TECHNICAL NOTE

Applicability and accuracy of the initially dry and initially wet contact filter paper tests for matric suction measurement of geosynthetic clay liners

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An initially wet contact filter paper test (IW-CFPT) and an initially dry contact filter paper test (ID-CFPT) were used to examine the wetting paths of geosynthetic clay liners, including non-contact filter paper tests for comparative purposes. The CFPTs were applied to both geosynthetic clay liner faces to examine the effect of geotextile type on capillary contact. The non-woven geotextile face was found to be more likely to cause capillary breaks than the woven geotextile face. Both IW- and ID-CFPTs were found to be applicable to geosynthetic clay liners within their accurate upper matric suction measurement limits of 146 kPa and 66 kPa, respectively.

KEYWORDS: geosynthetics; geotextiles; laboratory tests; suction; time dependence

INTRODUCTION

The primary function of bentonite within a geosynthetic clay liner (GCL) is to create impedance to the flow of migrating liquids, dissolved chemical species and gases or vapours (Bouazza, 2002; Rowe, 2005). This is achieved by the very low permeability of bentonite when fully hydrated after GCL placement, from the underlying or overlying soil (Gates *et al.*, 2009; Bouazza & Bowders, 2010). When in service, GCLs are often subjected to variable hydration states during initial hydration and thermal cycling, since they are typically manufactured at a low moisture content, yet should be hydrated to >100% moisture content to function adequately as a barrier to fluids, and may be exposed to thermal cycles or elevated temperatures (Rowe & Hoor, 2009; Hornsey *et al.*, 2010; Bouazza *et al.*, 2011, 2013, 2014). Hence, understanding the water retention behaviour of hydrating GCLs is essential to ensure their long-term longevity as hydraulic barriers under adverse conditions.

A limited number of studies have been carried out over the last decade on the water retention behaviour of GCLs using different suction measurement techniques (Abuel-Naga & Bouazza, 2010; Beddoe *et al.*, 2010, 2011; Bannour *et al.*, 2014; Rouf *et al.*, 2014). Among these techniques, the contact filter paper test (CFPT) is attractive owing to its simplicity and accessibility, but has been used with limited success, primarily related to the accuracy of the suction measurements (Barroso *et al.*, 2006; Acikel *et al.*, 2011). Therefore, a test programme based on the use of initially wet and dry contact filter paper tests (IW-CFPT, ID-CFPT), as well as a non-contact filter paper test (NCFPT) as a reference, was conducted to better adapt the filter paper technique to matric suction measurement of GCLs. IW-CFPT and ID-CFPT tests were performed to evaluate the effect of capillary contact and hysteresis on matric suction measurements. Test

times of 1 week and 4 weeks were used to investigate the effect of suction equilibrium time on matric suction by IW-CFPT. Standard 1-week ID-CFPT and NCFPTs were conducted as reference tests. All contact tests were applied to both the non-woven cover and woven carrier geotextile faces of the GCLs to investigate the impact of different geotextiles on the capillary contact condition between GCL and filter paper. Filter paper pore size distributions, obtained from scanning electron microscopy (SEM) imaging, provided a sound basis for discussing the results.

Background

Most filter paper calibration curves (Fawcett & Collis-George, 1967; Greacen *et al.*, 1987; Chandler *et al.*, 1992a, 1992b; Crilly & Chandler, 1993; Leong *et al.*, 2002; ASTM, 2010) follow a piecewise defined function considered to be a composite of two functions with a break point at their intersection. Table 1 shows the gravimetric water content of filter papers and corresponding suction values at the break points of the most common filter paper calibration equations recommended for Whatman no. 42 filter paper.

The wetting solid–liquid contact angles of solid–liquid–gas interfaces are considerably larger than their respective drying contact angles, resulting in contact angle hysteresis (Lu & Likos, 2004). Liukkonen (1997) investigated the wetting properties of paper components by measuring the contact angles of water drops on sample surfaces and by observing microscopic drops in an environmental scanning electron microscope (ESEM). Liukkonen (1997) reported that holocellulose and α -cellulose components of dry paper had initial contact angles of, respectively, 56° and 26°, but both decreased to 0° with wetting. A contact angle equal to 0 is described as a perfectly wetting material (Lu & Likos, 2004) or hydrophilic material in the context of geotextiles (Bouazza, 2014).

Lu & Likos (2004) and Fredlund (2006) described the different saturation zones of a typical water retention curve (WRC) as the boundary effect (capillary fringe) zone, transition (capillary) zone and residual (pendular) zone. Water transfer within the boundary effect zone can occur in the liquid phase, while in the transition zone it can be both

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Table 1. Water content and corresponding suction values of the break points of Whatman no. 42 filter paper calibration equations

Water content: %	Suction: kPa	Calibration
45.3	66.3	ASTM D 5298 (ASTM, 2010)
45.3	63.1	Fawcett & Collis-George (1967)
45.3	63.3	Greacen <i>et al.</i> (1987)
47	80.0	Chandler <i>et al.</i> (1992a; 1992b)
47	82.5	Crilly & Chandler (1993)
47	68.0	Leong <i>et al.</i> (2002)

liquid and vapour phase, but transfer in the residual zone can only be in the vapour phase. Liquid water transfer relies on connected capillarity whereas vapour transfer relies on open pores.

The 'entry' or 'bubbling' pressure of porous media is the threshold pressure for displacement between wetting and non-wetting fluids (Bear, 1972). In the wetting and drying paths under study, the air entry value of a drying curve is the threshold pressure where water is initially replaced by air. Likewise, the water entry value of a wetting curve is the threshold pressure at which air is initially replaced by water (Wang *et al.*, 2000). The suction value between transition and residual zones on the drying curve is defined by residual pressure.

MATERIALS AND METHODOLOGY

Materials

Whatman no. 42 filter papers and a granular bentonite based GCL were used. The needle-punched GCL (Table 2) was composed of a layer of bentonite sandwiched between a woven carrier and a non-woven cover geotextile, with the system being held together by needle punching.

Methods

Filter paper test. Geosynthetic clay liner specimens were cut at off-roll water contents using a hydraulic press and a sharp stainless steel cutter. The specimens were glued into polyvinyl chloride (PVC) rings (20 mm high, 50 mm internal diameter). They were then hydrated using sterile distilled water to targeted gravimetric water contents. The hydrated specimens were sealed and stored at a constant temperature of 22°C under a 1 kPa confining stress for 6 weeks to reach hydration equilibrium throughout the specimen. The ID-CFPT, IW-CFPT and NCFPT procedures were performed on the homogenised specimens. A strict sterilisation procedure (consisting of bleaching and ethanol flash-flaming the testing surfaces and tools, and flaming the surrounding air with a Bunsen burner, as well as using sterile disposable gloves and masks) was followed to minimise any microorganism growth in the system during the tests. Sterile distilled water was used to hydrate the GCL specimens.

Figure 1 shows the IW-CFPT procedure. A stack of three filter papers (50 mm protector–42.5 mm sensor–50 mm protector) were placed on both the cover and carrier geotextile faces of the specimens. The sensor filter papers were soaked in sterile distilled water for 1 h before being used for the IW-CFPT. The only difference between the ID-CFPT and IW-CFPT procedures was the initial gravimetric water content condition of the inner (sensor) filter paper, which was placed between two dry outer (protector) filter papers. In the ID-CFPT the sensor filter paper was dry, whereas in the IW-CFPT the sensor filter paper was saturated. A 1 kPa contact pressure was applied. For the NCFPT, capillary contact was not required, and therefore the filter papers (42 cm diameter and oven dried) were used only on the non-woven geotextile side with O-ring separators to prevent contact between GCL and dry

Table 2. Technical properties of the GCL used in the present investigation

<i>Mass per unit area: g/m²</i>	
GCL	
Measured	4698
MARV*	4000
Bentonite	
Calculated	4273
MARV*	3600
Carrier geotextile	
Measured	126
Cover geotextile	
Measured	299
Bentonite	
Particle type	Granular
Montmorillonite (XRD test results)†	82%
Initial (off-roll) gravimetric water content	12%
Liquid limit (ASTM D 4318 (ASTM, 2000))	370%
Plastic limit (ASTM D 4318 (ASTM, 2000))	36%
Swell index‡: ml/2 g (ASTM D 5890 (ASTM, 2011))	22
Hydraulic conductivity§: m/s (ASTM D 5887 (ASTM, 2009a))	5×10^{-11}
Structure	
Configuration (carrier/cover)	W/NW
Bonding	NP
Peel strength: N/m (ASTM D 6496 (ASTM, 2009b))	1247
Thermally treated	No

*MARV: minimum average roll value (from producer); SRNW: scrim-reinforced non-woven; W: woven, NW: non-woven; NP: needle-punched.

†XRD tests conducted at CSIRO Land and Water, Mineralogical Services, Adelaide laboratory.

‡Tests were performed on the bentonite specimens extracted from GCLs. Some inevitable remaining fibres might decrease the swell index values.

§Max. values as provided by the manufacturers.

||Tests were performed by Geofabrics Australasia, Geosynthetic Centre of Excellence, Queensland.

Fig. 1. Initially wet contact filter paper test (IW-CFPT) procedures

protector filter papers (Fig. 2). The specimens were then sealed and kept at a constant temperature of 22°C during the tests (1 and 4 weeks for IW-CFPT; 1 week for ID-CFPT and NCFPT).

SEM analysis of Whatman no. 42 filter paper. The filter papers were oven dried at 105°C overnight. The oven-dried specimens were coated with a very thin layer of iridium to avoid charging during SEM imaging. Then, the pore

Fig. 2. Non-contact filter paper test (NCFPT) procedures

sizes were measured from six SEM images by hand. Fig. 3 shows one of the SEM images where the pore sizes were measured.

A distribution analysis was performed on the measured pore size values. Pore sizes larger than 8 μm were not taken into consideration for pore size distribution analysis since very few pores exist at this range. The counts of the pore sizes measured from SEM images were extrapolated for a 1 mm^2 area. Fig. 4 shows a histogram for the pore size distribution of Whatman no. 42 filter paper. In the filter paper pore size range of 0.5–8 μm , the pores explicitly had a dominant size of 2 μm .

TEST RESULTS AND DISCUSSION

Geosynthetic clay liner wetting path suction measurement test results calculated using calibration equations recommended by ASTM-D5298 (ASTM, 2010) (Table 3) are presented in Fig. 5. The 1-week ID-CFPT and IW-CFPT gave comparable results for suction values $\sim < 70$ kPa; however, suction values of the ID-CFPT were significantly

higher compared to those of the IW-CFPT for the suction range ≥ 70 kPa. The ID-CFPT results eventually merged with the NCFPT with the increase of the suction values. For the suction range ≤ 100 kPa, the 4-week IW-CFPT gave slightly smaller suction values than the 1-week test. The suction results of CFPT obtained from the cover (non-woven) were greater than those obtained from the carrier (woven) geotextile.

The wetting path matric suction results of CFPTs are compared with wetting and drying path matric suction results reported by Beddoe *et al.* (2011) for the same GCL using a high-capacity tensiometer (HCT) in Fig. 6. The results of 4-week IW-CFPT applied on the carrier (woven) geotextile are highly comparable with the wetting path results of HCT. Compared to the tensiometer results, the ID-CFPT overestimated the matric suction at values > 70 kPa.

Capillary rise in an ideal cylindrical tube is defined by the Young–Laplace equation, which can be expressed as

$$\Delta p = \frac{4\gamma \cos \theta}{D} \quad (1)$$

where Δp is capillary pressure, γ is surface tension, θ is contact angle and D is the average effective diameter of pores. The surface tension of water at 22°C is 7.2×10^{-2} N/m.

The contact angles reported by Liukkonen (1997) were substituted in equation (1) to calculate capillary pressures of Whatman no. 42 filter paper for the particle retention values of the filter paper (2.5 μm) reported by the manufacturer as well as the peak pore size (2 μm) obtained from the SEM images (Table 4).

Different calibrations of Whatman no. 42 for drying and wetting paths (modified from Munoz-Castelblanco *et al.* (2012)), drying/wetting path hysteresis, as well as two break points are shown in Fig. 7(a). Fig. 7(b) was generalised from Fig. 7(a) as a conceptual WRC model for filter paper wetting and drying paths assuming filter paper had similar water retention behaviour as soils. According to this conceptual

Fig. 3. One of the SEM images of oven-dried Whatman no. 42 filter paper

Fig. 4. Pore size distribution of Whatman no. 42 filter paper as determined on pore < 8 μm diameter from SEM images (the pore size distribution counts were extrapolated per mm^2)

Table 3. Filter paper calibration equations recommended by ASTM D 5298 (ASTM, 2010)

$w < 45.3$	$\text{Log}_{10}(\psi) = 5.327 - 0.0779w^*$
$w > 45.3$	$\text{Log}_{10}(\psi) = 2.412 - 0.0135w$

* w is the water content (%) and ψ is the suction (kPa) of filter paper.

Fig. 5. One- and 4-week initially wet contact as well as 1-week initially dry contact and non-contact filter paper test results of the GCL wetting path

Fig. 6. Comparison of wetting path suction measurements of 1-week and 4-week initially wet contact filter paper tests, as well as 1-week initially dry contact filter paper tests with measurements of HCT by Beddoe *et al.* (2011) for the wetting path of the same GCL type

model the drying curve break point corresponds to residual pressure (the inflection point between residual and transition zones) of the drying path WRC, and similarly the wetting

curve break point corresponds to the water entry value of wetting path WRC. The break point of the drying (initially wet) and wetting (initially dry) curves (Fig. 7(a)) correspond

Table 4. Capillary pressure values calculated using the Young–Laplace equation (equation (1)) for possible filter paper pore sizes and contact angles

Capillary pressure: kPa	Contact angles: degrees		
	0	26	56
Pore size: μm			
2	144	130	81
2.5	116	104	65

Capillary pressure by Young–Laplace equation	During water entry ($\theta = 56^\circ$, $D = 2.5 \text{ mm}$)	After water entry ($\theta = 0^\circ$, $D = 2.0 \text{ mm}$)
	65 kPa	144 kPa

Fig. 7. (a) Calibration curves for Whatman no. 42 filter paper (modified from Munoz-Castelblanco *et al.* (2012)) (the two larger circles show the break points). (b) Conceptual model of filter paper water retention behaviour and hysteresis between wetting and drying paths

approximately to suctions of 146 kPa ($w=48\%$) and 66 kPa ($w=45\%$), respectively. The Young–Laplace equation gives 144 kPa (Table 4) for the wet case ($\theta=0^\circ$, $D=2.0\ \mu\text{m}$), which is very close to the suction value at the break point of the initially wet calibration curve, 146 kPa. The suction values at the break points presented in Table 1 (63.1–82.5 kPa) correspond to the calculated capillary pressure values of 65 kPa and 81 kPa for a dry contact angle of 56° (Table 3). The wetting path (initially dry) break point in Fig. 7(a) also corresponds to the calculated capillary pressure for an initially dry contact angle of 56° and particle retention value ($2.5\ \mu\text{m}$).

Since the CFPT requires capillary contact between GCL specimen and filter paper, the inflection point between the residual-transition zones of the drying curve and the water entry value of the wetting curve should give the accurate matric suction measurement limits of IW-CFPT and ID-CFPT, respectively. The requirement of capillary contact also explains why IW-CFPT and ID-CFPT gave comparable results up to ~ 70 kPa, which coincides with the accurate measurement limit of ID-CFPT. The suction results of both CFPTs have eventually merged with the NCFPT results after the proposed limit values of 146 and 66 kPa were passed.

The contact test suction values from non-woven cover geotextile side (Figs 5 and 6) merged with the values of NCFPT at lower suctions. This result indicates that the non-woven geotextile used had higher tendency to provide a capillary break than the woven geotextile.

CONCLUSIONS

Initially dry and wet contact filter paper test (ID-CFPT and IW-CFPT) methodologies were found to be applicable for GCL matric suction measurements. The ID-CFPT (the ASTM standard contact filter paper test) and IW-CFPT methods had theoretical measurement limits of ~ 66 kPa and ~ 146 kPa, respectively, based on measured pore size distributions of the filter paper used. The 4-week IW-CFPT applied to woven geotextile faces is recommended for matric suction measurement using the filter paper method for GCLs on the wetting path. A non-woven geotextile was found to be more likely to act as a capillary break than a woven geotextile.

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