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Experimental study on water evaporation from compacted clay using environmental chamber

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Abstract:

Water evaporation induces large volume change for clayey soils, often causing problems to geotechnical and geoenvironmental constructions. To better understand this process, an evaporation test on a compacted clay was conducted in a large-scale environmental chamber under controlled atmospheric conditions. Atmospheric parameters (wind speed, air temperature and relative humidity) and the response of soil parameters (volumetric water content, temperature, soil suction as well as desiccation cracks) were monitored. The results show that the soil temperature is strongly related to the air conditions, evaporation process and desiccation cracks. Unlike for sand, the evolution of volumetric water content is governed by both the high water retention capacity of clay and the effect of cracks. A three-stage evolution can be observed for not only the actual evaporation rate but also the surface crack ratio. Thus, the surface crack ratio can be considered as one important parameter in the evaporation analysis taking into account the effect of desiccation cracks.

Key words: environmental chamber; compacted clay; air/soil parameters; evaporation; surface crack ratio
Introduction

Water evaporation from clayey soils can result in significant changes in soil suction, water content and temperature, giving rise to significant soil volume change and hence strongly influencing the performance of the involved geotechnical and geoenvironmental constructions: the long-term behavior of pavement and embankments/dams can significantly change due to the desiccation cracks and settlement induced by the decrease of water content (Cui et al. 2010; Puppala et al. 2011, Tang et al. 2011a); buildings with shallow foundations and other geotechnical constructions can be seriously damaged due to the differential settlement induced by water evaporation (Silvestri et al. 1990; Cui and Zornberg 2008; Corti et al. 2009, 2011; Qadad et al. 2012); the behavior of soil covers used in mine tailings or other hazardous waste landfills (Wilson 1990; Wilson et al. 1994, 1997; Yanful and Choo 1997; Yang and Yanful 2002; Yanful et al. 2003; Cui and Zornberg 2008) and also the landfills for municipal solid waste disposal (Bligh 2006, 2009) can be also strongly affected by water loss due to evaporation; the safety of high-level radioactive waste repository as a result of changes in soil hydro-mechanical properties induced by ventilation during the construction and operation periods is also an important issue (Bond et al. 2013; Millard et al. 2013). These problems clearly show the importance of well understanding the mechanisms of water evaporation from clayey soils.

Indeed, when these mechanisms are well identified, it is possible to develop relevant water evaporation models for predicting soil deformation/settlement (e.g., Hemmati et al. 2010, 2012; Cui et al. 2013), and for designing geotechnical and geoenvironmental
constructions such as soil covers (e.g., Yanful and Choo 1997; Yanful et al. 2003).

Up to now, many experiments were conducted to investigate water evaporation from clayey soils. For instance, an evaporation experiment was performed by Garnier et al. (1997) on a swelling soil sample (48 mm in diameter and 50 mm in height) to determine the evaporation rate and soil hydraulic properties of soil. Yanful and Choo (1997) performed an evaporation test using an environmental chamber on a clay considered as a candidate cover soil. A clear evolution of drying front was observed through the water content profile; moreover, it was found that the soil temperature firstly decreases and then increases during evaporation and the evolution of evaporation rate presents typical three stages. Later, Yang and Yanful (2002) and Yanful et al. (2003) investigated the evaporation and drainage phenomena on a compacted sample of Halton clayey till (115 mm in diameter and 255 mm in height) with both constant (Yanful et al. 2003) and variable water table (Yang and Yanful 2002). The results showed that water table change has no significant effect on the evaporation and drainage processes, verifying the effectiveness of this soil for an oxygen barrier in sulfide-bearing mine waste covers. Wilson et al. (1997) studied the Regina clay with a small sample of 0.2-0.3 mm thick and found that the ratio of actual evaporation rate to potential evaporation rate and soil suction show a unique relationship, independent of soil properties and drying time. Lee et al. (2003) performed evaporation tests on Yulchon clay using a column of 240 mm diameter and 800 mm height and the results were used to verify a model of water evaporation rate.
from the surface of a deformable material.

On the other hand, desiccation cracking occurs easily for clayey soils upon drying. Many studies were conducted to the evolution of soil cracking with changes in water content. Nahlawi and Kodikara (2006) conducted a series of desiccation cracking tests on a thin clayey soil layer in some narrow perspex and metal molds under controlled relative humidity and temperature conditions. They observed that the water content at crack initiation generally increases with the increase of clay layer thickness. The water content values at the end of the tests under different initial conditions are similar when the air condition is the same. Tang et al. (2010) performed desiccation tests on soils from slurry state in a glass cup. They found that the initial critical water content which corresponds to the initiation of desiccation cracking increases with temperature. By contrast, the final critical water content which corresponds to the transition point where the surface crack ratio trends to reach a stable value is not significantly affected by temperature. Péron et al. (2006) carried out both free desiccation tests and constrained desiccation tests on a slurry clayey soil for investigating the mechanisms of desiccation cracking. They reported that the local suction and water content values at cracking initiation are close to the air entry values. Tang et al. (2011b) conducted desiccation tests on different soils for investigating the wetting-drying effect. They found that the water content at cracking initiation increases rapidly during the first three drying paths, and change slightly during the subsequent drying paths. Li and Zhang (2011) studied the initiation and development
of crack geometric parameters at the compacted soil surface and excavated soil surface in the field. They reported that the evolution of desiccation cracks can be divided into three stages: initial stage, primary stage, and steady state stage. Moreover, when the water content reaches a critical value cracks develop quickly, and when the water content approaches the shrinkage limit cracking reaches a steady state. Yesiller et al. (2000) reported a significant effect of fine content. In general, high suctions, rapid increases in suctions, and high amount of cracking were observed in soils with high fine contents. Summarizing, the above-mentioned studies mainly focused on the effect of temperature, thickness, soil type and wetting-drying cycles on the development of cracks, the effect of cracks on evaporation being rarely mentioned. Ta (2009) and Cui et al. (2013) conducted evaporation tests on a large Romainville clay sample (1000 mm length, 800 mm width, and 1000 mm depth) using an environmental chamber, showing significant influence of desiccation cracks on the evolution of evaporation rate.

Further examination of the experiments reported in literature shows that few tests were conducted with full control of atmospheric conditions and complete measurement of soil response to evaporation. Indeed, in most experiments the soil was poorly instrumented (e.g., Wilson et al. 1997; Garnier et al. 1997; Yanful and Choo 1997; Yang and Yanful 2002; Yanful et al. 2003; Lee et al. 2003), although the water evaporation process has been recognized to be governed by both atmospheric and soil conditions for bare soils.
In this study, the process of water evaporation was investigated on a compacted clay sample (1000 mm×800 mm×250 mm) in a large-scale environmental chamber which was previously used for investigating water evaporation from sand (Song et al. 2013, 2014) under controlled atmospheric conditions (i.e., controlled air relative humidity, temperature and air flow rate) and with a steady water table. The atmospheric parameters (air temperature, relative humidity) and the response of soil parameters (soil temperature, volumetric water content, matric suction and surface crack ratio) were monitored by various sensors for 83 days, including the soil parameters on the surface (soil surface temperature and matric suction). The obtained results help better understand the mechanisms of water evaporation from clayey soils, and they can also be used for further theoretical and numerical analyses.

**Materials**

The clayey soil selected for this investigation was used for the construction of an experimental embankment in Héricourt, France. Its geotechnical properties are presented in Table 1. The soil is a highly plastic clay according to the Casagrande’s classification criterion and belongs to the CH group following the unified soil classification system (USCS). The grain size distribution curve determined by wet sieving and sedimentation is shown in Fig. 1.
Experimental set-up

The evaporation test was performed in a specially designed environmental chamber system (Fig. 2). The environmental chamber system is a large acrylic transparent chamber combined with wind supply unit (Fig. 3), air collection unit (Fig. 4a), photograph collection unit (Fig. 4b), water supply unit (Fig. 4c) and data logging system (Fig. 4d), controlling the changes of atmospheric conditions and monitoring the evolution of soil responses. In the evaporation test, the compressed air was firstly adjusted by the air flow regulator and the real flow was measured by a flowmeter (Fig. 3a). Then, it was heated using heating hoses (Fig. 3b) with the temperature controlled by a temperature regulator (Fig. 3c). The air temperature and relative humidity were measured before air was diffused into the chamber by an air distributor. After passing through the chamber, the air stream was gathered by the air collection unit for measuring its temperature and relative humidity (Fig. 4a). During the test, the evolution of desiccation cracks was captured by the photograph collection unit (Fig. 4b). The water table was kept constant by the water supply unit, and the change of water table was monitored using a graduated tube (Fig. 4c). All data were recorded using the data logging system (Fig. 4d).

For monitoring the atmospheric conditions and the response of soil, various sensors were buried inside the soil or installed at different positions of chamber (see Figs. 2 and 5). In particular, four high-capacity tensiometers were installed at different depths along the chamber wall for measuring the soil matric suction; six soil
moisture sensor namely ThetaProbe (ML2x) were buried at different depths for measuring the volumetric water content; five soil temperature sensors (PT1000) were installed in the soil sample at different depths; five T3111 transmitters were installed at different locations for monitoring air temperature and relative humidity; five thermistors were fixed at different heights above the soil surface for monitoring air temperature; an infrared thermometer (Pyropen-D) was installed at the chamber cover for measuring the soil surface temperature. A digital camera (Canon EOS400D) was used for taking photos of soil surface. A flowmeter (MAS-3120) and an anemometer (Testo 435-2) were used to measure the air flow rate and the corresponding wind speed inside the chamber, respectively. More details of this environmental chamber and the sensors used can be found in Song et al. (2013).

Note that this chamber paid more attention to the parameters in the near soil surface zone than the one reported by Ta (2009).

**Test procedure**

The clayey soil transported from the Hércourt site was air-dried, sieved at 2 mm and then stocked in a large sealed plastic box. Note that the gravimetric water content of the clay powder was 6.4%. Prior to soil compaction, a 6.5 mm thick gravel layer was compacted on a geotextile layer above the bottom of chamber (Fig. 6a). The gravel layer surface was controlled by a level bar (Fig. 6a). This layer is termed as drainage layer. Another geotextile layer overlaid this layer and the edges of geotextile were taped to the chamber wall, avoiding migration of clay particles.
A mass of 59.58 kg of soil powder was poured into the chamber, smoothed using a wood plate with level bar (Fig. 6b) and compacted manually using a steel plate to have an uniform layer of 50 mm thick (Fig. 6c) with a dry density of 1.4 Mg/m$^3$. Note that this is also the in-situ dry density of the embankment soil at the site of Héricourt (Dong, 2013). This procedure was repeated for other layers until reaching the total height of 250 mm.

During the compaction, various sensors were installed in the soil between the layers. Five PT1000 sensors for soil temperature were installed every 50 mm (i.e., 50, 100, 150, 200 and 250-mm depths) (Fig. 6d). All these sensors were buried in the zone 300 mm far from the chamber wall (Fig. 6d) in order to minimize the effect of laboratory temperature changes. Six ThetaProbe sensors were buried at different depths. Three of them were at 80 mm, 130 mm and 230 mm below the soil surface, and the other three were in the near surface zone at 25, 40 and 55-mm depths, respectively. For the sake of minimizing the effect of sensor installation on the soil density, a hole with similar size as ThetaProbe was created at the defined depth for inserting the sensor (Fig. 6e). Then, the hole was backfilled by the same soil powder with the calculated quantity and then compacted manually to reach the same dry density of 1.4 Mg/m$^3$. Notably, the ThetaProbe was calibrated before installation according to the method proposed by Tang et al. (2009).
Three high-capacity tensiometers were installed at various depths (i.e., 25, 77 and 173 mm below the soil surface) along two sides of chamber wall for the matrix suction measurements during the saturation process. Five thermistors measuring the air temperature were fixed at different elevations (i.e., 50, 170, 235, 330 and 425 mm above the soil surface) along one inside wall of the chamber. Two relative humidity sensors (T3111 transmitters) were installed at 50 and 275-mm heights for monitoring the air relative humidity, while three other relative humidity sensors were installed for recording the relative humidity at inlet, outlet and in the laboratory. One tensiometer was installed at a depth of 15 mm below the soil surface for measuring the near surface matric suction. An anemometer with a telescopic handle was fixed at one side of the chamber cover, allowing measuring the wind speed at 50 mm above the soil surface. After these sensors were installed, the chamber cover was sealed by silicon to ensure the air-tightness. Moreover, an infrared thermometer was fixed on the cover to monitor the soil or water surface temperature at the center. Four Light Emitting Diodes (LEDs) were installed around the four edges of the transparent chamber cover, allowing the soil surface to be lighted for better photographing.

Finally, the bottom of chamber was connected to a water tank with its water level kept at the level of the soil surface. The saturation process was then performed with water flow from soil bottom firstly and then from soil surface for accelerating this process. Finally, a water layer was formed on the soil surface and the volumetric water content sensors showed stable values. After the saturation, the evaporation experiment was
started by imposing an air flow of 155 L/min and with a thin water layer (6-15 mm in thickness) on soil surface. The inlet air was heated at a temperature as high as 200 °C, so that a quite low relative humidity (1.5 % to 3 %) and a high temperature (56 ± 4 °C) at the inlet of the chamber were obtained. Furthermore, photographs of soil cracks were taken every 90 min. The surface crack ratio defined as the ratio of the surface area of cracks to the total initial surface area can be then determined using the digital image processing technique (see Tang et al. 2008). Note that the water level was controlled at the initial location by regularly adding water to the tank and the quantity of water added was also recorded.

The evaporation rate was determined based on the change of absolute humidity at the inlet and outlet of chamber and the air flow rate, as follows:

\[
E = \frac{86400 (h_{\text{outlet}} - h_{\text{inlet}})}{Q} \left/ \rho_w \right. \left/ A \right.
\]

where \(E\) is the actual evaporation rate (mm/day), \(h_{\text{outlet}}\) is the absolute humidity of air flow at the outlet of chamber (Mg/m\(^3\)), \(h_{\text{inlet}}\) is the absolute humidity of air flow at the inlet of chamber (Mg/m\(^3\)), \(Q\) is the air flow rate through the chamber (L/s), \(\rho_w\) is the water density (Mg/m\(^3\)), and \(A\) is the evaporative surface area of soil in the chamber (m\(^2\)).

More details about this method can be found in the works of Mohamed et al. (2000), Aluwihare and Watanabe (2003) and Song et al. (2013, 2014).
Results and discussion

Figure 7 depicts the evolution of air flow rate versus elapsed time. The air supply unit provided compressed hot air at a rate as high as 155 L/min (average value) with a fluctuation of ± 5 L/min. The value remained at 153 L/min in the first 1.9 days, and then increased to 165 L/min and remained at this value until t = 30 days. Afterwards, it decreased to 150 L/min.

The evolution of wind speed measured by anemometer at 50-mm height is presented in Fig. 8. The high air flow rate resulted in a wind speed as high as 0.4 m/s (average value) in the chamber. Note that the fluctuation of wind speed was induced by changes of air flow rate in the laboratory air compression system.

The changes of air temperature at the inlet and outlet and in the laboratory are shown in Fig. 9. On the whole, the air temperature was relatively constant. The highest air temperature was for the inlet with a value as high as 56 ± 4 °C, whereas the value at the outlet was lower and was increasing during the test from 26.5 °C to 33 °C. The laboratory room temperature varied from 17 °C to 24.5 °C and was lower than those at the inlet and outlet.

Figure 10 shows changes in air temperature over time at various positions. The values varied between 22 °C and 32 °C, following the evolution of air temperature at the inlet of chamber. The lowest value was for the 50-mm height. Furthermore, the values
were quite similar in the zone above 50-mm height and they are therefore termed as
“other heights” in this figure. Note that only the values at 50, 170, 235, and 330-mm
heights were recorded.

The evolution of soil temperature is shown in Fig. 11. In general, the soil temperatures
fluctuated during the whole test period except a relative stable stage occurring in the
first 15 days. The highest temperature occurred at the soil surface; it remained around
21 °C during the first 15 days, and then significantly increased up to 29 °C at \( t = 29 \)
days. Afterwards, it varied between 26 °C and 31.1 °C until the end of test. For the
temperatures at deeper levels (50, 100, 150, 200 and 250-mm depths), the values were
very close and varied between 18 °C and 24 °C during the 83-day evaporation test
except the near stabilization stage with a value around 20.5 °C in the first 15 days.
This is probably due to a stable energy exchange between the energy for evaporation
and for heating the soil by hot air in this stage. Note that the values at 100, 150 and
200-mm depths are termed as “other depths” in this figure. Actually, all values of
temperature at different depths decreased in the first day; the lowest value occurred at
50-mm depth and the highest one at 250-mm depth. Afterwards, the values remained
stable until \( t = 15 \) days. Then, the values fluctuated over time and they decreased over
depth after \( t = 19.8 \) days, the highest value being at 50-mm depth while the lowest one
being at 250-mm depth. Note that the evolution of soil temperature followed the air
temperature changes, especially the changes of air temperature at the inlet.
All temperature data recorded are used to plot the air-soil temperature profiles (Fig. 12). Generally, the air temperature was significantly higher than the soil temperature and large temperature gradient was observed at the air-soil interface. For the air temperature, the elevations above 170-mm height presented similar values and a large temperature gradient was observed from 50-mm height to the soil surface. Regarding the soil temperature changes, at the beginning of evaporation, the temperature at the soil surface was the lowest value and the temperatures below the 50-mm depth were quite similar, around 20.8 °C. Furthermore, the soil temperatures in the zone below 50-mm depth showed a linear distribution over depth: the soil temperatures in this zone increased over depth before t = 16 days while the trend was inversed after this time. On the other hand, a large temperature gradient occurred between the soil surface and the 50-mm depth and it became larger and larger after t = 16 days. However, the temperature gradient below this depth was small. Beyond the phenomena listed above, the soil temperature also increased with the increase of air temperature, suggesting that the energy for evaporation was from the hot air and that part of the energy was used for heating soil and air. Moreover, the decrease of temperature gradient between 50-mm height and soil surface can be attributed to the increasing energy used for heating soil and air when the evaporation rate decreased. The enlarged temperature gradient between the soil surface and the 50-mm depth showed a deepening of the drying front, as observed in the sand evaporation test (Song et al. 2013, 2014). For the soil temperature evolution, the changes of soil temperature with air temperature changes were found larger in clay than in sand (see...
Song et al. 2014). This phenomenon may be attributed to the effect of desiccation cracks: cracks change the evaporation process from one-dimensional to three-dimensional situation, allowing the air condition to affect the soil temperature in deeper zones through them.

The changes of air relative humidity are shown in Fig. 13. The imposed relative humidity at the inlet was extremely low, ranging from 1.5 % to 3 %. The values at other locations were much higher and showed a decreasing trend: the values at the outlet and at 235-mm height decreased from 40 % to 11 %; the value at 50-mm height was the highest and varied from 13 % to 55 %. On the other hand, the relative humidity in the laboratory varied with a large fluctuation between 10 % and 50 %, and presented a quite different evolution pattern with respect to other positions. On the whole, the variations of relative humidity in the chamber (50, 235-mm depth and outlet) can be divided into three parts: (1) a decrease with quite low rate in the first 15 days; (2) a sharply decline until t = 28 days; and (3) a slow decrease followed by a stabilization at the end of test. More precisely, the relative humidity at 50-mm height declined slowly from 55 % to 41 % during the first 15 days, then significantly from 41 % to 19 % until t = 28 days, and finally reached a value as low as 13 % at the end of test. Furthermore, the value at 235-mm height was a little higher than that at the outlet in the first 16 days and then they became similar during the rest of time. Note that the similar three-stage evolution of air relative humidity inside the chamber was found in the sand evaporation test (Song et al. 2014) and clay evaporation test (Ta
This phenomenon can be attributed to the loss of water vapor from soil with the decreasing evaporation rate.

Figure 14 presents the evolutions of volumetric water content at different depths. It appears that the volumetric water content of soil depends on both time and location. Indeed, all values decreased over time: the value decreased from 62% to 11.6% at 25-mm depth, from 59% to 11.8% at 40-mm depth, from 57.3% to 20% at 55-mm depth, from 57% to 30% at 80-mm depth, from 57.6% to 36.8% at 130-mm depth, and from 59.2% to 42% at 230-mm depth. On the other hand, the deeper the location the later the initiation of water content decrease: the water content started to decrease at $t = 5$ days at 25-mm depth, at $t = 7$ days at 80-mm depth. In the deeper locations, it began to decrease at $t = 24$ days and $t = 50$ days at 130 and 230-mm depths, respectively. As far as the first 80-mm layer near the soil surface is concerned, a three-part evolution can be identified (at 25 and 40-mm depth): at the beginning, the volumetric water content remained at the initial value, and then sharply decreased from $t = 6$ days to $t = 50$ days. Afterwards, it decreased at a lower rate and reached the stabilization at the end of test. For the volumetric water content at other two locations, the values remained stable within the first 7 days, and then presented a constant decrease trend in the rest of time. Note that the difference of volumetric water content between these two locations became larger after $t = 25$ days.

The profiles of volumetric water content are shown in Fig. 15. The evolution of water
loss over depth can be clearly identified in this figure, as well as the influence depth of evaporation. In the beginning of test, the volumetric water content showed a uniform distribution over depth except in the near surface zone (55-mm depth). At the beginning of evaporation, the volumetric water contents in the zone below 55-mm depth were around 57.8% while the values above this position were a little higher due to the decrease of density during the previous saturation process. In the first 6 days, only little water loss was observed in the zone above 40-mm depth. Then, a large amount of water was lost in the zone of 130-mm depth. Furthermore, the decrease of water content in the zone of 55-mm depth became quite slow after \( t = 48 \) days while that in deeper zone became faster, indicating that water evaporation was mainly from the deeper levels after this time. Finally, the values of volumetric water content at 25 and 40-mm depths were around 12% and only the water content in the zone below 130-mm depth presented a clear decrease. Note that the final water contents at 25 and 40-mm depths were close to the initial water content after compaction (i.e., 10-11.8%). On the other hand, as in the evaporation tests on sand (Song et al. 2014), a linear relationship between water content and depth can be identified and this gradient developed progressively toward the deeper zones. For instance, the linear profile appeared in the first 55 mm depth zone from the beginning to \( t = 60 \) days; it was observed from the 40-mm depth to the 80-mm depth after this time. This gradient was also the maximum for the whole depth.

The evolutions of volumetric water content at various depths can be clearly evidenced
through the contour map (Fig. 16). On the whole, the lines with low water content values appeared later than with higher ones: the line with 60 % water content appeared at the initiation of evaporation; the line with 50 % water content at $t = 13.5$ days; the line with 30 % water content at $t = 26$ days and the line with 15 % water content at $t = 39$ days. Furthermore, the lines advanced toward deeper zones, indicating that water loss gradually deepened. On the other hand, the densely-distributed contour lines in the zone of 80-mm depth indicated a large water loss. In other words, water evaporation occurred mainly in this zone. The evolutions of volumetric water content at each depth can also be observed in this figure. For the water content at 25-mm depth, the value decreased to 60 % at $t = 6.4$ days; it declined to 50 % at $t = 13$ days, to 40 % at $t = 14.2$ days, to 30 % at $t = 26.3$ days and to 20 % at $t = 32.8$ days. Finally, it became lower than 15 % after $t = 39$ days.

Fig. 14 confirms that the dense installation of sensors in the near surface zone allows a good monitoring of volumetric water content, avoiding determining the water content by the destructive oven-drying method (e.g., Ta 2009). In general, the surface soil layer lost water firstly and the deeper zone started to lose water only by the end of test. Similar results were obtained in the sand evaporation test by Song et al. (2014).

Comparison between the case of Fontainebleau sand and the case of clayey soil in this study shows that the scenarios are quite different: for the clay, only the water content at 25-mm depth decreased quickly at the initiation of evaporation, and then at deeper locations. However, for sand, the entire zone from the surface to the 55-mm depth lost water quickly. This can be attributed to the higher water retention capacity and lower
Regarding the water content profiles (Fig. 15), the change of profile in the zone from the surface to the 55-mm depth at $t = 12$ days indicated a rapid decrease of water content and suggested a possible transition of evaporation mode from one-dimensional to three-dimensional: the water inside soil evaporates only from soil surface firstly, and then from both the crack walls and soil surface. Similar phenomenon was observed by Konrad and Ayad (1997) in a field experiment. Similar evolution of water content profile was also observed in their study. A linear relationship between water content and depth was observed in the near surface zone, and this linear relationship extended to deeper zone as also observed in the sand evaporation test by Song et al. (2014). This linear relationship was also observed by Ta (2009) through measuring the water content by oven-drying.

The evolutions of soil matric suction at different depths are presented in Fig. 17. All values at various locations were increasing with water loss: the deeper the location the lower the suction and the later the initiation of increase of suction. The soil matric suction at 15-mm depth increased quickly from 10 kPa at $t = 11$ days to 1000 kPa at $t = 15.3$ days. Similarly, the suction at 25-mm depth also sharply increased up to the maximum value of 1305 kPa at $t = 19$ days. However, the suction at 77-mm depth increased slowly from approximately 10 kPa at $t = 13.1$ days to 30 kPa at $t = 26$ days, and then it sharply increased up to the maximum value of 1074 kPa at $t = 29.5$ days.
As far as the 173-mm depth is concerned, the value reached 10 kPa until \( t = 22.3 \) days, and then it increased at a low rate up to 37 kPa at \( t = 55 \) days, and finally reached its top value of 369 kPa at \( t = 63 \) days. It is noted that the suction at 25-mm depth increased more quickly than that at 15-mm depth. This can be attributed to the shrinkage of soil body when undergoing evaporation. Actually, the tensiometer at 25-mm depth was installed at the edge of chamber and in contact with soil, but the one at 15-mm depth was inserted into the soil from the surface. Thus, during evaporation the soil lost water and shrank. As a result, the water evaporation from the edge of soil was quicker than inside the soil.

The profiles of soil suction are shown in Fig. 18 (without considering the data at 25-mm depth). It can be observed that the matric suction decreased over depth with the largest suction gradient when approaching the soil surface. The suction gradient from 15-mm to 77-mm depth increased sharply after \( t = 16 \) days, from 0.06 kPa/mm at \( t = 16 \) days to 20.8 kPa/mm at \( t = 19 \) days. This phenomenon corresponds to a large variation of volumetric water content during these days (see Fig. 15). Furthermore, the suction gradient between 77-mm depth and 173-mm depth became larger after \( t = 19 \) days, indicating a deepening of evaporation process and thus an acceleration of water loss in this zone. Note that the fact that the largest suction gradient being at the surface zone was also observed in the sand evaporation experiment (Song et al. 2013, 2014).
The simultaneous measurements of suction and volumetric water content at various depths allow the determination of the soil water retention curve, as shown in Fig. 19. It appears that the relationships between the water content and suction at 15-mm and 25-mm depths are quite different with those at other depths. This is probably due to the difference in soil density over depth which was strongly affected by the swelling during saturation process on one hand and the development of surface desiccation cracks on the other hand. Indeed, the surface desiccation cracks increased quickly when the suction was larger than 10 kPa which corresponds to a volumetric water content of 53%.

The actual evaporation rate determined following eq. (1) is plotted in Fig. 20. Three stages can be identified: a stage of constant value around 2.3 mm/day during the first 15 days (constant-rate stage); a stage of sharp decrease down to 0.5 mm/day at t = 45 days (falling-rate stage); and a stage of decrease at a quite low rate of 0.3 mm/day followed by stabilization (slow-rate stage). Note that the similar three-stage evolution of actual evaporation rate was observed in the evaporation test on clayey soil conducted by Yanful and Choo (1997).

Figure 21 presents the evolution of the surface crack ratio during evaporation. It is observed that the evolution of the surface crack ratio can also be divided into three stages as for the actual evaporation rate (Fig. 20) and the relative humidity inside the chamber (Fig.13): (1) an increase stage until t = 10 days with low values close to zero;
(2) an rapid increase stage from $t = 10$ days to $t = 25.5$ days and (3) a steady stage with a value around 25.3% until the end of test. Comparing the evolutions of actual evaporation rate and surface crack ratio, a clear phenomenon can be identified: with the development of cracks, more water can be evaporated, leading to or keeping in a high evaporation rate (the constant-rate stage). With further development of cracks, there is less water being evaporated, leading to a decrease of evaporation rate (the falling-rate stage). Finally, the evaporation rate reaches the slow-rate stage and the evolution of cracks approaches a steady state when the soil water content is extremely low. This is consistent with the observation of Li and Zhang (2011). Furthermore, it is worth noting that the characteristic days for surface crack ratio do not correspond to those for the actual evaporation rate, the evolution of actual evaporation curve lags behind that of the surface crack ratio curve, suggesting that cracks are not the only factors affecting the evaporation process. It is important to mention that the surface crack ratio is an important parameter in the evaporation analysis taking into account the effect of cracks (Cui et al. 2013). In Fig. 21, the corresponding photographs of surface cracks at different times during evaporation are also shown in this figure for better appreciating the evolution of surface crack ratio.

Direct measurements of the depths and widths of cracks were carried out using a ruler, and the results are presented in Fig. 22. It is observed that the largest crack of 32 mm was in the central part of the soil surface, and the deepest crack of 230 mm was at the edges. Moreover, at the edges, cracks presented limited width variations (15-20 mm).
but significant depth variations (170-230 mm). This represents the influence of the
chamber wall. There is no clear relationship between depth and width, their ratio
varying from 1.2 to 14.

Conclusions

A comprehensive laboratory experiment on water evaporation from a clayey soil was
investigated using a large scale environmental chamber, with controlled atmospheric
conditions and constant water table. The atmospheric parameters (wind speed, air
temperature, and relative humidity) and the response of soil parameters (soil
temperature, volumetric water content, matric suction and surface crack ratio) were
monitored. The following conclusions can be drawn:

The soil temperature is strongly affected by the air conditions, evaporation process
and desiccation cracks. The soil temperature varied with the variation of air
temperature. With the decrease of evaporation rate, more energy was available for
heating soil. The development of cracks increased the evaporating surface and
therefore enhanced the influence of air condition on the soil temperature.

An obvious temperature decrease was observed at three locations: 50-mm height, soil
surface and 50-mm depth. The soil temperature increased with the increase of air
temperature, suggesting that the energy for evaporation was from the hot air, and that
part of the energy was used for heating soil and air. The decrease of temperature
gradient between the 50-mm height and the soil surface is attributed to the increasing energy used for heating soil and air along with the decreasing evaporation rate. The enlarged temperature gradient between the soil surface and the 50-mm depth suggests a deepening of the drying front.

The air relative humidity decreased with the decreasing evaporation rate. Three stages were identified: (1) a decrease at a quite low rate; (2) a sharp decline stage; (3) a slow decrease followed by stabilization.

The dense installation of sensors in the near surface zone allowed a rich measurements of volumetric water content, avoiding determining the water content by the destructive oven-drying method. The surface soil layer lost water firstly and the deeper zone started to lose water by the end of test. The evolution of volumetric water content in the near surface zone was quite different from that for sand, to be attributed to the higher water retention capacity and lower permeability of this clayey soil.

The rapid change of volumetric content profile during the early stage of evaporation in the zone from the soil surface to 55-mm depth suggested a rapid decrease of water content and a transition of evaporation mode from one-dimensional to three-dimensional. The linear relationship between water content and depth was identified for the near surface zone, as opposed to the case of sand where the linear relationship was observed for much deeper zone. Furthermore, the large change of
water content in the near surface zone suggests that evaporation mainly affected this zone. Obviously, the development of cracks helped to the evaporation to be extended to deeper zone.

The soil matric suction was found to decrease over depth, and the suction gradient increased over time especially in the surface zone. The evolution of suction gradient is consistent with the volumetric water content changes.

The evolution of the surface crack ratio can be divided into three stages as for the actual evaporation rate: (1) a slow increase stage with values close to zero; (2) a rapid increase stage and (3) a steady stage. The evolution of actual evaporation curve lags behind that of the surface crack ratio curve, indicating that cracks are not the only factors affecting the evaporation process.

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<table>
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<th>Physical property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
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<tr>
<td>Plastic limit (%)</td>
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<tr>
<td>Liquid limit (%)</td>
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<tr>
<td>Plasticity index</td>
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<tr>
<td>Clay (&lt;2µm) content (%)</td>
<td>78</td>
</tr>
<tr>
<td>Blue methylene value</td>
<td>7.5</td>
</tr>
</tbody>
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