Polymer applications to control soil expansion

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Polymer Applications to Control Soil Expansion

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SUMMARY: 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). 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, 2016). Its physical and mechanical characterization was done on earlier works (Marti et al., 2015). In this research, soil was stabilized with four types of polymers: Calcium lignosulfonate, Cationic Polyacrylamide (CPAM), Anionic Polyacrylamide (APAM) 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 presented significant changes in comparison to the unmodified clay.

KEYWORDS: Polymers, soil stabilization, expansive soils, matrix suction

1 INTRODUCTION

Expansive soils present high volumetric deformations that can affect the stability of structures and foundations (Chen, 1975, Orlandi et al 2015, 2016). To mitigate these effects there are various techniques as soil replacement, prevent soil-structure interaction, chemical stabilization, among others. Traditional inorganic additives used for treating expansive soils as chemical stabilization include cement, lime and fly ash. They have been used mainly in base materials of roads and highways, embankments and foundations.

New generation of polymeric organic additives has increased the interest of many researchers to treat different soils, changing their physical, hydraulic and mechanical properties (Schening 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 behavior of soil polymer mixtures.

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

The hydraulic and mechanical behaviour of the selected mixture of Calcium Lignosulfonate and Anionic Polyacrylamide are presented and show significant changes in comparison to natural clay. To evaluate the efficiency of different clay-polymer mixtures to control soil expansion, a series of free swell and eodometric test were carried out.

2 MATERIALS

2.1 Clay studied

A montmorillonite clay was selected. It comes from Golfo San Jorge basin and is extracted from a superficial deposit of Comodoro Rivadavia, Chubut province, Argentina (Ruiz et al. 2012). 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 shrinkage limit of 17,5%. Based on 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 the 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

USCS	#200 (%)	LL (%)	PL (%)	SL (%)	γ_{dmax} (kN/m^3)	ω_{opt} (%)	S_e (m^2/gr)
MH	96	80	39	17.5	13.0	31.0	337

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 the present research four polymers have been studied in order to compare their effectiveness as soil stabilizer. These polymers are Anionic and Cationic Polyacrylamide (APAM and CPAM), Starch, and Calcium Lignosulfonate. Two polymers have been thoroughly characterized because of their interesting application in civil engineering cases: Calcium Lignosulfonate (CLS) and Anionic Polyacrylamide (APAM).

In **Figure 1**, polymers are shown at room operating temperature.

Figure 1. Calcium Ligniosulfonate, starch and APAM at room temperature.

The anionic polyacrylamide additive used is a hydrophilic synthetic polymer called FAISAN AP-1011 Polyacrylamide at room temperature is presented as a white crystalline solid. It is water soluble, highly viscous and environmentally safe, able to stabilize different soil types (Marti et al. 2015).

The 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 such as glass transition temperature (Tg) and mass variation (Δm/m) against temperature had been determined by two tests: Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). In **Table 2** the obtained results are shown.

Table 2. TGA and DSC results

Polymer	Δm/m (%)	Tg (°C)
APAM	40	95
CLS	55	140

These temperature values indicate the range of workable temperatures of the polymers. For temperatures below Tg 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 four different polymers, at three different percentages by weight of dry clay. Some of the test are Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL), Specific Surface (Se), Cation Exchange Capacity (CEC), and Swell Index (SI). Tests had been done according to ASTM standards for USCS (ASTM D4318 and ASTM D 2487), Shrinkage Limit (ASTM D427) and Swell Index. Swell index test was done according to ASTM Standard 5890. CEC and Specific Surface tests, according to Santamarina et. al., 2001.

In **Table 3** are presented the results obtained given the following notation for each type of material:

- Natural CR Clay (Clay)
- Calcium Lignosulfonate (CSL)
- CPAM (C)
- Starch (S)
- APAM (A)

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 homogenous mixture with the addition of water. For example, CPAM polymer did not show any interaction with the soil.

Table 3. Physical properties of the clay soil

Mixture	LL (%)	PL (%)	SL (%)	Se (m^2/g)	CEC (meq/100g)	SI (%)
Clay	80	39	24,2	306	77,4	9
1.5%CLS	122	43	11,8	122	67,2	9
3% CLS	122	42	16,1	76	65,1	12
5% CLS	123	41	18,4	31	7,8	13
1.5% C	N	N	N	N	N	N
3% C	N	N	N	N	N	N
5% C	N	N	N	N	N	N
1.5% S	97	46	15,7	398	101,6	N
3% S	101	48	19,0	398	101,6	N
5% S	125	48	16,1	410	104,7	N
0.5% A	150	50	16,3	N	N	N
1.5% A	170	60	15,7	N	N	N

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 the percentage of polymer. This aspect could be a clear indication of the reduction of cation exchange and thus a reduction swelling potential. However, the variation of the liquid limit and the 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 the LL and Se increase with increasing the amount of polymer by weight, the SL increases and decreases for different percentages. Further research is needed for CR Clay-Starch interaction.

For CR Clay-APAM it is clear that the effect of the polymer increases the LL, PL and reduces SL for both percentages studied. This polymer shows an ability to interact at microstructural level reducing the pores average diameters and total pore volume (Marti et al. 2015). However, the effects on the expansiveness of the mixture are further enhanced with increasing APAM content.

In this study we will explore the behavior of CR Clay-CLS and CR Clay-APAM to assess the hydraulic behavior and swelling potential of mixtures.

3.2 Clay-polymers samples.

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

The maximum dry density (γ_{dmax}) and optimum moisture (ω_{opt}) content for the CR clay and percentage polymers mixture are summarized here:

1. Natural Soil, γ_{dmax}=13,0 kN/m^3, and ω_{opt}=31 %.
2. Mixture CR Clay–5 % CLS, γ_{dmax}=12,5 kN/m^3, and ω_{opt}=36 %
3. Mixture CR Clay–3 % CLS, γ_{dmax}=12,4 kN/m^3, and ω_{opt}=34 %.
4. Mixture CR Clay-1.5 % APAM, γ_{dmax}=12,4 kN/m^3, and ω_{opt}=23 %.

Results of the Proctor tests are shown **Figure 2**.

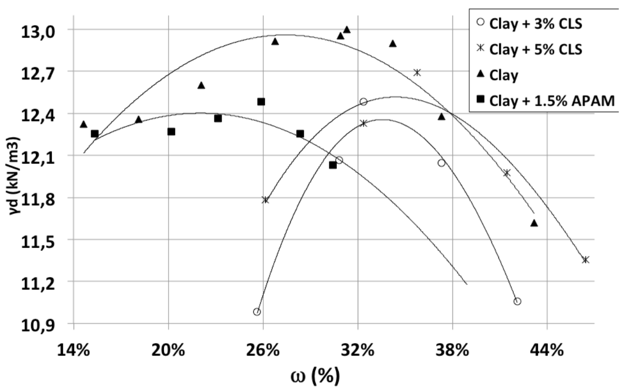

Figure 2. Proctor test for CR Clay, CR Clay+3 % CLS, CR Clay+5 % CLS and CR Clay+1,5% APAM.

The samples were prepared at 95 % of maximum dry density with different moisture content. Before changing the moisture content of the mixtures of CR Clay-polymer, materials were premixed in dry state. Previously the clay was sieved through the # Nº 10 ASTM series.

3.3 Water retention of clay-polymers mixtures

In order to determine the hydraulic effect of adding polymers to the Natural CR Clay, Soil – Water Retention tests were carried out. Tests had been done according to ASTM standards with the filter paper method.

Matric suction of unsaturated samples at 95 % of maximum dry density of the Natural Clay were tested.

Filter paper method consists in measuring the moisture content of a calibrated filter paper in contact with soil (matric suction) or in equilibrium with the partial vapor pressure in a sealed container (total suction). ASTM D 5298 proposes the calibration of the gravimetric water contents of the filter paper and suction measured adopted in this study.

Samples required a minimum of 7 days to reach equilibrium between the Whatman 42 filter paper and the Natural CR Clay-polymer mixtures. Fluctuations of temperature shall be less than 1 °C. With the method calibrated, the tests were carried out for Natural CR Clay, mixture CR Clay-1.5 % APAM, CR Clay-3 % CLS and CR Clay-5 % CLS.

Experimental results were fitted with van Genuchten function (1):

$$S_e = \left(1 + \left(\frac{s}{s_{ae}}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda} \qquad (1)$$

Where s_{ae} is air entry value, S_e is effective saturation degree and λ is a parameter of pore distribution. The calibrated parameters are shown in **Table 4**.

The matric suction versus effective saturation degree for different soils mixture is shown in **Figure 3** and **Figure 4**.

Table 4. Soil Water Retention Curves Parameters

Sample	λ	S_{ae} (kPa)	S_{res}	Curve Color
Clay	0,35	3500	0,20	Blue
1.5% A	0,35	2500	0,20	Green
3% CLS	0,35	4000	0,20	Orange
5% CLS	0,35	3000	0,20	Red

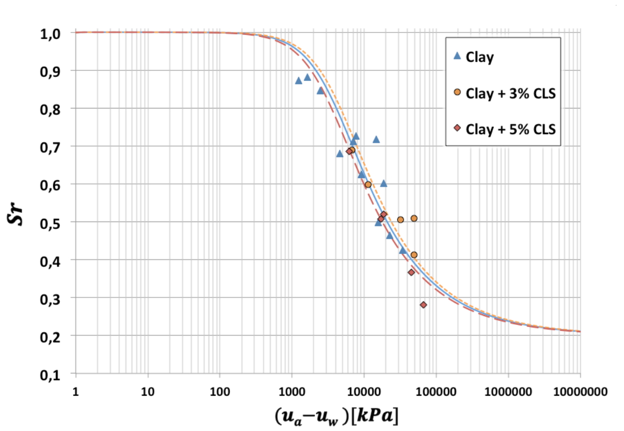

Figure 3. Soil Water Retention Curve for CR-Clay, CR Clay-3% CLS and CR Clay-5% CLS

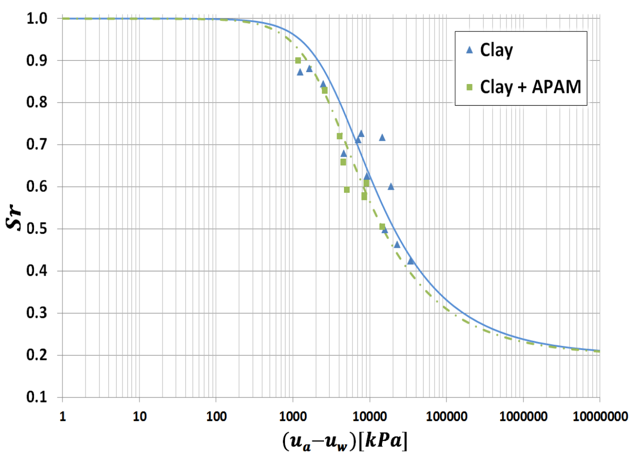

Figure 4. Soil Water Retention Curve for CR Clay and CR Clay-1.5 APAM

As indicated in **Table 4,** no clear trend in the tested samples is observed. Samples with 3% and 5% CLS are in the same range of the CR Clay. Reanalysis of data Marti et al 2015 and incorporating new tests shows that the samples with APAM suction values decrease for the same order of magnitude of the effective degree of saturation. This trend is observed in the calibration curve Van Genutchen.

The Natural CR Clay-polymer interaction alters the clay particle surface properties and influences water - clay to arrange in a different way.

Further research is being undertaken to study the arrangement of the Natural CR Clay-polymer mixtures with Scanning Electron Microscopy and Mercury Intrusion Porosimeter.

3.4 Expansion Index

Expansion Index tests was done according to ASTM D4829 standards. A total of six samples were tested in order to obtain average results for the three samples. The parameter EI is defined as a 1000 times the specific vertical deformation of the sample. The samples were mixed using dry Natural CR Clay and polymer in the necessary percentage and then mixed with distilled water. The mold is a 3 - pieces cylinder of 101,6 mm diameter, and the middle ring in which the test was done has a height of 25 mm. The sample is compacted dynamically with 15 uniformly distributed blows of a rammer in free fall of 305 mm of height for each layer, in two layers of equal volume. A scarification between layers is done to generate a reliable interface. Finally, the apparatus is dismantled and the sample trimmed to its initial height, a charge of approximately 6.9 kPa was applied for at least 10 minutes before inundating the sample and starting the test.

It is important to mention that the standard test limits the calculation of EI_{50} for samples with a degree of saturation between 40 % and 60 %, in which EI_{50} is the EI for a sample with degree of saturation equal to 50 %. The standard provides a classification of expansive soils according to the value of EI obtained, shown in **Table 5**.

Table 5. Potential Expansion according to EI

Expansion Index, EI	Potential Expansion
0-20	Very low
21-50	Low
51-90	Medium
91-130	High
>130	Very high

The results for Expansion Index are shown in **Table 6**. The swelling after 24 h is registered. It is important to remark the effect of adding more polymer. For the Natural CR Clay the potential expansion is labeled as "High", in the case of Natural CR Clay-3 % of Calcium Lignosulfonate it is classified as "Medium" expansion potential and finally, for the Natural CR Clay-5 % of Calcium Lignosulfonate, the expansion potential is "Low" and confirms that this polymer reduces the expansion of the soil and the more polymer added the greater the reduction.

Table 6. Expansion Index results

Mixture	Sr (%)	EI_{50}	Potential Expansion
Clay	43	114	High
3% CLS	46	71	Medium
5% CLS	44	40	Low
1.5% A	55	128	High

3.5 Free Swell

These tests had been done according to ASTM standards in an oedometer apparatus. The sample was statically compacted into a mold of approximately 18 mm height and a diameter of 76 mm. The test is load under a seating pressure of approximately 5 kPa. These tests had been made for the same dry density and same moisture content in order to compare directly the different values of deformation. This was not the case of the Natural CR Clay-APAM mixture, which was previously tested.

As illustrated in **Figure 5**, Natural Soil-1.5 % APAM mixture is the most expanding sample, followed by Natural Soil. For Natural Soil's specific variation of height, there is a polymer that increases the expansion (APAM, in approximately 20 %), and there is another that reduces it (CLS, approximately 15 %). In **Table 7** Free Swell obtained results are clearly compared.

Different percentages of CLS (3 % and 5 %) show a great reduction of the expansion of the Natural CR Clay, and the difference between each other is negligible.

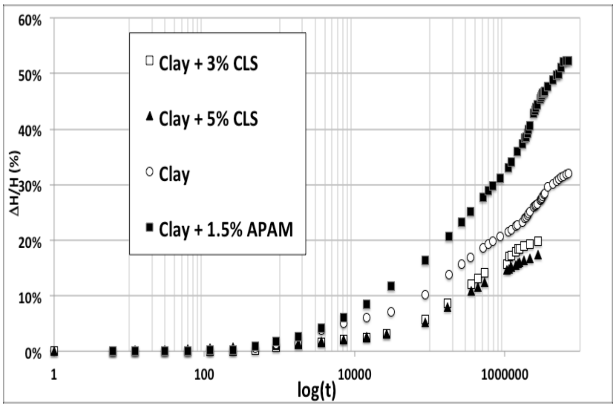

Figure 5. Free swell for Natural Soil, 1.5 % APAM, 3 % CLS and 5 % CLS

Further information is shown in **Table 6**.

Table 7. Free swell tests results

Mixture	ω (%)	Sr (%)	γ_d (kN/m^3)	ΔH/H (%)
Clay	29,2	69,6	12,4	32,2
1.5% A	28,1	76,1	13,0	49,3
3% CLS	34,1	84,3	12,7	19,4
5% CLS	32,8	83	12,8	17,3

3.6 Twenty-four hours free swell tests

To make an initial characterization of swelling magnitudes for different Natural CR Clay-polymer mixtures, twenty-four hours free swell tests were done. The tests had been done for the two polymers in study and the Natural CR Clay samples in order to compare their expansion. These trials were prepared in the same apparatus than Expansion Index test, but compacted statically to ensure a previously determined dry density (γ_d) and moisture content (ω).

The main idea of these tests is to compare the different specific deformation changing dry density and moisture to retrieve a trend of deformation.

In **Figure 6** the tests results are shown, and in **Table 8** the values obtained are compared.

The results for these tests confirm again that Natural CR Clay-APAM swell even more than Natural CR Clay, and Natural CR Clay-CLS mixtures swells less.

It is also interesting to stand out that higher percentages of Calcium Lignosulfonate do not reduce more the swelling recorded.

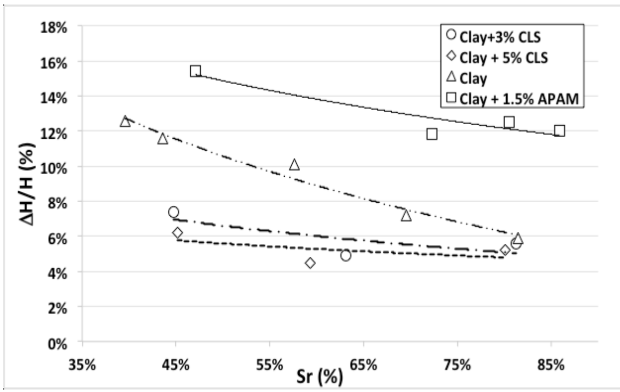

Figure 6. Twenty-four hours free swell tests, ΔH/H against Sr.

Table 8. Twenty-four hours free swell tests, results

Sample	ω (%)	γ_d (kN/m^3)	Sr (%)	ΔH/H (%)
$Clay_1$	17,4	12,4	39,6	12,6
$Clay_2$	17,9	12,8	43,6	11,6
$Clay_3$	22,7	14,4	69,5	7,2
$Clay_4$	23,0	13,0	57,6	10,1
$Clay_5$	32,5	13,0	81,5	5,9
1.5% A_1	23,5	11,5	47,1	15,4
1.5% A_2	37,6	11,9	80,5	12,5
1.5% A_3	37,6	12,4	85,9	12,0
1.5% A_4	29,9	12,8	72,2	11,9
3% CLS_1	21,6	11,7	44,8	7,4
3% CLS_2	21,7	14,0	63,1	4,9
3% CLS_2	21,7	14,0	63,1	4,9
3% CLS_3	34,1	12,7	81,3	5,6
5% CLS_1	23,6	11,2	45,6	6,2
5% CLS_2	34,0	10,6	59,3	4,5
5% CLS_3	32,8	12,8	80,1	5,2

4. FINAL REMARKS

Different polymers were proposed to mixture with natural soil on different percentages to study the effect on swelling potential on CR Clay. Calcium Lignosulfonate shows encouraging results in reducing the swelling potential of CR Clay up to 50 % compared to the behavior of natural CR Clay without additive. Furthermore investigation is undertaken in the CR Clay-Polymer interaction to have a complete characterization of the mixture.

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