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Effects of compaction on desiccation cracking of clayey soils

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ABSTRACT: Cracking on desiccating soils is an important topic in soil compacted works. This paper presents an experimental study on the effect of compaction on the cracking of a silty clay soil, which was subjected to drying conditions. The specimens were compacted at different initial moisture contents with the purpose of studying the effect that the amount of water has in the crack formation and propagation. As initial condition, different points were considered from the Standart Proctor curve. Three specimens were dried in an environmental chamber at a constant temperature and relative humidity while the main soil variables (suction, temperature and relative humidity) were recorded. On the other hand, a couple of specimens were subjected to drying in laboratory atmosphere conditions, measuring the weight loss along time. In both cases the drying process was monitored taking images at regular intervals that later were processed using image analysis techniques. From these analyses, the Crack Intensity Factor (CIF) was obtained. In both type of tests, the specimens compacted on the wet side of the Proctor curve tended to lose more water and had a higher CIF than the ones compacted on the dry side. The difference in behaviour can be explained by the microstructure generated by compaction on the dry or on wet side.

1 INTRODUCTION

The process of cracking during desiccation of silty or clayey soils is currently being investigated because cracks could be a problem for many geotechnical works such as landfills, embankments, earth dams and waste cover reservoirs. The generation of cracks will eventually induce a change in the hydromechanical behaviour. Rayhani et al. (2007) found that cracking due to drying increased the hydraulic conductivity by 12-34 times. The shrinkage cracks can compromise the primary function of cover systems, dams or slopes by promoting preferential pathways of water and leachate migration (Peron et al, 2005; Li et al, 2010)

Many previous experimental studies were focused on analyzing factors as the effect of initial conditions, propagation of crack patterns, and the influence of sample size and shape on the crack formation (Prat et al. 2006; Peron et al. 2009; Lakshmikantha et al. 2012; Sanchez et al. 2013). However, most of the works refer to initially saturated samples. The technique of image analysis is typically used to quantify variables related to cracking (i.e., area, length and thickness of cracks). The Crack Intensity Factor (CIF) proposed by Miller et al (1998) was adopted as a descriptor of the superficial cracking. The CIF is defined as the ratio of the surface cracking area to the total surface area of the sample.

Most of the geotechnical constructions prone to cracking involve compacted soils. It is well known that the compaction water content and the applied energy have a significant influence on the mechanical and hydraulic behavior of compacted soils (Sivakumar et al. 2000; Tarantino et al. 2008). Soils compacted on the dry side of optimum have a different structure than those compacted on the wet side (Diamond, 1970; Delage et al. 1996).

This work presents experimental results obtained in drying tests carried out on soil samples with different initial water content and dry density, to investigate the influence of the compaction on the crack pattern and water loss. An environmental chamber developed at the UPC's geotechnical laboratory (Lakshmikantha, 2009) was used to dry samples compacted on cylindrical trays. In addition, tests were performed under laboratory atmosphere on rectangular trays. The objective was to analyze the influence of compaction condition, size and shape of the specimen on cracking under different boundary conditions. The analysis of cracking due to desiccation involves the test of soil samples under boundary conditions of increasing level of complexity: environmental chamber, laboratory atmosphere and field conditions. Here, only the first two levels have been considered. In both cases, the weight was monitored to know the evolution of the global volumetric water content of the sample and photographs were taken at regular intervals to evaluate the shrinkage and crack formation. The images were processed using an image analysis technique to determine the area of cracks and then calculate the CIF.

Experimental results show that samples compacted on the wet side had a greater CIF and the crack pattern was more intense than those compacted on the dry side. The differences could be explained by the different behavior of the compacted soil.

2 MATERIALS AND METHODS

2.1 *Material properties*

The soil used in the experiments was a silty clay from Viladecans, Barcelona. It is a soil used in a field desiccation test described in a companion paper by Cordero et al (2018). The geotechnical classification and the basic parameters have been reported by Cordero et al, (2016). It is a low plasticity clay (CL), likely due to almost 10% of clayey components. The maximum dry unit weight obtained from the Standard Proctor test was 17.8 kN/m^3 and the optimum moisture content was 16%. Table 1 shows the most relevant parameters regarding soil classification.

Table 1. Index properties of the tested soil.

Index property	
Grain size distribution	
Sand content (≤ 2 mm, %)	48.3
Silt content (≤ 63 μm, %)	42.1
Clay content (≤ 2 μm, %)	9.6
Unit Weight of solid particles (kN/m^3)	27.0
Atterberg limits	
Plastic limit (%)	16.5
Liquid limit (%)	28.9
Plasticity index (%)	12.4
Unified soil classification system (USCS)	CL

2.2 *Test method*

Two soil samples with the same dry unit weight of about 17 kN/m^3 but having different water content were prepared, to investigate the influence of the compaction condition on desiccation cracking. The water content was adopted from the Proctor curve in order to have a sample compacted from the dry side (12%) and other from the wet side (21%) of optimum. A third sample at about Standard Proctor optimum conditions was also tested (Table 2).

The soil used was air dried and carefully crushed to destroy aggregates. Then, a 2 mm sieve was used to remove coarse particles. After that, the solid particles were mixed with water and compacted in the trays. Cylindrical trays were used in the environmental chamber, following the setup designed by Lakshmikantha (2009). They had circular grooves on its bottom to create a rough surface. Conventional rectangular plastic trays were used for experiments at laboratory atmosphere conditions, to notice the effect of the sample shape on cracking.

2.2.1 *Test in the environmental chamber*

Cylindrical specimens of 40 cm in diameter and 10 cm in height were dried in an environmental chamber at a constant temperature of 20º and relative humidity of 30%, while recording the main soil variables (temperature, suction, water content).

Samples were dynamically compacted using the rammer of the Proctor Marshall test. Five layers of 2 cm in high were compacted, applying 68 blows per layer. The number of blows corresponds to the same energy per unit volume as in the Standard Proctor test. After compaction, the weight and the moisture content were measured to obtain dry density.

The sensors available in the chamber were used. From the bottom of the tray, four tensiometers were installed vertically at different depths. According to the manufacturer, the tensiometers can measure the soil suction up to 185kPa (Model USM T5). In addition to that, two Vaisala sensors (model HMP-230) were located on the lateral wall of the tray to measure the relative humidity and the temperature. Another Vaisala sensor was located on the tray wall just above the soil surface to measure the relative humidity and temperature in the air close to the sample, as in the original design of the chamber.

The specimen was placed in the environmental chamber where the relative humidity can be imposed as a boundary condition by circulating dry or humid air. A photographic digital camera on the top of the chamber can take pictures at regular intervals of time. Sample weight was monitored from three load cells supporting the tray. A personal computer and a data acquisition unit controlled all variables during the test. Specific information of the environmental chamber can be found in Lakshmikantha (2009), and Cordero et al (2014).

Table 2. Tests performed in environmental chamber.

Test	Initial Dry Unit Weight [kN/m^3]	Initial Gravimetric water content [%]	Initial Void Ratio [-]
Test 1 (Dry side)	17.6	12	0.54
Test 2 (Wet side)	17.2	21	0.57
Test 3 (Optimum)	18.4	15	0.47

2.2.2 *Test under laboratory atmosphere condition*

Experimental drying test on rectangular specimens of 42x30x1 cm were carried out under laboratory atmosphere conditions. Large rectangular trays tend to generate more cracks if compared with circular trays (Lakshmikantha, 2009), and that was the main reason for choosing the trays, as atmospheric conditions in the lab were not much different from conditions in the chamber. Samples were prepared at an initial dry unit weight of 17 kN/m^3 and initial water contents of 12% (Test 4) and 22% (Test 5). The initial conditions of the samples were similar to those corresponding to Test 1 and Test 2. Due to the small thickness, samples were compacted with a roller. The laboratory had a controlled air conditioning system so temperature was fixed at 20±2ºC and relative humidity at 43±5%. As before, the initial weight and moisture content were measured to calculate the initial dry unit weight. During the test, the weight of the trays was registered twice a day and also photographs were taken to follow the evolution of the cracks. Both tests lasted for 170 hours.

3 EXPERIMENTAL DATA

The most important variables recorded during the test were the water loss and the superficial shrinkage of the samples. The water loss was determined through changes in weight of the samples, assuming that the weight of solid particles was constant. Moreover, images were taken to record the shrinkage process along time. An image analysis technique was used to quantify the shrinkage as CIF. Figures 1 and 2 present the crack patterns obtained at different times in Test 1 and Test 2. Figures 3 and 4, show the initial and final states of the rectangular samples desiccated under laboratory atmosphere conditions.

In Test 1 it is observed that at the beginning, a crack pattern is developed inside the soil matrix (Figure 1b). However, at the end of the test some cracks inside the matrix were closed and the edge crack increased. On the other hand, in Test 2 (Figure 2), only an edge crack due to the shrinkage was observed and it was greater than that developed on Test 1 (Dry side). Although the images are not shown, a similar behavior in the crack pattern to that in Test 1 was observed for Test 3.

In the rectangular samples desiccated at laboratory atmosphere, an important difference was observed between the two crack patterns. On the one hand, Figure 3 shows the initial and final states of Test 4. It can be observed that only an edge crack was developed. On the other hand, in Test 5 a more defined crack pattern was developed with an edge crack and cracks inside the matrix (Figure 4).

There were significant differences between the results from Test 2 and Test 5. This fact confirms that the size and shape of the sample affect the crack pattern (Prat et al. 2006; Lakshmikatha et al. 2012).

The change of gravimetric water content over time was determined by the weight of the specimen and will be discussed in the following section (Figures 5 and 7). Due to space limitations, only the main results and measurements are presented here.

4 ANALYSIS AND DISCUSSION

From the experimental data two analyses were carried out. First, the influence of the initial water content on samples with the same initial dry density was evaluated. Secondly, the influence of initial void ratio (or dry density) was studied using results from Test 1 and Test 3. Due to space constraints, results in terms of suction are not analysed here.

4.1 *Influence of the initial water content*

Figure 5 shows the variation of the gravimetric water content and the CIF over time for Test 1 and Test 2. It is important to note that the final gravimetric water content in the specimen compacted on the wet side is less than that obtained in the sample compacted on the dry side. This indicates that the retention capacity of the samples depends on compaction conditions which define the structure of the sample.

The drying rate (Figure 6) was evaluated at regular intervals of time. It is calculated as the ratio of the lost mass of water to the time interval and it represents the slope of curve corresponding to the gravimetric water content evolution in Figure 5. From these results it is possible to identify two stages during the drying process (Tang et al. 2011; Song et al. 2016). A first zone is identified where the drying rate remains constant (constant DR) which corresponds to about 0.10 mm/h for Test 2 and 0.04 mm/h for Test 1. When a change of the drying rate occurs, the second stage starts (falling DR). It appeared approximately at 180 and 300 hours after the start for Test 1 and Test 2 respectively. In terms of moisture content, the second stage began at a value of approximately 8% for the sample on the dry side while that value was 5% for Test 2 (Figure 5). It is important to highlight that, although at 230 hours both samples had the same water content, the final CIF had been reached already in Test 1 while in Test 2 it was still increasing at that time.

The final CIF obtained in both cases were very different (Figure 5): 1.15% for Test 1 and 8.12% for Test 2. Soils compacted on the dry side had a greater initial suction and a higher stiffness (Cui et al. 1996), and because of that are less prone to deform. Additionally, the drying shrinkage stops when the contraction index is reached and this value was close to the initial water content for Test 1. For rectangular samples the final CIF was 1.50% and 6.45% for Test 4 and Test 5 respectively and the evolution along time was similar to the one obtained in Test 1 and Test 2. The CIF was clearly bigger in the samples compacted on the wet side, irrespective of their shape, that is tests 2 (circular) and 5 (rectangular). For these tests, there was any noticeable difference on the final water content and rate of water loss for each case.

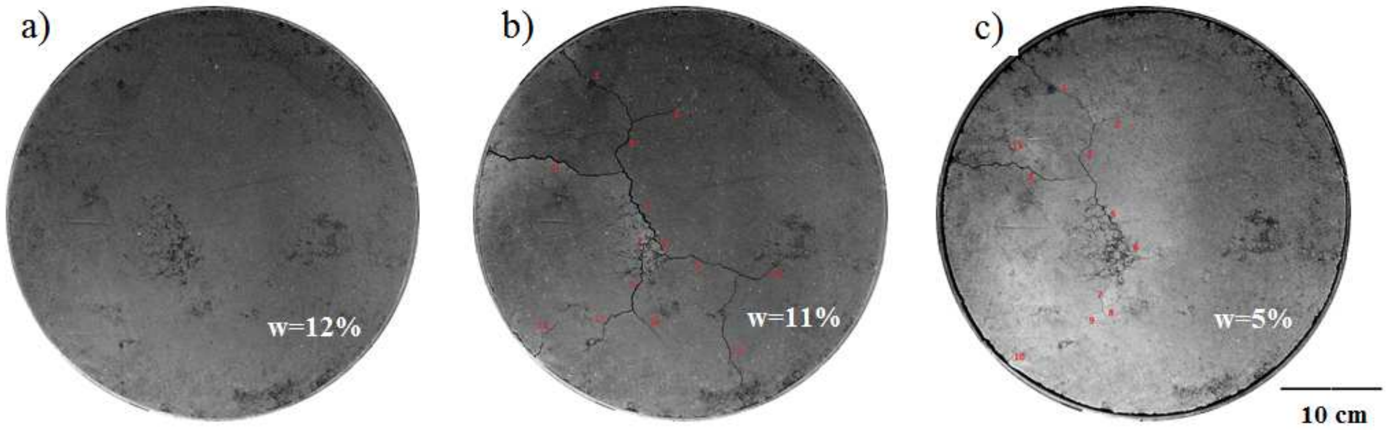

Figure 1. Crack pattern during Test 1 (Dry side). a) Time = 0hs. b) Time = 19hs. c) Time = 468hs.

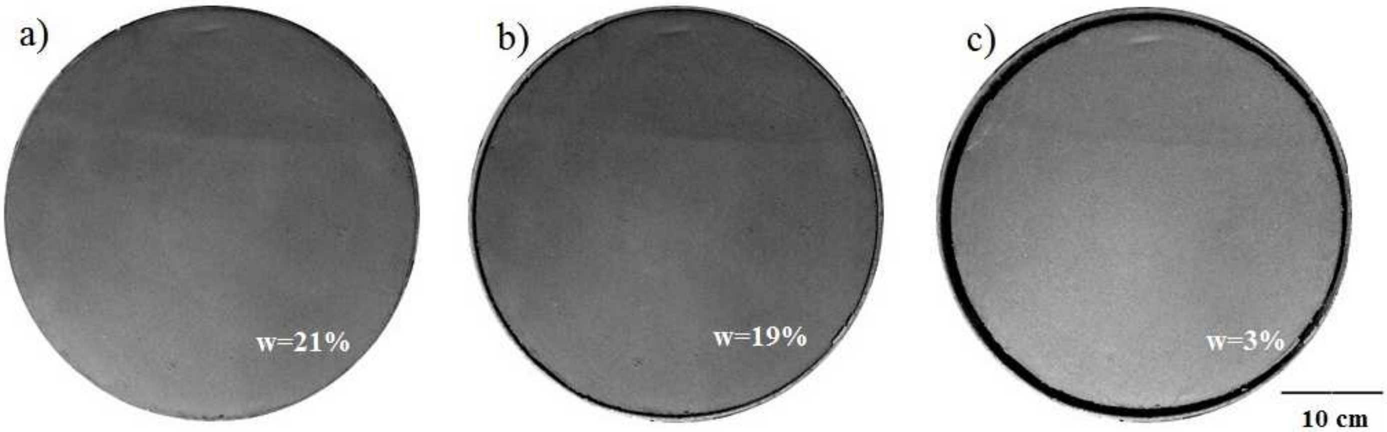

Figure 2. Crack pattern during Test 2 (wet side). a) Time = 0hs. b) Time = 80hs. c) Time = 592hs.

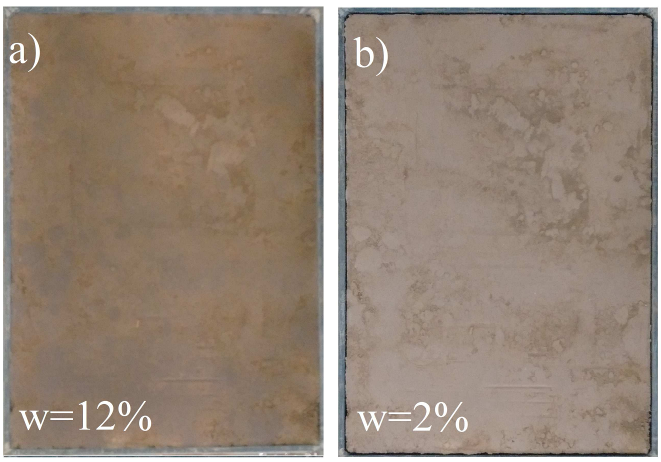

Figure 3. Soil compacted on dry side (Test 4), desiccated at laboratory atmosphere condition. a) Initial state. b) Final state.

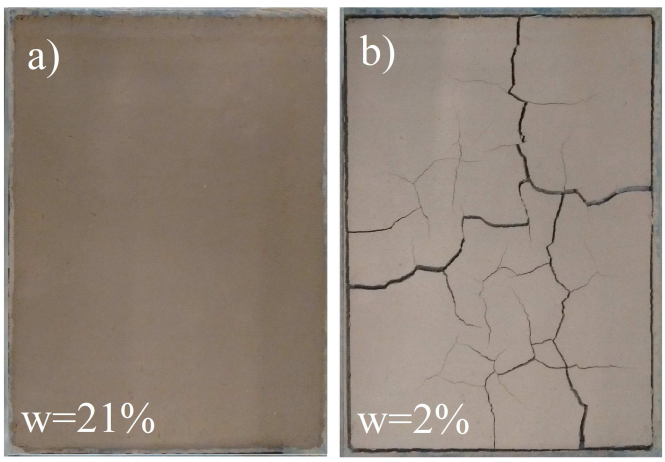

Figure 4. Soil compacted on wet side (Test 5), desiccated at laboratory atmosphere condition. a) Initial state. b) Final state

4.2 *Influence of the initial void ratio*

Results of the evolution of gravimetric water content and CIF for Test 1 and Test 3 are shown in Figure 7. The loss of water along time seems to be similar in both cases and the final gravimetric water content was approximately the same. In both tests, a crack pattern over the soil matrix was developed at the beginning of the test, then due to the shrinkage of the sample, some cracks closed and the edge crack grew up. The final CIF for sample compacted at optimum was 2.64% and for that on the dry side 1.15%. Although the initial water content in Test 3 was a bit higher than in Test 1, the difference on CIF values was lower than that obtained between Test 1 and Test 2. That suggests CIF is related to the initial water content at compaction.

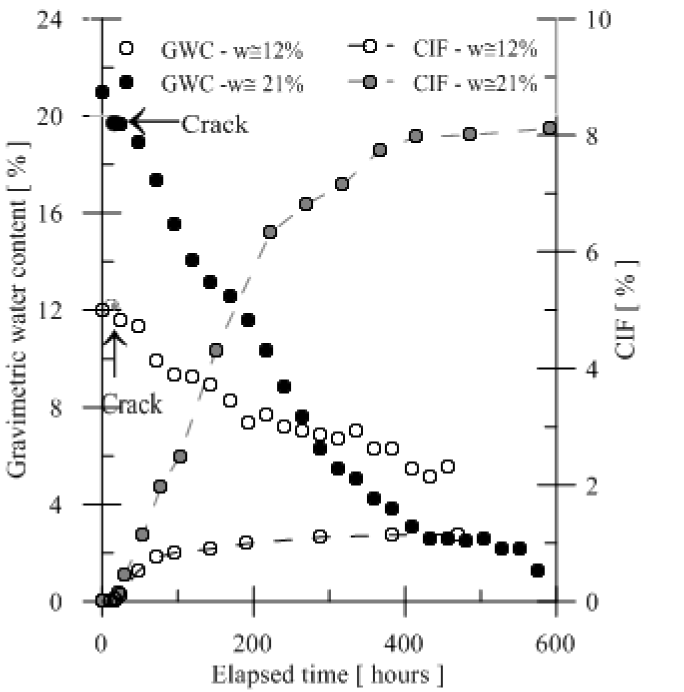

Figure 5. Evolution of gravimetric water content and CIF for samples with different initial water content and dried in the environmental chamber (Test 1 and 2).

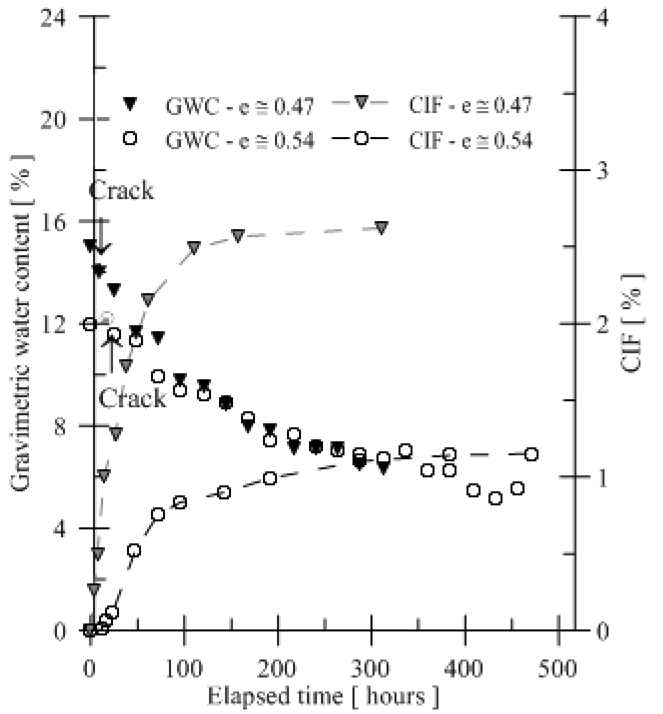

Figure 7. Evolution of gravimetric water content and CIF for samples with different initial void ratio and dried in the environmental chamber (Test 1 and 3).

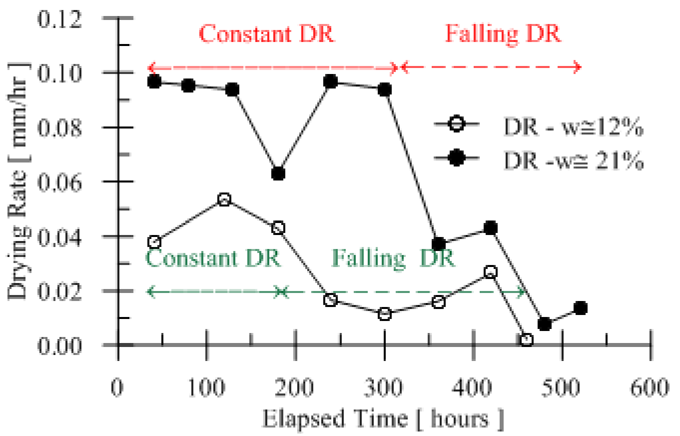

Figure 6. Evolution of drying rate for samples with different initial water content and dried in the environmental chamber (Test 1 and 2).

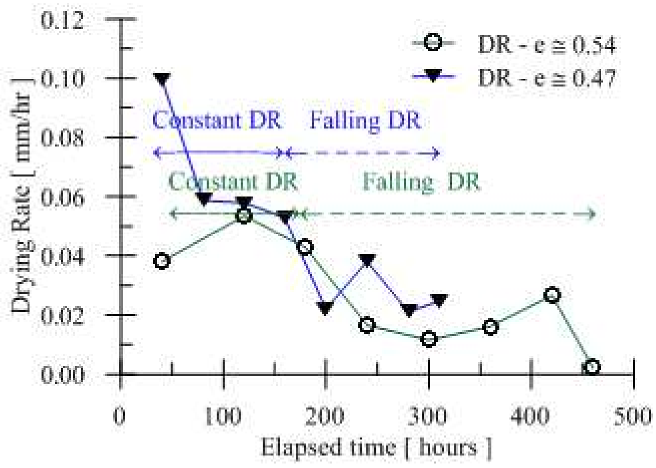

Figure 8. Drying rate for samples with different initial void ratio and dried in the environmental chamber (Test 1 and 3).

The drying rate over time (Figure 8) was similar for both samples. This result can be explained taking into account that the structure generated in compacted soils at optimum is similar to the structure of samples compacted on the dry side (Delage et al. 1996).

These experiments suggest that cracking pattern in compacted soils seems to be related to the structure generated by the compaction process.

5 CONCLUSIONS

Desiccation tests of compacted soils have been performed on an environmental chamber to evaluate the influence of the initial water content and dry density on the crack pattern and water loss. Additionally, desiccation tests under laboratory atmosphere conditions were carried out in rectangular samples to compare the results under different boundary conditions.

Results from tests developed on the environmental chamber showed that the initial water content had an important influence on the drying evaporation rate. At the end, soil compacted on the wet side of optimum had a lower water content than samples compacted on the dry side of optimum. The stage of constant drying rate was longer for the sample on the wet side. It is known that soils compacted at both sides of the optimum have different micro-structure generated during the compaction process and that may explain the behaviour in these desiccating tests. Regarding the influence of water content on the crack patterns, in both type of tests (environmental chamber and laboratory atmosphere) the CIF was lower on the dry side and it could be related to the greater stiffness of soils compacted at low water contents (dry side).

It is important to note that in the cylindrical sample compacted on the wet side, only an edge crack due to shrinkage was developed. For the soil compacted on the dry side a crack pattern was developed at first but as the test progressed some cracks closed. On the other hand, rectangular samples compacted on the wet side developed a crack pattern in the soil matrix and an edge crack. The difference in behavior between rectangular and cylindrical samples could be explained due to the stress state in each case; cylindrical samples develop a homogeneous tensional state while rectangular samples not, whereby the latter are more prone to cracking. However, for both shapes, CIF increased when increasing initial water content.

The influence of the initial void ratio was evaluated comparing the results for a sample compacted on the dry side (Test 1) with those of that compacted at optimum (Test 3). The variation along time of the gravimetric water content and the drying rate was similar for both cases. This could be explained because compacted soils at optimum had a structure similar to that of samples on the dry side. Cracking process was similar in both cases; at first a crack pattern was developed in soil matrix and then some cracks closed due to shrinkage.

Future research to confirm these trends will be required, including the measurement of the retention curve of the compacted material under the studied conditions as well as the behavior of the samples under drying and wetting cycles.

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