Soil-water characteristics curve of geosynthetic clay liners: effects of temperature and void ratio

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ABSTRACT: Geosynthetic clay liners (GCLs) are widely used as hydraulic or chemical barrier systems in geoenvironmental and hydraulic engineering. Despite the importance of maintaining GCLs in a hydrated condition for best performance, GCLs commonly operate under unsaturated conditions. Hence, knowledge of the soil water characteristic curve (SWCC) is important to describe the relationship between suction and water content. Despite previous efforts, a gap in our knowledge of the effect of temperature and void ratio on the SWCC of GCLs remains. The importance of void ratio emanates from the expansive nature of bentonite clay which leads to swelling or shrinkage of GCLs when hydrated or dehydrated. In this paper, we report an experimental investigation of the effects of temperature and void ratio on the SWCC of a GCL. We conduct a set of suction measurements, at different water contents, using Barcelona cells and Decagon's Vapour Sorption Analyser based on axis-translation technique and dew point technique, respectively. Results are presented and a preliminary relationship describing the effects of temperature and void ratio on SWCCs of GCLs is proposed.

Keywords: Void ratio and temperature-dependent SWCC, GCL, axis-translation, dew point method

1 INTRODUCTION

SWCCs define the relationship between suction and water content in a porous medium. The SWCC of GCLs are important in understanding the performance of composite lining systems. Widely used empirical equations for the SWCC (van Genuchten, 1980, Fredlund and Xing, 1994) were developed to fit measurements obtained under constant vertical stress and constant temperature. It has been shown that the SWCC relationship may change under different temperatures and/or void ratios (e.g. Romero et al., 2001; Khalili et al., 2008). Therefore, it is important to consider these effects on the SWCC of GCLs because GCLs experience relatively large void ratio change as a result of change in suction and load. In addition, composite lining systems used for basal protection are exposed to considerable temperature elevation. Despite a number of published experiments on the SWCCs of GCLs, our understanding of the effects of change in temperature and void ratio on the water retention capacity of GCLs remains incomplete.

2 THEORY

The effect of void ratio and temperature on the water retention properties of clay is an active field of research. Various methods for quantifying the effect of void ratio on the degree of saturation under different suctions, based on different theoretical conceptualizations of the coupling between mechanical and hydraulic behavior of clay, have been recently proposed in the literature (Khalili et al., 2008; Casini et al., 2011; Sheng and Zhou, 2011). However, no consensus has yet emerged about the best theoretical approach to the problem.

Gallipoli (2012) developed an empirical model based on van Genuchten's (1980) SWCC equation, which incorporates the effect of change in void ratio on the SWCC of deformable media. In the model of

Gallipoli (2012), the effect of void ratio is included through a modification of the air-entry parameter, now expressed as a power function of the void ratio. This method has been used in other SWCC equations such as that proposed by Russell (2014), where the SWCC is explicitly expressed in terms of the air-entry value. The effect of temperature, but under non-deformable conditions, was considered by Grant and Salehzadeh (1996) who combined a chemical-thermodynamic model based on the theory of Philip and de Vries (1957) with van Genuchten's (1980) SWCC equation.

Ghavam-Nasiri and El-Zein (2017) proposed a void ratio and temperature-dependent SWCC by implementing the combined theories of Grant and Salehzadeh (1996) and Gallipoli (2012) in van Genuchten's (1980) SWCC as follows:

$$S_e = \frac{S_r - S_{rs}}{S_s - S_{rs}} = \left(1 + \left(\frac{s}{P_0 \frac{\sigma}{\sigma_0} \left(\frac{e}{e_{ref}}\right)^{-\beta_e}}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda} \tag{1}$$

where:

S_e = effective degree of saturation
S_r = degree of saturation
S_s = maximum degree of saturation, S_s is assumed to be 1.0 in this paper.
S_{rs} = residual degree of saturation
P_0 = model parameter at reference temperature, T_0, and void ratio, e_{ref}
σ = surface tension, N/m
σ_0 = surface tension at reference temperature, it is 0.0727 N/m at 20°C
λ = model parameter
e_{ref} = reference void ratio
β_e = model parameter

and s is matric suction defined as:

$$s = P_g - P_l \tag{2}$$

where:

P_g = gas pressure, kPa
P_l = liquid pressure, kPa

The model parameter P_0 refers to a reference curve with a reference void ratio of e_{ref} and a reference surface tension of σ_0. Therefore, the value of P_0 is comparable to the original definition of the model parameter P. The reference surface tension is calculated for the reference temperature (i.e. 20°C in this study). In addition, the reference void ratio is either the void ratio at which the SWCC is measured under a constant void ratio test or, in the case of measurements in this study, a representative void ratio obtained from the measurements with constant load and variable void ratio. For more details about the derivation of the SWCC equation and constitutive equations used, the reader is referred to Ghavam-Nasiri and El-Zein (2017).

3 MATERIAL

The GCL under study is made of powdered Na-bentonite and polypropylene geotextiles with nonwoven and woven carrier and nonwoven cover configuration. In addition, it is reinforced by needle-punching of fibres that are thermally treated (ELCOSEAL geosynthetic clay liner grade X2000 manufactured by GEOFABRICS Australia). Table 1 shows properties of the GCL provided by the manufacturer.

4 EXPERIMENTAL PROGRAM

Two different methods were used to cover a wide range of suctions. SWCC tests based on the axis-translation method were performed for matric suctions from 0 to 700 kPa on the drying path, using pneumatic suction-controlled oedometers (Barcelona Cells). In addition, the dew point method was used for measurement of total suctions from 100 to 10 MPa and 30 to 250MPa on the wetting and drying paths, respectively, using a Vapor Sorption Analyzer (VSA) (Decagon Devices Inc., Pullman, WA, USA).

Table 1. Properties of the GCL reported by manufacturer. Typical values are presented

Property	Test method	Unit	
Configuration (Carrier/Cover)		-	W+NW/NW
k_s	ASTM D5887	m/s	1.6×10^{-11}
$M_{GCL\ @\ w=0\%}$	ASTM D5993	g/m^2	4960
$M_{Bentonite\ @\ w=0\%}$	ASTM D5993	g/m^2	4250
M_{cover}	AS 3706.1	g/m^2	300
M_{carrier}	AS 3706.1	g/m^2	410
Bentonite swell index	ASTM D5890	mL/2g	≥24

W: Woven; NW: Nonwoven; The typical values are the arithmetic mean of the measured values.

Moreover, SWCC measurements conducted on the same type of GCL using the vapour equilibrium technique (VET) by Rouf et al. (2016) were incorporated in the analyses. These measurements have been conducted for a range of total suctions between 3 and 350 MPa on both drying and wetting paths (Rouf et al., 2016).

All experiments were performed under temperature-controlled conditions. The axis-translation and VSA experiments were conducted under 20 and 35°C. Additional experiments at 40 and 60°C were also performed using axis-translation and VSA, respectively. The VET tests were obtained at 20°C. Moreover, a constant net vertical stress was applied to the samples for axis-translation (10, 20, and 50 kPa) and VET (<1 and 20kPa) experiments. A summary of the experiments performed are presented in Table 2.

Cutting dies made of steel were used to minimize bentonite loss when cutting GCL samples. Samples from the GCL sheets were cut at the as-received moisture content. The masses of the samples were measured and then samples were sealed in double plastic zip bags and stored in air-tight containers. For SWCC tests using the axis-translation method, a hydration setup was used to hydrate GCL samples under specific loads, which allowed volume changes to be measured during hydration without disturbing the sample. It included a hydration ring with a diameter of 50mm and height of 20mm made of stainless steel, two porous stones for top and bottom of sample, a hydration mould, a dial gauge, and a load hanger. Hydration of a sample inside a stainless steel ring is very important because the hydration ring permits only one dimensional deformation of the GCL during hydration. In addition, the ring prevented bentonite loss and maintained the circular shape of the samples during hydration.

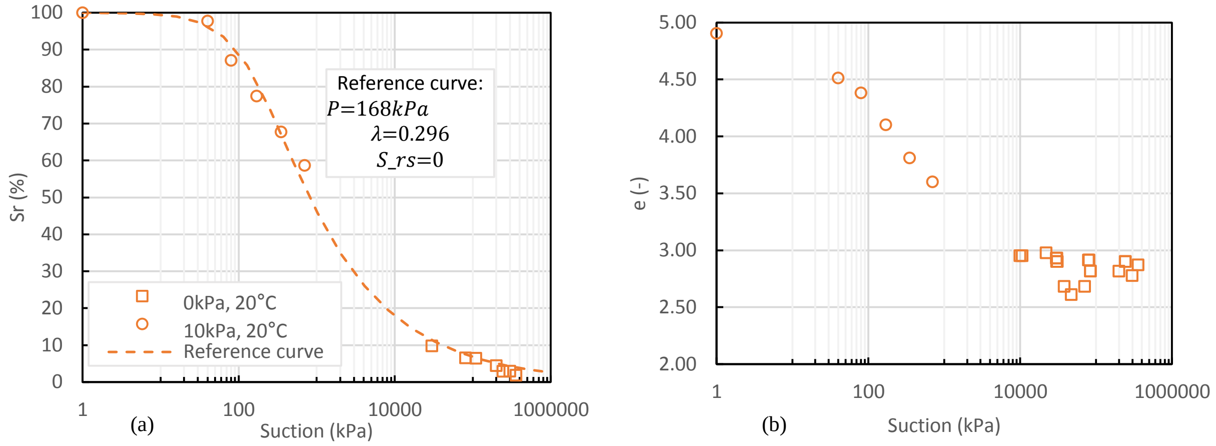
Table 2. Experimental program

Test method	Net vertical stress (kPa)	Temperature (°C)	Suction	Matric/Total suction	Path
Axis-translation	10, 20, 50	20, 35, 40	0 to 700kPa	Matric	Drying
VSA	0	20, 35, 60	100 to 10MPa	Total	Wetting
VSA	0	20, 35, 60	30 to 250 MPa	Total	Drying
VET (Rouf et al. 2016)	0, 20	20	3 to 70MPa	Total	Wetting
VET (Rouf et al. 2016)	0, 20	20	110 to 360MPa	Total	Drying

5 RESULTS

Ideally, the effect of void ratio in the SWCC equation should be quantified by conducting SWCC measurements with void ratios held constant during each experiment, and repeated at different void ratios at the same temperature. However, the swelling/shrinkage of the GCL's bentonite that accompanies hydration/dehydration during SWCC measurements does not allow void ratio to be kept constant. Therefore, the calibration of the equation to experimental data is conducted based on available experimental points in the *Sr-s-e-T* space. Only drying curves were studied in the fitting exercises presented in this paper.

As described earlier, a reference curve, at a reference void ratio, needs to be established first. In theory, there is no constraint on the selection of the reference curve, including the use of an imaginary representative reference curve, since the solution for this problem is not unique. Clearly, using different reference curves results in different P_0 and e_{ref} which may lead to different solutions for β_e and λ. However, in this section, the sets of data corresponding to experiments under temperature of 20℃ and loads of 0 and 10kPa were selected for determination of the reference curve (Figure 1). This is because the number of data points available on this curve is large, covering the broadest range of suctions in the data along the drying path. A good fit was obtained for the reference curve using the least-squares method. Fitting parameters for the void ratio and temperature-dependent SWCC (Eq. 1) are given in Table 3.



(a) (b)

Figure 1. Reference curve: a) Degree of saturation vs suction; b) void ratio vs suction

Table 3. Fitting parameters for the SWCC (Eq. 1)

P_0 (kPa)	λ (-)	β_e (-)	e_{ref} (-)	σ_0 (N/m)	S_s (-)	S_{rs} (-)
168	0.333	1.46	4.46	0.0727	1.0	0.0

Figure 2 shows comparisons of predictions and experimental measurements of degrees of saturation for experiments under 20 and 35℃, subjected to different net vertical stresses. Predictions were good for the dry end of the curves (i.e., suctions higher than 10MPa). In addition, predictions matched experimental data for the wet side of the curves under 20℃. However, the SWCC overestimates the degrees of saturation on the wet side of the curves, under 35℃ temperature, and for net vertical stresses of 20 and 50kPa (Figure 2d and 2f).

To evaluate the effect of elevation of temperature on the SWCC along the drying path, two main factors can be considered among others (Zhou et al., 2014): 1) reduction of surface tension of water; 2) softening of the soil. The former factor results in a lower retention capacity in terms of both degrees of saturation and gravimetric water content because lower surface tension reduces capillary pressure and the capacity of the soil to hold water (Grant and Salehzadeh, 1996). However, softening can result in a lower void ratio (Campanella and Mitchell, 1968) which can lead to two counter-acting processes: 1) increasing capillary pressure because of smaller pore sizes (Khalili et al., 2008; Gallipoli, 2012); 2) squeezing water out and reducing the total amount of water. In addition, other factors such as change in pore water chemistry and the differential thermal expansion of the three phases may be influential (Romero et al., 2001).

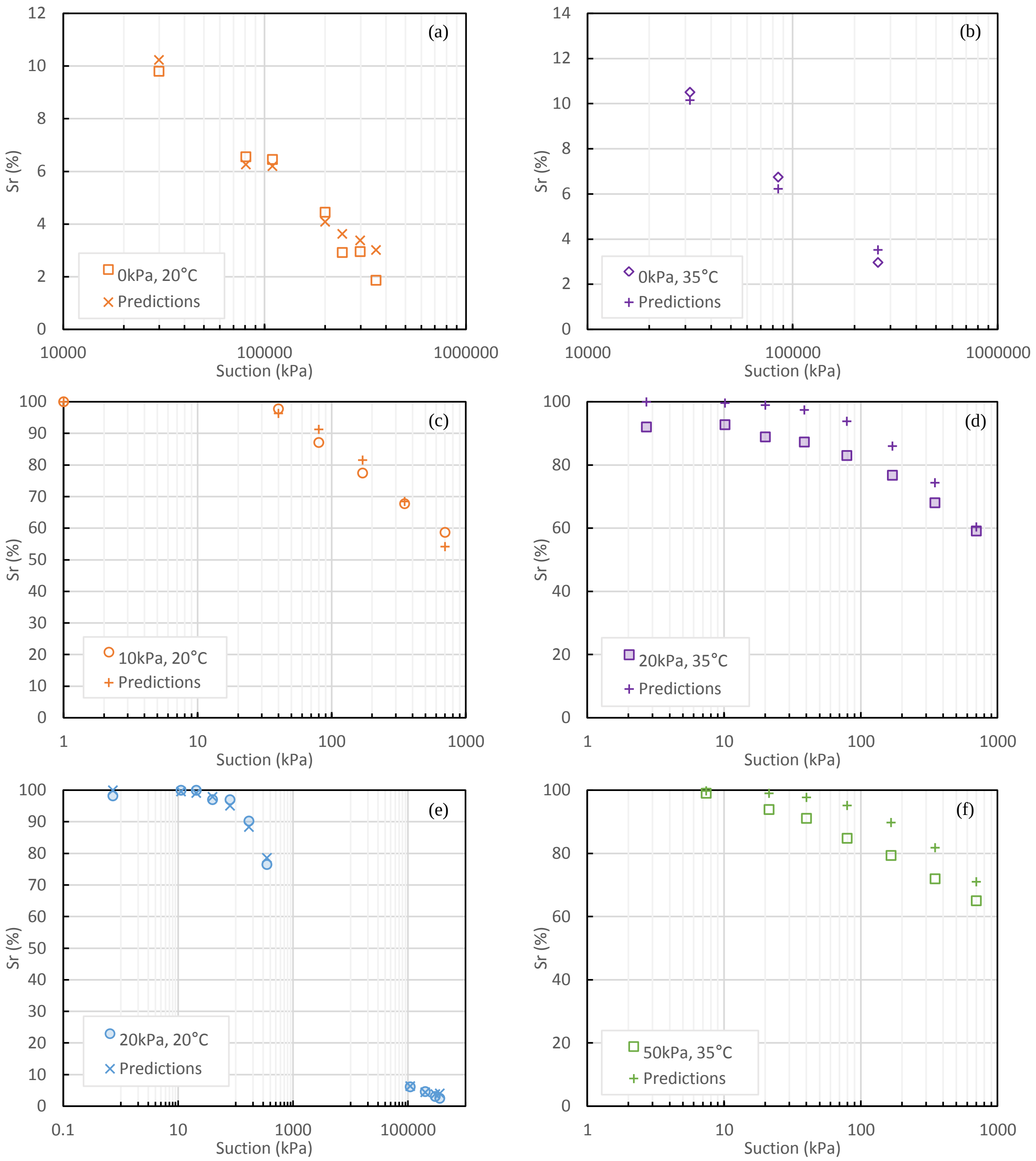


Figure 2. Predictions of degree of saturation based on the void ratio and temperature-dependent SWCC (Eq. 1)

6 CONCLUSIONS

The proposed SWCC by Ghavam-Nasiri and El-Zein (2017) performed well in predicting the effects of void ratio on SWCC based on the available data. It was found that the air-entry value increases as the net vertical stress increases for the experiments under the same temperature. Incorporating the effect of void ratio led to an improvement in fitting the SWCC data to estimated curves for the GCL used in this study. Note, however, that given the empirical nature of the approach, its ability to capture hysteresis and its applicability to other GCLs remains to be seen. On the other hand, the SWCC underestimated the effects of temperature, especially on the wet side of the curves. Therefore, it seems that a model based solely on the change of surface tension with temperature is not sufficient for predicting the effect of temperature on the SWCC of the GCLs studied here, and other mechanisms may be involved, such as changes in pore fluid chemistry as a result of increases in temperature.

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