Study of expansive soil and polymer interactions

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ABSTRACT: The purpose of this study is to evaluate the efficiency of different soil-polymers mixtures to control natural soil expansion. This work is part of an ongoing research project carried out at the School of Civil Engineering at Buenos Aires University. The soil-polymer mixtures were carried out with expansible high plasticity clay from Comodoro Rivadavia (Argentina, Chubut province). The clay exhibits plastic volumetric behavior over a wide range of moisture contents. Damages on light buildings caused by soil expansion were reported many times at the site (Orlandi et al., 2015). Its physical and mechanical characterization was done on earlier works (Ruiz et al 2012, Marti et al., 2015). In this research, soil was stabilized with three types of polymers: calcium lignosulfonate (CLS), cationic polyacrylamide (CPAM) and starch. To assess the impact of the polymer quantity within mixtures, three weight proportions were tested: 1.5, 3.0 and 5.0 % by weight of clay. The research was divided in two stages. Firstly, physical and mechanical characterization was carried out for all mixtures to determine polymer modifications and its proportion influence in controlling soil expansion. Finally, hydro-mechanical characterization of the selected mixture was performed: water retention curve was obtained and free swelling-swelling pressure tests were carried out. The attenuation of the expansion potential for the different percentage of four polymers is discussed. Results are presented in terms of variation on index properties, the effects of the polymer in the potential expansion of the soil and the relationship of suction-degree of saturation. The hydraulic and mechanical behavior of the selected mixture presented significant changes in comparison to the natural clay.

KEYWORDS: Polymers, soil stabilization, expansive soils.

1. INTRODUCTION

Expansive soils present high volumetric deformations that can affect the stability and proper utilization of structures (Chen 1975, Orlandi et al. 2015 & 2016). To mitigate these effects there are various techniques as soil replacement, prevent soil-structure interaction, chemical stabilization treatment, among others. Traditional inorganic additives used for treating expansive soils as chemical stabilization include cement, gypsum, lime and fly ash. They have been used mainly in base materials of roads and highways, embankments and foundations. However secondary effects such as sulphate attack on concrete and steel structures adjacent to gypsum treated soils, and problems with vegetation growth on lime treated soils due to high pH levels have been reported (Perry 1977).

New generation of polymeric organic additives has increased the interest of many researchers to treat different soils, changing their physical, hydraulic and mechanical properties (Schenning 2004). They have been extensively implemented in agriculture in arid and semi-arid areas to control fines migration and improve water retention properties. The use of polymers to control swelling potential is still in the learning stage.

In order to develop new treatments for expansive soils, this work aims to understand physical, chemical and hydro-mechanical behaviour of soil polymer mixtures.

The paper describes the swelling properties of different compacted clay-polymer mixtures as: Calcium Lignosulfonate, Cationic Polyacrylamide and starch. Index properties as Cation Exchange Capacity (CEC) and water retention of clay-polymer mixtures are analysed to highlight the effects of the polymer in the natural soil swelling potential.

The hydraulic and mechanical behaviour of mixture of Calcium Lignosulfonate are presented and properties variation studied.

2. MATERIALS

2.1 C*lay studied*

A montmorillonite clay was studied. This clay comes from Golfo San Jorge basin and is extracted from a superficial deposit of Comodoro Rivadavia, Chubut province, Argentina. CR-Clay is high plasticity clay with moisture content at the liquid limit LL of 80%, at the plastic limit PL of 39% and at the shrinkage limit of 17.5%. Based o the physical soil characteristics presented in Table 1, this soil is classified as MH according to the Unified Soil Classification System (USCS). However, 80 % of the minerals obtained by an XRD test are montmorillonite. The maximum adsorption of methylene blue corresponds to the specific surface of the clay particles. The specific surface of this clay is an expected value for a montmorillonite mineral.

Table 1. Physical properties of the clay soil

Parameter	Value	Parameter	Value
USCS	MH	γ_{dmax} (kN/m^3)	13.0
#200 (%)	96.0	ω_{opt} (%)	31.0
LL (%)	80.0	S_s (m^2/g)	306
PL (%)	39.0	Clay (%)	79.0
SL (%)	24.2	G_s (-)	2.70

2.2 *Polymers*

A polymer is a material formed by chemical reactions in which the basic molecule (monomer) appears n-times creating a long chain. It is an organic compound. Their physical and chemical properties depend on the basic monomer, the crosslink density and the operation temperature.

In order to compare the effectiveness as soil stabilizers, three polymers have been studied. These polymers are

Cationic Polyacrylamide (CPAM), Starch and Calcium Lignosulfonate (CLS). In Figure 1, polymers are shown at room temperature.

Figure 1. Calcium Lignosulfonate, Starch and CPAM at room temperature.

Calcium lignosulfonate is an environmental friendly, non-corrosive and non-toxic polymer that does not alter the soil pH upon treatment (Indraratna et al., 2008).

Their thermal properties of such as glass transition temperature (T_g) and mass variation ($\Delta m/m$) against temperature had been determined by three test: Differential Scanning Calorimetry (DSC), Thermogravimetric analysis (TGA) and Mechanic-Dynamic Analysis (DMA). Results obtained are shown in Table 2.

Table 2. TGA, DSC and DMA results

Polymer	$\Delta m/m$ (%)	T_g (ºC)
Calcium lignosulfonate	55	140

These temperature values indicate the range of workable temperatures of the polymers. For temperatures below T_g the polymeric material is in a glassy state, above it, polymer becomes more deformable.

3. EXPERIMENTAL PROGRAM

3.1 *Polymer election*

In order to choose a polymer to reduce clay expansion, preliminary tests were carried out to obtain index properties of the soil-polymer mixture. Soil was tested with three different polymers, at three different percentages by weight of dry clay. The tests proposed were Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL), Specific Surface (S_s) and Cation Exchange Capacity (CEC). Test had been done according to ASTM standards for USCS (ASTM D4318 and ASTM D2487). CEC and Specific Surface tests had been done by the methylene blue method (Santamarina et al. 1994).

In Table 3 results obtained are presented given the following notation for each type of mixture.

- CR Clay (Clay)
- Calcium Lignosulfonate (CLS)
- Starch (S)
- CPAM (C)

The letter "N" means that the test did not applied or could not be done. This happened mainly when it was not possible to obtain homogeneous mixture with the addition of water. For example, CPAM polymer did not show any interaction with the soil.

Table 3. Physical properties of the mixtures tested

Mixture	LL (%)	PL (%)	SL (%)	S_s (m^2/g)	CEC ($m_{eq}/100g$)
Clay	80	39	24.2	306	77.4
1.5% CLS	122	43	11.8	122	67.2
3.0% CLS	122	42	16.1	76	65.1
5.0% CLS	123	41	18.1	31	7.8
1.5% C	N	N	N	N	N
3.0% C	N	N	N	N	N
5.0% C	N	N	N	N	N
1.5% S	97	46	15.7	398	101.6
3.0% S	101	48	19.0	398	100.4
5.0% S	125	48	16.1	410	104.7

The effect of incorporating different percentages of polymers shows no conclusive results on reducing the swelling potential of the CR Clay.

These preliminary results show that the specific surface of mixture CR Clay-CLS reduces with the increase of polymer by percentage. This aspect is a clear indication of the reduction of cation exchange and thus a reduction of swelling potential. However, the variation of liquid limit and shrinkage limit are contrary to expectations. As mentioned, CPAM polymer could not be studied due to difficulties to prepare the mixture. This disables CPAM for use in field applications. Mixtures CR Clay-Starch did not show a clear tendency, while LL and S_e increase with increasing amount of polymer by weight, the SL increases and decreases for different percentages. Further research is needed for CR Clay-Starch interaction.

In this article the macro and microstructural behaviour of CR Clay-CLS will be studied.

4. MACROSCOPIC BEHAVIOUR

4.1 *Mixtures compaction*

The experimental program was carried out on compacted CR Clay and CR Clay polymer samples with CLS. All specimens were obtained from the standard Proctor compaction method according to ASTM D698 standards.

The maximum dry density (γ_{dmax}) and optimum moisture content (ω_{opt}) for the CR clay and polymer mixtures are summarized in Table 4.

Table 4: Proctor compaction parameters

Mixture	γ_{dmax} (kN/m^3)	ω_{opt} (%)
CR Clay	13.0	31.0
CR Clay-3% CLS	12.4	34.0
CR Clay-5% CLS	12.5	36.0

In the following tests, samples were prepared at 95% of maximum dry density with different moisture content. Before adding water to reach the moisture objective, materials are premixed in dry state.

The study was carried out on the soil-polymers mixtures (CR Clay, CR Clay-3% CLS and CR Clay-5% CLS) with the same density and water content (dry, optimum and wet side of optimum moistures) that the ones realized on the CR Clay. In Table 5 these moistures are shown.

Table 5: Moisture contents at 95% of γ_{dmax}

Mixture	$\gamma_{d95\%}$ (kN/m^3)	ω_{dry} (%)	ω_{opt} (%)	ω_{wet} (%)
CR Clay	12.4	18.0	31.0	37.0
CR Clay-3% CLS	11.8	28.0	34.0	40.0
CR Clay-5% CLS	11.9	27.0	35.0	44.0

4.2 *Expansion Index*

Tests had been done according to ASTM D4829 standards. A total of six samples were tested in order to obtain average results for the three mixtures. The EI parameter is defined as 1000 times the specific vertical deformation of a sample free to swell for 24 hours. The samples were mixed using dry CR Clay, polymer in the necessary percentage and mixed with distilled water. The mold is a 3 pieces cylinder of 101.6mm diameter, and the middle ring in which the test is performed has a height of 25mm. The sample is compacted dynamically with 15 uniformly distributed blows of a rammer in free fall of 305mm of height for each layer, in two layers of equal volume. A scarification is done to improve continuity between layers. Finally, the apparatus is dismantled and the sample trimmed to its initial height, a charge of approximately 6.9kPa is applied for at least 10 minutes before inundating the sample and starting the test.

The standard test limits the calculation of EI_{50} for samples with an initial degree of saturation between 40% and 60%, and then the obtained EI between theses degrees of saturation is extrapolated to EI_{50} corresponding to a degree of saturation of 50%.

ASTM standard used in these tests provides a classification of expansive potential shown in Table 6.

Table 6. Potential expansion according to ASTM D4829

Expansion Index EI_{50}	Potential Expansion
0-20	Very Low
21-50	Low
51-130	Medium
>130	Very High

The results for Expansion Index tests are shown in Table 7. This test provides a first approach to expansion behaviour, so lower potential expansion values are expected for mixtures with addition of CLS. As shown in Table **7** the increasing percentage of polymer the lower potential expansion is registered. For the unmodified CR Clay potential expansion is classified as High, being reduce to Medium for the addition of 3% CLS and to Low in the case of 5% CLS. These results agree with expectations.

Table 7. Expansion Index results

Mixture	S_r (%)	EI_{50}	Potential Expansion
CR Clay	43	114	High
CR Clay-3% CLS	46	71	Medium
CR Clay-5% CLS	44	40	Low

4.3 *Free Swell – Swelling Pressure*

Tests had been done according to ASTM D4546 in an oedometer apparatus. The sample was statically compacted into a mold of approximately 18mm height and a diameter of 76mm. The free swell test is done under a seating pressure load of approximately 5kPa. These tests had been made for the same dry density and same moisture content in order to compare directly swelling results.

In Table **8** the initial compaction properties such as initial moisture content, initial dry density and initial degree of saturation are presented.

Free swell test results are shown in Figure 2. The swelling pressure is the pressure needed for avoiding the expansion of the soil. In this work the swelling pressure is obtained by the initial void ratio method. This method aims to find the vertical pressure applied that makes the void ratio after swelling reach the initial void ratio before swelling and names it the swelling pressure of the soil. In Figure 3 the void ratio variation with the applied vertical pressure is shown for the three mixtures.

Table 8: Initial compaction properties of clay and CLS mixtures

Mixture	γ_{d0} (kN/m^3)	ω_0 (%)	S_r (%)
CR Clay	12.4	29.2	69.6
CR Clay-3% CLS	12.7	34.1	84.3
CR Clay-5% CLS	12.8	32.8	83.0

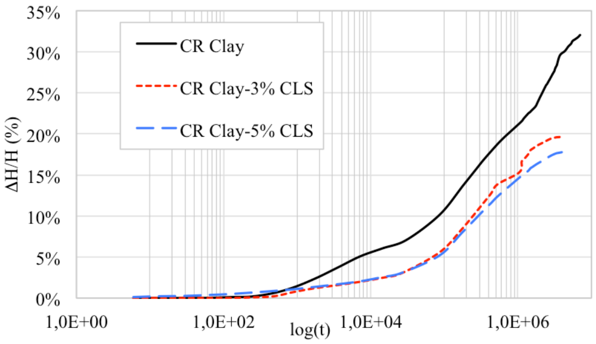

Figure 2. Free swell test for the three mixtures.

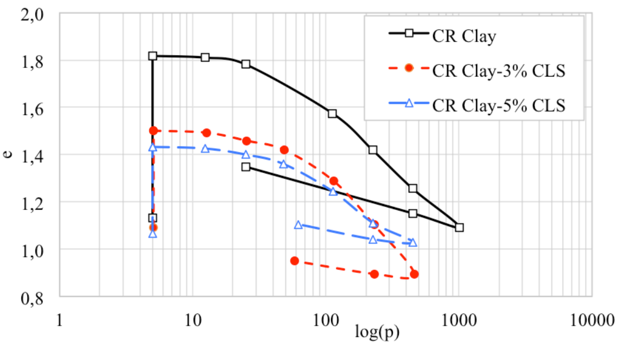

Figure 3. Swelling pressure test for the three mixtures.

Table 9. Summary of free swell and swelling pressure tests

Mixture	ΔH/H (%)	σ_{SP} (kPa)	C_c (-)	C_s (-)
CR Clay	32.0	845	0.51	0.16
CR Clay-3% CLS	19.6	240	0.65	0.09
CR Clay-5% CLS	17.8	330	0.34	0.09

In Table 9 free swell and swelling pressure results are summarized. There is an important reduction of the CR Clay swelling after the addition of CLS, 38% reduction for CR Clay-3% CLS and 45% reduction in the case of CR Clay-5% CLS. The swelling pressure reduction is greater, 72% for the mixture CR Clay-3% CLS, and 61% for CR Clay-5% CLS.

In addition, the primary compression line reduces its value for both mixtures with addition of CLS, and in the mixture CR Clay-5% CLS also reduces the virgin compression line.

4.4 *Unconfined Compressive Strength (UCS)*

This test provides a characterization of the unsaturated compressive strength of the different mixtures. These tests were done according to ASTM D2166.

To compare the behaviour of the mixtures in a wider range of initial moisture content, the tests were done for all the mixtures in the dry, optimum and wet side of the Proctor optimum moisture content. In Table 10 the results obtained are shown.

Table 10. Unconfined Compressive Strength results (UCS)

Mixture	ω_0 (%)	e_0 (-)	S_{r0} (%)	ε_f (%)	UCS (kPa)
CR Clay	17.7	1.28	37	0.85	95
	30.7	1.13	73	1.35	120
	35.5	1.46	66	1.73	69
CR Clay-3% CLS	19.0	1.42	36	1.26	115
	31.0	1.22	68	1.55	110
	35.8	1.22	79	3.27	68
CR Clay-5% CLS	21.1	1.18	48	1.15	140
	31.5	1.12	76	2.79	125
	36.5	1.19	83	4.40	86

Results show an increase of resistance in the CR Clay-5% CLS for the different initial moisture content in comparison with the CR Clay. In the case of CR Clay-3% CLS mixture, only the dry side of the optimum improves the resistance in comparison with the CR Clay.

For the mixtures with addition of CLS, there is a bigger deformation before the failure, which is shows a more ductile behaviour.

4.5 *Soil Water retention properties*

Aiming to compare the water retention properties of the treated soil mixtures, soil water retention curves (SWRC) with paper filter method tests were done according to ASTM D5829.

For this test, a minimum of ten samples for each mixture were used to adjust the soil water retention curve using the van Genuchten equation (see Eq. 1).

$$S_e = \frac{S_r - S_{res}}{1 - S_{res}} = \left\{1 + \left[\frac{(u_a - u_w)}{S_{ae}}\right]^{1/1-\lambda}\right\}^{-\lambda} \qquad (1)$$

where

S_e: Effective degree of saturation (%);

S_{res}: Residual degree of saturation (%);

$(u_a$-$u_w)$: Actual matric suction (kPa);

S_{ae}: Air entry value (kPa);

λ: Parameter of pore distribution (-).

The calibrated parameters are shown in Table 11. The matric suction versus the saturation degree is shown in Figure 4.

Table 11. Soil Water Retention Curve parameters

Mixture	λ (-)	S_{ae} (kPa)	S_{res} (%)
CR Clay	0.18	300	15
CR Clay-3% CLS	0.19	400	15
CR Clay-5% CLS	0.23	600	15

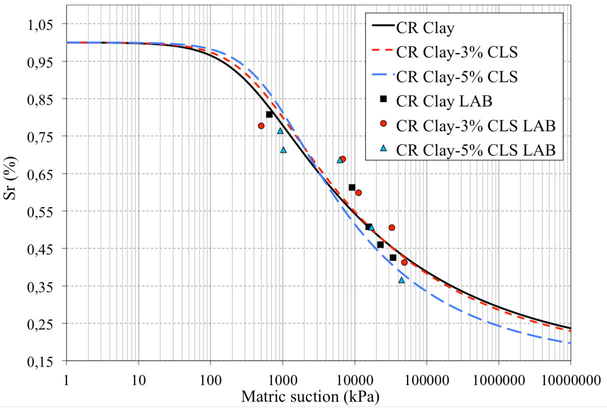

Figure 4. Soil water retention curves (SWRC) for the three mixtures.

The soil water retention curve relates the degree of saturation with matric suction. These curves have information of the unsaturated behaviour of the mixtures.

From Figure 4 it is mentioned that the three mixtures show similar behaviour in the obtained experimental points. As indicated in Table 11 the mixtures with addition of CLS increase the air entry value, and reduces the capacity of retaining water for higher suctions, measured by bigger values of pore distribution parameter, λ. These trends need to be further studied in order to get more accurate results.

5. MICROSCOPIC BEHAVIOUR

5.1 *X-Ray diffraction at low angles (SAXRD)*

The X-Ray diffraction test at low angles (2°<2θ<8°) was carried out for the three samples. Previously chemical composition and complete XRD tests were done. In the XRD test it was determined that the CR Clay is composed mostly of Montmorillonite mineral and the chemical test determined that this Montmorillonite mineral is principally sodium Montmorillonite. Sodium Montmorillonite mineral is more expansive than calcium Montmorillonite mineral. The objective of this test is to prove whether or not the polymer modify the interlaminar distance in the Montmorillonite crystal structure.

In Figure 5 the results are presented. In this figure the 2θ angle does not shift to bigger values, which is the expected behaviour for a lower interlaminar distance. There is no considerable variation of the 2θ angle for the mixtures with CLS addition. The maximum variation angle is Δ2θ=0.5°, between CR Clay and CR Clay-3% CLS mixture.

Based on these results it cannot be concluded that CLS polymer addition modify the interlaminar distance of the Montmorillonite mineral.

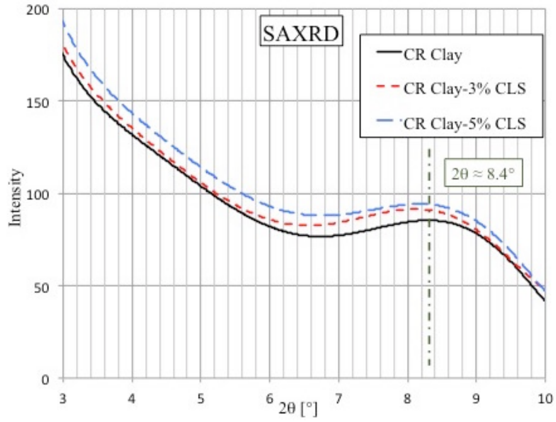

Figure 5. Low angles XRD for the three mixtures.

5.2 *Mercury intrusion porosimetry (MIP)*

In order to measure the porosimetry of all mixtures, mercury intrusion porosimetry tests were done. These tests were carried out for all the mixtures compacted to the same dry density and initial moisture content on the dry side of the optimum according to Proctor tests. In Table 12 the moisture content, void ratio, degree of saturation and obtained results of porosimetry are presented.

Table 12. Compaction conditions and total porosity results

Mixture	ω_0 (%)	e_0 (-)	S_{r0} (%)	Porosity (mm^3/g)
CR Clay	18.5	1.23	41	255.3
CR Clay-3% CLS	20.4	1.21	46	241.9
CR Clay-5% CLS	19.8	1.18	45	226.7

In Figure **6** and Figure **7** the pore size distribution (PSD) and the total void ratio variation are presented as a function of theoretical pore size diameter.

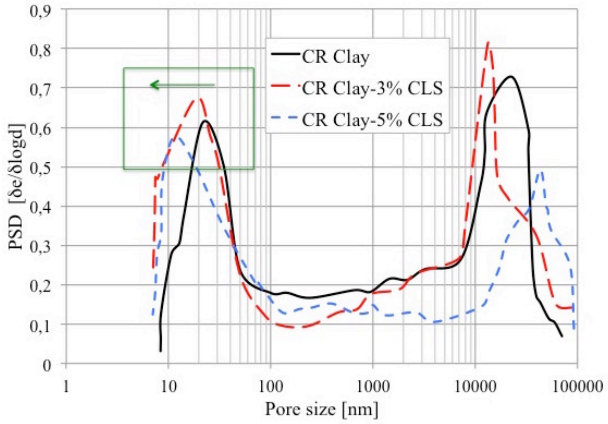

Figure 6. Pore size distribution from MIP tests

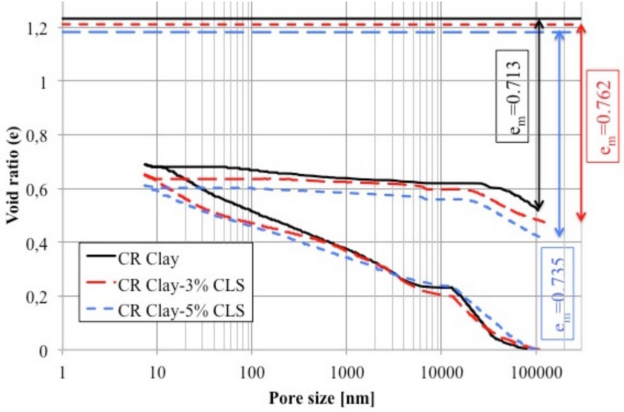

Figure 7. Intrusion and extrusion from MIP tests

As shown in Figure **6** the microstructural most representative pore diameter reduces its theorical width with the addition of CLS. In Figure **7** the microstructural void ratio is calculated as the reversible portion of mercury extruded from the samples (Delage & Lefebvre, 1984). In the figure, it possible to observe that CLS – soil mixture increases the microstructural voids reducing macro structural void. In Table **13** the micro and macroestructural void ratio are presented based on the results obtained in Figure **7**.

Table 13. Micro and macroestructural void ratio for all mixtures

Mixture	e_0 (-)	e_m (-)	e_M (-)
CR Clay	1.23	0.71	0.52
CR Clay-3% CLS	1.21	0.76	0.45
CR Clay-5% CLS	1.18	0.74	0.44

6. CONCLUSION

Different polymers at different percentages were proposed and evaluated to mitigate the CR Clay expansion. Calcium Lignosulfonate shows encouraging results in reducing both free swell and swelling pressure of the natural soil.

Different percentages of CLS barely modificates the swelling potential but improves deformability and increase resistance of the mixtures. The hydraulic behaviour of the mixtures shown a little increase of the air entry value, and reduces the water retention capacity of the soil at same degree of saturation comparing with CR Clay.

Microstructural tests shown that polymer addition reduces the total porosity of the soil, and increases the microstructural void ratio.

Future research is needed to accomplish the effect of varying the percentage of polymer addition. Moreover, DRX tests for all the 2θ angles for all mixtures, increase the MIP tests for different initial moisture content, and improve the SWRC for the different mixutes.

Finally, an important aspect in the soil-polymer interaction is the curing time. Studying the effect of the CLS interaction with the soil at different curing times is an investigation that is currently underway.

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