresponds to the lime fixation point and is represented with the point where further additions of lime does not bring about further changes in the plastic limits. Therefore, this is the optimum addition of lime needed for maximum modification of soil, and beyond this point, lime is available to increase the strength of the soil and begins the stabilization process. In this study, the lime fixation point corresponds to 2% of hydrated lime.

[1] http://www.austinwhitelime.com/

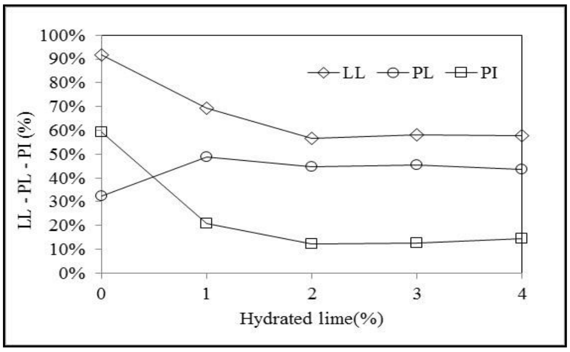

Figure 4. Atterberg limits variation with hydrated lime content.

The influence of the lime treatment on the compaction characteristics have been demonstrated in diverse works (Bell, 1996; Osinubi et al., 2006; Kavak & Akyarli, 2007). Considering the Standard Proctor compaction, the optimum moisture content (OMC) and the maximum dry density (MDD) of Eagle Ford clay was evaluated without addition of hydrated lime (0% HL) and a mixture of this soil with 4% hydrated lime (4% HL). Since the objective of this study was not to evaluate the compaction characteristics of lime-treated soils, the Standard Proctor tests were carried out only with the purpose of fixing values of moisture and dry density that will be constant for all the specimens.

The Standard Proctor compaction tests showed that the optimum moisture content of the untreated soil (0% HL) was 22% and for the mixture with 4% of hydrated lime was 26%. Thus, in our study, regardless the hydrated lime percentage in the mixtures, it was used 24% of moisture content as OMC (optimum moisture content), which is the average of these two moistures. In order to understand the moisture content variation effect on lime treatment, we established 21% of moisture content for DOP (dry of optimum moisture content) and 27% of moisture content for WOP (wet of optimum moisture content). In the same way, the maximum dry density (MDD) was kept constant, regardless the lime percentage applied in the treatment. Thus, for MDD an average value of 14.3 kN/m^3 was chosen.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Hydrated lime percentage and moisture content effect on swelling potential

The first analysis done was about the influence of the lime percentage on swelling behavior. Figure 5 shows the typical swelling potential result obtained by centrifuge test. This result corresponds to swelling evolution with time obtained in specimens with 0%, 1% and 2% of hydrated lime (HL), compacted at optimum moisture content and subjected to an effective stress of 10 kPa (approximately 28g's acceleration). The swelling is expressed as a percentage increase in specimen height.

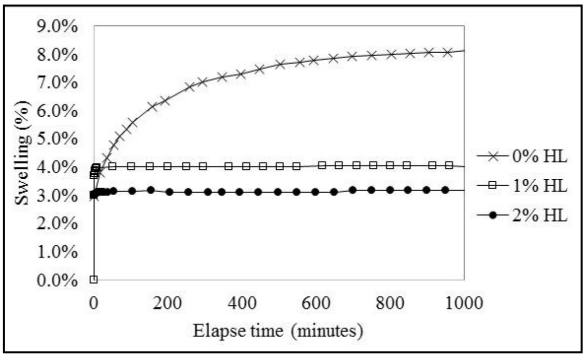

Figure 5. Evolution of swelling with time in centrifuge test.

The effectiveness of the centrifuge method can be seen in Figure 5. The swelling reached the stable value quickly because the centrifuge acceleration allowed to obtain fast infiltration of water into the specimens. Al-Mhaidib & Al-Shamrani (1996) reported that they needed about 3 days for reaching swelling equilibrium value in specimens with 1%, 2% and 3% of lime submitted to one-dimensional oedometer test (conventional free swell test), whereas, in this study, the specimens reached the swelling equilibrium in around 2 hours (120 minutes). Figure 5 also shows that the non-treated soil (0% HL) took more time than the mixtures with lime to reach swelling equilibrium value, whereas the treated soils reached the swelling equilibrium in few minutes. The specimen reached the stable swelling value faster than untreated specimen because the hydraulic conductivity increases after lime mixing, then the water infiltration was facilitated.

Independently of the moisture condition, which the specimen was compacted, the swelling potential decreased when the hydrated lime (HL) percentage was increased. Elkholy (2011) shows that there was significant improvement in swelling reduction of expansive soils when coarse grain soil was added to the expansive soil. Although sand does not have any chemical properties like hydrated lime to alter final properties of soil mixture, the flocculation and agglomeration processes that take place with lime addition into the soil could represent similar changes in grain size distribution produced by coarse grain addition. The agglomeration of clay particles, due to lime addition, produces aggregates separated by big inter-voids, and this new grain configuration reduces the swelling behavior of the expansive soil.

Figure 6 depicts the stable swelling value reached for several specimens varying the hydrated lime percentage. The specimens were compacted at constant density varying the moisture contents, i. e., DOP (w = 21%), OPT (w = 24%) and WOP (w = 27%). The results indicated that the total reduction of potential swelling depends on the moisture content during the specimen compaction. Holtz and Gibbs (1954) have shown that if a clayey soil is compacted at WOP moisture content, the swelling potential will be less than for the same soil compacted at DOP. Chen (2012) stated that the decrease in moisture content compaction results in increasing of water affinity due to the higher matric suction and the increase of swelling. These behaviors seems to be the same for lime-treated soils because specimens compacted at DOP moisture condition registered less swelling reduction than specimens compacted at OPT and WOP moisture conditions.

Moreover, when the lime-treated soil is prepare at WOP, the total reduction of swelling potential appears at 2% of hydrated lime, whereas in specimens compacted at DOP, 4.5% of hydrated lime was needed to achieve swelling potential lower than 1%.

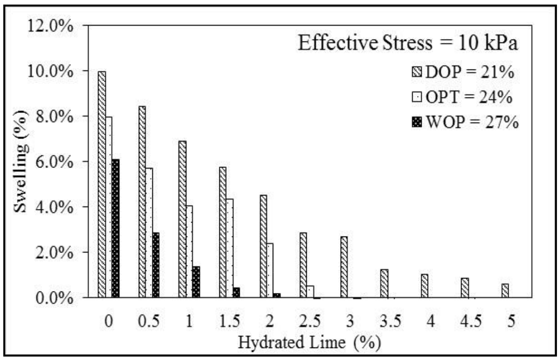

Figure 6. Swelling potential variation with hydrated lime percentage and compaction moisture content.

3.2. Centrifuge acceleration effect on swelling potential

The specimens used to analyze the effect of centrifuge acceleration were compacted at OPT moisture content (w = 24%) and MDD (14.3 kN/m^3). Three centrifuge accelerations were applied in the specimens treated with different percentage of lime. Figure 7 shows the results obtained in tests run at 5, 28 and 120g’s. These centrifuge accelerations produced effective stresses equivalents to 3, 10 and 50 kPa, respectively.

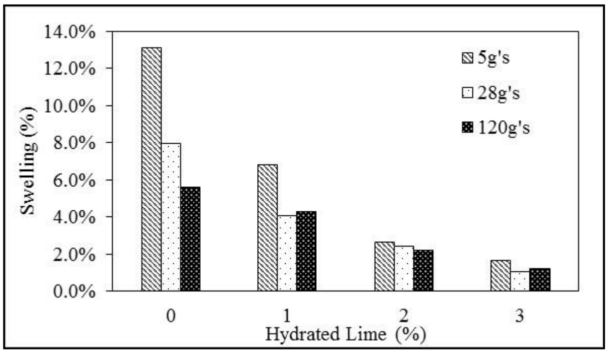

Figure 7. Swelling potential variation with G-level.

A noticeable drop in swelling occurs when g-level increases from 5 to 28g’s. However, once the specimens were subjected to stress relating to 120g’s, the swelling did not change significantly in specimens treated with 2% HL or higher percentages of hydrated lime. Therefore, the swelling reduction by lime treatment is independent of effective stress when Eagle Ford clay is treated with hydrated lime percentages above 2% by dry weight of soil.

3.2. Dry density compaction effect on swelling potential

Three groups of tests were done to analyze the effect of the ratio compaction on swelling potential of lime-treated expansive soils. These groups correspond to specimens prepared at DOP, OPT and WOP moisture contents. As described previously, the maximum dry density (MDD) used for all the specimens was 14.3 kN/m3. The specimens were compacted at 100% and 94% of relative compaction (RC) for the three moisture contents. Figure 8 shows the swelling potential measured in specimens compacted at DOP and varying the hydrated lime percentage and the dry density (RC). In the DOP moisture condition, the results showed that the higher the dry density (100% RC), the larger the swelling potential. Due to that the fact, in average, it was found 3.5% less swelling in specimens compacted at 94% MDD than specimens compacted at 100% RC with the same hydrated lime percentage.

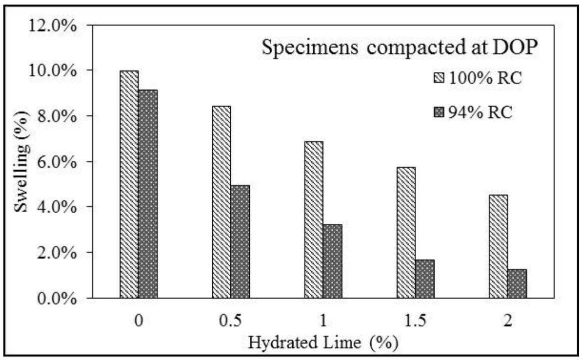

Figure 8. Swelling potential measured in specimens compacted at DOP with variation in compaction density.

When the specimens were compacted at OPT moisture content, it seems that the same DOP trend remains, because higher swelling potential was produced in specimens with higher density compaction (100% RC). However, the difference between swelling potential of specimens compacted at 94% RC and 100% RC was in average 1.0%, for samples with the same hydrated lime content (Figure 9).

On the other hand, different trend was observed in specimens compacted at WOP moisture content. Figure 10 shows swelling potentials slightly higher in specimens with lower density than in specimens compacted at 100% RC.

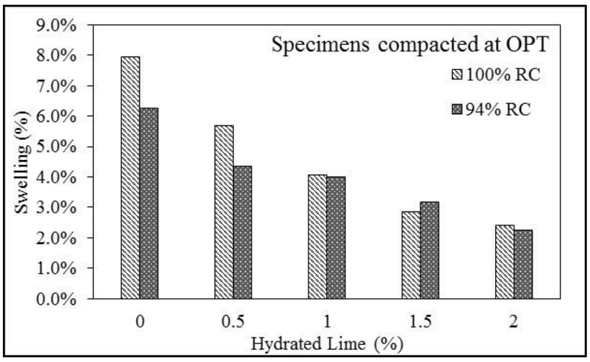

Figure 9. Swelling potential measured in specimens compacted at OPT with variation in compaction density.

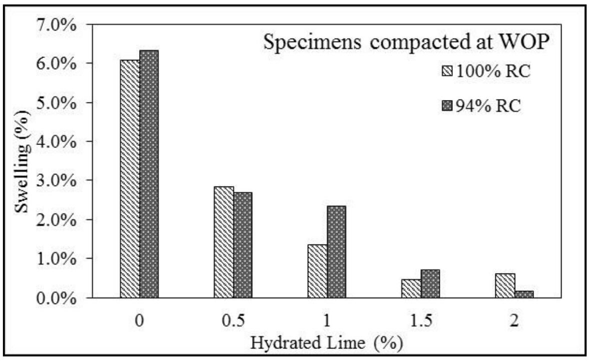

Figure 10 Swelling potential measured in specimens compacted at WOP with variation in compaction density.

4 CONCLUSIONS

According to results achieved from centrifuge permeameter tests, increment of lime content in the clayey soil Eagle Ford caused a decrement on the swelling potential. The test results indicated that 2% of hydrated lime was enough to avoid swelling in specimens prepared at wet of optimum moisture content (w = 27%), whereas, in specimens compacted at dry of optimum moisture content (w = 21%), 4.5% of hydrated lime was needed to achieve swelling potential lower than 1%.

The optimum hydrated lime percentage based on changes in plasticity index was 2% of hydrated lime that corresponded to the hydrated lime percentage needed to avoid swelling potential in specimens compacted at wet of optimum moisture content. In addition to that, swelling measured in specimens treated with hydrated percentages above 2% showed no dependency on effective stress (g-level in centrifuge tests).

In general, for constant moisture content between dry of optimum and optimum moisture content, the swelling potential is higher in specimens with high relative compaction density. However, specimens compacted at wet of optimum moisture content show lower swelling potential in higher compaction densities.

The compaction conditions, such as initial density and initial moisture content, are important factors that affect the swelling potential of lime-treated expansive soils. Consequently, this influences the adequate determination of the optimum lime content needed to avoid the swelling behavior of expansive soils.

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REFERENCES

Al-Mhaidib, A. I., & Al-Shamrani, M. A. (1996). Swelling characteristics of lime-treated expansive soils. *Geotechnical engineering*, 27, 37-54.

Al-Mukhtar, M., Lasledj, A., & Alcover, J. F. (2010). Behaviour and mineralogy changes in lime-treated expansive soil at 20 C. *Applied clay science*, 50(2), 191-198.

Al-Shayea, N. A. (2001). The combined effect of clay and moisture content on the behavior of remolded unsaturated soils. *Engineering geology*, 62(4), 319-342.

Armstrong, C. P. (2014). Effect of fabric on the swelling of highly plastic clays (*Master theses, University of Texas*).

ASTM D4318-10 (2010). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA. www.astm.org

ASTM D698-12 (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International, West Conshohocken, PA. www.astm.org

ASTM D854-14 (2014). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, ASTM International, West Conshohocken, PA. www.astm.org

Bell, F. G. (1996). Lime stabilization of clay minerals and soils. *Engineering geology*, 42(4), 223-237.

Boardman, D. I., Glendinning, S., & Rogers, C. D. F. (2001). Development of stabilisation and solidification in lime–clay mixes. *Geotechnique*, 51(6), 533-543.

Chen, F. H. (2012). Foundations on expansive soils (Vol. 12). Elsevier.

ElKholy, S. M. (2011). Improving the characteristics of expansive soil using coarse-grained soil. *Journal of Engineering and Computer Sciences*, 1(2).

Holtz, W. G., & Gibbs, H. J. (1956). Engineering properties of expansive clays. *Transactions of the American Society of Civil Engineers*, 121(1), 641-663.

Kavak, A., & Akyarli, A. (2007). A field application for lime stabilization. *Environmental geology*, 51(6), 987-997.

Komine, H., & Ogata, N. (1994). Experimental study on swelling characteristics of compacted bentonite. Canadian geotechnical journal, 31(4), 478-490.

Kuhn, J. A. (2010). Characterization of the swelling potential of expansive clays using centrifuge technology (*Doctoral dissertation, University of Texas*).

Mishra, A. K., Dhawan, S., & Rao, S. M. (2008). Analysis of swelling and shrinkage behavior of compacted clays. *Geotechnical and Geological Engineering*, 26(3), 289-298.

Plaisted, M. D. (2009). Centrifuge testing of an expansive clay (*Master theses, University of Texas*).

Osinubi, K. J., & Nwaiwu, C. M. (2006). Compaction delay effects on properties of lime-treated soil. *Journal of materials in Civil Engineering*, 18(2), 250-258.

Seed, H. B., Mitchell, J. K., & Chan, C. K. (1962). Studies of swell and swell pressure characteristics of compacted clays. *Highway Research Board Bulletin*, (313).

Walker, T. (2012). Quantification using centrifuge of variables governing the swelling of clays. (*Master theses, University of Texas*).

Zornberg, J.G., Armstrong, C.P., Plaisted, M.D., and Walker, T.M. (2013). Swelling of Highly Plastic Clays under Centrifuge Loading. *Center for Transportation Research (CTR)*, Product Report No. 5-6048-01-P2, Austin, Texas, May, 8 p.