IMPROVEMENT OF THE PERFORMANCE OF SOIL-CEMENT MIXTURES USING LOW COST ACTIVATORS

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ABSTRACT: This paper presents the results of a research study aimed at assessing the effects of using low cost activators and cement for stabilizing granitic residual soils, concerning the load bearing capacity and the durability. Results of compressive strength and tensile strength by diametrical compression have been recorded, aiming at evaluating the mechanical properties, whereas, for the durability, capillary water absorption and the loss of strength by saturation, of wetting-drying and freeze-thaw cycles, were assessed. In order to improve the performance of soil-cement mixtures, the effects of the use of low cost activators in small percentages were analyzed. Results show that the use of cement improves the mechanical performance and the durability of granite residual soils. Moreover, some of the studied activators significantly improve the mechanical performance of the mixtures, becoming, thus, a gainful alternative to the increase of the cement content.

KEY WORDS: Improvement, mechanical, durability, soil-cement, cost, activators.

1. INTRODUCTION

When natural soils do not have the necessary requirements to adequately perform the function they are intended, either when used in their natural state, in foundations or excavations, or when used as building material, one of the possible solutions is to change their characteristics in order to improve their behaviour, enabling them to respond satisfactorily to the requests. This change is known as soil stabilization.

The existing methods for soil stabilization may be divided into three groups, according to the means used, each group including several alternatives. The mechanical stabilization seeks to improve the soils characteristics through improved storage of their solid particles and/or correcting their granulometric composition. In physical stabilization, the soils properties are changed through the use of heat or by applying an electrical potential, whereas in chemical stabilization soils characteristics are modified by the mixing with other materials.

Being soils the oldest engineering material, it may be assumed that this need for their stabilization traces back to ancient times. However, the great momentum took place in the post II World War, in an attempt to address the need for construction of road pavements. But the thriving of the automotive industry, with its subsequent evolution, progressive increase of traffic volumes and of loads by vehicles axle, led to the early ruin of many of these pavements, and hence there was the need for more resistant solutions, through bases treated with hydraulic or bituminous binders and through thicker and better wear layers [1].

This road stabilization is mainly aimed at improving the mechanical properties of soils and the maintenance of their characteristics over time, that is, increased durability, which is achieved by decreasing their susceptibility to variations in water content. It should be emphasized that the construction of thoroughfares is the one that subjects soils to harsher conditions, since they are subjected to varying loads leading to fatigue, as well as variations in humidity content, ranging from almost complete dryness to saturation [2].

Chemical stabilization is the best alternative to make the soil stabilization for road purposes, by the mixing of materials added to soils, known as stabilizing agents. The materials which are most commonly used as stabilizing agents are lime, cement and bitumen.

The stabilizing agents may be more or less efficient, depending on the type of soil in question, given their enormous variety, both in physical and in chemical terms. Figure 2 outlines the most indicated agents, according to the results from the tests of granulometric analysis and of the Atterberg limits.

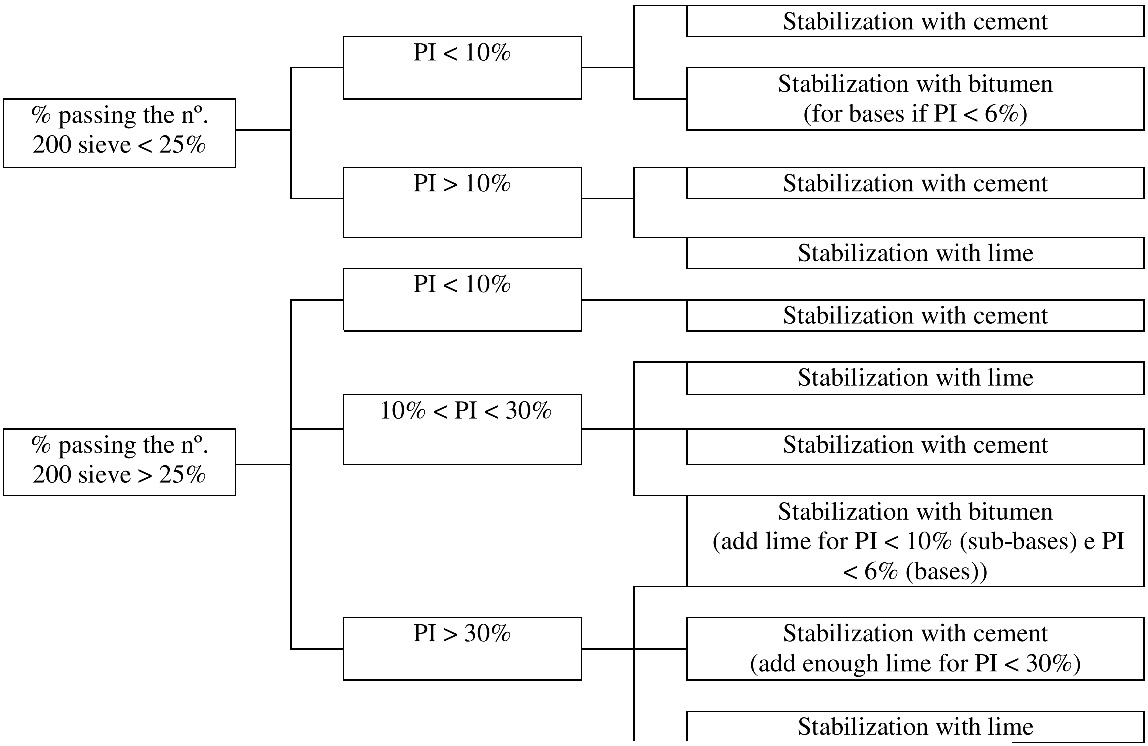

Figure 1. Choice of the stabilizing agent according to the type of soil [3].

Results show that chemical stabilization with lime or bitumen has a more limited scope, whereas the soil stabilization with cement is suitable for most soils. Thus, soil stabilization with cement is one of the most used ones to improve the soils behaviour, given its high availability and suitability to a wider variety of soils.

The stabilization of a soil through the addition of cement consists on the preparation of a homogeneous mixture of pulverized soil, cement and water in given proportions, in which the stabilizing action of cement may occur according to two distinct mechanisms, depending on the content added to the soil [4].

The mechanism that allows the increased mechanical strength is due to the agglutinant action of cement, which cements the soil particles. This effect occurs when the cement levels are higher, when the cement forms interconnected cores distributed by the mass of soil. For lower cement levels, there is essentially a modification of the soil clay fraction, which decreases its plasticity, with or without an increase of the mechanical strength, given that cement, in these cases, promotes flocculation of clay particles.

Through these two types of actions, three types of soil with cement mixtures may be distinguished, which usually have distinct uses. The type of mixture herewith studied is called soil-cement or compacted soil-cement, in which the amount of cement is enough to lead to its hardening, and it should be prepared with the water content needed for proper compaction and for the cement hydration. These mixtures are used in the construction of base and sub-base layers of roads and airfields pavements, pavements of lanes or small traffic roads, lanes for emergency landings, cores of earth dams [4] and also compressed earth blocks used for constructions on land.

2. OBJECTIVES AND METHODOLOGY

This research study was driven by the need for efficient use of Portland cement, which manufacture involves the production of greenhouse gases. It is acknowledged that the production of one ton of clinker releases one ton of CO2 into the atmosphere. Moreover, its cost is significant in the process of soils stabilization. Therefore, the efficient use of cement becomes an environmental and economic imperative.

Thus, a major objective of this study was the search of low cost chemical activators that may increase the reactions of soil particles with the products of cement hydration. The effectiveness of these reactions is assessed in terms of their contribution to the mechanical performance and durability. The mechanisms and the kinetics of reactions with the most promising activators will be the object of further research.

The methodology used consisted of evaluating, on the one hand, the efficiency of stabilization with cement and, on the other hand, the assessment of the effectiveness of the chosen activators in terms of improvements achieved in the performance of the final mixture. The stages of the assessment were:

- Assessment of the possibility of residual granitic soil stabilization with cement, as these soils may be found in large areas of the north of the country and there are not many data on the use of cement in this type of soils;
- Assessment of the possibility of improving the performance of soil-cement using reduced percentages of low-cost activators.

3. MATERIALS USED AND TESTS PROCEDURES

Soil characteristics may lead to success or failure of the process of stabilization with cement, or at least influence the economic aspects. Therefore, it is important to choose this process of stabilization only when soils are adequate. According to the LNEC E243 specification [5], the suitability of a soil depends on two physical properties, particle size and consistency limits, and on chemical properties, such as the presence of organic matter and the presence of sulphates, in addition to the general conditions these soils should have.

The soil used meets the criteria mentioned in the specification and it was manufactured in laboratory, by mixing 70% sand and 30% kaolin, which allowed obtaining a soil called Clayey Sand (SC), according to the unified classification proposed by the ASTM D2487-00 specification [6] and a soil A-2-6 (1), according to the AASHTO M145-82 road classification [7]. These results are, thus, in accordance with what is usually obtained for the granitic residual soils.

The kaolin used is a product of feldspar rocks alteration; these rocks are rich in silica and alumina, such as granites, gneisses, porphyries and pegmatites. Its essential component is kaolinite, a mineral present in higher percentage in clay particles of granitic residual soils, this mineral providing kaolin the most relevant properties.

The cement used was CEM II B-L 32.5 N, in percentages of 6 and 10% of the mass of dry soil. The water used was tap water, which meets the LNEC E304 specification [8].
The selected activators were sodium bicarbonate, calcium chloride, sodium hydroxide and Renolith, a product which is recommended for use in soil-cement mixtures, and which was kindly provided by the company that manufactures and sells it. The percentages of activators were determined with respect to the mass of cement. The description of the studied compositions and the nomenclatures adopted are presented in Table 1. For example, the S6Cbs2 composition refers to a mixture of soil with 6% cement and sodium bicarbonate as activator at 2% cement mass.

Table 1. Analyzed compositions.

Composition name	Symbol	% Cement (mass of dry soil)	% Activator (mass of cement)
Soil	S	0.0	0.0
Soil-cement	S6C	6.0	0.0
Soil-cement	S10C	10.0	0.0
Soil-cement + sodium chloride	S6Csc2	6.0	2.0
Soil-cement + sodium bicarbonate	S6Csb2	6.0	2.0
Soil-cement + calcium chloride	S6Ccc2	6.0	2.0
Soil-cement + sodium silicate	S6Css3	6.0	3.0
Soil-cement + sodium hydroxide	S6sh2	6.0	2.0

4. MANUFACTURING AND CURING TEST SPECIMENS

Compression tests were performed, according to the LNEC E197 specification [9], for the soil to stabilize and according to the LNEC E262 specification [10] for mixtures of soil-cement in order to determine the maximum dry specific mass and optimum humidity in the manufacture of the test samples. The cylindrical samples with 30 mm diameter and 45 mm height, thus meeting the height/diameter relationship of 1.5, were prepared by static compression. The samples were moulded with the optimum water content and maximum dry specific mass determined in the heavy compression test. The samples were cured in an environment with constant relative humidity of 100% and temperature of 21±2 ºC.

5. LABORATORY TESTS

5.1 Mechanical Characteristics

Tests of compressive strength and tensile strength by diametrical compression were carried out, in order to assess the mechanical characteristics of the samples with different ages.

Compressive strength: The compressive strength test allowed determining the hardening of the samples with curing time. Tests were performed at 7, 14, 28 and 56 days of curing, the result being the average values in 3 samples. This test followed, in general terms, the LNEC E264 specification [11].

Strength by Diametrical Compression: The test of tensile strength by diametrical compression allows determining the tensile strength of cylindrical samples when requested according to its generator, having been done to a curing time of 28 days, the final value of the test being the average of results obtained for 3 samples. The test was carried out according to the ASTM C496-96 specification [12]. The tensile strength by diametrical compression is obtained by $(2*F)/(\Pi*l*d)$, where F is the rupture force, l is the length of the sample and d is its diameter.

5.2 Durability

Given that humidity plays an important role in the performance of stabilized soils in current applications, tests were carried out of water absorption by capillarity, compressive strength after saturation, wetting-drying and freeze-thaw cycles.

Effects of saturation on the compressive strength: The samples were immersed in water for 24 hours before the test. Tests were performed for 7, 14, 28, and 56 days of curing, the final value of the test being the average obtained in 3 samples.

Water absorption by capillarity: The test of water absorption by capillarity aims at evaluating the absorption rate of the hardened sample of soil-cement when in contact with water. The final result from the test was the average of the values obtained in 2 samples with 28 days of age. The samples were dried in a stove for three days and their bottom side was impermeabilized, so water would be absorbed only by its base (Figure 2). The specification of LNEC for concrete, E393 [13], was followed in general terms, with the necessary adaptations to the case under analysis. The mass of dried samples (M0) was recorded, and they were put in contact with water, its level being no more than the aforementioned impermeabilized part. Masses were determined for pre-established periods of time (Mi). Water absorption by capillarity, for the time (ti), is given by (Mi - M0)/A, where A is the area of the sample in contact with water.

Figure 2. Impermeabilization of the sample.

Wetting-drying: In the wetting-drying test, the samples, after a curing period of 7 days, were immersed in water for 5 hours and subsequently placed in a stove at 71 °C for 42 hours. The compressive strength of the samples was determined after 12 cycles of wetting-drying and the value presented is the average of the results of 4 samples. The assessment is made in terms of loss of strength when the samples were subjected to the wetting-drying cycles. This test followed, in general terms, the procedures in the LNEC E263 specification [14].

Freeze-thaw: Susceptibility to freezing is only a problem if the stabilized layer is at such a distance from the surface of the thoroughfare that it enables the treated soil being subject to freezing, or if the stabilized layer is left without coverage during the winter months. The samples with 7 days of curing were subjected to cycles of freezing, at a temperature of -23° C, for 24 hours, and of thaw for 23 hours at a temperature of 21 °C. During the thaw cycles, the samples' water absorption occurs by capillarity. These procedures are repeated for 12 cycles, the compressive strength recording the average values obtained in 4 samples. This test followed, in general terms, the standard procedures of the ASTM D560-03 specification [15]. However, changes in volume and water content were not recorded, as indicated in the regulation, but rather the strength of control samples, not subjected to the cycles, and of samples subjected to the freeze-thaw cycles.

6. TESTS RESULTS

This section presents the results of the tests performed on samples of untreated soil, soil with 6% and 10% cement without any activator and soil samples with 6% cement where activators were added, in order to assess their efficiency in soil stabilization.

6.1 Mechanical Characteristics

Compressive strength: Figure 3 presents the results of the increase in compressive strength for curing times of 3, 7, 14, 28 and 56 days, for the compositions S6C, S10C, S6Chs2, S6Cbs2 and S. The increase of strength occurs mainly up to 28 days of curing, and additions are minor after this age. It is also noted that, at 7 days, the obtained strengths are usually higher than 50% of the values achieved at 56 days.

Considering the mentioned issues, the option was to perform the overall analysis of the various compositions for curing times of 7 and 28 days (Figure 4). This analysis allows comparing, in terms of percentages, the compression strengths of the various compositions tested, taking as standard the S6C control mixtures. The non-stabilized soil presents strength between 18 and 25% of the control stabilized soil (S6C). This difference shows the clear beneficial effects of the use of cement in the stabilization of these soils.

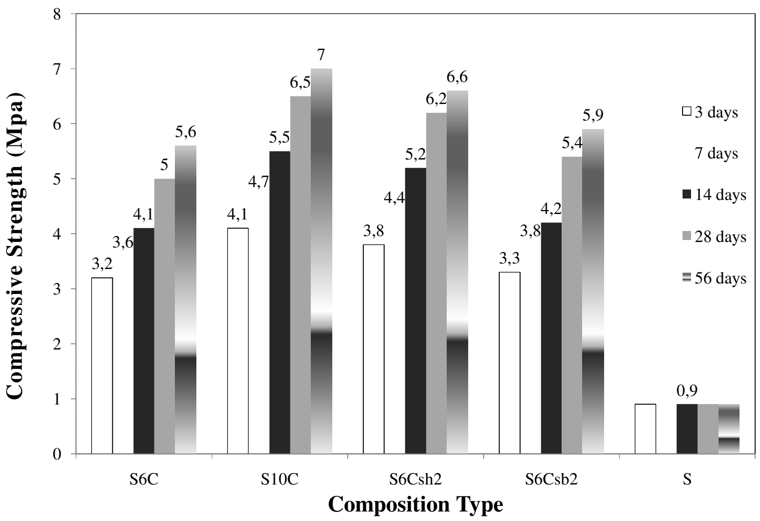

Figure 3. Compressive strength for 3, 7, 14, 28 and 56 days of curing.

The analysis of Figure 4 indicates that, from the viewpoint of compressive strength, compositions containing sodium bicarbonate and renolith have a relatively modest effect, with increases of 8 and 11%, whereas the composition with calcium chloride demonstrates a negative effect of 6% at 7 days and with no positive effects at 28 days. In turn, the mixture with sodium hydroxide (S6Chs2) provides good results in terms of strength, since with only 0.12% of sodium hydroxide (in relation to the mass of dry soil) and 6% cement, it is able to achieve improvements of about 23% over those achieved in the control mixtures. The values obtained are about 6% lower than the results achieved with 10% cement.

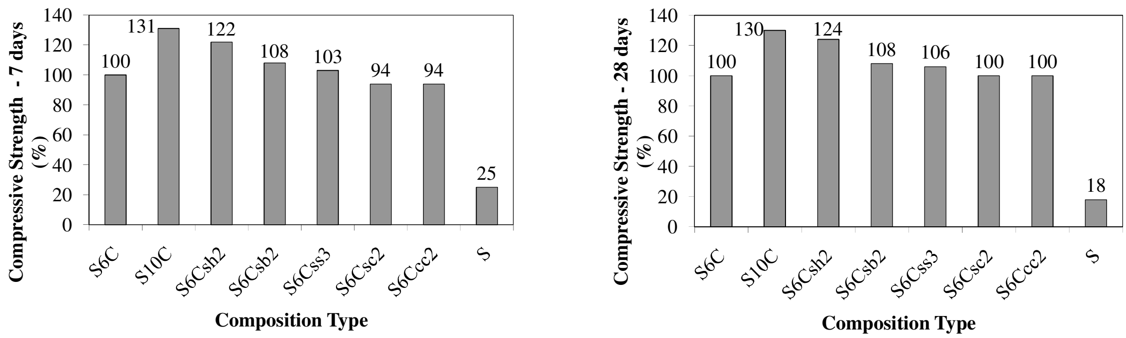

Figure 4. Compressive strength for 7 and 28 days.

Strength by Diametrical Compression: The overall results for this mechanical characteristic are shown in Figure 5, in percentage, considering as standard the S6C compositions. Not stabilized soil samples present a tensile strength of about 31% compared with the one obtained in the S6C mixtures, which allows highlighting the better performance on the part of the stabilized soil.

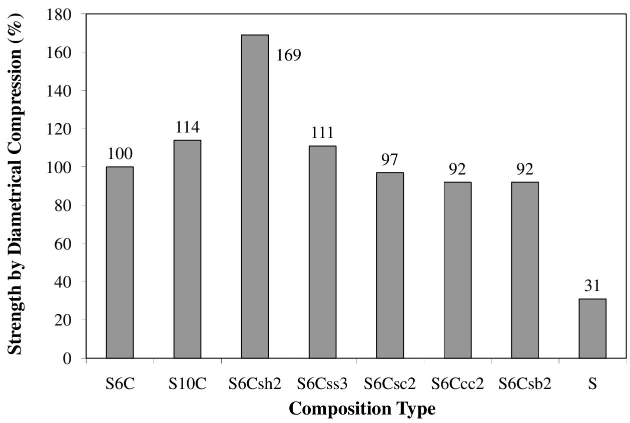

Figure 5. Tensile Stregnth.

Concerning the analyzed activators, the best result was found for samples with 2% sodium hydroxide, which show a significant gain of tensile strength, with an increase of almost 70% over compositions with the same percentage of cement but without activator, and even surpass the samples with 10% cement by about 50%. These tests were repeated in order to ensure that the results had not been affected by other factors, which allowed confirming these results. All the other activators have inferior or slightly superior values to those obtained in the control mixtures with 6% cement.

6.2 Durability

Given that the non stabilized soil samples disintegrate completely in contact with water, it was not possible to assess their performance in durability and, therefore, results for this material are not presented.

Effects of saturation on the compressive strength: Figure 6 presents, for all compositions, the losses of strength, in percentage, regarding the strength of the non saturated samples, for 7, 28 and 56 days of curing. The analysis of the results indicates that, for all compositions, the loss of strength decreases with the increase in the curing time, which shows the decrease of sensitivity to the water effect. This may indicate that, in young ages, the loss of strength is merely due to the elimination of the potential for suction. It is expected that for longer curing periods the loss of strength by saturation will have a more reduced effect. The compositions that showed lower strength losses are those with sodium hydroxide.

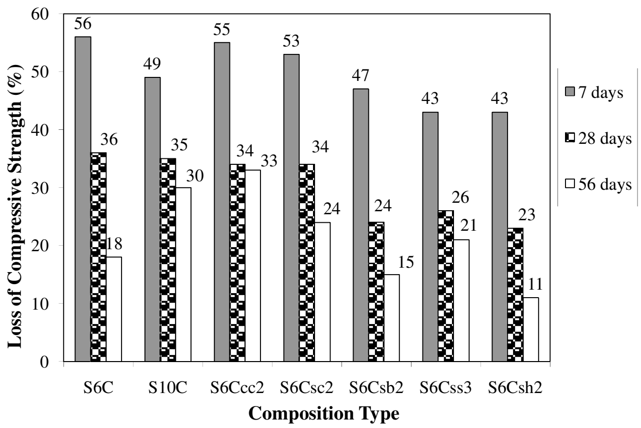

Figure 6. Loss in compressive strength with saturation.

Water absorption by capillarity: In order to assess the absorption of water by capillarity, the absorption coefficient was calculated, determined in a "water absorption" versus "time square root" graph according to the value of the descent of the initial part of the line fitted to that graph. Figure 7 presents the relationship between the values of the absorption coefficients, in percentage, for the various compositions, considering that the standard is the S6C mixture.
The compositions with activators present absorption coefficients which are slightly lower than the standard composition one. This test indicates the speed of water absorption by capillarity in the early hours of contact with water. The mixtures with calcium chloride and renolith have a better performance, with a difference of about 20% compared to the S6C compositions. This test for the S6Chs2composition was not carried out.

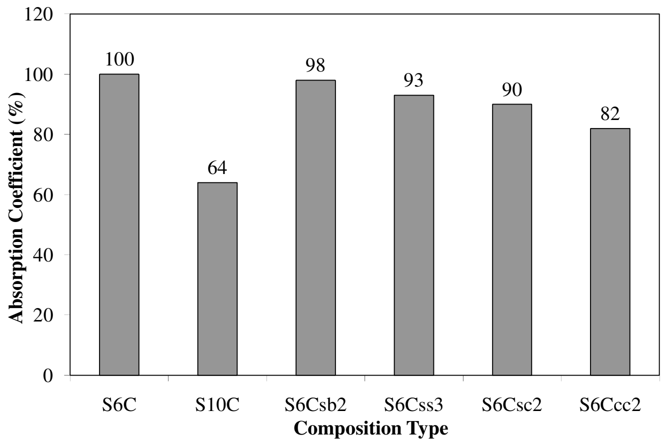

Figure 7. Absorption coefficients.

Wetting-drying: Figure 8 presents the results of the wetting-drying test, by indicating the percentage of the durability index (compressive strength after the cycles/compressive strength without cycles), for the compositions tested. The obtained values indicate that the activators analyzed show lower results than the control mixture. However, it should be noted that the values are obtained in relation to the strengths of each mixture, so in absolute terms mixtures with activator may present greater strengths than the standard ones after the wetting-drying cycles.

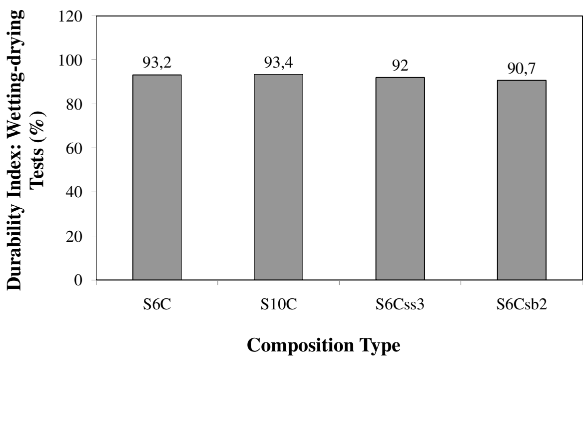

Figure 8. Durability index: wetting-drying tests.

Only the increase in the amount of cement caused the decrease in strength, due to wetting-drying cycles, to be smaller. Mixtures with better behaviour, in relation to the control mixture with 6% cement, that is, which had a smaller loss of strength when subjected to wetting-drying cycles, were those containing 3% sodium bicarbonate and sodium hydroxide. Given that the test for the S6Chs2 composition was not carried out, it was not possible to assess whether it maintained the good performance revealed for the mechanical characteristics.

<u>Freeze-thaw</u>: The results of the freeze-thaw tests, by the percentage value of the durability index (strength with cycles/ strength without cycles), for the compositions tested are shown in Figure 9. The values obtained show that mixtures with activators have a lower longevity index than the control mixture. Only the mixture with the increased amount of cement showed a higher level than the standard mixture.

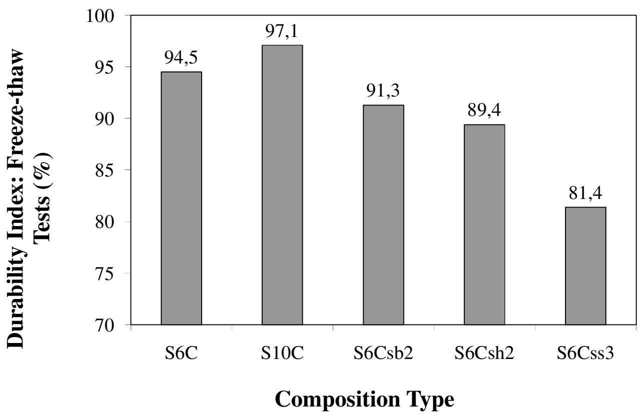

Figure 9. Durability index: freeze-thaw tests.

7. CONCLUSIONS

This study allowed drawing the following relevant conclusions:

- In the compressive strength values of untreated soil were about 20% of those registered in the mixtures with 6% cement, whereas in the tensile strength the values obtained in soil samples (S) were around 30% of the S6C results.
- In the evaluation of durability, the better performance of the mixtures of stabilized soil with cement is significant, given the fact that the compositions of untreated soil suffered a complete disintegration.
- Regarding the activators, the S6Chs2 compositions allowed obtaining significant improvements in the studied mechanical characteristics. In the compressive strength, there was a 23% increase compared to the S6C mixture, being only about 6% lower than the values registered in the S10C samples. Tensile strength values were surprising, being about 70% higher than the S6C mixtures and 50% higher than those recorded in the S10C samples. This indicates that with only 0.12% of the activator, results are close or even superior to those achieved with an increase of 4% cement. The assessment of the effect of saturation on compressive strength showed that the mixture with sodium hydroxide has a better performance, compared with the other compositions tested, showing lower strength losses, including the S10C mixtures.
- In the evaluation of strength loss after the freeze-thaw cycles, the behaviour of the S6Chs2 composition showed a higher loss, of about 5% than the one that occurred in the control mixtures.

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