Soil cracking propagation due to dryness and its relation to suction

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Abstract. Investigation of Crack Intensity Factor is essential as it affects the mechanical and hydraulic behaviour of soils. Soil water coming from the wet seasons or from the water table, is removed by evaporation during the driest season. The loss of water provokes a significant increase in suction. When it exceeds the tensile strength of the soil, cracks occur that can modify the mechanical and mainly hydraulic properties of the soil, creating preferred paths for water infiltration. Little research is conducted on quantifying cracking in soil relating it to its hydraulic properties. This research aims to investigate the cracking of soils with focus on analysing its relation to water content and soil suction. Soils from a specific region in Brazil with clay predominance are collected and characterized. Unsaturated soil specimens are prepared and subjected to environmental real conditions in order to progressively check the consequences caused by the environment in soils with different clay content during four weeks. The Crack Intensity Factor is measured along the time through image processing. The water content is monitored through volume water content sensors. The measured results are evaluated to correlate crack intensity factor as function of weather variables and soil water content.

1 Introduction

Clayey soils, in general, are prone to cracking during the long cycles of wetting and drying or freezing and thawing. This can compromise their integrity by interfering on their behaviour (Albright et al., 2006 [1]; Andersland & Al-Moussaw, 1987 [2]; Costa et al., 2013 [3]; Li et al., 2016 [4]; Li & Zhang, 2010 [5]). Desiccation cracks have been a major concern not only in clay layers and soil barriers (Li et al., 2016 [4]; Hewitt & Philip, 1999 [6]) but also when shear strength is a concern (Shin & Santamarina, 2011 [7]; Silva, 2018 [8]).

The desiccation cracks become a severe problem that affects the long term hydraulic and mechanical behaviour of cohesive soils. Cracks can meaningfully speed up water infiltration into the clayey soils (Li et al., 2009 [9]; Li et al., 2011 [10]; Rayhani et al., 2008 [11]; Snow, 1969 [12] ; Yuen et al., 1998 [13]) and in turn, it can reduce the soil strength due to suction.

This paper investigates the cracking behaviour in clayey and silty soils in order to provide new relations between the type of soil and its fine content and cracking propagation due to real weather. Three compacted soil samples were carefully prepared. The cracking behaviour in these soil specimens was observed and quantified. The cracking intensity factor (CIF) of the three soil samples were monitored during four weeks.

Results shed light on the knowledge of different soil response to drying periods that are recently becoming a new concern on geotechnical field. Apart from fines content, other soil properties can exert influence on cracking pattern and quantity but they are out of the scope of this paper. For the sake of brevity, and because all the presented soil herein have at least 30% of clay, in the following sections the soils are often referred as clayey soils.

2 Materials and Methods

2.1. Soil sample preparation

Three different soils were collected in Irati, Paraná, Brazil. The experimental setup consisted of three cone trunk soil samples that were equipped with moisture content sensors. The soils were carefully compacted in the black plastic cone trunk recipient (130 mm in height and 220 mm in average diameter). The soils were compacted in three layers using a 2,5kg hammer. Each final sample was 8cm deep. To avoid any influence of the roughness of the walls of the container, vaseline was used at the walls before compaction process. The samples were molded to have the same initial void ratio. A variation of 5% after compaction was acceptable.

The bottom of the samples had 8 small holes 8.0 mm in diameter for water drainage. Through one of them a moisture content sensor EC-05 type was installed. The EC-5 sensor has a frequency of 70MHz and determines volumetric water content by measuring the dielectric constant of the medium. The moisture content sensors monitored the water content changes in the soil samples, with a measuring range of 0 to 50% and an accuracy of 1 to 2%. Calibration curves were used accordingly to the type of soil following the manufacturer's instructions. The moisture content sensors were connected to a data-logger, which continuously records water content readings However, data were stored only from 7th day on. During

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the first week, humidity sensors were not available for installation. Details from the described above can be seen at Fig. 1.

The samples were then placed outdoor and exposed to the elements of weather. Cracking evolution was measured during four weeks using high resolution camera. All photos had 9MP resolution and were daily taken at the same time of the day and the same distance from soil surface. An apparatus was manufactured to ensure the equal distances for all photos as well as the centralization.

Processing image was used later according to Li and Zhang 2010 method (J. H. Li & Zhang, 2010 [5]).

Fig. 1. Soil sample equipped with EC 05 sensor.

During the same period, a meteorological station located 1,5km away from the experiment registered precipitation, temperature and relative humidity during the 28 days. The station is a conventional meteorological station of INMET (The Brazilian National Institute of Meteorology) that is installed in Irati since 1966.

During the four weeks, only two days had a small registered of precipitation. The 19th and the 28th day had registered 0,1 and 0,7 mm respectively. For being not a representative amount, the data was not considered in the analyses. The meteorological station registers hourly temperature data. The maximum day temperature was used in this study. Data collected are presented in **Fig. 2**.

Finally, soil characterization was made in laboratory. The particle size distribution was measured according to ABNT NBR 7181:2016 (ABNT, 2016a [14]) and the Atterberg limits according to ABNT NBR 6459:2016 and ABNT NBR 7180:2016 (ABNT, 2016b [15], 2016c [16]).

Based on their original location, the samples were geologically described as part of the Teresina Formation or Serra Alta Formation. Both are part of the Passa Dois geological group which comprehend part of southwest of the Parana State in Brazil. (Liccardo et al., 2016 [17]). Basically, the major difference between the two formations is that the first one is mostly composed by silticides while the second one is by mudstones.

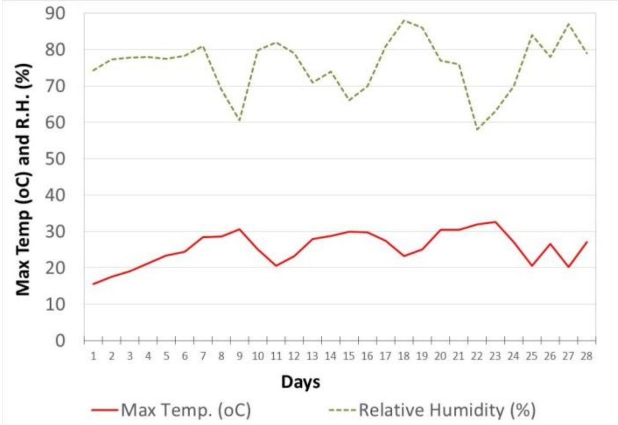

Fig. 2. Temperature and relative humidity data during the monitored period (INMET, 2020 [18]).

Based on their geological characteristics and on their classification at USCS (Unified Soil Classification System), the soil samples were named Silt of low plasticity from Teresina formation (ML_T), Silt of high plasticity from Teresina formation (MH_T) and Silt of high plasticity from Serra Alta formation (MH_SA). The main soil properties are summarized in Table 1.

Table 1. Basic properties of the soils.

Property	ML_T	MH_T	MH_SA
Liquid limit, wL	35	58	85
Plastic limit, wp	25	34	53
Plastic index, Ip	10	24	32
Clay Content (%)	36,4	72,8	65,3
Fines Content (%)	91,0	93,8	97,8
Unified Soil Classification System (USCS)	ML	MH	MH
Geological origin	Teresina Fm.	Teresina Fm.	Serra Alta Fm.

After characterization, the method presented by Zapata et al (2000) [19] was used to estimate the Soil Water Characteristic Curve (SWCC) (Zapata et al., 2000 [19]). This estimation method uses the plasticity index (PI) to provide a simple approximation of SWCC for a fine soil and can be fitted with the Fredlund and Xing fitting parameters (Fredlund & Xing, 1994 [20]). Saturated volumetric water content for each curve was assumed as equal to porosity (n) of each soil sample. Fig. 3 presents the SWCC curves obtained. Laboratory tests to measure the SWCC curve for each soil are in progress and will be added in future analysis of the samples, which are still being imaging monitored.

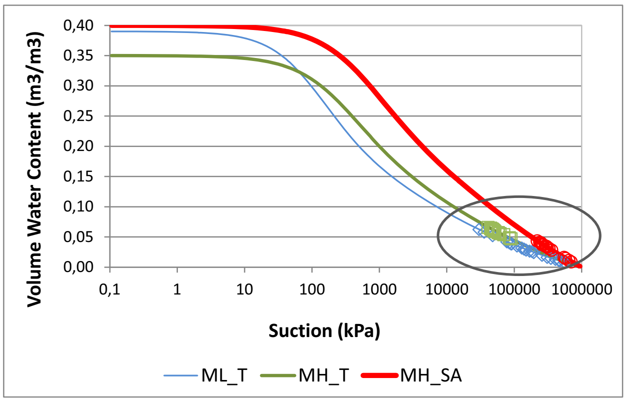

Fig. 3. Estimated SWCC curve for each soil sample.

2.2. Experimental procedure

Image analysis was conducted to investigate the influence of soil type on cracking development. The soils were monitored along 28 days (from august 21st to September 18th, 2020). The soil specimens were firstly compacted and then put outdoor and exposed to the elements of weather for four weeks. During this period, daily photos were taken from all samples.

During cracking, soil contraction generates a gap between plastic container and soil. In order to avoid a preferential path for water in this circumferential gap, the space between soil and container were filled with bentonite. Once the bentonite also starts cracking, due to dryness, the bentonite layer was reinforced. The space filled with bentonite was out of the area considered on imaging analysis. Thus, this procedure did not interfere on image monitoring.

The crack image analysis was conducted in all photos. A digital imaging method (J. H. Li & Zhang, 2010 [5]) was used to log the crack development during the four weeks of exposure. Photographs were taken every day on the soil surface with the camera fixed at the same place and height to ensure the quality. Camera resolution was 3000 × 3000 pixels.

ArcGIS software was used to transform all the photos into a binary image, i.e. black and white images (Fig. 5) where it was possible to count black and white pixels. This methodology, along with the good resolution of the photos, made it possible to detect new cracks over time and also to detect if existing ones had contracted or expanded.

During the exposure, changes in water content at the soil samples were recorded and used to determine suction variation.

3 Results and Data interpretation

3.1. Crack intensity factor

A crack intensity factor (CIF) is often used to quantify the cracking on the soil surface, which is defined as the ratio between the crack area and the entire soil surface area (Miller et al., 1998 [21]; Yesiller et al., 2000 [22]).

$$CIF = Ac / As$$

Where Ac is the area of cracks on the soil surface, and As is the total area of the soil surface.

During the four weeks, an inexpressive amount of precipitation was recorded. So, it can be assumed that the monitored period was a dryness period from which humidity is expected to decrease while suction is expected to increase. Fig. 4 shows the difference between cracking behaviour for the three different soils.

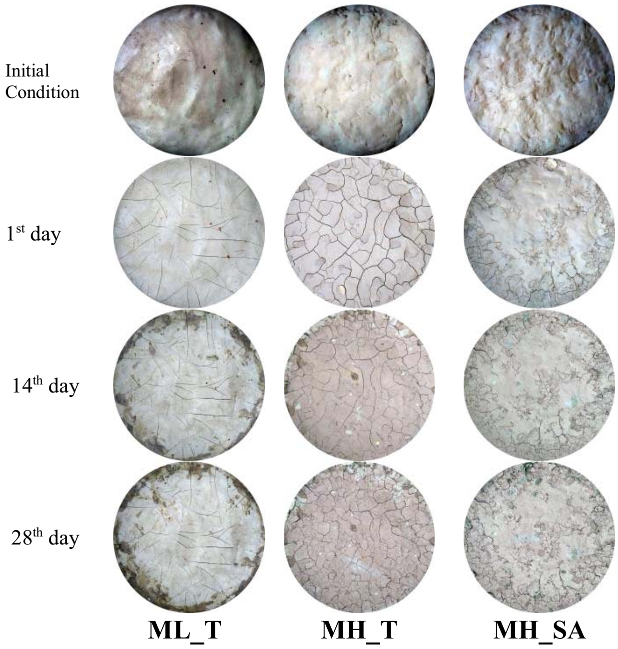

Fig. 4. Photographs of surface cracking evolution.

To calculate the areas, and consequently the CIF, the photographs were transformed into binary images. The pixels that are occupied by the cracks and by the soil surface in a binary image were counted separately. Fig. 5 shows one example of cracking evolution on binary image.

3.2. Effects of clay on cracking

The clay content of each sample was determined during characterization. CIF evolution against time was plotted for all soils in order to analyse the influence of clay presence on cracking development (Fig. 6 and Fig. 7).

Both, the silty soil of low plasticity from Teresina formation (ML_T) and the silty soil of high plasticity from Teresina formation (MH_T) have a clear increase in CIF during the dryness period assessed. However, the primer, which has Ip and clay content considerable lesser then the second, apparently is more sensitive to weather (temperature and humidity) changes. Between the 7th and 9th day of observation, when relative humidity decreased, ML_T soil presented a significant increase in its CIF. The same was observed at the end of the four weeks.

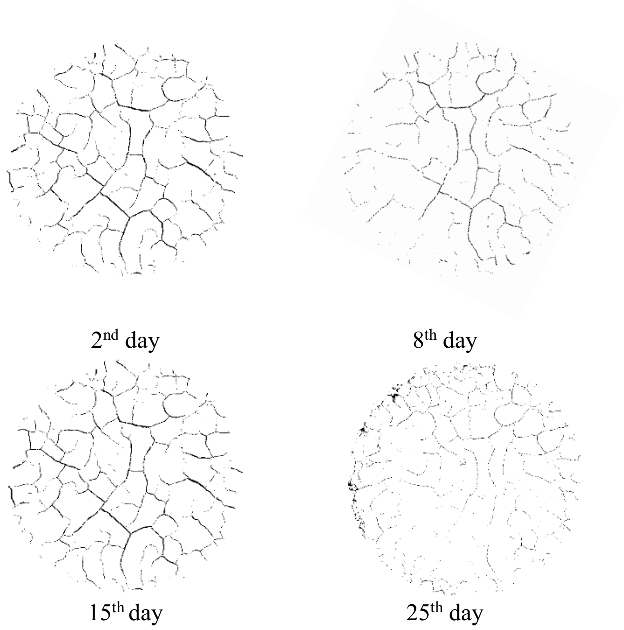

Fig. 5. Example of cracking evolution on binary image for soil MH_T.

The silt of high plasticity from Serra Alta formation (MH_SA), which is the most plastic soil (wL=85 and Ip=32) had a completely different behaviour facing the same weather. In the beginning, after CIF increased rapidly during the first two days, soil presented contraction for the subsequently five days, after what it conserve CIF as almost constant, showing alternated small expansion and contraction.

Volumetric water content was measured at the bottom of the samples. Unfortunately, the first week could not be recorded. Even though, the three final weeks measurements could elucidate behaviour difference between the soils (Fig. 8).

Silt of low plasticity from Teresina formation (ML_T) and silt of high plasticity from Serra Alta formation (MH_SA) showed almost constant decrease on volume water content (VWC) values during the recorded data while their cracking intensity factor, even though oscillating, were growing in average.

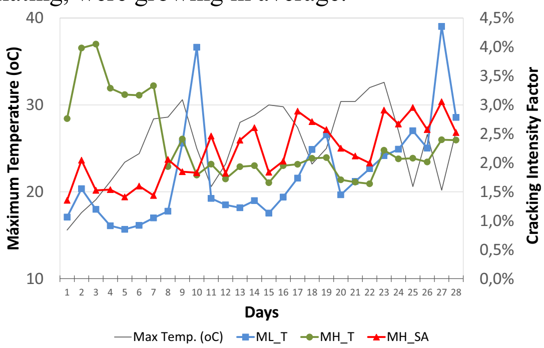

Fig. 6. Maximum temperature and CIF evolution for all soils.

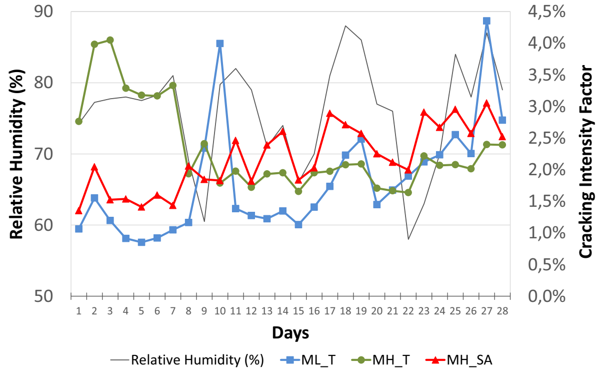

Fig. 7. Relative humidity and CIF evolution for all soils.

The sine wave behaviour of the CIF for MH_SA is justified for the up and downs registered on the VWC recordings. Not all upwards or downwards registered by image analysis were directly related to a VWC variation showing that image analysis could register more sensitive variations due to weather then VWC sensors. It is important to mention that once the sensors were installed at samples bottom, a time delay is expected when comparing image analysis data against VWC data.

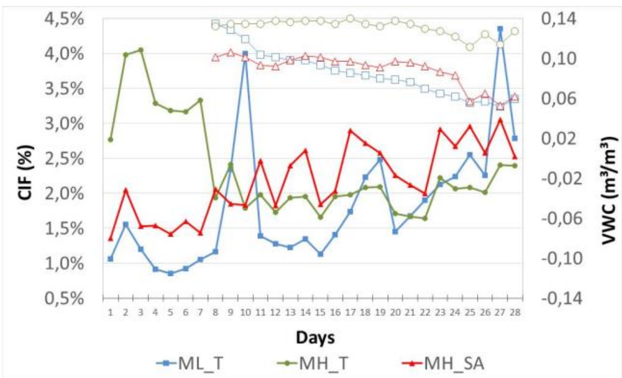

Fig. 8. Volumetric water content x CIF evolution for all soils.

On the other hand, the peak points observed on CIF oscillation of the ML_T soil behaviour apparently are not related to VWC measured. The sensors, in this case, registered continuous decreasing readings while photos more than one time registered a higher cracked soil followed by a less cracked soil again.

The silty soil from Teresina formation (MH_T) showed almost constant VWC readings. The readings can be compatible with the photos monitoring, which showed also almost constant values from the second week on. Unfortunately, especially for this soil, the first week VWC registers would be fundamental for a more deep interpretation on the relation of cracking and soil type.

From the SWCC estimated curves (**Fig. 3**) suction range experienced by each soil sample could also be estimated. **Fig. 9** shows the estimated path taken from each soil during the monitoring period.

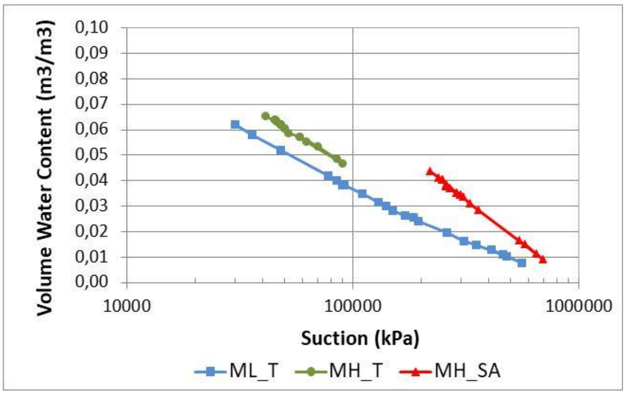

Fig. 9. Suction values associated with VWC readings.

All the readings recorded are closer to the residual volume water content, which implies higher suction values. Again, the lost readings from the first week could enrich this discussion.

The Silty soil from Teresina formation (ML_T), the one with less clay content between the three (36,4%) has experienced the larger range of suction values: from 30 MPa to 550 MPa approximately.

The Silt with high plasticity from Teresina formation (MH_T), as discussed previously, showed almost constant VWC readings. It implies in a small suction range, 50 to 90 MPa. This material has 72,8% of clay content.

In turn, the silty soil from Serra Alta formation (MH_SA), which is the most plastic soil (wL=85, Ip=32 and Clay content of 65,3%) achieved even higher values of suction than ML_T but in a smaller range; from 200 to 700MPa.

4 Conclusions

The research quantified cracking in three different soil samples and related its development to its hydraulic properties. Soils from Irati, Paraná, Brazil, with clay predominance, were collected and characterized. Unsaturated soil specimens were prepared and subjected to environmental real conditions in order to progressively check the consequences caused by the weather in soils with different clay content. The experiment took four weeks.

The samples were subjected to a natural drying processes through solar radiation and heating. No significant precipitation was registered during the four weeks that could allow any observation on the wetting processes. After four weeks of almost total dryness, cracks developed freely at the three soil samples surface in different ways, patterns and quantities.

The less plastic and cohesive soil (ML_T) showed increased in cracking during the dryness period observed and some peaks representing a large CIF variation after some drop in humidity or temperature rise. Its volumetric water content was gradually decreasing in an almost constant rate along the largest suction variation.

The intermediate soil (MH_T), considering plasticity and clay content, showed a big decrease in cracking after the first day increase. After, that cracking intensity factor kept almost constant, with no remarkable variation. In accordance, volumetric water content also had small changes, which reflects in the smaller range of suction.

For its part, the most plastic and clayey soil (MH_SA) had similarly soil cracking behaviour to the first one except for the peaks. This soil presented the larger values of cracking. Its humidity behaviour was also similar to the first soil but instead of a constant rate dropping, a step function dropping was observed. Although its humidity values are comparable with the ones in the less cohesive soil, its suction range could reach much higher values. It happens as a consequence of the different SWCC's that were adjusted for both soils considering their properties.

All samples are still being monitoring. Soil water characteristic curves will be determined in laboratory, through Filter paper method and confronted with the ones estimated in this paper. Artificial rain will finally complete the experiment, in order to obtain the differences in the wetting path of the soils and not only in the drying path.

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