Water retention curves and tensile strength for studying desiccation cracking of compacted clay soils

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Abstract. Desiccation cracking is a natural phenomenon caused by drying in near-surface earth soils subjected to constrained shrinkage. In this research, the water retention curve of two clayey soils, prepared by compaction under standard proctor conditions, are determined to study the desiccation cracking. Two techniques of suction control are applied to control the drying process and to reach the water retention curve of the soils. For the suction values higher than 4 MPa, the saline-solution method was used to impose various relative humidity and so, various suctions. In addition, the osmotic method was applied for the suction values between 0.5 MPa and 2 MPa. Additionally, the dynamic vapor sorption (DVS) technique is used to corroborate the water retention curves obtained with the two other techniques. The volume changes is also tracked showing significant shrinkage upon drying. To reach the tensile strength of the soil, the Brazilian test is performed on samples prepared by compaction and submitted to various suctions. According to the results, for the two tested soils, the soil with the higher plasticity index shows consistently the higher retention capacity and the larger shrinkage upon drying. Also, the obtained water retention curves exhibit a smooth transition when the suction control technique change (at suctions between 2 and 4 MPa).

1 Introduction

Desiccation cracking is a natural phenomenon caused by drying in near-surface earth soils subjected to constrained shrinkage [1]. This phenomenon is more common in dry and partially dried regions. Extreme weather and climate change on a worldwide scale have exacerbated critical desiccation cracking concerns in recent years. In geotechnical engineering applications, the resulting creation of desiccation cracking networks changes soil properties and endangers soil structure integrity.

Clay has wide applications in geotechnical engineering such as buffer barriers in deep geological nuclear waste disposal, clay liners in landfill, and earthen slopes and embankments. However, most clay soils are more likely to crack as a result of extreme weather-induced moisture loss. Desiccation cracking in clayey soils is a complex phenomenon investigated by researchers over many decades. Cracking due to desiccation of the soil surface is a common occurrence associated with soil-atmosphere interaction. In fact, during dry seasons, there is an increase in soil suction in this area due to significant pore water evaporation close to the soil surface [2].

In order to study desiccation cracking, it is essential to investigate the soil water retention curve (WRC). For this purpose, it is required to control the drying process. Different experimental techniques for controlling suction were adopted. The method of controlling suction by imposing a particular relative humidity (saline-solution method) was considered for high suction values (4-110 MPa). The osmotic technique was used to lower suctions (0.5-2 MPa).

On the other hand, one of the other critical factors governing the cracking behavior of soil is the soil's tensile strength. From a macro-mechanical point of view, clay tensile strength is highly dependent on the water content and corresponding suction[3]. The tensile behavior of soil is important in a variety of engineering applications [4]. Understanding the formation and progression of soil cracks is a significant element in fields such as geological, geotechnical, and environmental engineering [5]. Tensile cracks in soil, induced by desiccation, are generally related to its hydraulic and mechanical characteristics [6]. Indeed, desiccation cracking occurs when the induced tensile stress or strain exceeds the capacity of the soil [7].

In this research, water retention curves and tensile strength of two compacted clayey soils are investigated to study the desiccation cracking.

2 Materials and methods

This research determines the water retention curve of two clayey soils, prepared by compaction under standard proctor conditions. Two techniques of suction control are applied to control the drying process and to deduce the water retention curve of the soils. The Brazilian Tensile test (called also the indirect tensile test) was considered to measure the tensile strength of the soils. Also, the dynamic vapor sorption (DVS)

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technique is used in this study to corroborate the water retention curve obtained from the two other techniques.

2.1 Soil

Two types of soil are considered in this study. Their geotechnical characteristics are reported in Table 1. All of the samples in this study were prepared by compaction under optimum standard proctor condition. The initial matric and total suctions under as-compacted conditions were measured according to the filter-paper technique [8].

Table 1. Soil geotechnical characteristics.

Soil name	Soignies	Kruibeke
Specific Gravity (g/cm3)	2.63	2.81
Liquid Limit (%)	36.4	56.0
Plastic Limit (%)	18.6	29.7
Plasticity Index (%)	17.8	26.3
Soil type (USCS standard)	CL (low plastic clay)	CH (high plastic clay)
Maximum Dry Unit Weight under standard proctor compaction (g/cm3)	1.72	1.45
Optimum Water Content under standard proctor compaction (%)	18	27
Initial Degree of Saturation under as-compacted state (%)	87	81
Initial matric suction (MPa)	0.36	1.5
Initial total suction (MPa)	0.88	2.5

According to particle size analysis results (Figure 1), Kruibeke soil contains 75% of silt and 4.45% of clay. On the other hand, Soignies soil contains 71% of silt and 14.6% of clay.

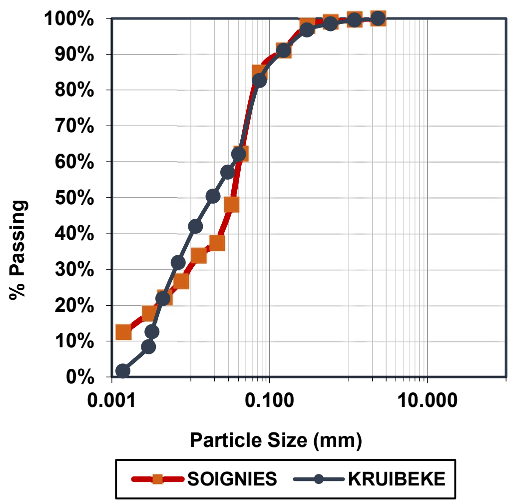

Fig. 1. Particle size distribution curves.

2.2 Suction control methods

In order to evaluate the water retention curve, it is required to control the drying process. For this purpose, suction control tests are performed. Two techniques of suction control are applied. For the suction values higher than 4 MPa, the saline-solution method was used to impose various relative humidity, leading to various suctions. Additionally, the osmotic method was performed for suction values between 0.5 MPa and 2 MPa. The samples used for the suction control experiment have dimensions of 33.2 mm in diameter and 7.6 mm in height.

2.2.1 Saline-solution method

The saline solution method involves adjusting the relative humidity of the air surrounding the sample. Samples are placed in a desiccator containing a saturated solution of a given salt. A specific relative humidity is imposed inside the desiccator in accordance with the physicochemical characteristics of the solution. Water exchanges take place between the solution and the sample via vapor transfer. When vapor equilibrium is reached, the sample is subjected to a specific suction. Since very high suctions can be applied in dry atmospheres, there is practically no upper limit to this technique [9].
The relationship between relative humidity and suction is given by the Kelvin law, as follows

$$s = \frac{RT}{Mg} \ln \frac{P}{P0} \qquad (1)$$

where s is the suction; R is the perfect gas constant (R=8.3143 J mol K^{-1}); T indicates the absolute temperature (T=293 K at 20°C); M stands for the molar mass of water (M=18.016 g mol^{-1}); g is the gravity acceleration (g=9.81 m s^{-2}); $P/P0$ is the relative humidity.

2.2.2 Osmotic method

In the osmotic method, the specimen is hermetically enclosed in a semi-permeable membrane that is permeable to water. The specimen and the membrane are immerged in an aqueous solution containing large-sized soluble polyethylene glycol molecules (PEG). Because the PEG molecules cannot pass through the membrane, an osmotic suction is applied to the specimen through the membrane [10]. PEG molecules come in a variety of sizes, which are defined by their molecular weight. PEG solutions with molecular weights of 6000 and 20000 g/mol are the most frequently used [9]. The PEG solution used in this research has molecular weights of 20000 g/mol. The suction value in the osmotic method is determined by the concentration of the solution; The suction increases as the concentration does. The following equation represents the relation between suction and concentration [9]:

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$$s=11c^2 \tag{2}$$

where s considers suction in MPa and c indicates concentration (g PEG per g water).

2.3 Brazilian tensile test

During desiccation, tensile cracking in the soil occurs when tensile stress overpasses tensile strength. Consequently, it is essential to study the soil tensile strength in cracking-related research. The Brazilian tensile test (also called the indirect tensile test) is considered in this study.

The Brazilian test is a convenient and indirect technique to measure the tensile strength of fragile materials including concrete and rocks [11]. According to ASTM D3967, the cylindrical specimen is placed in a specially designed cell that consists of two steel parts that are assembled together so that they make contact with the sample in two diametrically opposite sides [12]. The test involves applying a compressive load to a vertical cylindrical disk sample via two rigid and opposed platens. The expanding compressive load creates a perpendicular tensile stress between the two platens across the surface until the specimen fails [13]. According to the elastic theory, soil stress is considered to be constant along its diameter. The tensile strength can be measured by the following equation [14]

$$\sigma t = \frac{2P}{\pi D L} \tag{3}$$

Where σ_t is maximum tensile stress; P is the load at failure; D is the diameter of the sample, and L is the thickness of the sample.

Brazilian tests were applied to the soil samples under as-compacted conditions (i.e., just after compaction under standard proctor conditions) and also under various suctions ranging from 4 MPa to 110 MPa (applied through saline solution method). The sample's dimensions are 50.75 mm in diameter and 40.8 mm in height.

2.4 Dynamic vapor sorption (DVS)

Dynamic vapor sorption (DVS) measures the amount of a solvent absorbed by a sample as well as the rate of uptake. This gravimetric technique determines the changes in mass caused by varying the vapor concentration around the sample. Water sorption isotherms are measured by exposing a specimen to a series of increasing (and/or decreasing) relative humidity (or water activity) and evaluating the mass change as a function of time. The water retention curve is produced by recording equilibrium mass values at each humidity step (see www.carpor.uliege.be). In this research, the soil samples of both soils were analyzed by the DVS method. With this technique, the applied suction ranges from 14 MPa to 670 MPa.

3 Results

3.1 Saline solution technique

Two specimens of each soil were prepared for the suction values of 4.2, 14.5, 22.4, 38.7, 63.7, and 110 MPa, for a total of 24 samples (12 of each soil). Figure 2 shows the mass evolution, as a function of time. The corresponding suction value is written beside each graph.

3.2 Osmotic technique

Suction values ranging from 0.5 to 2 MPa were imposed on each soil. Two specimens per soil and per imposed suction are considered, for a total of 16 specimens (8 of each soil) were prepared. Figure 3 shows the mass evolution, as a function of time.

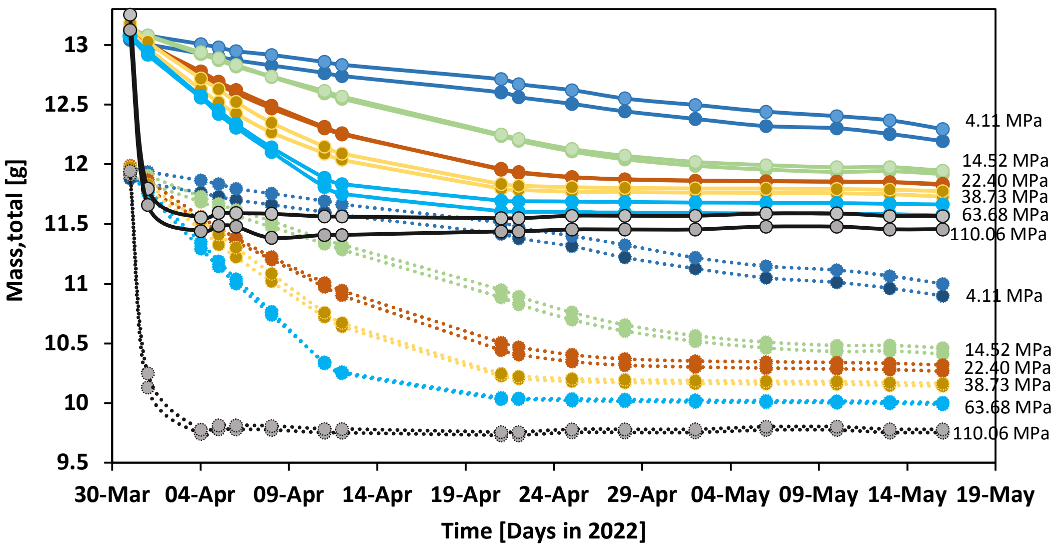

Fig. 2. Evolution of mass vs. time of specimen tested with the saline-solution technique (full line=Soignies, Dashed line = Kruibeke).

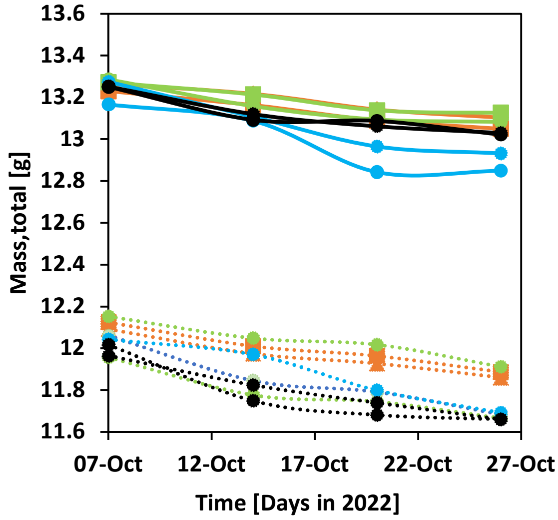

Fig. 3. Evolution of mass vs. time of specimen tested with the osmotic technique (full line=Soignies, Dashed line = Kruibeke; the lines with the color orange, green, blue, and black correspond to suction values of 0.5, 1, 1.5, 2 MPa, respectively).

3.3 Water retention curve

The water content corresponding to each suction is obtained from the suction control, tensile strength, and DVS techniques and reported in Figure 4. In order to study desiccation process, the water retention curve is plot for suctions equal and higher than the initial suction. The results are consistent between all the techniques as they fit each other very well.

3.4 Brazilian tensile test

Three specimens of each soil were tested under as-compacted conditions (i.e., immediately after the preparation of the specimens without applying any suction). The average value of tensile strength reached by the Brazilian method is 40.8, and 41.5 KPa for Soignies and Kruibeke soils, respectively. Figure 5 shows the tensile strength values for the specimens prepared under suction values ranging from 0 to 110 MPa. The Saline-solution method (section 2.2.1) was adopted to apply the suction to the samples. According to the results, by increasing the suction, the tensile strength of the samples is increased. Applying 4.2 MPa suction to the samples increased the tensile strength of Soignies by 395 % and Kruibeke by 573 % with respect to as-compacted conditions. Applying suction improved the tensile behavior of Kruibeke more, compared with Soignies.

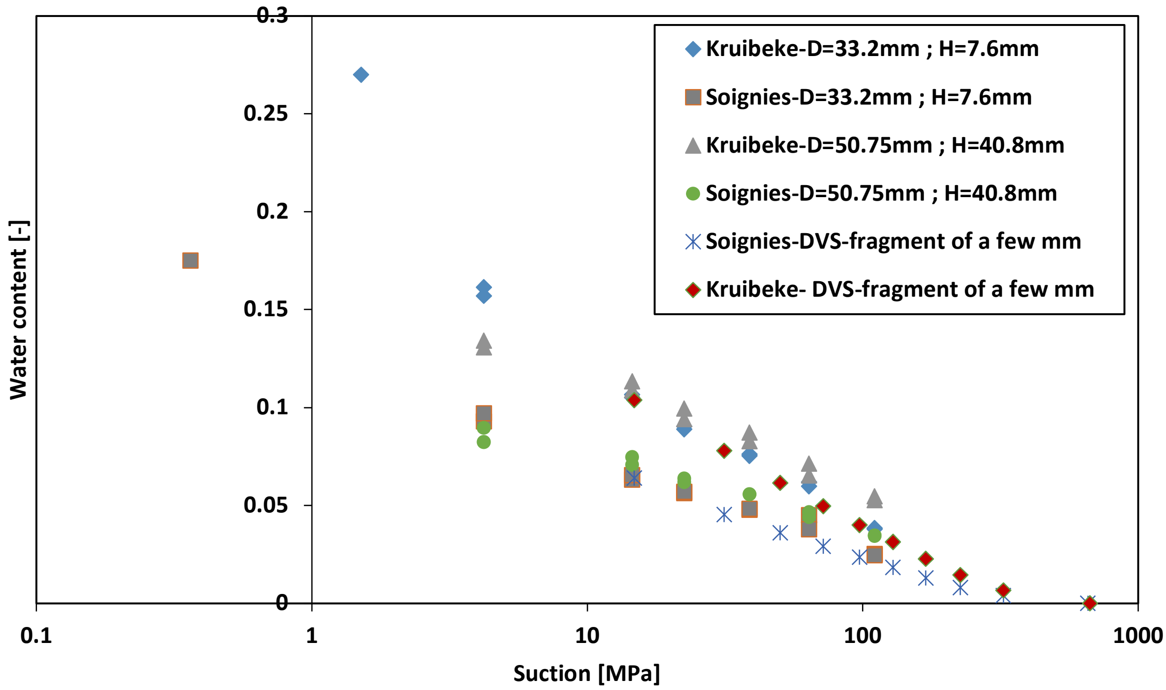

Fig. 4. Suction vs. water content, considering different techniques.

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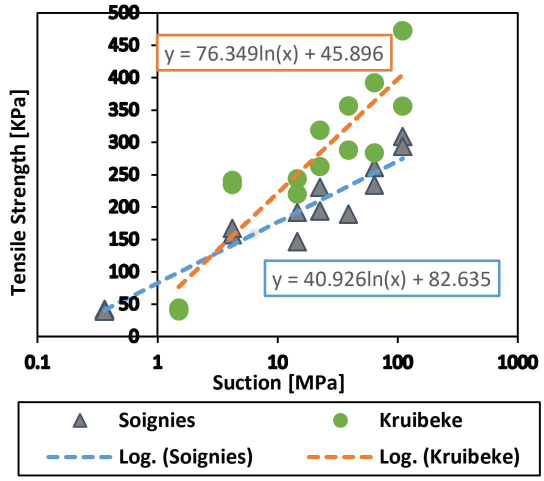

Fig. 5. Tensile strength vs suction.

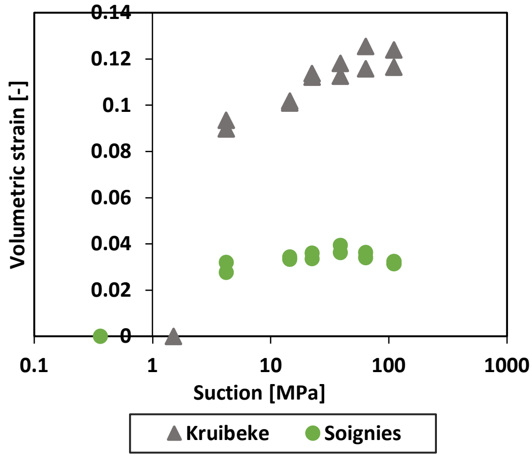

Fig. 6. Suction vs. volumetric strain, shrinkage (i.e., contraction strain) are considered as positive.

3.5 Volumetric deformation

At each suction imposed by the saline solution method, the size of the specimen was measured by a caliper. Only the bigger specimens (D= 50.75mm, H=40.8mm) dedicated to tensile tests provide accurate results because smaller specimen induces a too high relative error of the measurement. The volumetric strain corresponding to each suction value is investigated and reported in Figure 6. As the suction increases the volumetric strain increases.

4 Interpretation

As the degree of saturation of the soil is a function of the water content and volume variation, the water retention curve (degree of saturation vs suction) for the two soils is deduced from saline solution and osmotic methods. The shape of water retention curves can be calibrated by several models, one of them is the Van Genuchten model. The calibration model can obtain by the following equation [15].

$$S_r = [\ 1 + (s/P_r)^n]^{-(1-\frac{1}{n})} \quad (4)$$

where S_r is saturation degree; s is suction; n and Pr are two material parameters. By fitting the equation 4, based on these parameters, the best-fit parameters for the water retention curve can be calibrated (Table 2). The calibration by Van Genuchten method and logarithmic line is investigated in this study. The results are reported in Figure 7. Considering the water retention curve the results obtained by saline solution and osmotic methods are consistent with the Van Genuchten method and logarithmic line. The points at 0.5 MPa and 1 MPa for Kruibeke soil are probably slightly erroneous due to the degradation of the specimen (loss of solid particles) during suction control with the osmotic technique.

Table 2. Parameters of Van Genuchten model.

	P_r	n
Soignies	0.154	1.230
Kruibeke	0.603	1.274

The void ratio corresponding to each suction value is investigated and reported in Figure 8. As the suction increases the void ratio decreases.

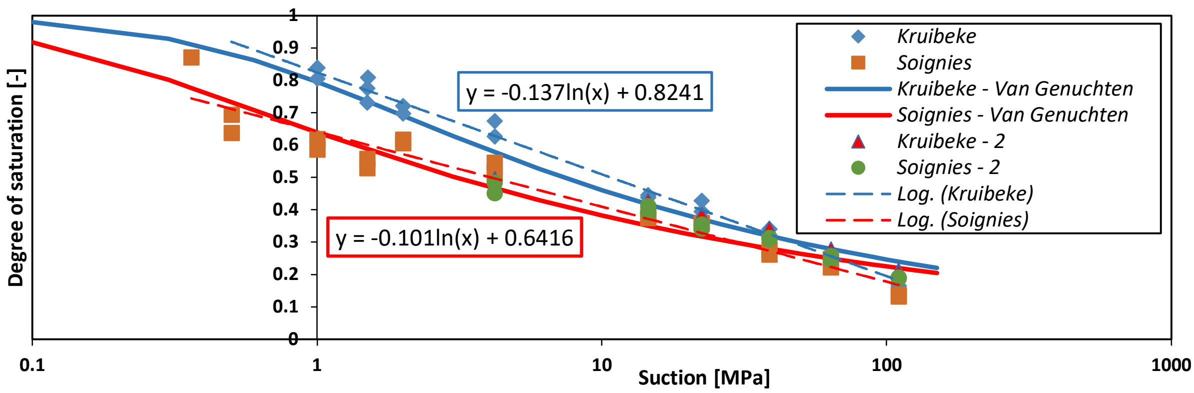

Fig. 7. Soil water retention curve.

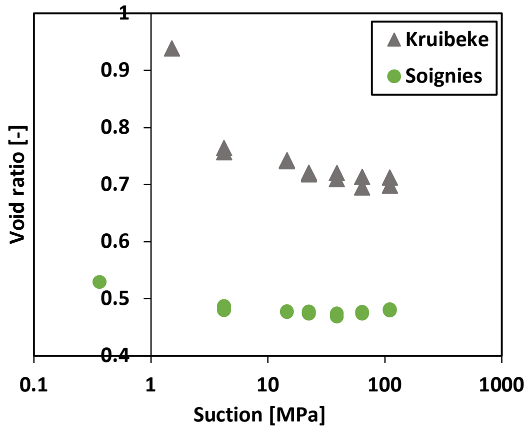

Fig. 8. Suction vs. void ratio.

5 Conclusion

According to the results, for the two tested soils, the retention capacity (i.e., the degree of saturation for a given suction) is consistently higher for the soil with the higher plasticity index. Also, the obtained water retention curves exhibit a smooth transition when the suction control technique change (at suctions between 2 and 4 MPa). The tensile strength evolution as a function of the suction is analyzed. The tensile strength is significantly improved during drying and the effect is more marked for the soil with the higher plasticity index. As a perspective, those results will be integrated in a hydro-mechanical numerical computation (through the finite element method) of a strain-constrained drying test to predict the occurrence of desiccation cracking.

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