The Effect of Mellowing and Coal Fly Ash Addition on the Behavior of Sulfate-Rich Dispersive Clay after Lime Stabilization

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ABSTRACT: Dispersivity and swelling induced by the formation of expansive minerals are deleterious phenomena that can be observed in naturals and treated soils. The former is common among sodium-rich soils that are characterized by the deflocculation of the soil's particles in contact with water. The latter happens due to the growth and hydration of calcium sulfo-aluminate minerals as expected in sulphate-rich soils treated with calcium-based stabilizers. The present study assesses the behavior of the Paraguayan sulphate-rich, dispersive as well as expansive, clayey soil after lime stabilization based on an extensive experimental work, which includes unconfined compression, pulse velocity, durability and free swell tests. This work was designed employing a fractional factorial design in the selection of the experimental runs which enabled the statistical evaluation of influence of dry unit weight, lime and fly ash content, curing period, mellowing process and molding moisture content. Results showed that the addition of fly ash, followed by the dry unit weight, were the most influential factors regarding the treated soil's response in performed tests. In addition, mellowing proved to be essential in reducing the volumetric variation verified in the swelling tests. Besides, scanning electron microscopy (SEM) analysis revealed that the ettringite formation was less pronounced when fly ash was added.

Key words: Sulfate; dispersive clay; expansive minerals; lime stabilization; strength; durability; laboratory tests.

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INTRODUCTION

The stabilization of dispersive soils through the addition of calcium-based stabilizers, as hydrated lime, has been broadly studied (Hayden and Halliburton 1976; Umesha et al. 2009; Vakili et al. 2012; Consoli et al. 2016; Premukar et al. 2016). However, when soils combine the dispersivity characteristics with high sulphate contents, the stabilization process becomes significantly more complicated. This is the case of the Paraguayan region of Chaco that presents soils with dispersive and expansive characteristics, causing several damages on infrastructures (Fig. 1), especially on road embankments, which require constant maintenance through palliative solutions. Furthermore, the lack of granular materials in this region aggravates the situation because the in situ existing clayey soils are one of the few options available which imply, besides the problematic features of this soil, in poorly graded road embankments.

The dispersivity phenomenon is characterized by the deflocculation of soil particles in presence of relatively pure water, which implies high susceptibility to erosion, piping, and other earth instability issues (Elges 1985). Clays containing high exchangeable sodium percentages (ESP) are usually predisposed to dispersion. The low charge of sodium ions, weakly bounded to clay minerals (CRC 2001), explains such behavior. Hence, the diffuse double layer (DDL) is thicker than in non-sodic soils and the repulsive forces exceed the attractive forces in saturated conditions, resulting in deflocculation. Through the replacement of sodium by cations with higher valence ions, such as calcium or aluminum, the potential of soil dispersivity can be reduced, since the soil structure becomes denser, as a result of the reduction of the DDL thickness. This condition can be achieved by the incorporation of hydrated lime (calcium hydroxide) or similar additives to the soil.

Now, in presence of a dispersive sulfate-rich soils, sulfates present in various forms interact with the calcium-based stabilizers, making soil susceptible to develop inconvenient pathologies. Stabilizing method can lead to side problems, instead of improving original properties (e.g., Hunter 1988; Dermatas 1995; Petry and Little 1992; Kota et al. 1996; Puppala et al. 2005; Puppala et al. 2010, amongst other researchers). Indeed, in hydrated and highly alkaline environment ($pH > 10.5$), the alumina from clay minerals (or other source) is released into solution and can react with sulfates contained in soil and/or groundwater. In these conditions, it can form ettringite, which is a highly expansible calcium alumino-sulfate mineral, with a needle-like structure (Mitchell and Dermatas 1992). As stated by Puppala et al. (2005), this reaction continues until enough ettringite crystals are formed in the soil to produce a phenomenon called sulphate-induced swelling. For temperatures below 15°C, the transformation of ettringite to thaumasite (a very expansive mineral when exposed to water) is possible. If the system is limited by insufficient dissolved clay (pH<10.5) as well as insufficient ions of either, calcium or sulphate, ettringite/thaumasite formation and expansion is terminated (Dermatas 1995).

Dermatas (1995) claims there are two separate mechanisms that could be responsible for the extensive sulphate-induced swelling generally associated with ettringite and thaumasite: (i) crystal growth, or (ii) hydration. On the one hand, Aluminum, calcium, and sulfate ions present in solution could concentrate around the ettringite nucleation sites, and combine to induce ettringite crystal growth. As ettringite crystals grow, they exert significant pressures to the material matrix, and if these pressures are high enough, swelling of the material can be developed due to crystal growth. However, in geomaterials where void ratios are larger than concrete, these crystals could be accommodated until a certain point without damaging the geomaterial. On the other hand, a number of researchers, such as Mehta and Wang (1982), have affirmed that the main mechanism of expansion is the adsorption of water by ettringite crystals. Struble and Brown (1984) demonstrated that when ettringite is undergone to a drying-wetting cycle, at 25°C, it loses about 30% of its mass upon drying. Nevertheless, when rewetting it gains considerably more mass than what has been lost during drying, up to 125% of its initial mass. Although, without any explanation on how this process occurs, the additional mass has been attributed to adsorption of water by ettringite.

In this context, the mechanical behavior of stabilized soils can be properly assessed through methods that express its overall performance by carrying out tests such as unconfined compressive strength, initial shear modulus, durability and volume change due to swelling. In this sense, Consoli et al. (2016) studied those parameters in a sodium rich clay treated with hydrated lime and attested that it was effective in reducing the dispersivity of the soil and in proportioning significant strength gains. The incorporation of a pozzolan (i.e. fly ash) with a calcium-based material (i.e. hydrated lime, calcium carbide residue and lime kiln dust) in the improvement of geomaterials was studied by Petchuay et al. (2016), Consoli et al. (2017, 2018), Hoy et al. (2017), Arulrajah et al. (2017), among others. Jha and Sivapullaiah (2018), in turn, assessed the swelling behavior of a gypseous clayey treated with lime and fly ash and verified that the 20% was the optimum fly ash content in minimizing the volume change behavior due to ettringite crystals growth and/or hydration.

Thus, this paper aims a better understanding of the interactions between soil from Paraguayan Chaco area and calcium-based treatment, as well as to develop feasible solutions through experimental tests. This issue is well recognized in the region of the Paraguayan Chaco, where the effects of having such soils are persistently observed on the road infrastructure (Fig. 1), which requires constant maintenance through palliative solutions. Therefore, a wider comprehension of this problem and the development of feasible solutions, through experimental studies, are required. An alternative treatment is the use of a pozzolanic material-lime mixture. When this mixture is incorporated into the soil, it can create a cementitious matrix able to resist to the swelling-induced stresses produced by the ettringite hydration and/or growth. Hence, in order to assess the natural and the treated soil behavior, a thorough physical, chemical and mineralogical characterization was carried out. This encompassed the influence of variables (such as the dry unit weight, the lime or moisture content, the pozzolanic material content and the mellowing) in the mechanical response of the treated soil. A fractional factorial design was used to define the experimental plan.

EXPERIMENTAL PROGRAM

Materials

The soil (S), the lime (L) and the fly ash (FA) were characterized in the laboratory in order to determinate their physical, chemical and mineralogical properties. The soil was classified as a lean clay (CL), according to the standard ASTM D2487 (2006), and clay (A-6), according to the standard AASHTO M 145 (1991). Its physical properties are presented in Table 1 and its grain size distribution is shown in figure 2

The chemical analysis of pure water put in contact with soil revealed the presence of sodium (44.9 mEq/l), potassium (0.2 mEq/l), calcium (15.8 mEq/l), and magnesium (4.5 mEq/l) as the main released species after washing. The total soluble salts (TDS) were 65.4 mEq/l and 68.6% of TDS corresponded to sodium (PS). Thus, it can be described as a potential dispersive soil as stated by Sherard et al. (1976). In addition, this soil is classified as moderately dispersive (D2) according to the pinhole test and dispersive (grade 4) according to the crumb test The water-soluble sulphate content according to the standard ASTM C1580 (2015a), revealed the presence of $CaSO_4$ (5,372 ppm), K_2SO_4 (93 ppm), $MgSO_4$ (1,351 ppm) and Na_2SO_4 (7,576 ppm), corresponding to a total of 14,392 ppm of soluble sulphate salts. It is above the sulphate content threshold recommended by NCHRP (2009).

Parallel to sulfate phases, X-ray diffraction pattern (Fig. 3) revealed the presence of smectite, chlorite, kaolinite, illite, and quartz. The unit weight of the soil grains is 26.9 kN/m³.
The pozzolanic material used in this study is a coal fly ash. It is a residue produced by a thermal power plant, with a mainly amorphous structure (~80%). Its main constituents are silica (65.7%), alumina (20.3%) and iron oxide (4.6%). The FA particles size distribution indicates that 85% of the grains are located in the silt range and 15% are distributed between the fine and medium sand range. The FA grains unit weight is 20.1 kN/m³. Hydrated lime was used as an alkaline activator. With a grains unit weight equal to 24.1 kN/m³, it is composed of 81% of $Ca(OH)_2$ and 9.4% of $CaCO_3$ (determined stoichiometrically).

Experimental plan

The effects or coupled effects of 5 parameters (dry unit weight, lime or moisture content, the pozzolanic material content and the mellowing) have to be studied. In order to reduce the number of tested specimens, a half fraction factorial design – 2_V^{5-1} – was employed to define the laboratory experiments regarding the stabilized dispersive sulphate-rich Paraguayan soil. In this type of design (resolution V), no main effect or two-factor interaction are aliased with any other main effect or two factor interactions, but main effects are aliased with four-factor interactions and two-factor interactions are confounded with three factor interactions (Montgomery 2009). In this sense, considering that higher order interactions were negligible (sparsity effect principle), it was possible to estimate the main effects (5) and two-factor interactions effects (10) through only 16 runs, without conducting a huge range of experimental runs, as it would be the case if a more traditional parametrical analysis was conducted. In addition, two intermediate treatments were developed, for the unconfined compression strength tests, to check the linearity assumption of the model, using intermediate factors corresponding to the average of the two extremes.

The measured variables were the unconfined compressive strength (UCS), the initial shear modulus, the accumulated loss of mass (wet-dry durability test) and the volumetric variation. The curing periods considered (28, 60 and 90 days for the UCS tests and 7 days for the remaining tests) were treated as separated blocks. The varying factors were dry unit weight

(14.5 kN/m³ and 16.8 kN/m³), lime content (4% and 8%), molding moisture content (12% and 15%), the fly ash (FA) content (0% and 25%), and the mellowing time (0 h and 48 h). The latter is a delay in the compaction that allows the stabilizer to diffuse through the moist soil intending to anticipate the formation of the expansive minerals through the sulfates – lime reactions (Rahmat and Kinuthia, 2011). Hence, those can be rearranged and/or broken during the compaction, what would diminish it s deleterious effects along the material's lifespan. Table 2 summarizes each treatment.

In addition, an analysis of the soil microstructure was carried out using scanning electron microscopy (SEM) to determine the potential occurring of ettringite. The dry unit weight and molding moisture content range was established based on standard Proctor compaction test using standard effort in according to ASTM D698 (ASTM 2012) performed on a 4% lime-soil mixture. It yielded a maximum dry unit weight and optimum moisture content of 17 kN/m³ and 15%, respectively.

The 4% of lime content is relative to the dry mass of soil and was defined after the minimum lime amount for particle flocculation was established using the 'initial consumption of lime' method (ICL). This method, thoroughly described in the literature (Rogers et al. 1997), is based on the pH variation of the soil-lime blend as a function of the added lime. The pH value increases with the addition of lime until a threshold value is reached and this threshold corresponds to the ICL lime content. Theoretically, all the added lime beyond this point would be available to promote the pozzolanic reactions, which are responsible for the most significant portion of the strength increase. The results of an ICL test performed on the Paraguayan soil from Chaco revealed that the minimum amount of lime is 4%. In the experimental plan, a maximum lime content of 8% was chosen considering international experience (Mitchell 1981, Consoli et al. 2001, 2008, 2016; Thomé et al. 2005).

The amount of fly ash was determined based on previous researches (Consoli et al. 2015; Consoli et al. 2011; Kumar, Walia and Bajaj 2007; McCarthy et al. 2009, 2012; Puppala et al. 2001a) and calculated in relation to the weight of the dry materials (soil plus lime).

The molding and the curing of specimens

Cylindrical specimens, with 50 mm in diameter and 100 mm high, were used for the UCS tests, while cylindrical specimens with 100 mm in diameter and 127 mm high were used for initial shear modulus and durability tests. The volumetric expansion tests were performed with cylindrical specimens with 54 mm in diameter and 21 mm high.

After the soil, fly ash (when used) and lime were weighed, they were manually dry blended until a visual uniformity was reached. Then, distilled water was added to the mixture that is blended by hand until a homogenous paste was produced. When no mellowing was imposed before compaction, the mixture was immediately molded by static compaction in three layers (for strength, stiffness, and durability tests) or in one layer (for volumetric expansion test), into cylindrical split casts. After molding, specimens were weighed and measured with precisions nearly 0.01 g and 0.1 mm in order to check the tolerances regarding the maximum variation of the dry unit weight (± 0.5 g/cm³) and dimensions (1% of the target dimension). Then, they were sealed in plastic bags and forwarded to be cured between 7 to 90 days in a humid room (95 ± 2 %) with controlled temperature (23°C ± 2°C).

When mellowing was used before compaction the mixed hydrated materials were sealed in a special thick plastic bag for 48 hours before proceeding to the molding. This allowed the occurrence of the deleterious sulphate-calcium-alumina reactions and, hence, the possible formation of ettringite before the compaction process. Thus, the formed ettringite crystals could be theoretically broken and/or reallocated throughout the molding process, which would minimize its harmful effects during the stabilized soil lifespan (Harris et al. 2004).

The testing of the specimens

Unconfined compression tests were carried out in according to ASTM C 39 (ASTM 2010) with a loading rate equal to 1.14 mm/min. In order to minimize suction effects, the specimens were immerged in water for 24 h to reduce suction (Consoli et al. 2011). All specimens were made in triplicates and their characteristics are summarized in Table 2.

The initial shear modulus (G_0) of an elastic medium can be related by Eq. 1, to its specific weight (ρ) and to the propagation velocity of a shear wave (V_s) through the medium. So, G_0 can be quantified by measuring the velocity of an ultrasonic wave (ASTM D2845 2008). The pulse velocity tests were carried out on specimens just before the durability tests.

$$G_0 = \rho \ x \ V_s^2 \quad (1)$$

In order to assess the performance of the studied (lime, FA) – soil mixtures when subjected to extreme conditions, durability tests consisting in wetting-drying cycles were performed following ASTM D 559 (2015). The method aims to determine the mass loss throughout 12 wet-dry cycles. After the 7 days curing period is completed, every cycle starts by immerging the specimen in water, for 5h at 23^o±2^{o}C. After stove-drying for 42h at 71^o±2^{o}C, specimen is finally brushed 18 to 20 times around its circumference and 4 times on the top and bottom surfaces, by using a force of 13 N.

The swelling tests were carried out in oedometer cells (without the application of any load) in accordance with ASTM D4546 (2014). Immediately after the curing period of 7 days was terminated, the specimens was put in contact with water for 7 days, after the filling of the tank of the oedometer cell. After this period was concluded, the specimens were oven-drying at 100°C for 24h, and again immerged in water for an additional 14-day period. Linear variable differential transducers (LDVT) were used to record the vertical displacement of the specimen during the free swelling test.

RESULTS AND ANALYSIS

The presentation pattern of results below is maintained for each test, and it consists in quantitative responses in a (i) vertical bar chart graphic, the standardized effects of factors is drawn in a (ii) Pareto chart graph and the first order main effects is given in a (iii) line scatter plot. The bar chart graphs (i) are functional to present the magnitude of a measured parameter for each experimental run (indicated in the abscissa with the corresponded treatment summarized in Table 2). The Pareto chart (ii) is a useful way to show the importance and statistical significance of the main effects and its interactions by plotting each factor (and interactions) as a separated bar, with a magnitude equal to the standardized effect. Thus, if the bar crosses the reference line, the factor is statistically significant considering the adopted significance level (α). This line is the quantile (1- α/2) in the Student´s t-distribution and depends on α, which was selected as 95%. Each factor is denoted as a letter and the second order interactions are designated by the combination of the respective letters of factors. Despite of its statistical significance, all main factors are shown in the Pareto graphs presented herein. On the other hand, only the significant two-order interactions are presented. Line scatter plots (iii) are a convenient manner to show the quantitative importance of each factor in altering the measured response and are presented herein with a dotted line that indicates the average of the measured variable for each test.

Unconfined Compressive Strength

Each value presented is the average of three tests in figure 4(a). The Pareto chart, presenting the magnitude of the standardized effects and the reference line, is shown is figure. 4(b) and the main effects plot is presented in figure 4(c). The Pareto chart shows that the addition of fly ash (E), the dry density (B), and the curing period (F), are, in this sequence, the most influential factors in terms of the strength development, followed by the interactions between fly ash and dry density (BE), curing period and fly ash (FE), and curing period and dry density (FB). The effects of the lime content (C), the mellowing time (A) and the molding moisture content (D) are practically not significant for the response variable.

The highest effectiveness of the fly ash and curing period on unconfined compressive strength (given by the highest slopes of the 3 points lines) can be explained by the pozzolanic reaction of fly ash, available to react quickly with lime, resulting in a cementitious matrix composed of calcium silicates hydrates (C-S-H) and calcium aluminates hydrates (C-A-H) (Herzog and Mitchell 1963; Mateos 1961; Moh 1965). Reactions can also take place between lime and clay minerals in soil. However, those reactions are slow due to the long induction period required by soil particles, during which the soluble silicates and aluminates are dissolved and released in the interstitial solution, to be transformed later in binding gel (Diamond et al. 1963; Müller 2005). Longer curing periods result in a greater consumption of lime and, thus, the precipitation of more binding compounds (Müller 2005; Consoli et al. 2011, 2016).

The dry density is an indication of the compaction and interlocking between the soil grains and between the soil particles, lime and fly ash. Hence, the proximity of those grains, besides favoring the mechanical resistance of the mixture, favors the occurrence of both short and long-term reactions (interactions BE and FB). The effects of adding different lime contents and different molding moisture contents were quite small considering the range of values studied herein. The mellowing time, likewise, was practically non-significant, probably due to the mechanism of growth of the ettringite crystals, requiring continuous hydration to develop and expand (Puppala et al. 2005; Nair and Little 2011). If those conditions were possible during the curing period, swelling phenomenon and the propagation of cracks would have been observed along this period.

Pulse Velocity Tests

The initial shear modulus (G_0) results, measured, before the start of durability tests, are presented in figure 5. The values obtained range between 0.29 to 1.77 GPa and the higher values were observed in the same treatments that presented higher unconfined compressive strength results. The Pareto chart (figure 5 b) shows that only the addition of fly ash (E) and the dry density (B) are significant single factors regarding the G_0. On the other hand, the interactions between lime content and fly ash (CE), molding moisture content and mellowing time (DA), and dry density and fly ash (BE) are significant in altering the dependent variable response. The amounts of lime (C), mellowing time (A), and molding moisture content (D) are statistically insignificant. The main effects plot is presented in figure 5 (c). The reasons why the mentioned variables have significant influences on the G_0 are the same that were presented for the UCS tests. However, only a curing period equal to 7 days was considered in this case. The significance observed in the interaction between molding moisture content and mellowing (DA) can be partially explained by the high percentage of mellowing time (48 h) relatively to the curing period (7 days). The mellowing time corresponds to almost 30% of the curing period.

Durability Tests

The accumulated loss of mass (*ALM*) registered after 12 cycles of the durability test is shown on figure 6(a). The experimental runs that are omitted in this figure lost their structural integrity after the first two cycles and its results contributed to the statistical analysis as an accumulated loss equal to 100%. It is possible to infer that the treatments that presented higher values of strength and stiffness performed better in the durability test (i.e. smaller *ALM* values). The Pareto chart, in turn, is presented in 6(b) and the main effects plot in figure 6(c). In this sequence, the addition of fly ash (E), the dry density (B) and the lime content (C) are the most significant factors affecting the durability of the studied mixtures. Other factors and their interactions are not influential in this response.

The addition of fly ash and a higher lime content added to soil favors the development of pozzolanic reactions throughout the 12 wetting-drying-brushing cycles and it contributes to enhance the performance of the compacted blends, as the test progresses (Consoli et al. 2017; Saldanha et al. 2017). The dry density, as stated before, is an indicative of grains proximity, their packing and interlocking. However, there is a paradox considering the compaction level and the enhancement in the performance of the studied blends. At one glance, it is expected that higher compaction levels imply in smaller mass losses due to the packed and interlocked structure. However, if the structure is dense but with low reinforcement (low amounts of additives) there is no space to comport the expansion of the minerals and the structure of the specimen tends to collapse due to cracks propagation. Also, in this case, the strength of the cementitious matrix is low and unable to resist the swelling of the minerals. Those are probably the reasons why the specimens without the addition of fly ash and/or lower amounts of lime did not performed well in the durability test, even the denser ones.

Mellowing time was not significant, probably because of the catalyzer effect during the 72°C oven-drying periods, which enhances the development of the cementitious matrix. Besides the improvement caused by the addition of the proposed stabilizers, the durability requirements for clayey soils stated by USACE (1984) and PCA (1992), were not fulfilled. The former standard allows a maximum weight loss of 6%, after twelve cycles, while the latter allows a maximum loss of 7%.

One-Dimension Free Swell Tests

The volumetric variation (ΔV), obtained with a one-dimensional free swell test, is presented in figure 7 (a). The larger expansion values were observed amongst the specimens where no mellowing was employed and with minimum degrees of cementation due to the absence of fly ash. In general, most of treatments presented volumetric variations lower than 5%, with exception of 6, 7, 8, 11 and 16. The last two exhibited ΔV larger than 20%, which is probably related to the lack of mellowing, no usage of fly ash and large amounts of lime (8%) prompt to react with the sulfates presented in the soil forming expansive minerals. Based on expansion index classification those mixtures can be classified as having expansion potential varying between very low (0 – 20%) to low (21 – 50%) (ASTM 2011c) and non-expansive in according to CMC (2003). Nevertheless, the selection criteria depend on infrastructure types that the site soils support in the field. Low overburden structures including pavements and embankments are distressed by moderate volumetric soil movements (Punthutaecha et al. 2006). Existing literatures recommend a volumetric swell expansion of 5%, swelling pressure of 0.05 MPa and a volumetric shrinkage strain of 17% as nonproblematic levels (Chen 1988; Nelson and Miller 1992; Punthutaecha 2002). Hence, the proposed treatments were effective in reducing the swelling tendency, particularly in the highly cemented specimens.

The respective Pareto chart is shown in figure 7(b) and revealed that, excluding the molding moisture content (D) and the lime content (C), all other factors are significant in changing the response variable. Besides, the interactions between dry density and fly ash (BE), fly ash and mellowing (EA), lime content and molding moisture content (CD), and dry density and mellowing (BA) are also influential regarding the volumetric variation. The main effects plot is presented in figure 7 (c).

The great effects observed by the use of fly ash, dry density and their interactions can be explained through the enhancement in the pozzolanic reactions and, hence, in the strength of the cementitious matrix, which diminishes the stabilized soil swell along the test. Indeed, mellowing was significant in reducing the volume change along the experiment, probably by allowing the formation of ettringite before the compaction procedure (Harris et al. 2004). The significance attested in the interactions between mellowing and fly ash and mellowing and dry density seem to be, as well, related to the efficiency of the cementitious matrix in encapsulating the ettringite crystals when they are reallocated during the compaction procedure.

Observation of the soil microstructure

To assess the growth and formation of ettringite through a visual method, and to analyze the effect of the addition of fly ash on such process, SEM images from two specimens were obtained. Both specimens were molded without fly ash. The first was cured for 130 days (Figure 8a), while the second was the experimental run number 3 (8% of lime) submitted to the durability test (Figure 8b).

In both cases the pH measurement was 10 (pH<10.5), therefore, formation and expansion of ettringite crystals are finished (Dermatas 1995). It is important to remark the effect of wet-dry cycles as a catalyzer of ettringite growth and expansion. Firstly, a pH of 10 was reached after the time of 12 wet-dry cycles (31 days) whereas in the specimen that was cured standardly the pH after 30 days was 12.5 and just after 130 days was 10. Secondly, because of the facility of finding ettringite in the specimen subjected to 12 wet-dry cycles during the SEM test and the sizes of the found crystals in relation to the specimen cured for 130 days. This phenomenon probably due to the hydration drying and rehydration of the specimens containing ettringite during wet-dry test.

The SEM image presented in Figure 9, of a specimen containing 8% lime and 25% fly ash, shows ettringite crystals that formed after 130 days (Figure 9a). Figure 9b is of a specimen containing 8% of lime and 25% of fly ash, which was submitted to the durability test (experimental run number 4).

The presence of ettringite crystals is shown less pronounced in specimens molded with lime and fly ash considering the difficulty of finding ettringite and the sizes of its crystals during SEM tests (Fig. 9). Ismail et al. (2012) relates that from other published studies, alkali activated slag/fly ash binder systems are generally reported to have better resistance to sulfate attack than Portland cement. Most of these conclusions have been drawn from changes in physical appearance and compressive strength, but the mechanisms controlling this behavior on a microstructural level are not yet well understood, and the analysis of sulfate resistance of blended fly ash/slag binders has not previously been reported in detail.

CONCLUSIONS

The conclusions based on results on strength, stiffness, durability and free swell tests performed on sulfate-rich dispersive expansive clay-lime and clay-lime-fly ash blends, are the following:

- Unconfined compressive strength is highly susceptible to changes in amount of fly ash, dry density and curing period (in this order). This trend is compatible with previous studies with fine-grained soils treated with lime and/or with lime and fly ash (e.g. Consoli et al. 2011, 2016). For the range of values applied herein, lime content, mellowing time and molding moisture content had negligible effects on q_u.
- Considering the conditions applied in the present study, the initial shear modulus seems to follows the same trend as q_u.
- The stabilization with fly ash and lime was successful in the enhancement of the durability performance in comparison with the lime stabilization performance. The use of fly ash and dry density were the most significant factors affecting its response (Consoli et al. 2017; Saldanha et al. 2017). However, the USACE (1984) and PCA (1992) requirements regarding the maximum allowable loss of mass were not fulfilled.

- The creation of a more resistant cementitious matrix, through the addition of fly ash, was effective in reducing the swelling during the expansion test. The mellowing process was also effective in this sense, probably by the reasons stated before.
- Based on the observations of SEM images, ettringite crystals appeared in treated sulphate-rich Paraguayan soil. Nonetheless, crystals were more developed among the durability specimen, probably due to the constant supply of water during the cycles. The formation of such crystals was attributed to the presence of calcium and, likewise, of reactive silica, alumina and soluble sulfates (Mitchell 1986; Nair and Little 2011; Puppala et al. 2004)

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NOTATION

G_0	*initial shear modulus*
q_u	*unconfined compressive strength*
t	*curing time*
V	*total volume of specimen*
V_s	*velocity of a shear wave*
γ_d	*dry unit weight*
ρ	*specific weight*
w	*moisture content*
ALM	*accumulated loss of mass*

Table 1 – Physical properties of the soil sample.

Parameter	Value
Liquid limit (%)	33
Plastic limit (%)	17
Plastic index (%)	16
Unit weight of the soil grains (kN/m^3)	26.9
Silt (0.002 mm < diameter < 0.075 mm) (%)	80
Clay (diameter < 0.002 mm) (%)	20
Mean particle diameter, D_{50} (mm)	0.065
Soluble sulfates (ppm) (ASTM C1580-15)	14,300
Sodium Absorption Ratio (SAR)	14.1
Pinhole Test (ASTM D4647 – 13)	D2
Crumb Test (ASTM D6572 – 13)	Grade 4
Soil Specific Surface Area (m^2/g)	26.2
USCS class (ASTM 2006)	CL

Table 2 – Experimental runs.

Experimental Run	**γ_d (kN/m³)**	**Lime Content (%)**	**FA Content (%)**	**Molding Moisture (%)**	**Mellowing Time (h)**
1	14.5	4	25	15	48
2	14.5	8	25	12	48
3	14.5	8	0	15	48
4	14.5	8	25	15	0
5	16.8	4	25	12	0
6*	15.65	6	12.5	13.5	24
7*	15.65	6	12.5	13.5	24
8	16.8	4	0	15	48
9	16.8	4	25	15	0
10	16.8	8	25	12	0
11	16.8	8	0	15	0
12	16.8	4	25	12	48
13	16.8	8	0	12	48
14	16.8	8	25	15	48
15	14.5	4	0	12	48
16	14.5	8	0	12	0
17	16.8	4	0	12	0
18	14.5	4	0	15	0

*Intermediate Points

Figure 1 – Typical road pavement failure in Paraguayan Chaco.

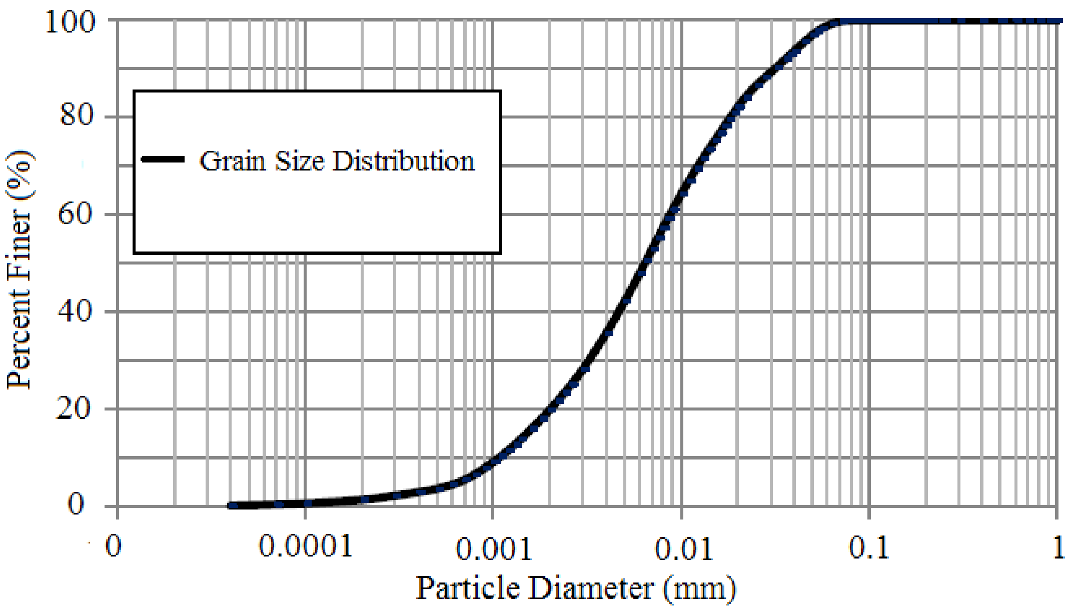

Figure 2 – Grain size distribution of the soil.

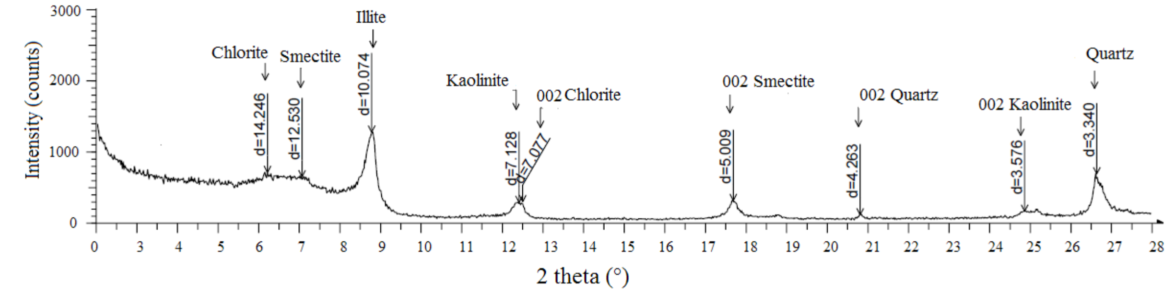

Figure 3 – XRD pattern of soil.

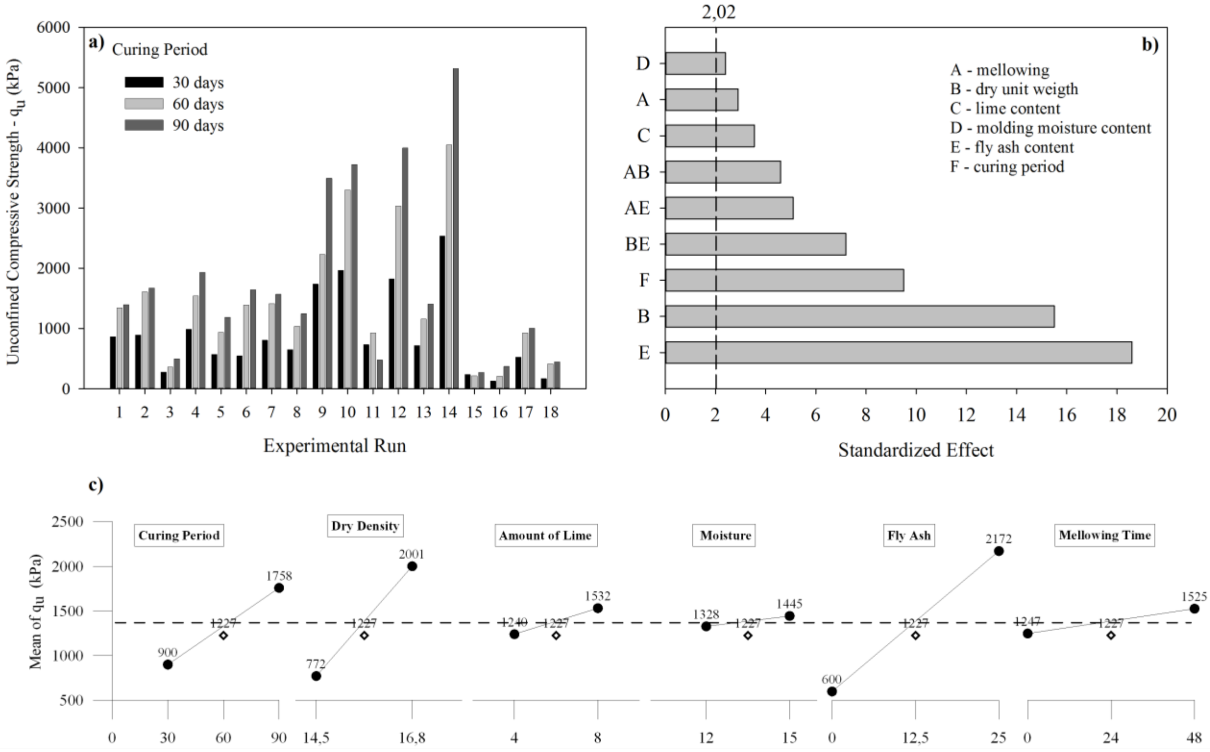

Figure 4 – (a) UCS results (b) Pareto Chart (c) Main effects plot.

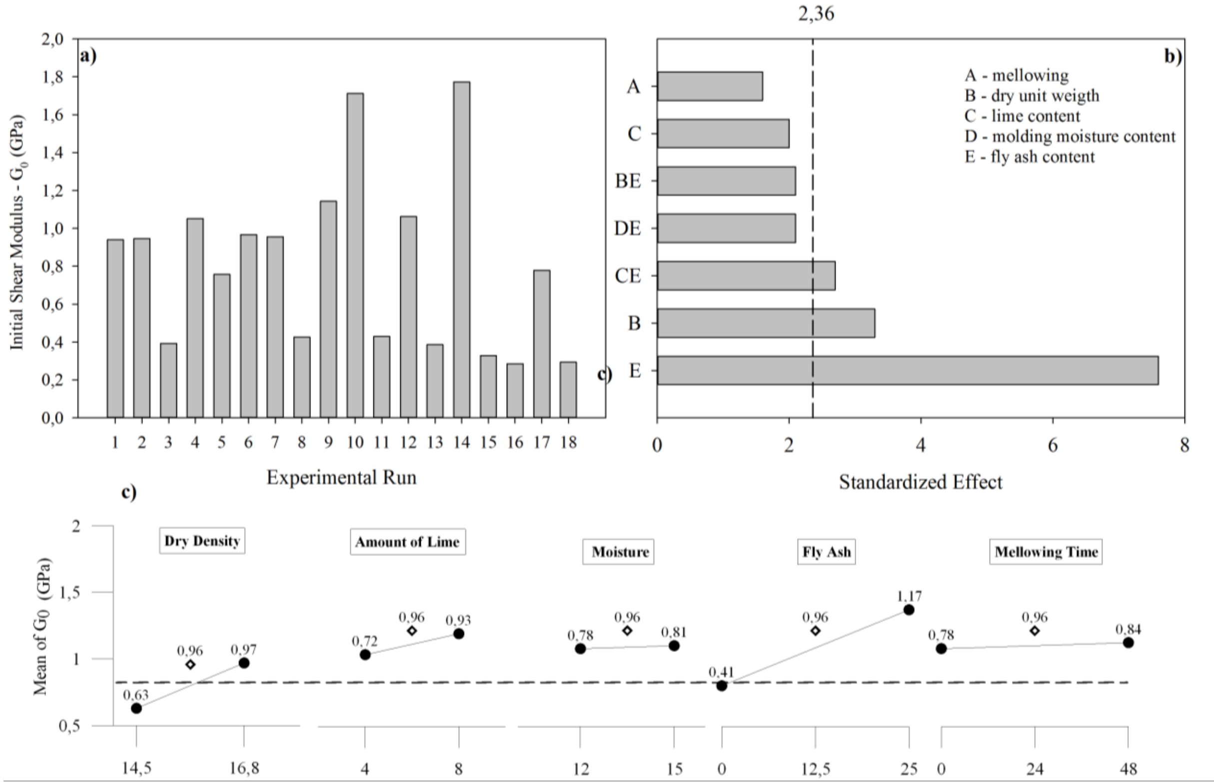

Figure 5 – (a) Pulse velocity tests results (b) Pareto Chart (c) Main effects plot.

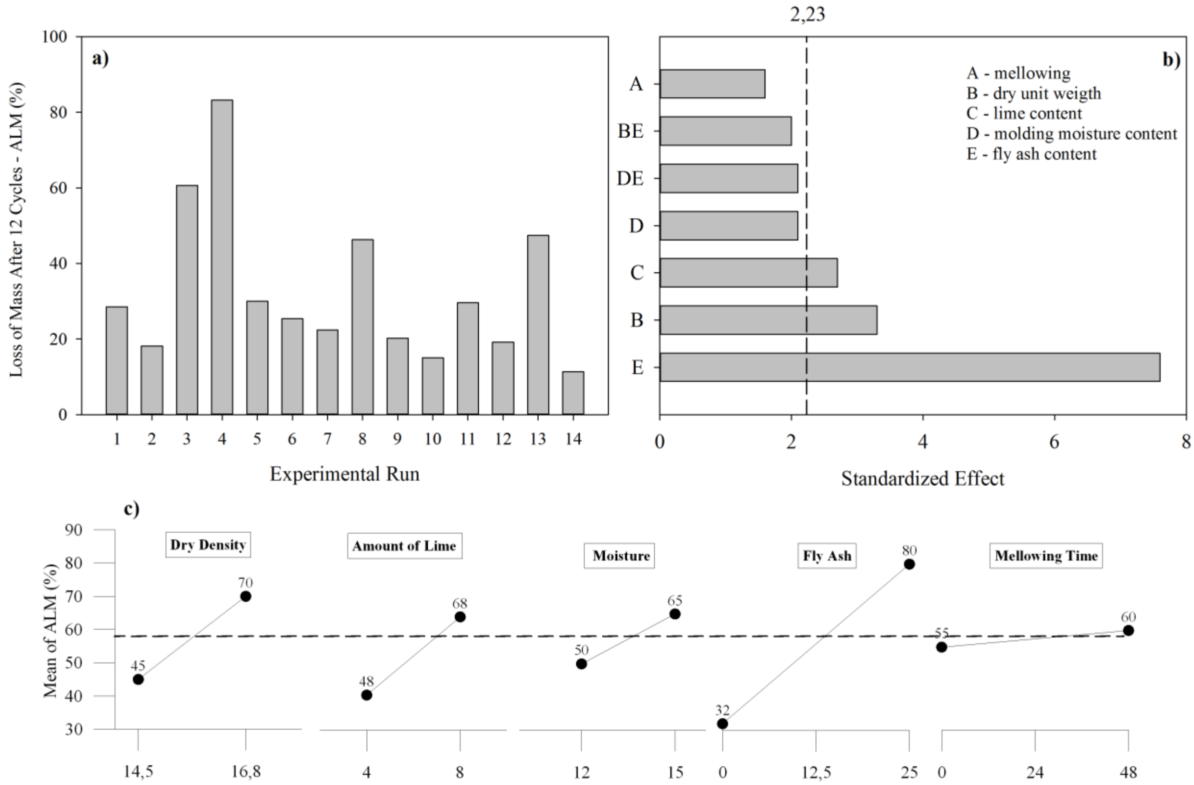

Figure 6 – (a) Durability test results, (b) Pareto Chart, and (c) Main effects plot.

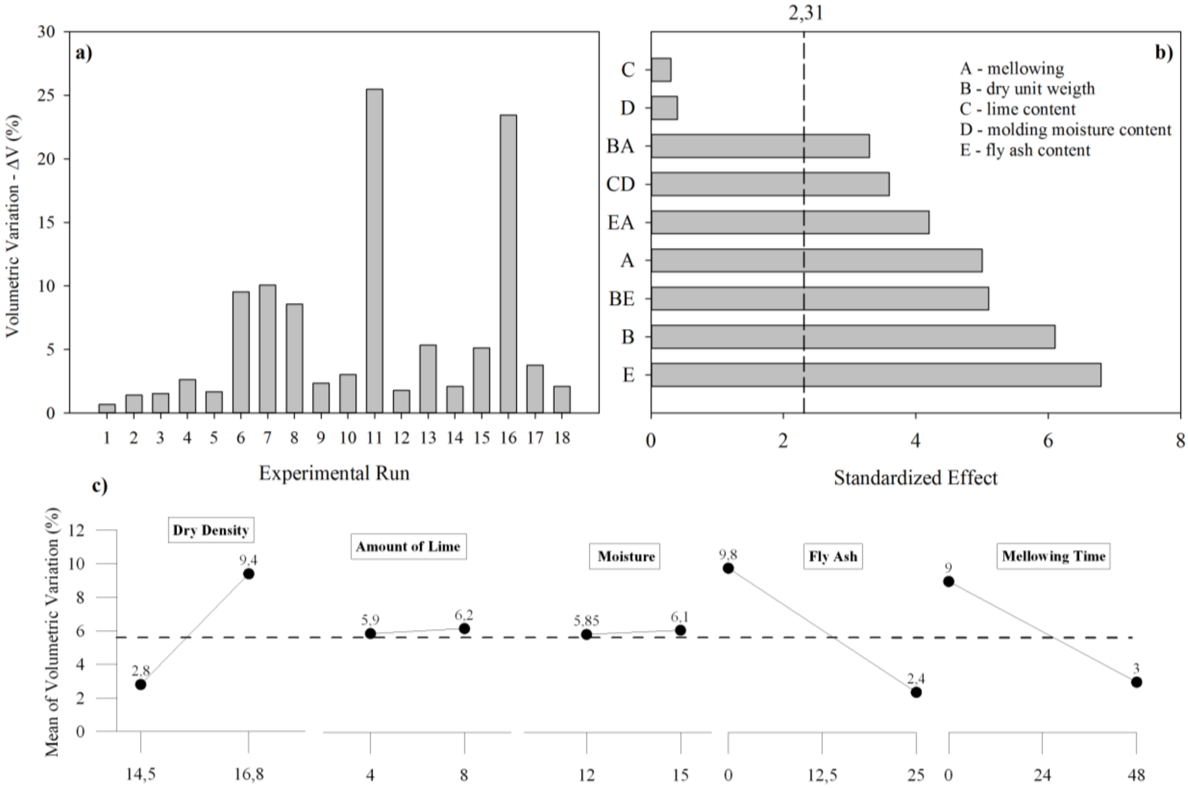

Figure 7 – (a) One –dimension free swell tests results, (b) Pareto Chart and (c) Main effects plot.

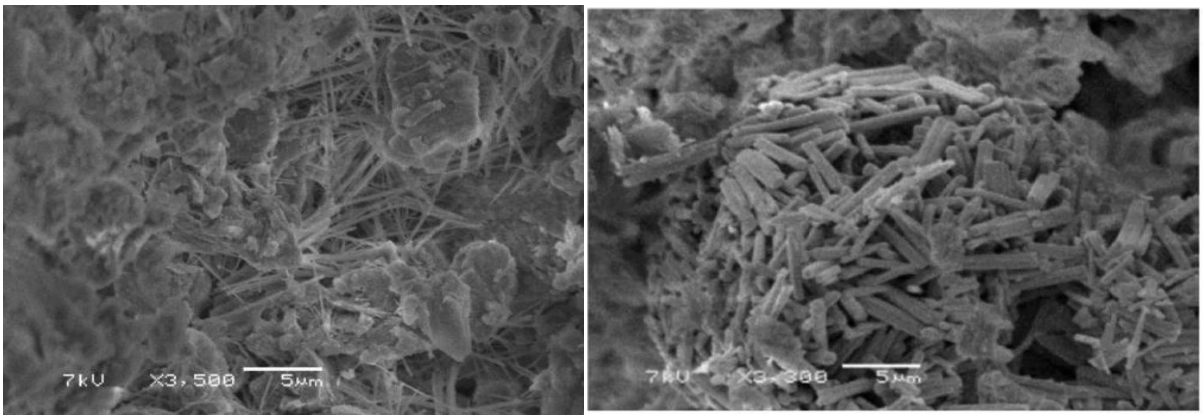

Figure 8 - Microstructural observation by SEM without fly ash considering: (a) specimen cured for 130 days and (b) specimen subjected to 12 wet-dry cycles.

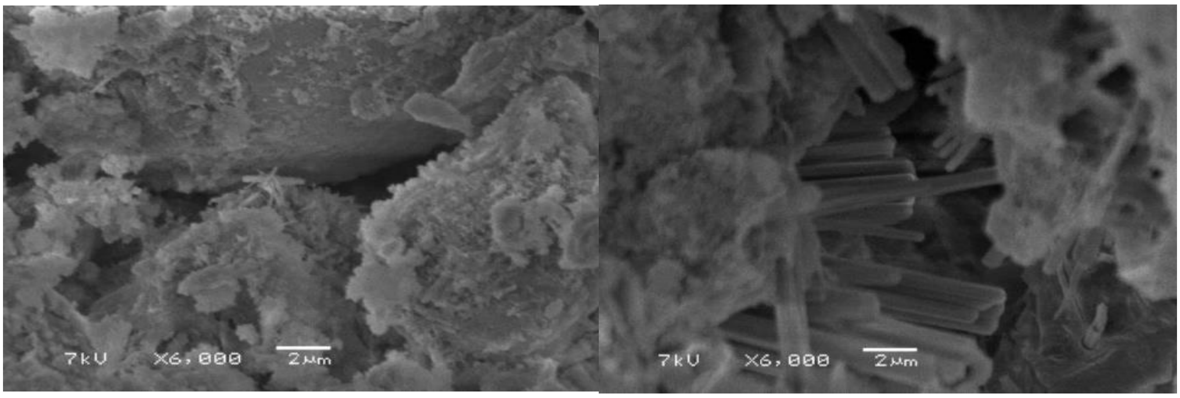

Figure 9 - Microstructural observation by SEM containing fly ash considering: (a) specimen cured for 130 days and (b) specimen subjected to 12 wet-dry cycles.