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Magnesium hydroxide, seawater and olive mill wastewater to reduce swelling potential and plasticity of bentonite soil

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HIGHLIGHTS

- We prepare samples of clayey soil mixed with olive mill wastewater, mg-hydroxide and seawater.
- We study the changes in geotechnical and mineralogical properties of the soil.
- The high swelling potential of clayey soil diminishes after treatment.
- Some of the treatments could make the soil be suitable for use in construction.

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ABSTRACT

The improvement in physical properties of expansive soils after addition of non-conventional additives is studied. The tested agents were magnesium hydroxide, seawater and olive mill wastewater. The use of these materials, which can be obtained from natural sources or as by-products derived from industrial processes, can lead to greater sustainability of the construction process. In the case of olive mill wastewater, its management is still an issue in many regions where production of olive oil is a main economic activity. The untreated soil used was a sample of pure bentonite. To evaluate the effects of the additives, the physical properties of the soil such as compaction, consistency, bearing capacity and swelling pressure were studied. The mineral compositions of the treated soils were evaluated by XRD tests. Test results showed that the non-conventional additives tested reduced the plasticity and the swelling potential of the soil. Indeed the tested agents proved to be very effective to produce reductions in the swelling pressure of 60–87% in comparison with the original swelling pressure of the untreated bentonite. X-ray diffraction tests proved that magnesium hydroxide, seawater and olive mill wastewater promoted mineral changes within bentonite, especially smectite to illite conversion. This conversion is due to the alterations promoted by the additives on conditions such as pH and concentration of different cations (magnesium, calcium, potassium, etc.) The mineral modifications occurred are behind the sharp reductions in swelling pressure and plasticity of bentonite.

1. Introduction

The use of natural resources and industrial by-products in civil works can lead to a more sustainable construction process. Especially, the use of non-conventional additives for soil stabilisation can offer an interesting alternative to reduce the damaging effects of expansive clays. In recent years, many authors have tested the effectiveness of a wide range of alternative stabilisation agents, from biomass to recycled materials [1–11]. Some studies focus on the mechanical behaviour of the treated soils whilst some other focus on the evolution of the microstructure, studying the electrical conductivity, mineralogy or formation of cementitious gels. However, and probably due to the difficulty of quantification of the mineral composition of fine-grained soils, not much is yet established about the relationship between changes in the mineral composition of the soil and the evolution of its physical properties, especially when non-calcium based additives are used.

The clarification of this aspect is crucial when testing new additives, since the swelling potential and plasticity of the soil depend on the minerals present in the soil, the montmorillonite being the most expansive [12]. According to Drief et al. [13], the smectite to illite conversion is controlled by temperature, pH and concentra-

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Table 1
Properties of bentonite.

Chemical composition (%)		Physical properties	
SiO_2	50.23	Standard proctor maximum dry density (Mg/m^3)	0.91
Al_2O_3	7.21	Standard proctor optimum moisture content (%)	66.10
Fe_2O_3	2.17	California Bearing Ratio (CBR)	1.3
K_2O	1.54	Liquid limit (%)	294.9
MgO	17.77	Plasticity index (%)	250.9
Na_2O	2.36	Swelling pressure (kPa)	220
TiO_2	0.42	pH	9.5
MnO	0.04	Particule size (μm)	75
P_2O_5	0.06		

tion of potassium. According to Elert et al. [14], the hydroxides such as KOH and NaOH are more efficient than $Ca(OH)_2$ when it comes to destroying clay minerals.

Petry and Little [15] presented a thorough review on the use of calcium-based additives for soil stabilisation: lime, cement and coal fly ash. Nowadays It is known that the most significant of these traditional binders, lime, promotes a quick effect called flocculation-agglomeration of particles and a slow pozzolanic reaction which is responsible for the strength of lime-treated soils [16]. However, some authors found lime to pose serious disadvantages for soil stabilisation in regions with great seasonal variations, marly soils, etc. [17,18,11]. Hence the importance of testing new additives.

But which specific properties are required for a potential stabilisation agent? Based on the information provided by Solanki and Zaman [16], we would search for materials with a high amount of free lime and/or pozzolanic potential, i.e., alkalinity and high percentages of silica and alumina [19]. Such an additive would improve the mechanical behaviour of a cohesive soil. But according to White [12] and Drief et al. [13], the swelling potential and plasticity of the soil depends strongly on the presence of expansive clay minerals within the soil.

Xeidakis [20,21] studied the effects of a solution of magnesium hydroxide on a suspension of swelling clays, finding that the swelling potential of clays was reduced. The effects of the magnesium hydroxide in a powder form when it is added to a soil following conventional mixing techniques deserves to be further studied. The same can be said on the effects of seawater and olive mill wastewater. In the existing literature there are studies reporting the effects of the sodium chloride [22–28] and olive cake residue [29,30] on the physical properties of expansive soils. The chemical compositions of both seawater and olive mill wastewater involve elements such as calcium, potassium and magnesium which could promote a cation exchange when added to clay minerals. Hence the interest of a further research on the effect of this agents on the expansive soils.

This paper investigates the effects of non-conventional additives such as magnesium hydroxide, seawater and olive mill wastewater on a sample of bentonite, a clay of high plasticity and high swelling potential. The study is focused on the mineral changes promoted by the additives and their influence on the swelling potential and plasticity of bentonite. The main physical properties of soil, such as compaction, consistency, bearing capacity and swelling pressure are investigated. X-ray diffraction tests were carried out to analyse the evolution of the mineral composition of bentonite.

2. Materials

2.1. Bentonite

The soil used in this study was a sample of bentonite. This soil was chosen for being a well known pure clay. It is a highly expansive material which undergoes significant volume changes when the environmental moisture varies.

The Bentonite was analysed in the laboratory, and found to have poor engineering properties. It was characterised for its low-load bearing capacity, high swelling potential and plasticity.

X-ray diffraction (XRD) tests were conducted to analyse the mineral composition of the expansive soil. The main mineral constituent of the bentonite used in this study was Montmorillonite with small amounts of other clay minerals and quartz. Montmorillonite is a clay mineral within the group of smectites. The most expansive clay minerals belong to this group.

Table 1 presents the engineering properties and chemical composition of the expansive soil, while Fig. 1 shows the X-ray diffraction pattern of the untreated soil. Two types of montmorillonite were found to be present in the bentonite, with their first peak located at 2-theta angles of 5.895° and 7.076° respectively.

2.2. Magnesium hydroxide

Magnesium hydroxide ($Mg(OH)_2$), which can be found in nature in the form of brucite, is also obtained nowadays from certain industrial by-products [10,11,20,21,31]. The magnesium hydroxide used in this study was a very pure commercial type supplied in a powder form. Previous works showed the reduction of swelling potential of clays, when introducing magnesium hydroxide solutions in

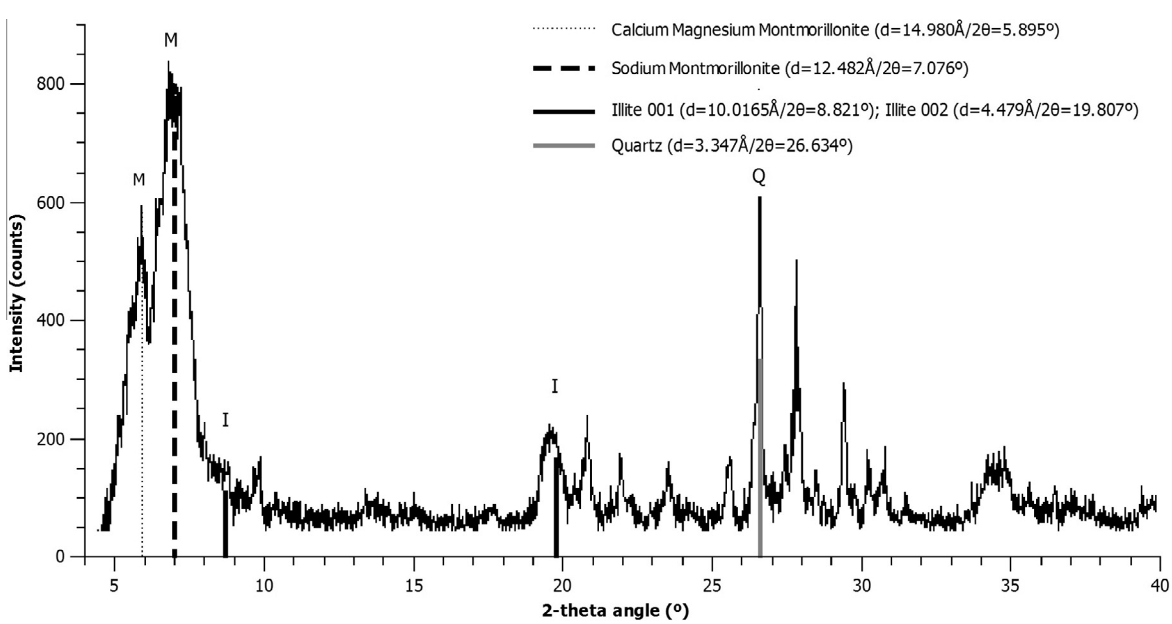

Fig. 1. XRD pattern of bentonite.

Table 2
Chemical composition of seawater according to Hodge [33].

Element	Concentration (mol/kg)	Element	Concentration (mol/kg)
Cl	0.546	N	3.0×10^{-5}
Na	0.468	Li	2.5×10^{-5}
Mg	0.0532	Rb	1.4×10^{-6}
S	0.0282	Mo	1.1×10^{-7}
Ca	0.0103	Ba	1.0×10^{-7}
K	0.0102	V	3.0×10^{-8}
Br	8.4×10^{-4}	As	2.3×10^{-8}
Sr	9.0×10^{-5}	Al	2.0×10^{-8}
F	6.8×10^{-5}	U	1.4×10^{-8}

* Compounds with concentration $>1 \times 10^{-8}$.

Table 3
Chemical composition of OMW according to Garcia Tortosa et al. [36].

pH = 5.38			
P (g kg^{-1})	0.8	Cu (g kg^{-1})	0.022
K (g kg^{-1})	10.4	Mn (g kg^{-1})	0.056
Ca (g kg^{-1})	8.0	Zn (g kg^{-1})	0.017
Mg (g kg^{-1})	3.1	Pb (g kg^{-1})	0.004
Na (g kg^{-1})	0.3	Cr (g kg^{-1})	0.019
S (g kg^{-1})	1.1	Ni (g kg^{-1})	0.055
Fe (g kg^{-1})	2.4	Cd (g kg^{-1})	nd

clay suspensions [20,21]. In this study, a powder of magnesium hydroxide was added to the soil following conventional mixing techniques to evaluate the effects of this agent on the expansive soil in the presence of water and emulate the real conditions of stabilisation process in construction sites.

2.3. Seawater

The widespread availability of seawater makes it very interesting for its beneficial use in construction activities, always searching for a more sustainable construction process. To carry out this study, natural seawater from the Mediterranean sea was collected in Malaga, Southern Spain coast.

Bruland [32] carried out a thorough review on the chemical composition of seawater. More recently, Hodge [33] published the average values of the elements contained in this natural resource. According to these previous works, the main elements which can be found within seawater are sodium (Na^+) and chlorine (Cl^-), but the presence of other ions such as calcium, magnesium and potassium is not negligible. Table 2 shows the main values of the chemical composition of seawater according to Hodge [33].

2.4. Olive mill wastewater

The olive mill wastewater (OMW) is a by-product of the olive oil industry. It is generated in centrifuges during the production of olive oil in the so-called two-phase extraction system. OMW used in this study, which had a humidity of 62%, was produced in Jaen (SE Spain) where the olive grove covers a total extension of 5900 km^2. Previous studies on the characterisation of OMW concluded that it has a high content of potassium [34–36]. Table 3 shows the results of the study carried out by Tortosa et al. [36] which established the chemical composition of the solid phase of the same OMW used in this study.

3. Methodology

3.1. Preparation of samples

In this work, the untreated bentonite soil was firstly characterised. Afterwards, several non-conventional stabilisation agents were added to the original untreated bentonite soil: magnesium hydroxide, seawater and olive mill wastewater (OMW). The mixtures were prepared with three different dosages of additive (5–10–15%).

All mixes were prepared under the same conditions in a laboratory with a controlled temperature of 21 ± 1° C. After weighing the exact quantities of dry soil and dry additive, they were placed in a mixing tray and thoroughly mixed for at least 10 min. Water was then added to the mix in order to reach the optimum moisture content calculated for the original untreated soil (66%). The soil, additive and water were mixed in an industrial mixer for at least ten more minutes. Afterwards, the mixes were placed in a curing room for the required length of time. The curing room had the following conditions: temperature of 21 ± 1°C, humidity of 95 ± 3%.

Two experiments were conducted. On one hand, all the specimens made were tested to determine their engineering properties. On the other hand, X-ray diffraction (XRD) tests were developed, obtaining the XRD pattern of the samples. All the tests were carried out at two curing times: 15 days and 30 days.

3.2. Geotechnical tests

To determine the engineering properties of the original soil and the soils prepared in the laboratory, tests were carried out to obtain compaction properties, consistency limits, bearing capacity and swelling potential. Fig. 2 shows pictures of the equipment used: (a) soil and cell for swelling pressure test; (b) Proctor compaction moulds; (c) oedometers.

3.2.1. Standard Proctor test

The samples of treated soil were subjected to the standard Proctor test at 15 and 30 days of curing to compare the results with those obtained for the original untreated soil.

The standard Proctor tests were carried out according to the Spanish standard UNE 103500 [37]. Following this standard, several samples of soil are to be prepared at different moisture contents. The sample is compacted in a mould using a hammer of 2.5 kgs. The test must be repeated for samples with different moisture contents which promotes a variation of the compaction degree achieved in the mould. A curve can be plotted which shows the relationship between moisture of the samples (%) and density of the samples (Mg/m^3). The maximum value of density is called maximum dry density (MDD). The moisture at which MDD is achieved is the optimum moisture content (OMC).

Fig. 2. Pictures of lab equipment: (a) preparation of swelling pressure cell; (b) molds for standard Proctor test; (c) oedometers.

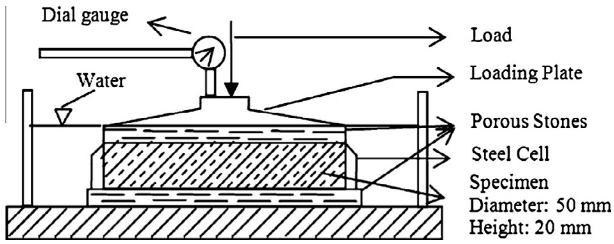

Fig. 3. Swelling pressure test apparatus, according to Akcanca and Aytekin (2012).

3.2.2. Atterberg limits

The Atterberg consistency limits were determined in accordance with the Spanish standards. The standards UNE 103103 [38] and UNE 103104 [39] present a methodology to obtain the liquid limit (LL) and plastic limit (PL) respectively. Plasticity index (PI) is obtained according to the following formula: PI = LL–PL.

3.2.3. California bearing ratio

California Bearing Ratio (CBR) test on stabilised soil specimens was conducted as per Spanish standard UNE 103502 [40]. To carry out the CBR test, the specimens were first assessed under a Modified Proctor Test in accordance to the standard UNE 103501 [41]. The specimens were then cast into the CBR-mold with the same compactive energy per volume as in the Modified Proctor Test.

3.2.4. Swelling pressure test

Spanish Standard UNE 103602 [42] was followed to determine the swelling pressure of the original untreated soil and all the mixtures prepared in this study. Both the samples of untreated and treated soil for the swelling pressure tests were prepared at the optimum moisture content calculated by the Standard Proctor test ($OMC_{bentonite}$ = 66.1%)."

To carry out the swelling pressure test, the same equipment used for consolidation tests is required. The objective of this test is measuring the pressure exerted by the soil on the upper layers due to a swelling phenomenon. For that, a sample of soil is placed in the consolidation cell between two porous stones and confined laterally using several collars. Afterwards, the sample is subjected to saturation. The vertical strain of the specimen must be prevented during the whole test. If the initial saturation promotes an upward movement, the seating pressure applied must be increased to hold the reading of the gauge at the initial value. Finally, the swelling pressure value (Ph) is obtained by the following formula: $Ph = (Q/S) \times 103$ (kPa), where Q is the equilibrium loading and S is the section area of the sample. For low permeability soils, the equilibrium loading can be reached after at least 24 h of testing.

A picture of the cell and oedometer is depicted in Fig. 2. Fig. 3 shows a diagram of the swelling pressure test apparatus according to Akcanca and Aytekin [43].

3.3. Mineralogy: X-ray diffraction

In this study, X-ray diffraction (XRD) techniques were used to assess the evolution of clay minerals after the treatments focusing on the intensity and position of the first peak of montmorillonite.

XRD patterns were obtained using the powder method (total fraction) and preparing oriented aggregates (fine fraction). The oriented aggregates are usually divided in two subsamples, one of which can be subjected to ethylene–glycol (EG) vapor exposure which allows to characterise more accurately the first peak of montmorillonite. All the samples prepared were analysed with a Philips X'Pert–MPD diffractometer using an anticathode Cu Kα at 45 kV and 50 mA. A scan rate of 2°(2θ)/min was used for the powder samples over the range 2–70°(2θ) while the scan rate for oriented aggregates was 1°(2θ)/min. In this study, the identification of the mineral phases in the soils prepared was made by using the specific software Xpowder 2004 [44].

4. Results and discussion

4.1. Effect on compaction

The values of maximum dry density (MDD) and optimum moisture content (OMC) in the treated samples are plotted in Figs. 4 and 5 respectively.

In this study, a relationship was found to exist between the MDD of the sample and the percentage of additive present (linear correlation factor R^2 = 0.88). The values of MDD obtained at oldest samples with the highest dosage of additive were 1.09 Mg/m^3 (15% $Mg(OH)_2$, 1.09 Mg/m^3 (15% seawater) and 1.03 Mg/m^3 (15% olive mill wastewater). Those values represent an increase over the original value (0.91 Mg/m^3). This increase in the MDD can be attributed to changes in the grain size since the additives used in this study had not high unit weights but they could promote changes in the particle size distribution.

Fig. 5 shows that addition of magnesium hydroxide, seawater or olive mill wastewater yields to decreases in the OMC. There are

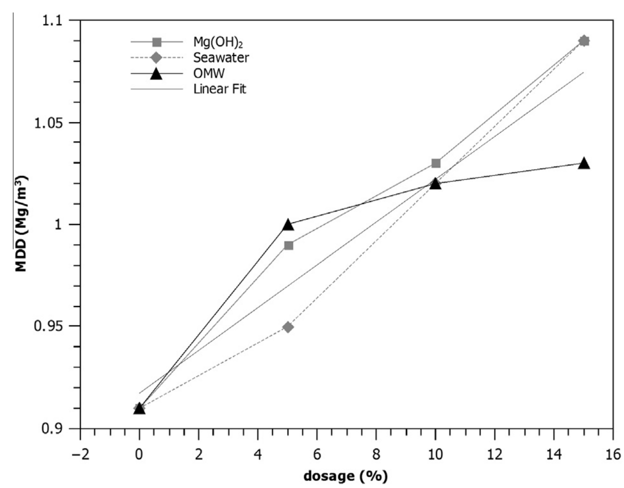

Fig. 4. Maximum dry density of treated samples after 30 days of curing.

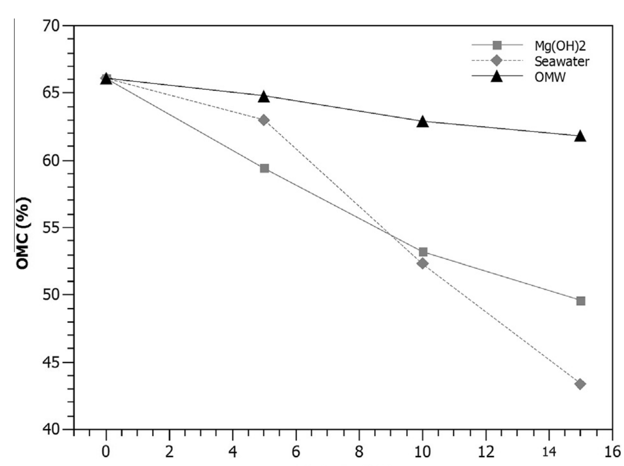

Fig. 5. Optimum moisture content of treated samples after 30 days of curing.

Table 4
Results of Atterberg Limits tests.

Combination	1st Stage of curing			2nd Stage of curing		
	5%	10%	15%	5%	10%	15%
Liquid limit (%)						
Mg-hydroxide	216.2	193	169.1	283.5	199.4	177.6
Seawater	253.7	234.7	206.6	238.6	215.6	193.9
OMW	211.5	199	178.9	205.5	197.6	163.5
Plastic limit (%)						
Mg-hydroxide	46.9	48.9	42	44	58.9	53.1
Seawater	35.6	34.4	33	39	30.9	32.6
OMW	41.5	42.7	43.7	41	46.8	34.6
Plasticity index (%)						
Mg-hydroxide	169.3	144.1	127.1	239.5	140.5	124.5
Seawater	218.1	200.3	173.6	199.6	184.7	161.3
OMW	170	156.3	135.2	164.5	150.8	128.9

studies in which the addition of fly ash [45] or rice husk ash [46] promoted an increase of the optimum moisture content, probably due to the porous properties of ashes and the increasing amount of water required to achieve MDD when soil is mixed with fine grained materials [47,48].

4.2. Effect on consistency

The results of the Atterberg limits tests carried out for soil treated with magnesium hydroxide, seawater and olive mill wastewater are summarised in Table 4.

The addition of magnesium hydroxide to bentonite clay rapidly produced a sharp decrease in PI from 250.9 to values under 170, as displayed in Fig. 6. The PI values were proved to maintain a decrease tendency during the second stage of curing, decreasing slowlier than in the first stage.

The addition of seawater to the sample of bentonite also yielded a decrease in PI of treated soils, although the final value obtained were not as low as the values achieved by adding magnesium hydroxide or olive mill wastewater (Fig. 6). This reduction of plasticity of the soil is consistent with the results of the study carried out by Horpibulsuk [49] which show a reduction of plasticity in clays when the percentage of sodium chloride increases. According to Horpibulsuk [49], the reduction of plasticity is due to the compression of the diffuse double layer of kaolinite particles.

As seen in Table 4 and Fig. 6, the addition of olive mill wastewater (OMW) to the soil reduced the plasticity of the soil. Regarding the initial value of PI of bentonite (250.9), dosages of 5%, 10% and 15% of OMW produced reductions of 34%, 40% and 48% over the total value of the plasticity index respectively.

Given the different plasticity of soils depending on their mineral composition [12], the reduction of plasticity promoted by magnesium hydroxide, seawater and OMW can be attributed to the alteration of the pH and the alteration in the concentration of calcium, magnesium and potassium, etc. which leads to transformations from expansive phases (smectite) to non-expansive clay minerals (such as illite). In addition, as explained by Xeidakis [20], the adsorption of magnesium hydroxide by clays is similar to the adsorption of calcium hydroxide. This could have promoted a coarser particle size distribution and hence a reduction in plasticity in the samples treated with magnesium hydroxide.

4.3. Effect on bearing capacity

In general, the treatments carried out in this work produced an increase in the CBR values of the samples (Fig. 7). This is because the addition of magnesium hydroxide, seawater and olive mill wastewater produces a flocculation of particles, due to the variations of pH and the cation exchange induced in clays. As a result, the physical properties of bearing capacity and compaction are modified. Indeed a relationship was found to exist between the CBR and the MDD of samples in this study, with a linear correlation factor $R^2 = 0.72$. This means that, to some extent, the changes in CBR were related with the compaction properties of the soil.

In the first stages of curing, low dosages (5%) of seawater and OMW produced a decrease in the CBR of the bentonite, which can be partially attributed to the formation of voids in the soil as a consequence of the flocculation of particles, without achieving a well graduated particle size distribution. For the rest of dosages, the CBR increased from the first stages of curing. Within curing time, the continuation of the flocculation can produce the readjust-

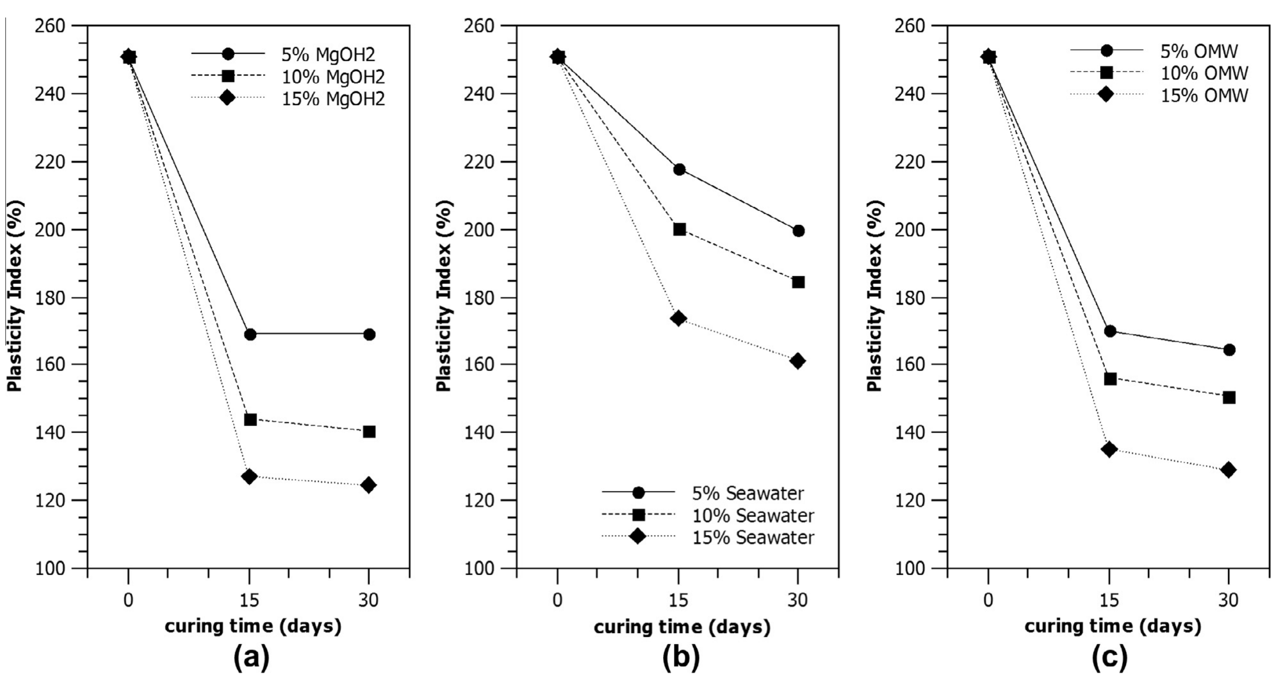

Fig. 6. Evolution of plasticity index in treated samples: (a) magnesium hydroxide; (b) seawater; (c) OMW.

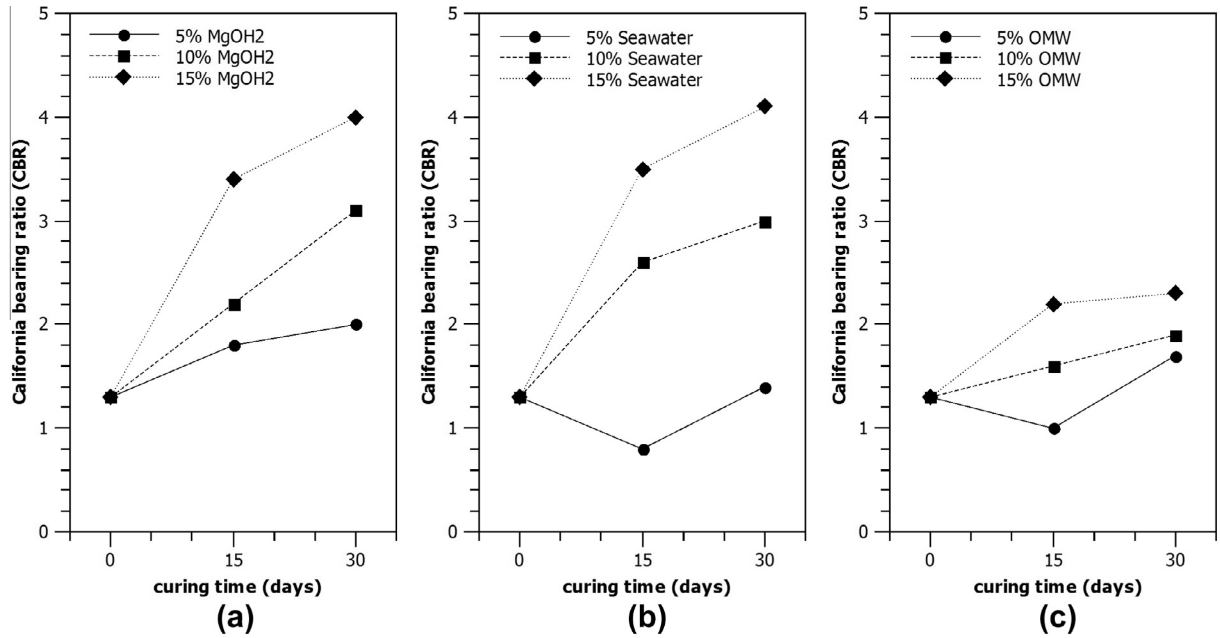

Fig. 7. Evolution of CBR in treated samples: (a) magnesium hydroxide; (b) seawater; (c) OMW.

ment of particles leading to a more compacted sample and hence a sample with higher bearing capacity.

The results obtained with OMW were slightly lower than those obtained with magnesium hydroxide and seawater. Given magnesium hydroxide and seawater provide a more alkaline environment, this could be behind this difference.

In Spanish standard PG-3 [50], a minimum CBR of 3% is required to classify the soil as tolerable for its use in core of embankments. The initial California bearing ratio (CBR) of bentonite clay was 1.3%. After 30 days, the CBR values of all the samples prepared were higher than the initial one. The increase of CBR due to the addition of 10% and 15% of magnesium hydroxide and seawater was significant enough as to change the classification of the soil to tolerable.

4.4. Effect on swelling pressure

Given the undoubted necessity of reducing the swelling potential of expansive soils, these results are the most significant of this study. As a first statement, it can be claimed that magnesium hydroxide, seawater and olive mill wastewater produced, when added to the expansive soil, a dramatic decrease in the swelling pressure of the bentonite. The evolution of swelling pressure is presented in Fig. 8.

The initial swelling pressure of the original bentonite was 220 kPa. After the addition of magnesium hydroxide, the swelling pressure obtained was 90 kPa (for 5% additive), 75 kPa (for 10% additive) and 40 kPa (for 15% additive). This means reductions of 59–81% in the swelling pressure of the soil. As it can be seen in

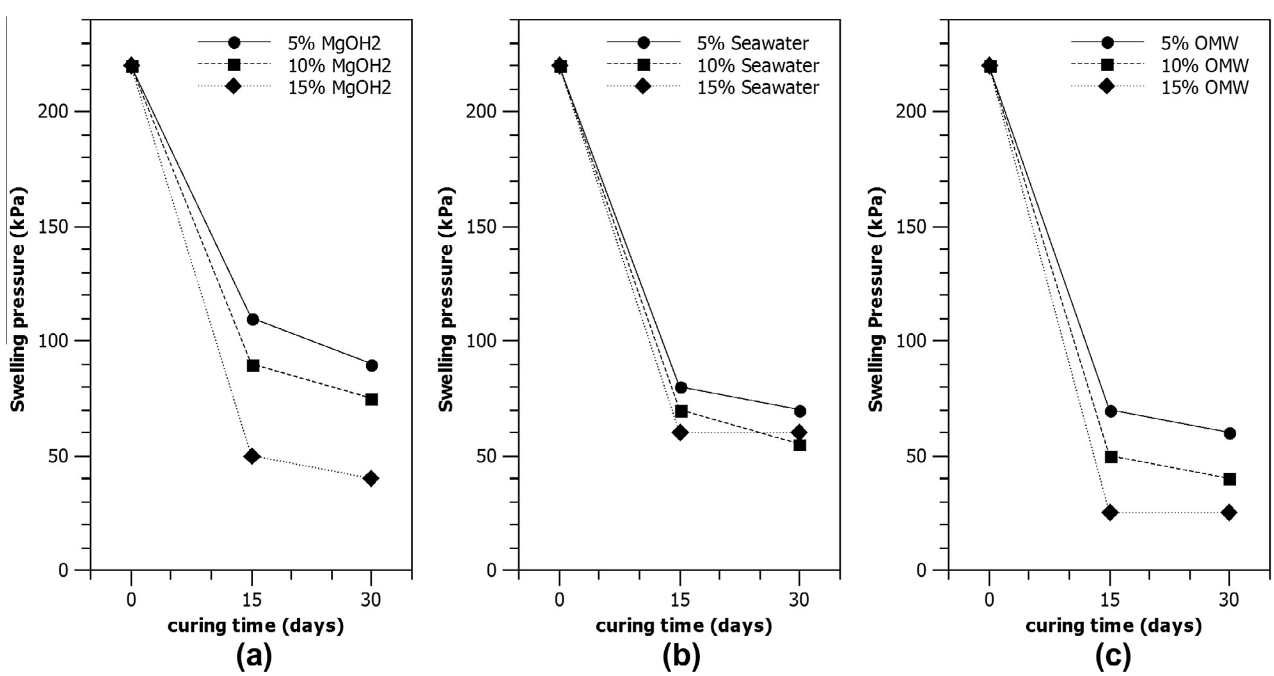

Fig. 8. Evolution of swelling pressure in treated samples: (a) magnesium hydroxide; (b) seawater; (c) OMW.

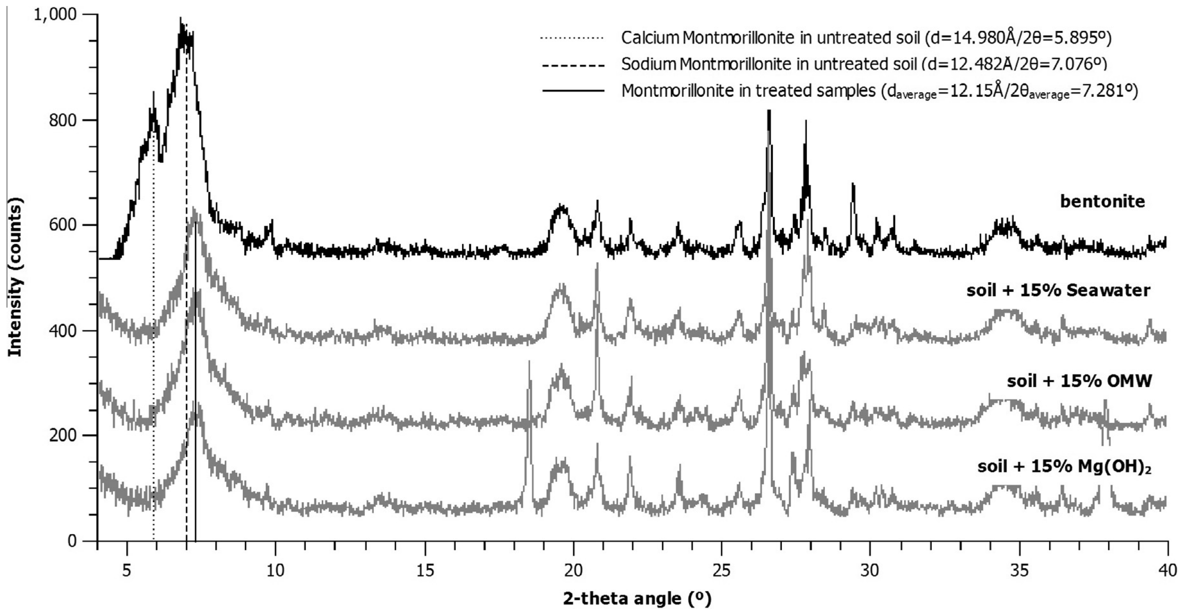

Fig. 9. XRD pattern of untreated bentonite and samples treated with 15% dosage of additives. Evolution of first peak of montmorillonite.

Fig. 8, the addition of different percentages of seawater and OMW produced reductions of the swelling pressure of bentonite ranging from 68% to 75% in the case of seawater and from 73% to 89% in the case of OMW. The final values of swelling pressure achieved for the OMW-treated samples were between 25 and 60 kPa, depending on the dosage of additive, and between 55 and 70 kPa in the case of samples treated with seawater.

Using up to 3% of lime, Akcanca and Aytekin [43] achieved reductions of 78% in swelling pressure of an expansive soil made of sand and bentonite, leading to final values of swelling pressure as low as 30 kPa. Despite the fact that the dosages of lime used in the mentioned work were low, these results are comparable to the results presented in this paper, especially taking into account that the expansive soil tested in the mentioned study had 50–80% content of sand which do not contribute to the swelling potential.

The reasons for such reductions in the swelling pressure of the treated samples are related to the weak stability of montmorillonite. Elert et al. [14] studied the destruction of both expandable and non-expandable clay minerals in alkaline environments. Furthermore, Drief et al. [13] pointed out that montmorillonite to illite conversion is easily enabled. Both magnesium hydroxide and seawater alter the pH of the soil, whilst OMW increases the concentration of potassium, both of them being main parameters to destroy montmorillonite, whose presence is responsible for the swelling potential of expansive soils. Therefore, all the additives tested had accurate properties to produce changes in the mineral composition of bentonite, and those changes are behind the reduction of swelling pressure of treated samples.

4.5. Effect on mineralogy

The effects of the additives tested in this study on the mineral composition of bentonite have been observed by X-ray diffraction (XRD) tests. Fig. 9 shows the pattern of treated samples with 15% of each additive in comparison with the XRD pattern of bentonite. In the pattern of bentonite, two different types of montmorillonite with their first peaks located at 2θ angle of 5.895° and 7.076° were identified as calcium montmorillonite and sodium montmorillonite, respectively.

According to Moore and Reynolds [51], the name of sodium, calcium or magnesium montmorillonite refers to the main interlamellar cation. The cation exchange capacities (CECs) of montmorillonite is high, and expansion takes place as water or some polar inorganic compound enters the interlayer space [51].

It can be seen that in the treated samples, regardless of the additive used, these two peaks have turned into just one located at 2θ angle of 7.281°. This peak, identified as the first peak of a montmorillonite, was not only shifted to the right in the pattern but it also had lower intensity of reflection. According to Moore and Reynolds [51], this entails a reduction in the amount of montmorillonite present in the sample along with a reduction in the d-spacing from 12.482 Å and 14.980 Å to just 12.15 Å.

The presence of imbalance electrical charge, sodium based clay minerals and CEC constitutes the swelling nature of bentonite [52]. Magnesium hydroxide, seawater and OMW changed the pH of the medium. Magnesium hydroxide and seawater provided magnesium and calcium. OMW altered the concentration of potassium. Therefore, this shift of the first peak of montmorillonite can be attributed to the exchanges taken place among different cations, namely Ca^{2+}, Mg^{2+}, Na^{+} or K^{+}. This exchange can produce a reduction in the interlamellar spacing leading to more stable structures.

Table 5 shows the exact position of the first peak of montmorillonite in all the samples treated with magnesium hydroxide, seawater and OMW. The same effects previously described (lower intensity of reflection and right-shift of first peak of montmorillonite) can be observed for all the treated samples.

Therefore, on the basis of these results, it can be stated that the treated samples proved to have a lower amount of montmorillonite, and the montmorillonite present proved to have lower expansion potential. The additives used produced a noticeable change in the mineral composition of bentonite, tending to a reduction of montmorillonite present in the sample. Since montmorillonite is responsible for the swelling potential but also for the high plasticity of the soil, whilst illite is a non-expansive mineral, these changes let us understand the reductions in plasticity and swelling pressure observed in the treated samples and addressed in previous sections.

4.6. Summary of results and comparison of additives

The non-conventional additives tested in this study (magnesium hydroxide, seawater and OMW) produced similar effects on

Table 5
Evolution of first peak of montmorillonite in treated samples.

Sample	Intensity (counts)	d-Spacing (Å)	2-Theta angle (°)
Untreated samples			
Bentonite			
Sodium montmorillonite	802	12.48280	7.076
Calcium magnesium montmorillonite	591	14.97996	5.895
Treated samples			
Bentonite + 5% $Mg(OH)_2$	305	11.96278	7.384
Bentonite + 10% $Mg(OH)_2$	372	12.13123	7.281
Bentonite + 15% $Mg(OH)_2$	406	12.21725	7.230
Bentonite + 5% seawater	461	12.11074	7.293
Bentonite + 10% seawater	512	12.10050	7.281
Bentonite + 15% seawater	470	12.18410	7.281
Bentonite + 5% OMW	508	12.12820	7.281
Bentonite + 10% OMW	580	12.13123	7.281
Bentonite + 15% OMW	522	12.07290	7.332

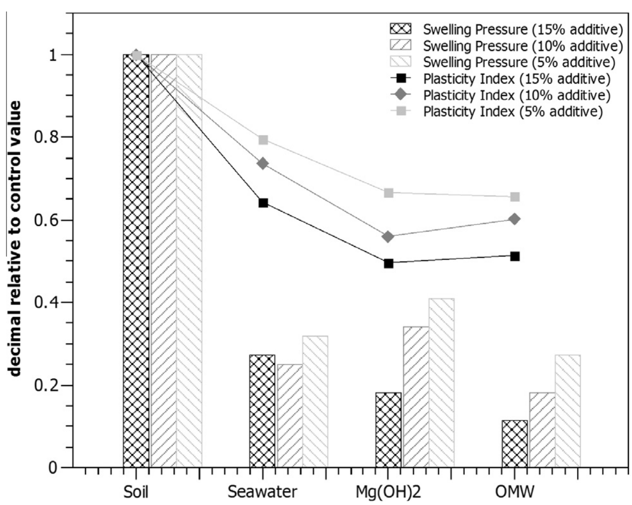

Fig. 10. Comparison of additives in terms of plasticity and swelling pressure of the treated soils.

the bentonite. First, a flocculation of particles responsible for the changes in the compaction and bearing capacity of the soil. Second, a change in the mineral composition of bentonite, tending to decrease the amount of montmorillonite present in the sample. The alteration of the original conditions of formation of montmorillonite can easily enable the smectite to illite conversion. As stated by Drief et al. [13], this conversion is mainly controlled by the pH, temperature, curing time and access to potassium.

Magnesium hydroxide and seawater were able to alter the pH of the medium and provide cations for the cation exchange. Furthermore, OMW contained a high concentration of potassium. All these conditions altogether are behind the changes occurred in the mineral composition of bentonite. And the influence of the mineral composition on the physical properties of the soil was remarkable, since the reduction of montmorillonite was accompanied by a sharp decrease in the plasticity and swelling pressure of the treated samples.

In terms of comparison, the results obtained by addition of magnesium hydroxide, seawater and OMW were very similar, as seen in Fig. 10. The final values of plasticity index achieved by treatment with magnesium hydroxide were slightly better than those obtained with the other additives. In terms of swelling pressure, OMW led to the greatest reductions. The addition of seawater also produced significant improvements in the plasticity and swelling potential of the soil. Hence, all the additives tested proved to have promising properties to reduce the plasticity and swelling potential of the additives while improving other physical properties such as compaction and bearing capacity. The effects of different combinations of these additives on the expansive soil deserve a further investigation.

5. Conclusions

In this study, different dosages of magnesium hydroxide, seawater and olive mill wastewater were added to a sample of bentonite. On the basis of the results of the geotechnical and mineral tests, the following conclusions can be drawn:

– The results of this study showed that the high swelling pressure and plasticity index of bentonite depend on its mineral composition, i.e., the amount of expansive phases such as montmorillonite present in the sample. Changes in the intensity and position of the first peak of montmorillonite and illite in the samples correspond with noticeable changes in plasticity and swelling pressure.
– The addition of magnesium hydroxide, seawater or olive mill wastewater to the bentonite promotes a reduction in the amount of montmorillonite present in the soil, partially due to the cation exchange capability enabled by introduction of cations (magnesium, potassium, calcium, sodium, etc.).
– In addition, the variation of the original conditions in which montmorillonite was formed can easily enable the montmorillonite to illite conversion. After addition of magnesium hydroxide, seawater or olive mill wastewater to the bentonite, this soil suffers sharp decreases in swelling pressure and plasticity index, due to the alterations promoted by the additives on conditions such as pH and concentration of different cations (magnesium, calcium, potassium, etc.)
– Along with the improvement on plasticity and swelling potential, the non-conventional additives tested in this study produced increases of maximum dry density and California bearing ratio (CBR) of the bentonite, whilst the optimum moisture content of the treated samples was always inferior to that of the original bentonite. The samples treated with at least 10% of additive reached CBR index above 3%, which is the value required for Spanish standard PG-3 to use a soil in core of embankments [50].

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