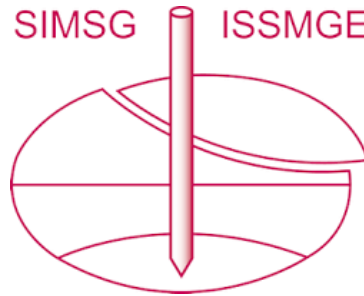


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Temperature effects on the mechanical behavior of saline soils stabilized with lime

Effets de la température sur le comportement mécanique des sols salins stabilisés à la chaux

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ABSTRACT: Several problems related to earthen structures have been registered in the Occidental region of Paraguay known as the Paraguayan Chaco. Sedimentary fine sand and silty clay soils containing salts are typically found in this region, and these salts are mainly conformed by sodium chlorides, sodium sulfates, and calcium sulfates. In the Paraguayan Chaco, dispersive soils also known as erodible soils, were responsible for the failure of a number of slopes and embankments whereas sulfated soils caused several damages over hundreds of kilometers of pavements conformed by soil-lime bases and sub-bases. This work seeks to evaluate the use of lime in the improvement of the mechanical behavior of both dispersive and sulfated soils. To achieve that, unconfined compression tests, durability tests, and expansion tests are performed on dispersive and sulfated soils stabilized with different lime contents, dry unit weights and curing times. Moreover, two temperatures (23°C and 40°C) are assessed in the molding of specimens, considering the high temperatures commonly developed in this region. It is observed that the use of lime is efficient in the stabilization of dispersive soils, eliminating dispersive phenomenon and improving the strength and durability of the new geomaterial. However, in the case of sulfated soils, high swelling besides poor strength and durability evident that lime stabilization technique may be a new problem instead of a solution. Additionally, it is shown that subjecting soil-lime samples to 40°C improves the performance of the geomaterials conformed by both dispersive and sulfated soils.

RÉSUMÉ: Plusieurs problèmes liés aux structures en terre ont été enregistrés dans la région occidentale du Paraguay connue sous le nom de Chaco paraguayen. Les sols sédimentaires de sable fin et d'argile limoneuse contenant des sels se trouvent généralement dans cette région, et ces sels sont principalement constitués de chlorures de sodium, de sulfates de sodium et de sulfates de calcium. Dans le Chaco paraguayen, les sols dispersifs aussi appelés sols érodables, ont été responsables de la rupture de plusieurs talus et remblais alors que les sols sulfatés ont causé plusieurs dégâts sur des centaines de kilomètres de chaussées conformées par des assises et sous-couches sol-chaux. Ce travail vise à évaluer l'utilisation de la chaux dans l'amélioration du comportement mécanique des sols à la fois dispersifs et sulfatés. Pour y parvenir, des tests de compression non confinée, des tests de durabilité et des tests d'expansion sont effectués sur des sols dispersifs et sulfatés stabilisés avec des teneurs en chaux, des poids unitaires secs et des temps de durcissement différents. De plus, deux températures (23°C et 40°C) sont évaluées lors du moulage des éprouvettes, compte tenu des températures élevées couramment développées dans cette région. On observe que l'utilisation de la chaux est efficace dans la stabilisation des sols dispersifs, éliminant le phénomène de dispersion et améliorant la résistance et la durabilité du nouveau géomatériau. Cependant, dans le cas des sols sulfatés, un gonflement élevé en plus d'une résistance et d'une durabilité médiocres montre que la technique de stabilisation à la chaux peut être un nouveau problème au lieu d'une solution. De plus, il est démontré que le fait de soumettre des échantillons de sol-chaux à 40 °C améliore les performances des géomatériaux conformés à la fois par des sols dispersifs et sulfatés.

KEYWORDS: soil stabilization, lime, dispersive soils, sulfated soils.

1 INTRODUCTION

Soils with rich soluble salts are widely distributed around the globe and there are always concerns when dealing with saline soils as a construction material. The most common soluble salts in soils are the cations calcium (Ca^{+2}), magnesium (Mg^{+2}), and sodium (Na_+) and the anions chloride (Cl^-), sulfate (SO_4^{-2}), and bicarbonate (HCO_3^-). Smaller quantities of potassium (K^+), ammonium (NH_4), nitrate (NO_3^-), and carbonate (CO_3^{-2}) are also found in most soils (Gartley et al., 2011). It was found after recent investigations that most of the soils present in the Occidental region of Paraguay known as the Paraguayan Chaco, are fine soils containing high concentration of whether sodium chlorides or sodium sulfates and calcium sulfates.

Clays with a preponderance of sodium cations in the pore water are known as dispersive clays (Consoli et al. 2016). Erosion of dispersive clays appears under small seepage velocity, leading to earth stability problems which were noted on various embankments and dams built in this region. By the addition of chemical modifiers such as hydrated lime, dispersive soils can be completely converted into nondispersive soils. Thus, lime

stabilization was the preferred technique to enhance the mechanical properties of these soils to be used as embankments and road pavement structures for a long time in the Paraguayan Chaco. However, this practice showed to be inefficient in several road pavements cases, where serious damages were noted. It was found that these soils contained high sulfate concentrations and the use of lime as stabilizer leads to a new problem instead of mitigating it (Consoli et al. 2019a).

When sulfated soils are treated with calcium-based lime or cement stabilizers, the available sulfates in the soils react with calcium from the stabilizers and free reactive alumina from soils to form a crystalline mineral known as ettringite. Upon crystal growth and hydration, this mineral contribute to a large amount of heaving in soils, known in the literature as sulfate-induced heave (Puppala et al. 2019). This phenomenon causes considerable damage to buildings, pavements, runways, and embankments. This is the case for the Paraguayan region of Chaco that presents sulfated soils with dispersive characteristics, causing damage to infrastructure, especially on road embankments (Consoli et al. 2019a).

This paper aims at better understanding of the interactions between dispersive and sulfated soils and calcium-based treatments such as lime treatment. To achieve this, the mechanical properties of lime treated soil blends were evaluated in terms of unconfined compression strength and volumetric stability. This encompassed the influence of variables such as the dry unit weight, lime content and curing time of soil-lime blends. Additionally, the curing temperature of these soils when stabilized with lime was analyzed due to the fact that high temperatures are normally expected in the Paraguayan Chaco. Figs. 1 and 2 illustrate the average and maximum temperatures of the last 20 years in Pozo Colorado, central region of the Paraguayan Chaco obtained from the Modern-Era Retrospective Analysis for Research and Applications (MERRA).

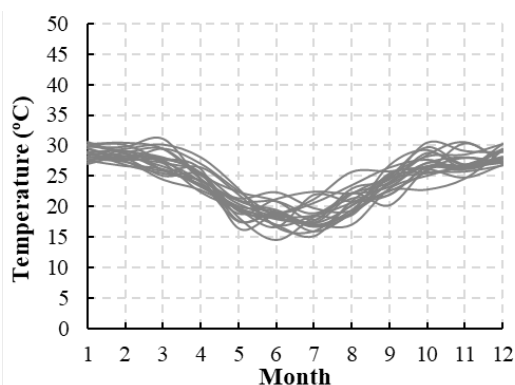


Figure 1. Average temperatures of the central region of the Paraguayan Chaco

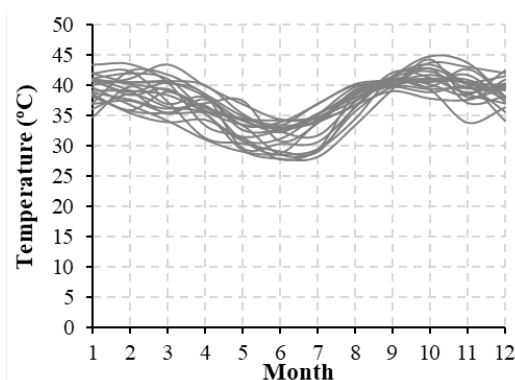


Figure 2. Maximum temperatures of the central region of the Paraguayan Chaco

Authors such as (George et al. 1992, Consoli et al. 2019b) demonstrated that the curing temperature acts as a catalyzer, accelerating the pozzolanic reactions enhancing the geotechnical properties of stabilized soils. Thus, this paper also studied the effect of curing temperature on the strength and volumetric stability of soils containing salts when treated with lime.

2 METHODOLOGY

2.1 Experimental Program

The experimental program was carried out in three parts. First, the geotechnical properties of the two soils studied and lime were characterized. Next, dispersivity of the soils was evaluated through the pinhole test. Then, chemical characterization of soluble salts was carried out on both soils.

Finally, a number of unconfined compression and unidirectional swell tests were undertaken.

2.2 Materials

Two different soils from the same region were considered for this investigation. The soil characterization test results are presented in Table 1. After chemical and pinhole tests, one of the soils was named as 'Dispersive' and the other as 'Sulfated'. The dispersive soil showed to have less than 1,000 ppm of sulfates whereas the sulfated soil 20,000 ppm. Soluble sulfates comprised mostly sodium sulfates following by calcium sulfates.

Hydrated lime was used as the cementing agent. The specific gravity of the lime grains was 2.60.

Table 1. Physical properties of dispersive sulfated soils.

Properties	Dispersive	Sulfated	Standard
Liquid Limit (LL)	42.4	44.3	ASTM D4318
Plastic Limit (PL)	21.1	15.9	ASTM D4318
Plasticity Index (PI)	21.3	28.4	ASTM D4318
Bulk Unit Weight (kN/m ³)	26.10	26.29	ASTM D854
Passing sieve #200	92%	93%	ASTM D6913
Dispersion (Pinhole)	Intermediate ND4	Lightly dispersive ND3	ASTM D4647
Dispersion (SAR)	Dispersive area	Non-dispersive area	Sherard [13]
Soluble sulfates	<1,000 ppm	20,000 ppm	ASTM C1580 / SMEWW
Classification USCS	CL	CL	ASTM D2487
Classification AASHTO	A-7-5	A-7-(6)	ASTM D3282
pH	9	9.3	ASTM D4972

Modified and standard Proctor compaction tests were carried out on the two soils resulting in the curves illustrated in Fig. 3.

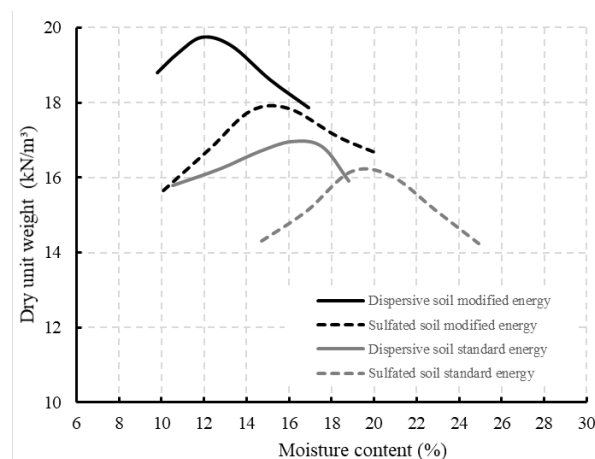


Figure 3. Proctor compaction test results

Hydrated lime was used as the cementing agent. The specific gravity of the lime grains was 2.60. Distilled water was used in the preparation of the all the specimens.

2.3 Molding and curing of specimens

For the unconfined compression strength tests, cylindrical specimens 50 mm in diameter and 100 mm in height were used. For the unidirectional swell tests, cylindrical metallic molds allowed the preparation of 54 mm diameter and 28 mm height specimens. After the

soil and lime were weighed, they were mixed until the mixture acquired a uniform consistency. Distilled water was then added to reach target moisture content of 13% for the dispersive soil and 16% for the sulfated soils. The mixing then continued until a homogeneous material was created. In the next step, the specimens were statically compacted in three layers inside a cylindrical split mold for unconfined compression strength tests and in a unique layer for unidimensional swell tests.

A target dry unit weight for a given specimen was then established through the dry mass of soil–lime divided by the total volume of the specimen. Porosity (η) is defined as the ratio of voids (in volume) over the total volume of the specimen (V). As shown in Eq. (1) (Consoli et al. 2019c), porosity (η) is a function of dry unit weight (γ_d), hydrated lime (L), and soil content (S). Each material (soil and lime) has a unit weight of solids ($\gamma_s S$ and $\gamma_s L$), which also needs to be considered for calculating porosity.

$$\eta = 100 - 100\gamma_d S / 100 + L / 100 S / 100 \gamma_s S + L / 100 \gamma_s L \quad (1)$$

In order to assess the influence of the blend dry unit weights, the molding points were chosen considering dry unit weights of 17.0, 18.0, and 19.0 kN/m³ for dispersive soils–lime blends whereas molding points of 16.0, 17.0, and 18.0 kN/m³ for sulfated soils–lime blends. Lime contents of 5%, 8% and 11% were selected to evaluate the influence of the amount of lime and the volumetric lime content (L_{iv}) was calculated (percentage of lime volume to the total volume of the soil–lime mix).

Porosity (η) and volumetric lime content (L_{iv}) ratio allowed the assessment dosage parameter, porosity/volumetric lime content index (η/L_{iv}). This index showed to control various mechanical properties (Consoli et al. 2018), that can be used in the field when dealing with pavement construction (Consoli et al. 2020) and can even assess other non-geotechnical important parameters (Gravina da Rocha et al. 2021).

Finally, to investigate the effect of curing time and temperature, specimens were cured in a humid room at 21 ± 2°C and 40 ± 2°C with relative humidity above 95%. Unconfined compression test specimens were cured for 7 days and 28 days whereas the swell test specimens were cured for one day.

2.4 Unconfined compression tests

Unconfined compression tests followed ASTM C39. Before carrying out testing, the specimens were submerged in a water tank for 24 h for saturation to minimize suction (Consoli et al. 2011). Then, the unconfined compression test was carried out and the maximum load reached by the specimen recorded.

2.5 Unidirectional swell tests

The swelling tests were carried out using a group cylindrical metallic molds following a similar scheme of oedometer cells but allowing immerse and test nine specimens at the same time. Tests were undertaken in accordance with ASTM D4546 (without the application of any load). Immediately after the curing period of 1 day was terminated, the specimens were completely immersed in tanks with water temperatures of 21 ± 2°C and 40 ± 2°C for 20 days. The axial strain was measured through dial gauges located at the top of each specimen.

3 RESULTS AND ANALYSIS

3.1 Pinhole Test

After the addition of 5% of lime, both the dispersive and sulfated soils were classified as ND1 (non-dispersive) according to ASTM D4647.

3.2 Unconfined compression tests

Figures 4 and 5 exhibit the unconfined compression test results (q_u) as a function of the adjusted porosity/volumetric lime content index (η/L_{iv}) for the dispersive lime-treated soils. It can be noted that the effect of varying the mix unit weight and lime content on q_u is controlled by η/L_{iv} . The use of lime shows to be very effective in the stabilization of dispersive soils.

The effect of temperature after 7 days and 28 days of curing is shown in Figures 4 and 5, respectively. In both cases, the positive impact of augmenting curing time and temperatures is evident. Curing dispersive soils treated with lime for 7 days at 40°C instead of 21°C results in an average enhancement of q_u of 2.5 times. The same enhancement proportion is noted when the specimens are cured for 28 days.

From these observations it can be noted that q_u is controlled by an equation with the form:

$$q_u \text{ (kPa)} = A\eta L_{iv}^b \quad (2)$$

After adjusting power, scalars represent the difference in strength results for specimens cured under different temperature and period of times.

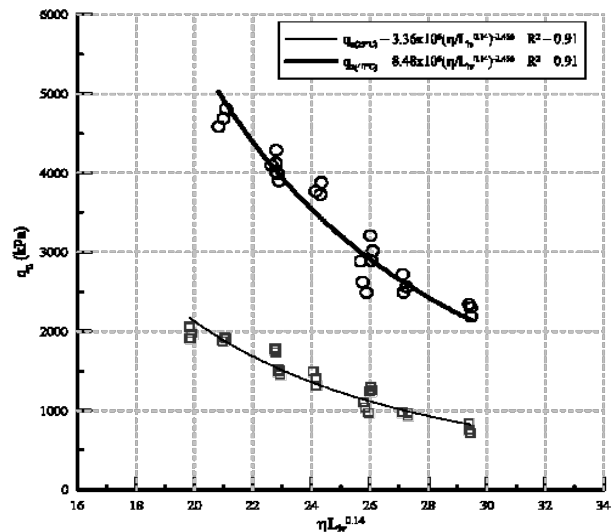


Figure 4. Unconfined compression test results of lime treated dispersive soil after 7 days of curing at 21°C and 40°C

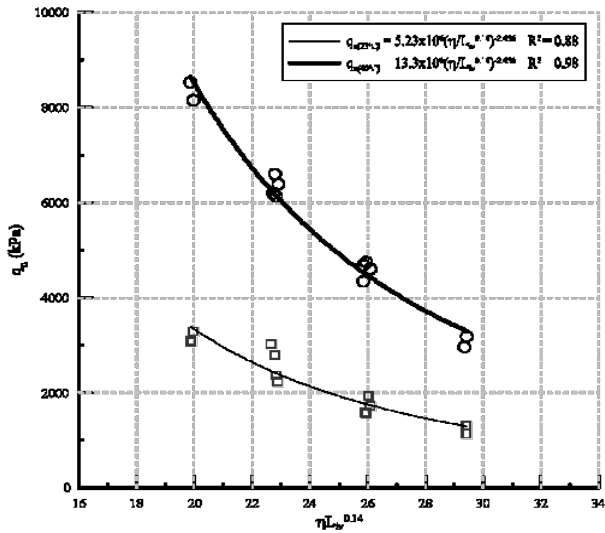


Figure 5. Unconfined compression test results of lime treated dispersive soil after 28 days of curing at 21°C and 40°C

Figures 6 and 7 illustrate the unconfined compression test results (q_u) for the sulfated soil treated with lime at curing periods of 7 days and 28 days, respectively. The effect of temperature on sulfated soil-lime mixes after 7 days of curing is showed in Figure 6. Specimens cured at 21°C did not overcome the water submersion of 24 hrs, evidencing that no beneficial reactions between water, lime, sulfates, and clay minerals occurred. Samples cured at 40°C with 5% of lime and dry unit weight of 17 kN/m³ and 18 kN/m³ did not overcome the water submersion of 24 hrs. The remain specimens showed q_u values depicted in Figure 6.

The effect of temperature on sulfated soil-lime blends after 28 days of curing is exhibited in Figure 7. Specimens cured at 21°C showed marginal strength, not higher than 50 kPa. However, samples cured at 40°C showed reasonable strengths that are up to ten times higher than the ones cured at 21°C.

The low coefficient of correlation when applying Equation 2 to q_u results comprising curing time of 7 days to suggests that there is not a straight relationship with η/L_{iv} in this case.

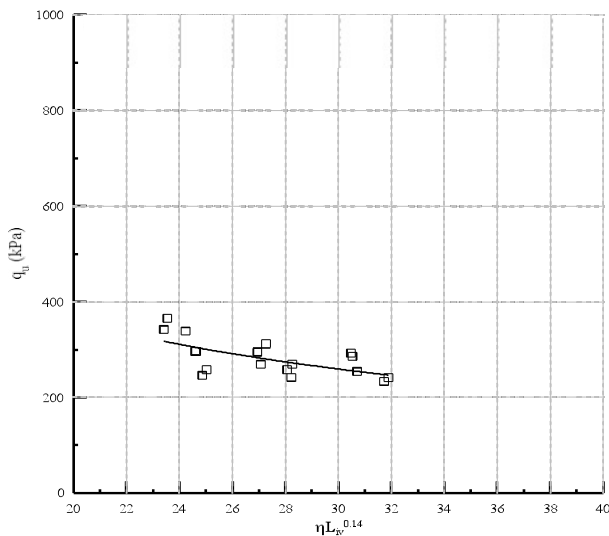


Figure 6. Unconfined compression test results of lime treated sulfated soil after 7 days of curing at 40°C

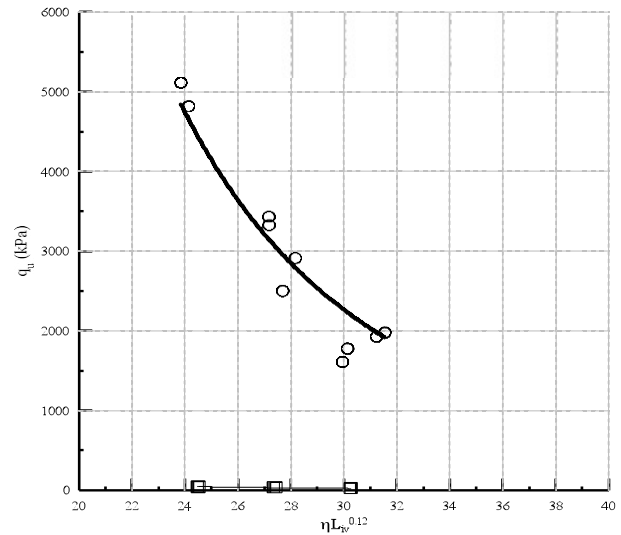


Figure 7. Unconfined compression test results of lime treated sulfated soil after 28 days of curing at 21°C and 40°C

3.3 Unidimensional swell tests

The expansion measured on the dispersive soil and sulfated soil without treatment was 3.8% and 5.1%, respectively. When the dispersive soil was treated with lime, the expansions showed to be marginal, less than 0.12% in all the cases. Nonetheless, lime treatment of the sulfated soil generated high sample expansions. Figure 8 exhibits the swelling measurements of sulfated soils treated with 5% lime, compacted at unit weights of 16 kN/m³ to 18 kN/m³ and subjected to 21°C and 40°C water immersion. It can be noted the high expansions recorded for 20 days and the stabilizing effect of higher temperatures on the swelling behavior of sulfated soils treated with lime.

In an attempt to find a relationship between expansion and η/L_{iv} , swelling results were plotted against this index in Figure 9. It is observed that the level of swelling is related to the amount of lime and the unit weight of the samples. Moreover, the effect of temperature is clear in this figure. Specimens subjected to temperatures of 40°C showed a reduction in expansion of 40% to 55% when compared to samples subjected to 21°C. It can be concluded that higher temperatures improve the volumetric stability of sulfated soils stabilized with lime.

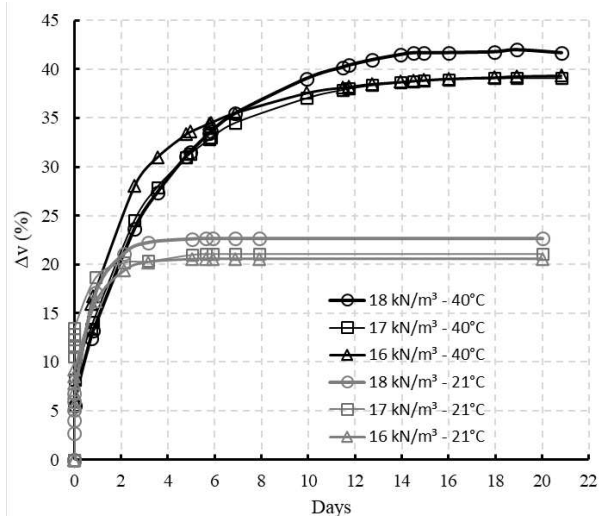


Figure 8. Effect of temperature on 5% lime-treated sulfated soil at different unit weights

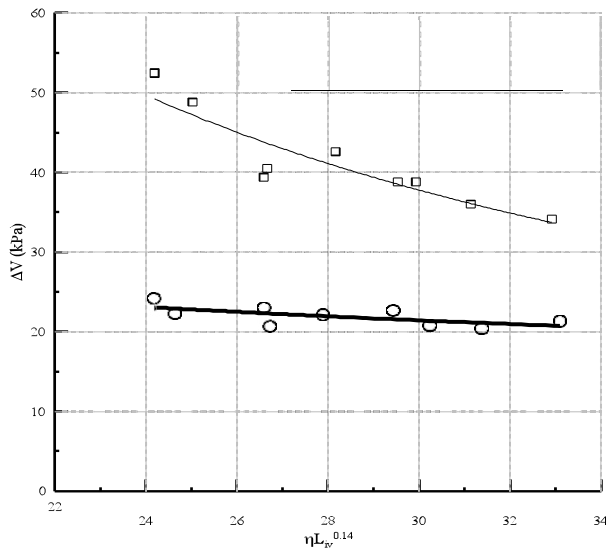


Figure 9. Unidimensional swell test results of lime treated sulfated soil after 28 days of curing at 21°C and 40°C

4 DISCUSSION

The effect of temperature is an important factor to consider in the presence of soils containing salts due to the chemical reactions taking place in soil stabilization. For the dispersive soil, higher temperatures showed to be a catalyzer of pozzolanic reactions generating substantial improvements in resistance. Additionally, Equation 2 showed to fit in predicting the mechanical performance of dispersive soils considering different curing temperatures.

In the case of sulfated soils, the reactions taking place during lime stabilization are more complicated. These reactions can be split in pozzolanic and ettringite formation reactions. Both consumes water, lime, and clay minerals, but ettringite formation takes the soluble sulfates present in the system (Dermatas 1995). Considering this, the low strengths (null in some cases) noted in Figures 6 and 7 can be due to the pozzolanic elements being absorbed by the creation (and growth) of ettringite and therefore no cementation components are formed. The lack of proper pozzolanic reactions can be the reason why Equation 2 does not correlate well with q_u in 40°C cured samples for 7 days.

This observation is in compliant with the swell test results observed in Figures 8 and 9. The formation of ettringite is generating significant swelling in sulfated soil samples stabilized with lime. Additionally, the temperature to 40°C showed to improve the mechanical response of these blends by reducing expansion and generating material resistance. Thus, high temperatures seem to reduce ettringite formation (and growth) and allow some pozzolanic reactions.

The index η/L_{iv} showed to fit reasonably well to correlate the swell behavior of sulfated soils treated with lime with a coefficient of correlation 0.83 (Figure 9).

$$\Delta L (\%) = 2457\eta L_{iv}^{0.14} - 1.23 \quad (3)$$

However, this correlation does not fit when the samples were subjected to 40°C. It appears that the expansion stabilizes (flat line in Figure 9) and it does not depend much on the amount of lime and unit weights of the specimens anymore. These results are comparable with the observation of Dermatas (1991), that the parameters affecting the sulfate-claylime reactions are: soil mineralogy, amount of clay-size particles, amount and type of lime used, amount and type of soluble sulfates present, curing time and temperature, pH, availability and

flow of pore water, soaking temperature and relative humidity, water content and dry density of the lime-treated soil.

5 CONCLUSIONS

- The application of lime has been shown to stabilize the dispersion behavior of dispersive soils.
- The porosity/lime index (η/L_{iv}) has been shown to be an appropriate index parameter to assess q_u of dispersive soil treated with lime. However, for the stabilized sulfated soil, η/L_{iv} did not correlate well with short term q_u .
- The use of the porosity/lime index (η/L_{iv}) can be a useful way to predict the swelling behavior of sulfated soils stabilized with lime at standard laboratory temperature. However, more research considering this relationship should be done.
- Curing and immersion temperature of 40°C has been shown to be beneficial on the mechanical behavior of both dispersive and sulfated soils treated with lime. In the case of sulfated soils, a better understanding of the reactions occurring is necessary to comprehend the effect of temperature.
- The temperature of 40°C reduced the expansion of sulfated soils stabilized with lime by 40–55%. Nevertheless, this swelling level is still inappropriate for construction proposes due to the amount of soluble sulfates present in the soil.
- Mixing, compacting, and curing bases or sub-bases of lime treated soils under high temperatures such as 40°C is beneficial to the mechanical behavior of these structures.
- Although high temperature showed to be beneficial to the mechanical behavior of sulfated soils stabilized with lime, the amount of soluble sulfates in the soil-water-lime system is the factor which influence the most.

6 ACKNOWLEDGEMENTS

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