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Hydro-mechanical processes in soil desiccation problems. Application to Bogotá clay

Processus hydro-mécaniques de dessiccation des sols. Application a l'argile de Bogotá

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ABSTRACT
In the last 15 years surface cracks have frequently appeared in a rural area close to Bogotá (Colombia). The phenomenon is related to the soil volume changes produced when subjected to desiccation and a comprehensive research work was initiated in order to understand the hydro-mechanical processes involved. The soil from the area is a high plasticity clay, and some basic properties, both in the saturated and unsaturated state were obtained. The paper presents some laboratory experiments involving desiccation of that clay in different moulds. The aim of the work was to find out the conditions of the crack formation and the patterns of the crack propagation. From those tests it was possible to obtain the desiccation rate, the conditions (water content) for crack initiation, the effect of boundary conditions (smooth or rough base, size and shape of the mould), and the effect of a new hydration. Digital pictures were taken and a quantitative analysis of the size of the cracks was also performed. The results have provided some insight into the behaviour of this clay when subjected to water loss processes.

RÉSUMÉ
Les 15 dernières années ont vu l'apparition fréquente de fissures superficielles dans une zone rurale proche de Bogota (Colombie). Le phénomène est à relier aux changements de volume par desiccation du sol, constitué par une argile très plastique. Un programme de recherche exhaustif a été commencé afin de comprendre les processus hydro-mécaniques agissant et plusieurs propriétés fondamentales du matériau saturé et non saturé ont été obtenues. L'article présente les essais de dessication de l'argile réalisés dans plusieurs moules en vue de déterminer les conditions de formation et les patrons de propagation des fissures. Ces essais ont permis d'identifier le taux de dessication, les conditions de formation en terme de teneur en eau, l'effet des conditions aux limites (base du moule rugueuse ou lisse, taille et forme du moule), et les effets d'un nouveau mouillage. Des photographies digitales ont été prises et une analyse quantitative de la taille des fissures réalisée. Les résultats permettent une meilleure compréhension du comportement de cette argile soumise à un processus de perte en eau.

1 INTRODUCTION

Morphological characteristics and evolution of cracks may be analysed at different scales of observation, from regional scale cracking to micro-cracking and in all cases there are some common morphological patterns that may give important information about the hydro-mechanical processes involved in the desiccation problem. The scale of observation described in this paper may be called intermediate or meso-cracking and it is related to the evaluation of some morphological and hydro-mechanical characteristics of remoulded soil samples subjected to desiccation.

Four different moulds were used in the experiments and detail observations of morphological and cracking processes were carried out as function of water content variation, desiccation rate and restrictions to free contraction imposed by the shape of the moulds. Additionally a quantitative analysis of cracking was done by digital measurement of cracking areas during desiccation.

These results are part of a comprehensive research program that was initiated to study the problem of soil cracking in Bogotá city where vast areas have been affected causing an important economical and environmental damage.

2 DESCRIPTION OF IN-SITU CRACKS AND SURFACE DEFORMATIONS DUE TO SOIL DESICCATION

Bogotá city is located on an extended flat area called "Sabana de Bogotá", placed at 2640 m over see level. Geologically it is an unconsolidated deposit, composed of many plastic clay layers with some interstratification of sand, gravel and volcanic ash lenses. Maximum measured depth of this deposit is 780 m and it occurs in the western sector, whereas in the eastern sector, depth gradually reduces until it reaches a boundary imposed by mountains of sedimentary rocks (Ingeominas, 1996).

In the last 15 to 20 years surface soil cracks have been appearing in the western rural area of the "Sabana", with notorious increment in size and density in the last 5 years. Because most of the area is covered with grass, at first sight is not easy to detect many cracks and they look like surface deformations; however as vegetation cover is removed, cracks become evident and some of them have more than 20 m length, 2 m opening, more than 6 m depth and they are internally interconnected (Ávila, 2003, Vesga et al, 2003). Cracks affect agricultural use because they difficult tillage and dramatically increase soil permeability, inducing additional surface desiccation. Furthermore, rapid drainage causes loss of organic matter which is gradually removed to lower levels and after some years that may produce a very important environmental damage.

Aside from the land use deterioration, highways, secondary roads and some houses have also been affected by soil cracking, requiring important investments in repairs and maintenance. On the other hand, large settlements are frequently observed in urban areas, especially close to big trees, producing recurrent deterioration of streets, differential settlements in houses, breakage of pipe lines, etc.

Important reduction of piezometric levels has been detected in urban areas where piezometric levels have lowered up to 20 m in the period 1996-2003 (Ávila, 1998, 2003) and in rural areas where Lobo-Guerrero (1992) reported rates of lowering of piezometric water levels between 3 and 5 m/year, probably due to the extensive groundwater extraction for flower crop industry.

3 CLAY PROPERTIES AND DESICCATION EXPERIMENTS

Samples for soil characterization were taken in the urban area between 2 and 4 m depth. This material corresponds to a medium to high plasticity clay (W_L = 62-65%, PI = 30-35% and Activity = 0.52-0.57) and it represents the typical layer subjected to cracking by desiccation.

Desiccation experiments were carried out with remoulded samples, using moulds of different sizes and shapes as shown in Figure 1. Square moulds or Trays (TR) were of two types and the only difference between them was the height of the lateral wall, which was 5 mm in TR-1 and 10 mm in TR-2. The base of these moulds had grooves of 1 mm depth in orthogonal directions to induce restriction to soil contraction as desiccation was in progress. Small moulds (SM) and micro moulds (MM) were double T shaped and in these cases main restriction to lateral contraction was imposed by the shape of the moulds because the samples rested on a smooth base of glass.

Samples were prepared at different initial water content and they were left to dry to an open atmosphere. Weight of the samples and readings of temperature and relative humidity of the surrounding atmosphere were taken as a function of time from the beginning of desiccation process.

Special care was taken during weighting the samples to avoid any alteration of the material and to have reliable data of the moisture content variations. Also, a detailed observation of the samples during desiccation was carried out to detect the moment of crack initiation and to describe the morphological evolution of crack propagation. At different stages digital pictures were taken and they were used to make a quantitative analysis, as described later.

4 DESICCATION CURVES AND CONDITIONS OF INITIAL CRACKING

Typical variation of moisture content, with time *(t)* is presented in Figure 2, where vertical arrows show the point of crack initiation and the slope of the curves represent the desiccation rate (λ), expressed in percentage of moisture loss in unit time. It is observed that under similar atmospheric conditions, the higher the initial moisture content (w_o), the higher the moisture content at crack initiation (w_{cr}). Desiccation curves showed three characteristic sectors (Fig. 2): the first sector is linear and occurs at the beginning of desiccation, showing a high desiccation rate (λ_o), accompanied by most of the morphological changes in the sample, including volumetric restricted contractions, initial soil cracking, crack propagation and sometimes secondary cracking. The second sector is non linear and it corresponds to a transition between high and low desiccation rates, but in this clay this transition is in general very short and eventually may be omitted. Finally the third sector occurs at the end of the desiccation process where desiccation rate (λ_f) is very low and hence few morphological variations are noted.

In the first sector the variation of moisture content (w) as function of initial water content and desiccation rate may be simply represented by the linear equation

$$w = w_o - \lambda_o t \quad (1)$$

Kodikara et al (2000) proposed an exponential equation for the desiccation curves that may give a good representation of some types of soils when they show a more gradual variation of moisture content with time or in other words, when the second desiccation sector is not negligible. It should be noted that those desiccation curves are similar to the conventional shrinkage curves.

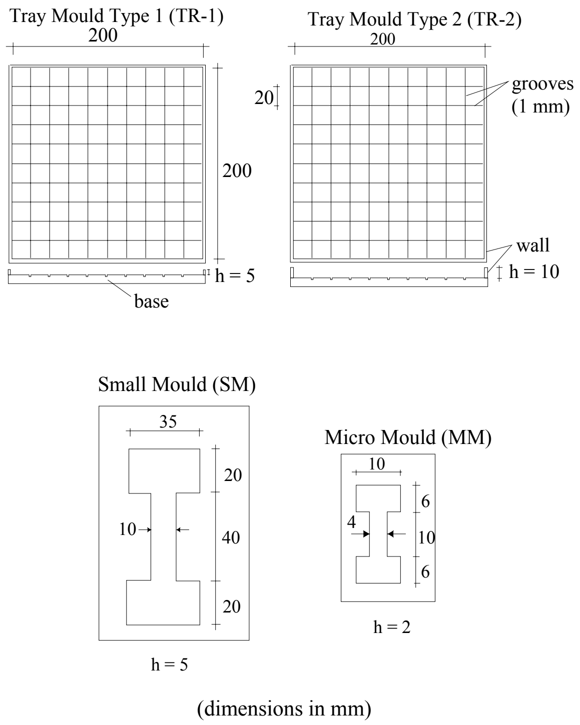


Figure 1. Moulds used in the desiccation tests.

For samples starting at the same moisture content, moisture content at cracking tend to decrease as desiccation rate increases. This may be observed in terms of values of normalized moisture content at cracking (Wc_N) defined as Wc_N = Wcr/Wo, as shown in Figure 3. Although data show broad dispersion, this general trend is in accordance with the behaviour reported by Kodikara et al (2000) and by Lloret et al (1998) for other soils subjected to desiccation in controlled laboratory conditions.

With respect to the mould type it was observed that for TR and SM moulds, cracking occurred between the liquid limit and the plastic limit but for MM moulds, cracking initiated at much lower moisture content, some times below the plastic limit.

Figure 4 shows that moisture content at cracking varies linearly with respect to initial moisture content and it is also clear the difference between cracking in MM moulds with respect to that observed in TR and SM moulds.

Relations between initial water content and soil suction at cracking may also be obtained by means of the retention curve. Based on the retention curve of the Bogotá clay and on the desiccation curves, it was found that for TR and SM moulds, crack initiation occurred in saturated conditions but for MM moulds cracks initiated under partially saturated conditions (between 85% and 95%).

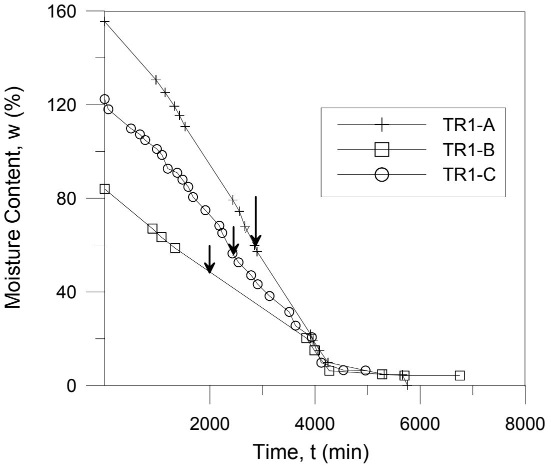


Figure 2. Measured desiccation curves

These results show that moisture content at cracking is not a material property but it depends, among other variables, on the initial moisture content, on the desiccation rate and on the restrictions to free shrinkage imposed by the moulds.

5 EVOLUTION AND QUANTIFICATION OF CRACKING IN TR SAMPLES

In TR samples restriction to free contraction is basically provided by the friction between the soil and the mould base and this causes a complex stress distribution that will influence the final pattern of cracking. However, in the TR-1 samples (5 mm depth) primary cracks show certain uniformity with tendency to occur in diagonal direction, normal to the inferred directions of major tension stresses, while in TR-2 samples (10 mm depth) less uniformity was observed and 3 to 4 preferential directions could be inferred.

It was noted by changes in the sample colour that drying tends to advance from the perimeter (especially from the corners) to the center of the sample and this may be explained by the possibility of surface and lateral evaporation at the perimeter while in the center only surface evaporation may occur. This non uniform desiccation process induces additional stress gradients inside the sample that may generate curling and irregular strain distribution that have great influence in the secondary cracking and in the final cracking pattern.

From the measurement of digitalized areas of cracks at different times of the desiccation process, a quantitative analysis was carried out, using the Crack Intensity Factor (CIF) method, proposed by Mi (1995, cited by Yesiller et al , 2000) and by Miller et al (1988). CIF is defined as the area of cracks divided by the total area of the sample

$$CIF(\%) = \frac{A_{cracks}}{A_{total}} x100 \qquad (2)$$

As an indication, in the sample B2A (Fig 5a), with severe and open cracking CIF = 11.2 while in the sample B2C (Fig.5b) whit incipient and relatively close cracks, CIF = 0.7. CIF also showed an inverse linear relation to lateral contraction of samples (Fig. 6) and this indicates that if the base restriction to lateral contraction is effective, cracking is greater than if restriction is less effective.

Some samples were hydrated after final cracking and it was noted that normally new cracks appeared very soon. However, depending on the amount of added water, existing cracks may reduce their opening because soil expands due to matric suction reduction.

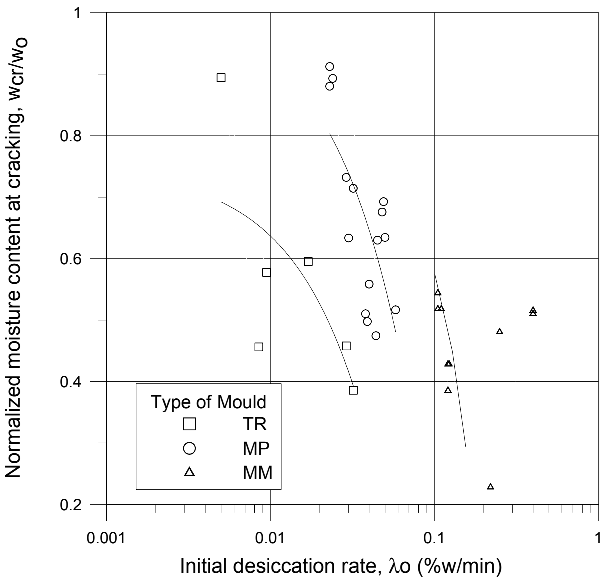


Figure 3. Moisture content at cracking as function of desiccation rate.

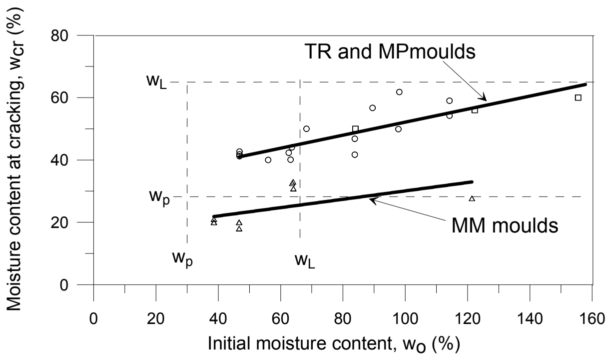


Figure 4. Moisture content at cracking as function of initial moisture content

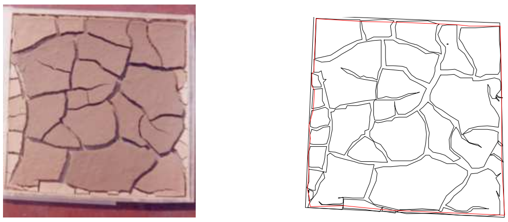
Based on Bazant and Cedolin (1991), Kodikara et al (2000) proposed a geometrical characterization of cracking patterns, considering the relationship between mean cell area (Am) and specific crack length (Ls), where Am is defined as total cell area divided by the number of cells and Ls is defined as total crack length divided by the total surface area. For triangular, square and hexagonal shapes respectively they present the following relations

$$A_m = 5.19/L_s^2,\ A_m = 4/L_s^2 \ and \ A_m = 3.47/L_s^2 \qquad (3)$$

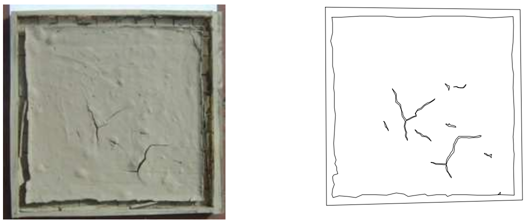
In a plot of Ls versus Am these theoretical relationships define a narrow band where most of experimental data tend to be included as shown in Figure 7 (Kodikara et al, 2000). In this figure are also plotted data from TR samples and it is noted that they follow the same trend.

6 CONCLUSIONS

Desiccation and cracking problems have important economical and environmental impact in Bogotá city and in other areas in the world. The experimental program presented in this paper allows understanding the physics of the phenomenon and constitutes a first step previous to the numerical analysis of the associated hydro-mechanical problem.



a) Test B2-A, CIF = 11.2



b) Test B2-C, CIF = 0.7

Figure 5. CIF calculated for two TR samples.

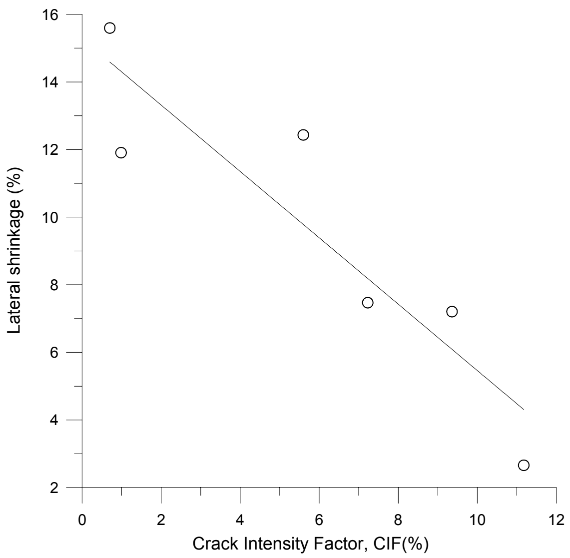


Figure 6. Linear relation between CIF and lateral contraction in TR samples.

Desiccation curves for the studied clay showed a bi-lineal behaviour and initial cracking almost always occurs in the first sector of the curve and under saturated conditions, except when restrictions to contraction are too low as observed in MM samples that cracked in partially saturated conditions. Therefore, moisture content at crack initiation is not a material property, but it depends on initial water content, desiccation rate and especially on the restriction to free contraction imposed by the moulds.

Parameters as CIF and geometrical cell relations give a useful and objective procedure to characterize and compare different cracking processes and they may help in the future when calibrating constitutive models.

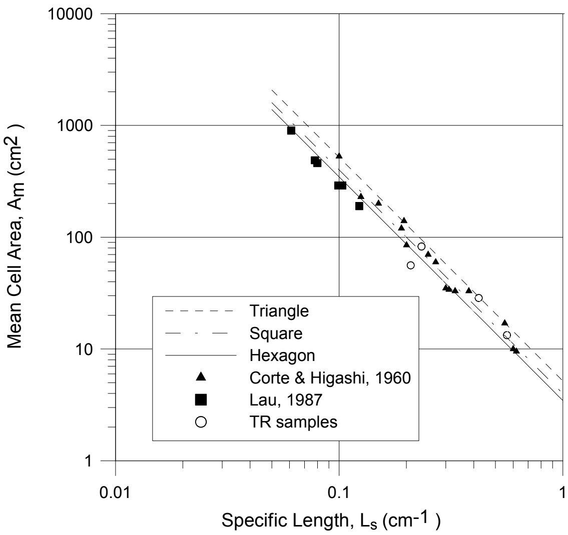


Figure 7. Theoretical and experimental relations between specific crack length (L_s) and mean cell area and (A_m). (After Kodikara et al, 2000)

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