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Stabilization of expansive soils for use in construction

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ABSTRACT

Expansive clay soils are extensively distributed worldwide, and are a source of great damage to infrastructure and buildings. These soils can cause heavy economic losses, as well as being a source of risk to the population. This article presents an experimental study in the stabilization of an expansive soil, consisting of the reduction of its swelling capacity and the improvement of its mechanical capacities by the addition of by-products and waste materials of industrial origin. This achieves the double objective of reducing the problems of this type of soil, and also of providing a use for the additives, thus eliminating the economic and environmental cost involved in managing them. From the point of view of expansivity, it was possible to reduce it to levels well below what Spanish legislation contemplates for expansive soils. As to the improved mechanical capacities of the soil, all treatments tested offered improvements of between two and four times the compressive strength of the untreated soil. Of the waste materials, the most notable is the behavior of Rice Husk Fly Ash, highly effective in stabilizing soil from the two aspects considered in this experiment.

1. Introduction

"Expansive soils" are those which experience great changes in volume when their water content varies. These types of soil are widely distributed throughout the world (Huang and Wu, 2007; Sabtan, 2005), although they are especially abundant in arid zones, where conditions are suitable for the formation of clayey minerals of the smectite group such as montmorillonite or some types of illites (Avsar et al., 2009; Nowamooz and Masrouri, 2008; Sabtan, 2005). These clays are characterized by having a very small particle size, a large specific surface area and a high Cation Exchange Capacity (CEC) (Fityus and Buzzi, 2009; Nalbantoglu, 2004; Nalbantoglu and Gucbilmez, 2001). The swelling of this type of clay is related to three types of factors: geology, the engineering factors of the soil, and local environmental conditions. Geology primarily determines the presence in the soil of these types of expansive clay minerals. Among the engineering factors included are the soil moisture content, plasticity and dry density. The most important local environmental conditions to consider are the amount of the clay fraction in the soil, its initial moisture conditions, and confining pressure (Sabtan, 2005). Volume changes of these types of soil are a major cause of natural disasters, since they cause extensive damage to the structures and infrastructure on top of them (Assadi and Shahaboddin, 2009; Avsar et al., 2009; Chen et al., 2007; Ferber et al., 2009; Huang and Wu, 2007). This has even led some authors to refer to them as "calamitous soils" (Chen et al., 2007).

The stabilization of expansive soils by the use of additives such as lime, fly ash or cement is well documented (Du et al., 1999; Nalbantoglu, 2004; Nalbantoglu and Gucbilmez, 2001; Rao et al., 2001; Yong and Ouhadi, 2007) and has traditionally concentrated on the elimination of the expansive power of the soil. In this type of soil, additives with calcium oxide produce the flocculation of the layers of clay by the substitution of the monovalent ions by the Ca^{2+} ions. This balances the electrostatic charges of the layers of clay and reduces the electrochemical forces of repulsion between them. The adhesion of the particles of clay into flocs then occurs, giving rise to a soil with improved engineering properties: a more granular structure, lower plasticity, greater permeability and above all lower expansivity (Du et al., 1999; Kinuthia et al., 1999; Langroudi and Yasrobi, 2009; Lin et al., 2007; Nalbantoglu, 2004; Nalbantoglu and Gucbilmez, 2001; Rao et al., 2001; Yong and Ouhadi, 2007). In addition, the presence of the OH^- ions produces an increase of the soil pH up to values of approximately 12.4. In these conditions, pozzolanic reactions take place, when the Si and the Al which form part of the sheets of the clay dissolve and combine with the available Ca^{2+} giving rise to cementing compounds such as Calcium Silicate Hydrates (CSH) and Calcium Aluminate Hydrates (CAH) (Chen and Lin, 2009; Guney et al., 2007; Nalbantoglu, 2004; Yong and Ouhadi, 2007). These compounds are responsible for improving the mechanical properties of the soil, as well as helping to reduce its expansivity by their cementing action. This article discusses the experimental results of the improvement of the properties of an expansive soil when it is treated with different additives. Thus, the stabilization of expansive soils has been considered from the standpoint of eliminating their capacity for swelling or shrinkage, and also from the standpoint of improving those of their mechanical properties which are of interest in civil engineering. This

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experiment has been based on civil engineering tests with a view to the use of these types of soil as a building material, and of the prevention of natural disasters related to their capacity for swelling or shrinkage. In the following sections of this paper we present an experimental study carried out with a highly expansive clay which was submitted to anti-expansive treatment by adding different additives. Having analyzed the reduction of the swelling capacity of the soil, a second treatment was performed in order to establish the improvement of the bearing capacity of the soil and its evolution over time due to the development of pozzolanic reactions.

2. Materials

2.1. Expansive soil

For this study we extracted a sample of expansive clays in the vicinity of Tudela (Spain). From a geological point of view, these soils are a set of tertiary materials, mainly clay, with varying levels of carbonate and sandstone known as the “Facies of Tudela”. This geological structure is extensively developed in the region of Tudela and the Bardenas, SE of the Navarro-Rioja basin, and extends westward along the synclines of Sesma and Miranda de Arga (see Fig. 1).

This material was analyzed in the laboratory, and found to have a plastic limit (PL) of 24.9% and a liquid limit (LL) of 43.5%. The mineralogy of the sample was estimated based on the chart proposed by Al-Rawas (1999). Based on the Standard Proctor Test (SP) following [Spanish] Standard UNE 103500 (AENOR, 1994), the unconfined compressive strength of the natural soil was determined, calculated at 0.399 MPa. The free swelling was determined in an oedometer, following [Spanish] Standard UNE 103601 (AENOR, 1996) for a remolded sample using the SP test, and was estimated at 4.65%. Spanish legislation defines expansive soils as those with free swelling in excess of 3% and sets limits to their use; it also prohibits the use of soils whose free swelling reaches 5%. This soil is consequently at the limit of what is legally permitted in Spain, and well over the values of swelling which are technically advisable.

2.2. Additives

The additives tested in this experiment were of two types: first there were commercial additives. Within these lime was considered as a benchmark for assessing the effect on the soil of other additives, since together with cement it is the only additive permitted by Spanish legislation for the treatment of expansive soils (Bustos, 2004). The second commercial additive considered was a non-standard stabilizer called the Consolid System (CS) (Eren and Filiz, 2009), which was used as a comparison with the results of a classic stabilizer such as lime and other alternative stabilizers that were also tested. These were mostly industrial waste or by-products materials, selected for their high mineral content. The dual aim was to achieve an improvement in the properties of expansive soils, together with an increase in value of the by-products and waste materials, and a reduction of the environmental problems currently involved in their disposal. From the point of view of the composition of the additives, four issues were addressed: firstly, products rich in divalent ions were selected to produce the effects of flocculation and cementing gel formation, thereby reducing the expansive nature of the clay. Secondly, additives rich in silicon and aluminum oxides were considered in order to promote pozzolanic reactions in the soil, which also contribute to limiting its expansivity and improving its mechanical properties. Thirdly, additives rich in monovalent cations were selected. These have the ability to balance the electrostatic charges of the clay sheets; but due to their monovalent nature they produce the dispersion of the clays, having a positive effect on the expansivity of the treated soil. Finally, additives were considered which are rich in sulfates that, depending on the cations associated with them, will cause flocculation (divalent cations) or dispersion (monovalent cations) of the clays. Furthermore, the SO_4^{2-} ion can form a crystalline compound called ettringite in the soil, contributing to the improvement of its mechanical properties (Degirmenci, 2008; Degirmenci et al., 2007; Kinuthia et al., 1999).

From the point of view of expansivity, we took as the reference stabilizer lime CL-90-S with a content of 82% of $Ca(OH)_2$, since it is an additive whose stabilizing effect on this type of soil has been amply documented (Du et al., 1999; Nalbantoglu, 2004; Nalbantoglu and Gucbilmez, 2001; Yong and Ouhadi, 2007).

The by-products and waste materials, whose high content in Ca, Mg, Si or Al oxides, make them suitable to be used as stabilizers were: magnesium oxide, rice husk fly ash, fly ash from cereal straw, steel fly ash and gypsum. The magnesium oxide was obtained from a commercial by-product called PC-7. This is produced from the industrial calcination of natural magnesite. The Natural Gypsum (NG) used was obtained from a commercial producer of this material. Rice Husk Fly

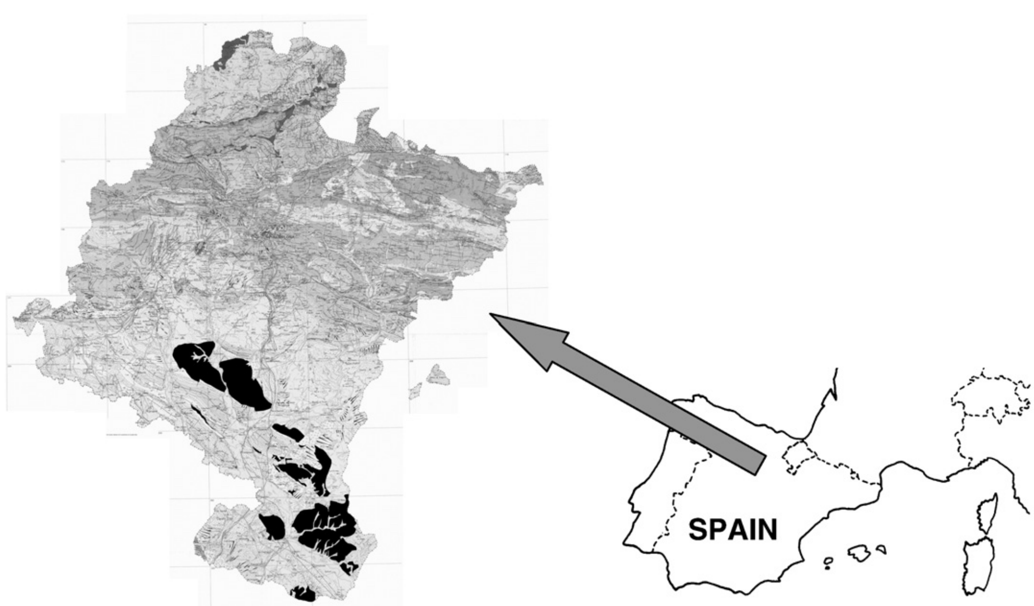

Fig. 1. Geological map of the environment of the study area from which the soil sample originated. The “Facies of Tudela” is shown in black.

Table 1
Average content of the different additives of minerals of interest for the stabilization of soils.

% oxides	Lime	PC-7	Natural Gypsum (NG)	Rice Husk Fly Ash (RHFA)	Coal Fly Ash (CFA)	Coal Bottom Ash (CBA)	Steel Fly Ash (SFA)	Aluminatum Filler (AF)
CaO	–	8.5	–	–	–	38.5	–	1
MgO	–	72	–	–	–	11.4	–	6
$Ca(OH)_2$	82	–	–	–	–	–	–	–
$CaCO_3$	8	–	–	–	–	–	–	–
$CaSO_4$	9	–	99	–	–	–	–	–
Fe_2O_3	–	3	–	–	–	2.1	17	1
SiO_2	–	3.5	–	99	–	36.6	–	8
Al_2O_3	–	–	–	–	–	9.2	5	70
K_2SO_4	–	–	–	–	62	–	–	–
KCL	–	–	–	–	16	–	27	–
$K_3Na(SO_4)$	–	–	–	–	22	–	–	–
NaCl	–	–	–	–	–	–	50	–

Ash (RHFA) is the residue from the combustion of waste rice husk to produce electrical energy in biomass plants. Cereal Fly Ash (CFA) is the waste deriving from the use of cereal straw for energy production. Coal Bottom Ash (CBA) comes from the industrial combustion of coal in power stations. Steel Fly Ash (SFA) is a waste product of the industrial process of steel furnaces. Aluminate Filler (AF) has its origin in the industrial process of aluminum recovery. Table 1 shows the content of the principal minerals of interest in the various additives used.

3. Methodology

The treatment proposed for expansive soils has two phases: the first consists of an anti-expansive treatment aimed at reducing the expansiveness of the natural soil. Dry soil samples with the established quantities of additives in powder were thoroughly mixed in an industrial mixer before gradually adding the quantity of water to get the optimum moisture content calculated for each combination. The ingredients were then properly mixed for about 5 minutes, verifying the correct mixing of the soil and the additives. After this, samples were remolded in the SP test, following Standard UNE 103500 (AENOR, 1994), and their free swelling was determined after 1 day of curing time in the edometer, following Standard UNE 103601 (AENOR, 1996). After this first treatment the combination of additives with the greatest efficiency in its ability to reduce natural swelling was chosen.

The second treatment consisted of performing a further operation, based on the most effective combination of additives from the first treatment, with the aim of improving the mechanical properties of the treated soil. In this second treatment the aim was to maximize the pozzolanic reactions in the soil-additive combination; the main additives were thus chosen as being the richest in divalent oxides (lime and PC-7), and as secondary additives those containing aluminum and/or silicon oxide, as well as a polymeric stabilizer. The results of this treatment were evaluated by the unconfined compression test following UNE 103400 (AENOR, 1993) for the soil specimens, prepared under the optimum conditions of the SP test of each combination, for curing periods of 7, 14 and 28 days. The curing of the samples was carried out in plastic bags in a warm humid chamber at 20 °C and with a relative humidity of 100%.

Table 2
Combinations and proportions of additives used in the anti-expansive treatment.

Combination	Additives	Dry density (g/cm^3)	Optimum moisture content (%)
0	Soil	1.79	14.6
1	Soil + 2% lime	1.72	16.0
2	Soil + 4% lime	1.68	17.5
3	Soil + 2% PC-7	1.73	18.2
4	Soil + 4% PC-7	1.78	16.5
5	Soil + 1% lime + 2% PC-7	1.72	18.0
6	Soil + 2% lime + 1% PC-7	1.68	18.8
7	Soil + 5% CFA	1.75	
8	Soil + 5% RHFA	1.68	
9	Soil + 5% CSFA		
10	Soil + 5% GYPSUM		
11	Soil + 5% SFA		

4. Results

4.1. Anti-expansive treatment

Lime percentages were established based on civil works' manuals and experts' recommendations. For the PC-7 the same percentages were chosen to compare the effect of magnesium with that of calcium. Combined percentages of 2% and 1% for lime and PC-7 where tested to establish possible synergic effects between Ca and Mg ions. For the other additives a 5% was chosen based on their lower content of divalent cations and therefore an anticipated lower efficiency. The tested combinations, their SP maximum densities and optimum water content are shown in Table 2.

Fig. 2 shows the result of the swelling test for each of the combinations tried.

As can be seen, the addition of lime in a proportion of 2% was not enough to produce an appreciable reduction in the expansivity of the

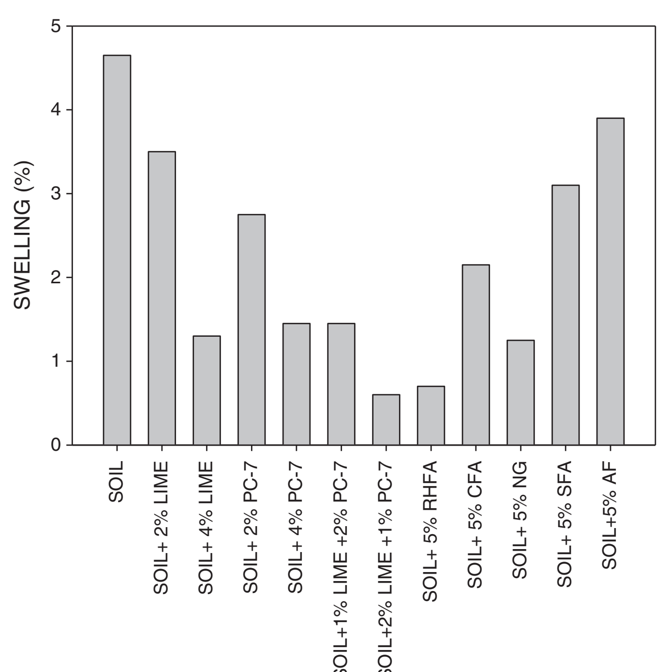

Fig. 2. Free swelling results obtained of the different soil-additive combinations considered for the anti-expansive treatment.

clays; this improved considerably when the dose goes up to 4%, with swelling values of 3.50 and 1.30% respectively. For the same percentages, MgO (PC-7) showed better results, with a free swelling of 2.75% for the 2% dose, although in the case of the 4% dose the free swelling was 1.45% somewhat higher than in the case of 4% lime. The combination of 1% lime with 2% PC-7 reduced free swelling to 1.45%, while 2% lime and 1% PC-7 showed further improvement up to 0.6% of free swelling. The RHFA at 5% dosage lowered swelling to 0.7%. Treatment with 5% of NG, CFA and SFA in turn gave intermediate results, with free swelling of 1.25, 2.15 and 3.10% respectively, while the AF only improved the soil to 3.9%.

Once the results from the first treatment had been analyzed, the best combination was chosen as that consisting of 2% lime and 1% of PC-7, since it produced the best results of those obtained with a low percentage of additives.

4.2. Treatment to improve mechanical properties

The additives and combinations used for this treatment are shown in Table 3.

In this experiment, the performance of the various combinations tested was analyzed by means of their unconfined compressive strength, according to UNE 103400 (AENOR, 1993). For the preparation of each of the samples tested, the maximum density and optimum moisture obtained by the SP test were taken as reference. The tests were performed for cure times of 7, 14 and 28 days, in order to assess the strength development properties of the samples over time. Fig. 3 shows the results of each of the combinations for the different curing times.

As can be seen, by the seventh day all combinations increased the simple compressive strength of the soil from 0.399 MPa up to values of between 0.675 MPa, obtained with PC-7 and CBA, and 0.926 with polymer (CS). After 14 days there was a further increase in strength for all the stabilizer combinations, except for that of lime with CBA, which fell slightly from 0.829 to 0.817 MPa. The greatest increases in strength from 7 to 14 days curing are shown by the combinations of PC-7 and CBA, PC-7 and RHFA and lime and RHFA; the latter combination achieved the greatest resistance after 14 days with 1.142 MPa. After 28 days further increases in strength were noted in all combinations, which all exceeded the value of 1 MPa. The stabilized mixture which showed the biggest improvement between 14 and 28 days was that formed using lime and RHFA, which reached 1.572 MPa. The combination of PC-7 and RHFA achieved the second highest strength value at 1.269 MPa.

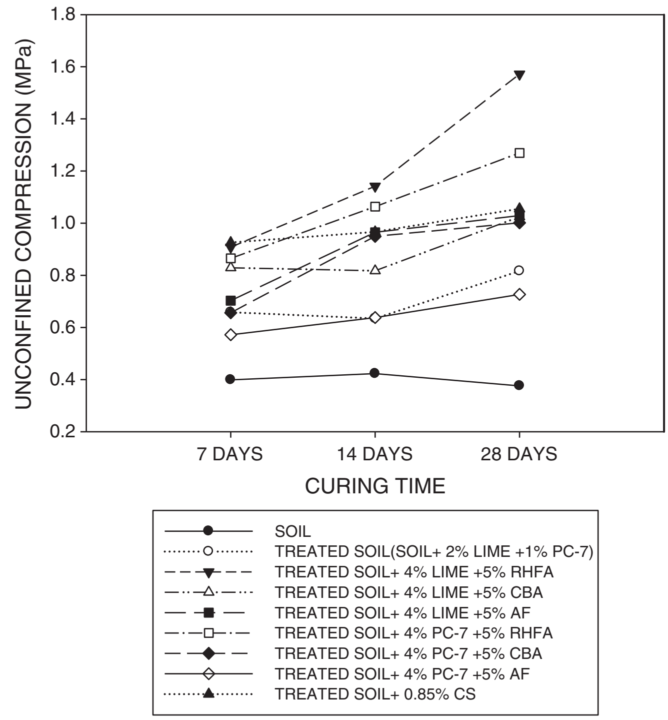

Fig. 3. Time evolution of the compressive strength values obtained for each soil-additive combinations considered in the treatment to improve the mechanical properties of the natural soil.

5. Conclusions

This experiment shows that there is potential in using different additives for specific soil treatments. The free swelling characteristic of several clay soils were improved by the use of usual and non-conventional additives as used in this trial. The results obtained suggest that the use of these additives alone or a combination between them can improve important engineering soil properties: they have demonstrated a considerable reduction of the potential free swelling as well as the improving bearing capacity. This result can allow the use of this kind of low quality soil in the civil engineering field when it is otherwise not recommended or even prohibited. From another viewpoint the use of wastes as additives contributes to a more sustainable civil engineering, reducing the disposal of these kind of wastes and reducing the consumption of conventional additives.

The detailed conclusions obtained in this experiment were:

1. Several of the combinations of additives have produced good results regarding the reduction of the expansive capacity of the natural soil, in particular the combinations of 2% lime + 1% PC-7. The different result obtained with the 1% lime + 2% PC-7 may indicate a synergetic effect of the Ca and the Mg in the soil in suitable proportions.
2. In low concentrations, a magnesium compound has proved more effective than a calcium compound for the reduction of the swelling capacity of the soil. At higher concentrations calcium was more effective, although the difference from magnesium is small. This enables us to establish the suitability of magnesium compounds as a substitute for calcium in the flocculation of this type of clay.
3. The use of additives rich in sulfates such as cereal fly ash and gypsum has shown their capacity to reduce free swelling of expansive clays.
4. Additives rich in monovalent cations have shown a positive effect on the swelling capacity, which validates the dispersion of the clay as an anti-expansive treatment in this type of soil.
5. The chosen anti-expansive treatment not only implies the reduction of swelling capacity, but also an improvement of almost three times in the unconfined compression of treated soil, compared with untreated soil. All the treatments tested for improving the mechanical properties of the soil have shown improvements of between two and four times, compared to the simple compaction resistance of untreated soil, particularly those combinations containing RHFA.
6. The CS is notable for reaching very high values after 7 days curing, and these practically do not change significantly with increasing curing time. Another noteworthy feature of this stabilizer is the low

Table 3
Combinations and proportions of additives used in the treatment for improving the mechanical properties of the soil.

Combination	Additives
1	Soil
2	Treated soil(soil + 2% lime + 1% PC-7)
3	Treated soil + 4% lime + 5% RHFA
4	Treated soil + 4% lime + 5% CBA
5	Treated soil + 4% lime + 5% AF
6	Treated soil + 4% PC-7 + 5% RHFA
7	Treated soil + 4% PC-7 + 5% CBA
8	Treated soil + 4% PC-7 + 5% AF
9	Treated soil + 0.85% CS

dose required, which enables the achievement of the same effects as with much higher doses of other stabilizers.

7. The good results of RHFA both on the swelling capacity of soil and on the improvement of its mechanical properties, together with the fact that this is a waste product which currently has no use and is produced in great quantities, particularly in developing countries, make this product a potential low-cost improver of the geo-mechanical properties of soils.

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