

# Development of suction measurement techniques to quantify the water retention behaviour of GCLs

R. A. Beddoe<sup>1</sup>, W. A. Take<sup>2</sup> and R. K. Rowe<sup>3</sup>

<sup>1</sup>Research Student, Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6, Telephone: +1 613 533 3124, Telefax: +1 613 533 2128, E-mail: ryley.beddoe@ce.queensu.ca

<sup>2</sup>Assistant Professor, Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6, Telephone: +1 613 533 3124, Telefax: +1 613 533 2128, E-mail: andy.take@civil.queensu.ca

<sup>3</sup>Professor and Vice-Principal (Research), Queen's University, Kingston, Ontario, Canada K7L 3N6, Telephone: +1 613 533 6933, Telefax +1 613 533 6934, E-mail: kerry@civil.queensu.ca

Received 01 June 2009, revised 21 May 2010, accepted 07 July 2010

**ABSTRACT:** Geosynthetic clay liners (GCLs) have the potential to act as excellent hydraulic barriers, and have been successfully used in numerous barrier system applications, including composite landfill liners. In order to function effectively in the role of a hydraulic barrier, these products must first hydrate through the uptake of moisture from the subsoil. They then must demonstrate adequate dimensional stability during any subsequent moisture loss, to avoid separation of the panel overlaps. The key to understanding these moisture uptake and retention phenomena is the constitutive relationship between suction and moisture content. This relationship is commonly referred to as the water retention curve (WRC) of a material. Despite the significance of this relationship for the final success of the barrier, only a few studies have successfully quantified portions of water retention curves, and for only a subset of available GCL product types. This scarcity of data is due primarily to the inherent difficulty of determining this function experimentally for a composite material such as a GCL, and to the difficulty in measuring the wide range of suctions that need to be investigated. In response to this data gap, a dual-technique strategy for the quantification of WRC for GCLs is investigated in this paper, in which two different suction measurement techniques (high-capacity tensiometers and capacitive relative humidity sensors) have been assessed to see whether they are capable of experimentally quantifying the relationship between moisture content and suction for a GCL. This paper discusses the sample preparation techniques and required equilibration times for these techniques, and demonstrates that they can provide water retention data for GCLs that are consistent with published results.

**KEYWORDS:** Geosynthetics, GCL, Water retention curve, Suction, Unsaturated soil

**REFERENCE:** Beddoe, R. A., Take, W. A. & Rowe, R. K. (2010). Development of suction measurement techniques to quantify the water retention behaviour of GCLs. *Geosynthetics International*, 17, No. 5, 301–312. [doi: 10.1680/gein.2010.17.5.301]

## 1. INTRODUCTION

A geosynthetic clay liner (GCL) is a composite geosynthetic material. It commonly consists of a thin bentonite clay layer (typically of the order of 5–10 mm thick) that is either bound by needle-punched geotextiles or bonded to a geomembrane with an adhesive. The performance of GCLs has been the subject of much recent research (e.g. Andrejkovicova *et al.* 2008; Bouazza *et al.* 2008; Müller *et al.* 2008; Saidi *et al.* 2008; Vukelić *et al.* 2008; Guyonnet *et al.* 2009). As a result of the very low hydraulic conductivity of the bentonite layer, GCLs have the potential to act as an excellent hydraulic barrier (e.g. Rowe *et al.* 2004), and have been successfully used in

numerous barrier system applications, including composite landfill liners, tailing ponds, dams, and railway lines (e.g. Bouazza 2002).

In order for a GCL to act as an efficient hydraulic barrier, the bentonite component of the GCL must be sufficiently hydrated. This phenomenon has been clearly demonstrated in the laboratory through the investigation of advective flow of various permeants through initially unsaturated GCLs (e.g. Daniel *et al.* 1993). These studies have indicated that the moisture content of a GCL needs to be above a certain threshold degree of saturation prior to the GCL being exposed to non-aqueous phase permeants, to achieve a low hydraulic conductivity. However, the initial state of the bentonite within the GCL is at an

as-manufactured moisture content that is insufficient for the GCL to act as a hydraulic barrier. As a result, it is expected that the hydration process will begin at the time of installation of the GCL, and should be complete prior to significant contact with contaminants (i.e. the placement of municipal solid waste).

The source of water for GCL hydration in a single composite landfill liner system is the underlying soil foundation layer. Despite the importance of hydration to the overall effectiveness of the barrier system, surprisingly little research has addressed this aspect of GCL behaviour. What work has been published (e.g. Daniel *et al.* 1993; Rayhani *et al.* 2008) has shown that the final moisture content achieved by the GCL and the length of time needed to achieve this are functions of the soil type and initial soil moisture content. The key to understanding this hydration behaviour is the relationship between suction and moisture content: this relationship is known as the water retention curve (WRC). This relationship is also a necessary requirement for definition of the unsaturated permeability function. In other words, a well-quantified WRC for both the GCL and attenuation layer soil is a prerequisite for the estimation of both the ultimate degree of saturation that the GCL will obtain, and the length of time required for this hydration process to occur.

The initial hydration of GCLs after field installation may be just the first part of the moisture uptake and retention cycle for a GCL. In cases where the composite landfill liner is left exposed (e.g. delayed placement of an overlying soil layer), the heating of an exposed geomembrane overlying the GCL may result in moisture loss from the GCL. Heating cycles and consequent GCL shrinkage are thought to have given rise to the movement of GCL panels and the formation of gaps between GCL panels in some composite barriers (e.g. Thiel and Richardson 2005; Koerner and Koerner 2005; Thiel *et al.* 2006), although there are other cases (Gassner 2009) where GCLs in exposed composite liners have not experienced shrinkage. Again, as was the case for the GCL hydration issue, the WRC for the GCL and subsoil is the prerequisite to understanding and modelling this problem.

Despite the significance of this relationship for the overall success of the barrier, only a few studies have been performed to quantify the WRC of GCLs (Daniel *et al.* 1993; Barroso *et al.* 2006; Southen and Rowe 2007). As a result of this data gap, considerable uncertainties exist that preclude our ability to adequately predict hydration and shrinkage behaviour. The primary reason for the scarcity of WRC data for GCLs is the inherent difficulty of determining this function experimentally for a composite material such as a GCL, and the wide range of suctions that need to be investigated. The objectives of this paper are: (1) to investigate whether suction measurement techniques consisting of a combination of high-capacity tensiometers and capacitive relative humidity sensors are capable of experimentally quantifying the relationship between moisture content and suction for a GCL; and, if successful, (2) to propose sample preparation techniques and evaluate the required equilibration times for their use to define the WRC of GCL samples.

## 2. BACKGROUND

### 2.1. Water retention curves

The WRC of a geomaterial is the constitutive relationship between moisture content (expressed as degree of saturation, or volumetric moisture content, or gravimetric moisture content) and suction. Here the term 'suction' describes the thermodynamic potential of soil pore water relative to a reference potential of free water (Lu and Likos 2004). The pore water in a soil is typically viewed as being held in place by two components of suction: matric suction and osmotic suction, where matric suction is the component of suction arising from interactions between the pore water and the soil solids, and osmotic suction is the component of suction arising from the presence of dissolved solutes (Lu and Likos 2004). The term 'total suction' is therefore defined as the summation of these two components of suction.

In order to quantify the WRC of a GCL, one must measure both the moisture content and the suction of the composite material. The quantification of this relationship for GCLs is a particularly challenging experimental task, for two reasons.

- (1) For a GCL, the composite nature of the product has the potential to significantly influence its water retention behaviour. To illustrate the differences in water retention behaviour between geotextiles and clays, the test data of Bouazza *et al.* (2006) are included as Figure 1, which compares a typical WRC for a nonwoven geotextile with that of a low-plasticity clay. These data indicate just how different these materials are: geotextiles hold more water when saturated (by volumetric fraction), but typically lose all of their water under very small suctions of approximately 1 kPa. Clays, on the other hand, have a lower porosity (and therefore volume fraction of water when saturated), but require much higher suctions to achieve residual moisture conditions. For the case of a GCL, the contrast in behaviour between the soil and geotextile components will actually be much higher than demonstrated in Figure 1, as the air entry value for bentonite is several orders of magnitude higher than that for the low-plasticity clay of Figure 1. The impact of the composite nature of the product has the potential to be much more than the obvious differences between the two materials shown in Figure 1. In particular, the needle-punching fibres between the cover and carrier geotextiles confine the sample and influence the bulk void ratio of the GCL during swelling (Lake and Rowe 2000). As a result of the confinement provided by these fibres, it is to be expected that the WRC of a GCL will differ from that of pure bentonite, and will probably vary by GCL product.
- (2) Measurement of the moisture content of a soil sample is straightforward, but the measurement of soil suction is a much more complicated experimental task. For a GCL, the high air entry and residual saturation value of the bentonite component

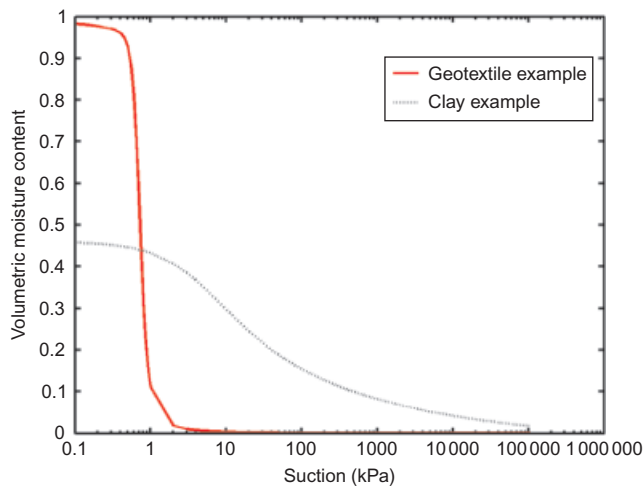


Figure 1. Water retention curves for a typical geotextile and low-plasticity clay (modified from Bouazza *et al.* 2006)

dictate that a wide range of suctions need to be investigated to define the full water retention curve for this material (i.e. suctions ranging from 1 kPa when fully saturated all the way to potentially 1 000 000 kPa at the driest of the as-manufactured bentonite moisture contents). While today there are numerous methods available to measure soil suction, no one measurement technique is capable of spanning the wide range of suction values that are relevant to a GCL (Figure 2). As a result, an experimental strategy that combines at least two of these measurement techniques is required so that the full water retention behaviour of GCLs can be quantified.

## 2.2. Techniques for suction control

In order to generate a WRC for a GCL, a known value of suction needs either to be imposed on a GCL sample or to be measured within it. Since detailed reviews of suction control and measurement techniques have previously been published with regard to their advantages and disadvantages for testing different types of soil (e.g. Ridley and

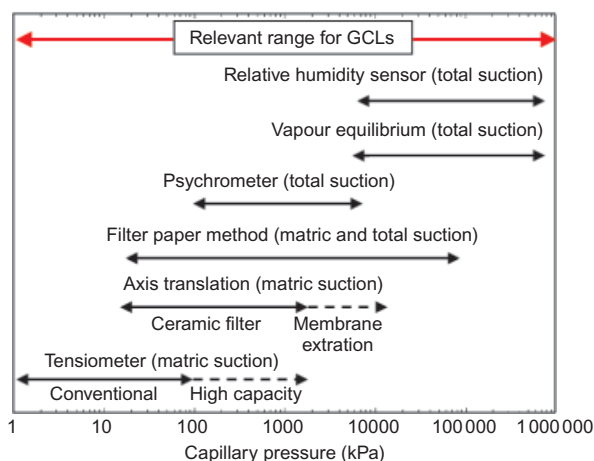


Figure 2. Applicable ranges for techniques for the control or measurement of suction (modified from Likos and Lu 2003)

Wray 1996; Likos and Lu 2003; Agus and Schanz 2005; Tarantino *et al.* 2009), the suitability of these various candidate techniques is only briefly reviewed here in the context of their applicability to the measurement of suction in GCLs.

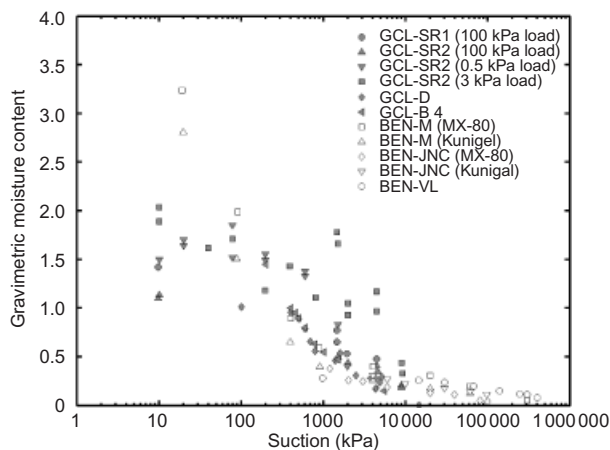
The two primary candidate techniques for the control of suction are the vapour equilibrium technique (VET) and the axis-translation technique (ATT). The first of these, the VET, is based on the observation that the relative humidity in the airspace above a salt solution is unique to the concentration and chemical composition of that solution (e.g. Young 1968; Greenspan 1977). Therefore, by choosing a chemical solution with the correct target relative humidity, a GCL sample placed in a closed system with this solution will absorb or yield water vapour to the airspace until it comes into equilibrium with that solution. Given the equilibrium relative humidity of the airspace, it is possible to calculate the total suction using Kelvin's equation (e.g. Fredlund and Rahardjo 1993),

$$s_t = \frac{-RT}{M_w(1/\rho_w)} \ln(\text{RH}) \quad (1)$$

where  $s_t$  is total suction,  $R$  is the universal gas constant (8.31432 J/(mol K)),  $T$  is the absolute temperature (K),  $M_w$  is the molecular weight of water (18.016 kg/mol),  $\rho_w$  is the unit weight of water (kg/m<sup>3</sup>), and RH is the relative humidity (partial pressure of pore water vapour/saturation pressure of water vapour).

The VET has the advantage of being able to target exact areas of interest on the WRC for testing over a wide range of suctions (Figure 2), and has been successfully used by Daniel *et al.* (1993) to obtain points on a WRC for a geomembrane-backed GCL. The disadvantages of this technique are the number of different salt solutions that would be required to fully quantify the WRC of a GCL, and the length of time required for each GCL sample to come into equilibrium with its solution. For example, the VET tests performed by Daniel *et al.* (1993) on the geomembrane-backed GCL required two months' equilibration time, and those performed on pure bentonite by Tang and Cui (2005) were shown to require approximately three months.

The alternative method to control suction is the axis-translation technique. In this technique, a known air pressure is set above a GCL sample that has been placed in contact with a saturated porous ceramic. Once the sample has come into equilibrium with this imposed matric suction, the resulting equilibrium state can be used as a point on the WRC. The axis-translation technique has been successfully used to quantify the wetting and drying water retention curves of many soils over ranges of matric suction from 0 kPa to 1500 kPa. This range of suctions corresponds to the range of air entry values of commercially available porous ceramics (Figure 2). Higher imposed suctions can be performed by replacing the porous ceramic by a membrane. Such a device has been used by Southen and Rowe (2007) to investigate the drying curve of GCLs; however, these researchers found that considerable scatter existed in the data at these high suctions (Figure 3). The researchers attributed this scatter to the



**Figure 3. Comparison of drying water retention curves of GCLs (solid symbols) and bentonite (open symbols): GCL-SR, Southen and Rowe (2007); GCL-D, Daniel *et al.* (1993); GCL-B, Barroso *et al.* (2006); BEN-M, Marcial *et al.* (2002); BEN-JNC, JNC (2000); BEN-VL, Villar and Lloret (2004)**

difficulty in ensuring adequate contact between the GCL and the porous membrane. This is to be expected, as it has already been demonstrated in Figure 1 that geotextiles achieve residual saturation conditions at very low suctions. As a result, the geotextile bounding the bentonite core of the GCL isolates the bentonite from the saturated ceramic/membrane, and does not allow the water within the bentonite to escape the GCL as the air pressure is increased. Therefore, although this method has successfully been used for soils with a wide range of matric suctions, the range of suctions that can be reliably imposed on a GCL using this method is considerably smaller.

### 2.3. Techniques for suction measurement

The alternative experimental strategy for generation of the WRC of a GCL is the measurement of suction in GCL samples that have been prepared to various moisture contents along the desired drying or wetting path. Candidate measurement techniques include devices for measurement of relative humidity (e.g. thermocouple psychrometer, capacitive relative humidity sensor, and filter paper) and a device designed to measure matric suction directly: the high-capacity tensiometer.

The theoretical basis for the measurement of total suction using a relative humidity sensor is Kelvin's equation, which was presented in Equation 1 and relates the relative humidity of an airspace at equilibrium above a GCL sample to the total suction in that GCL sample. Relative humidity sensors are typically designed either to span a wide range of suctions (0–100%) or to resolve accurately between values of high relative humidity near 100%. One device particularly well suited to measure high relative humidity values is the thermocouple psychrometer. This device, pioneered by Spanner (1951), is capable of measuring the relative humidity of air accurately in the range 98–99.9%, which corresponds to a range of measurable total suctions of 100–8000 kPa. Using this technique, Daniel *et al.* (1993) were able to measure several

points along a WRC for a geomembrane-backed GCL in this range of total suctions.

Devices designed to measure wide ranges of relative humidity are generically described as 'relative humidity sensors' for the purposes of Figure 2, and include capacitance relative humidity sensors (e.g. Likos and Lu 2003), and the Xeritron relative humidity sensor (e.g. Siemens and Blatz 2005). The accuracy and range of relative humidity measurements enabled by these sensors vary by manufacturer and by product line, but are typically in the range 0–99% RH at an accuracy of  $\pm 1\%$  RH. Using Kelvin's equation, this corresponds to a measurable range of total suction of 5000–700 000 kPa, although with measuring inaccuracies and human error a more conservative range of measurable suction is 7500–700 000 kPa (Agus and Schanz 2007). One of the biggest potential advantages of using a capacitive relative humidity sensor to measure suction in GCL samples is the speed with which it can reach equilibrium, which has been reported to be as little as 20 min (Agus and Schanz 2005). Although capacitive relative humidity sensors have been successfully used to measure total suction in soil samples, they have not yet been used for testing GCLs.

An alternative indirect measurement of the relative humidity in the airspace above a soil is the non-contact filter paper technique (ASTM D5298). In this technique, a specific type of filter paper (typically Whatman No. 42 or Schleicher & Schuell No. 589) is placed in a sealed environment above, but not contacting, a soil sample. The initially oven-dry filter paper then absorbs moisture from the airspace until it reaches vapour equilibrium with the airspace and soil sample. At this point, the gravimetric water content of the filter paper is measured. It has been found that the relationship between this moisture content and applied suction is unique for a specific lot of filter paper. As a result, a calibration relationship can be developed between total suction and filter paper moisture content to infer suction in GCL samples. In a slight modification to this technique, the filter paper can be placed in contact with the sample, and can therefore be used to measure the matric suction in the sample (ASTM D5298). Such a strategy was adopted by Barroso *et al.* (2006), who successfully measured points along a drying curve for a GCL within the suction range 10–10 000 kPa. This method has the advantage of being able to measure both total and matric suctions, but has the significant disadvantage of requiring a long equilibration time (minimum 7 days; ASTM D5298) between the filter paper and the GCL.

The final candidate technique for the measurement of suction in GCLs is the water-filled tensiometer. These devices work by measuring the pressure behind a water saturated porous filter placed in contact with a soil sample. Once contact is made, water is drawn from the reservoir behind the saturated filter into the soil sample until equilibrium is reached. At this point, the pressure measured in the reservoir of the tensiometer is the matric suction of the soil. These devices are therefore able to provide a direct measurement of the matric suction in the soil. Conventional tensiometers are, in practice, limited in

range to suctions up to 90 kPa (e.g. Stannard 1992). The reason for this has been demonstrated by Take and Bolton (2003). If a pre-existing free bubble exists in the water reservoir, suctions higher than 90 kPa cannot be measured, as the minimum pressure in the bubble cannot go below 0 kPa absolute pressure. If no free bubbles are present, conventional tensiometers will experience cavitation at a suction of 100 kPa. This suction measurement ceiling for water-filled tensiometers has been overcome by the work on preconditioning techniques by Ridley (1993). In these techniques, the reservoir system of the device is subjected to large positive pressures to encourage potential cavitation nuclei into solution. As a result, the water in the device is permitted to enter a metastable state and avoid nucleation at suctions greater than 100 kPa (Marinho *et al.* 2008). Devices capable of measuring these large matric suctions are called high-capacity tensiometers (HCT); they use these preconditioning techniques to extend the range of matric suction measurable using tensiometers past the cavitation limit (100 kPa) to the maximum air entry value of commercially available porous ceramics (1500 kPa).

The clear advantages of tensiometric measurement of matric suction are the direct nature of the measurement (i.e. suction is not inferred indirectly from a measurement of another property) and the short equilibration times (of the order of several hours) that have been reported in the literature (e.g. Oliveira and Marinho 2008). However, to apply this technique for the measurement of suction in GCLs, direct contact must be made between the high-capacity tensiometer's filter element and the bentonite component of the GCL. As a result, there needs to be an incision in the cover geotextile to expose the bentonite to the porous ceramic filter of the HCT to enable a measurement of suction. Although this suction measurement technique appears promising, it has yet to be adopted for the measurement of suction in GCLs.

#### 2.4. Published water retention curves for GCLs

Three experimental studies have been published in the literature that provide data on the water retention behaviour of GCLs (Daniel *et al.* 1993; Barroso *et al.* 2006; Southen and Rowe 2007). In these studies, the vapour equilibrium technique, the axis-translation technique, the filter paper method and the thermocouple psychrometer have all been successfully used to control or measure suction in GCLs. These results are combined in Figure 3, where they are presented in terms of gravimetric moisture content against suction as solid marker symbols. Also included in this figure are measured points on the WRC of pure bentonite as tested by JNC (2000), Marcial *et al.* (2002) and Villar and Lloret (2004). The bentonite results, presented in Figure 3 as open marker symbols, indicate a clear difference in water retention behaviour between GCLs and bentonite in the low-suction region (i.e. <1500 kPa) owing to the suppression of swelling afforded by the GCL's needle-punching fibres. In the high-suction range, above 10 000 kPa, no comparison can be made, as no data have been reported for GCLs at these high levels of suction.

The results of Southen and Rowe (2007) indicate clear

differences in gravimetric moisture content between GCL products GCL-SR1 and GCL-SR2, particularly at low suctions. From these results one can conclude that the effect of the needle-punching fibres on the gravimetric WRC for each GCL is likely to be product dependent. However, this relationship has yet to be quantified for many GCL products, particularly on both the wetting and drying branches of the curve. In addition, Figure 3 illustrates the amount of scatter for a given GCL type, indicating the potential variability in the measurement of suction in GCLs and the equilibrium moisture content at these suctions. One strategy to deal with this variation is to test a large number of samples for each type of GCL. If such a strategy were to be adopted, there would therefore be a significant advantage in using techniques to measure suction that have a rapid measurement time.

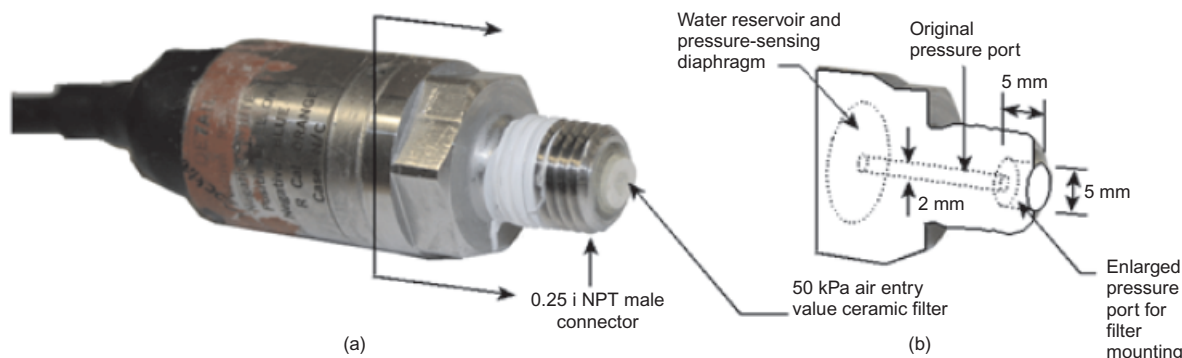
Whereas all the suction measurement and control techniques (with the exception of the axis-translation technique) can be reliably used to generate points on the WRC of GCLs, the combination of the high-capacity tensiometer (for the measurement of low suctions) and the capacitance relative humidity sensor (for the measurement of high suctions) holds particular promise for the rapid testing of the large number of GCL samples required to quantify the full WRC behaviour. Together these techniques can measure nearly the full range of suctions expected in GCLs (Figure 2), with only a small gap of suction values between 1500 kPa to 5000 kPa that these two methods do not cover. Although the two methods selected will not be able to measure suction directly in this gap, the data obtained in the low and high range of suctions will be sufficient to obtain fitting curves to cover the complete range of suction of a GCL.

### 3. METHODS AND MATERIALS

#### 3.1. High-capacity tensiometer

The essential design components of a high-capacity tensiometer (HCT) include a robust pressure-sensing diaphragm, a small water reservoir, the elimination of spaces likely to trap bubbles, and a high air entry ceramic filter (Ridley 1993). The manner in which these design requirements have been met by different researchers has led to a range of different designs for high-capacity tensiometers being proposed in the literature, from the fabrication of custom-made sensors to the modification of existing pressure transducers (Marinho *et al.* 2008).

The high-capacity tensiometer used in the present study was fabricated by modifying a stainless steel GE-Druck PDCR 4010 pressure transducer (Figure 4a). This pressure transducer is 120 mm long, with an external diameter of 30 mm, and has a 2 mm diameter pressure port that links the internal stainless steel measurement diaphragm to the tip of the sensor (Figure 4b). In the particular configuration of the pressure sensor used in the present study, the tip of the pressure transducer consists of a threaded 0.25 in NPT connector that has a face diameter of approximately 12 mm. A 5 mm diameter hole was then drilled into the face of the sensor to a depth of 5 mm



**Figure 4. Modifications made to a GE-Druck PDCR-4010 pressure transducer to convert the device into a high-capacity tensiometer: (a) external view; (b) internal view**

(Figure 4b). As a result, a cylindrical cavity, 5 mm long and 5 mm deep, was created in the stainless steel body of the pressure sensor, into which a 500 kPa air entry value ceramic filter could be recessed and securely bounded using epoxy. Once fabricated, the devices were oven dried and saturated using the two stage saturation procedure – a first stage in which the dry ceramic filter was subjected to a high vacuum prior to coming in contact with water, and a second stage in which a high positive pressure of 3000 kPa was applied to precondition the ceramic and water reservoir. Further details on the saturation process, equipment and calibration methods can be found in Take and Bolton (2003).

The advantages of this particular HCT design are the excellent sensor performance characteristics of the commercially available pressure sensor and the relatively minor modifications required to convert this device into a HCT. Also, in the male  $\frac{1}{4}$  NPT configuration used, the body of the device is sufficient to connect to saturation and calibration systems without the need for any additional components. The disadvantage of this design is the relatively large volume of the internal reservoir of the sensor. This large volume decreased the success rate of saturation for devices fitted with a 1500 kPa air entry value ceramic, but did not offer any significant issues in the saturation of sensors when fitted with a 500 kPa air entry value ceramic filter. Because of the ease of saturation of these devices with the 500 kPa air entry value ceramic, this configuration was used for the measurement of suctions in GCLs.

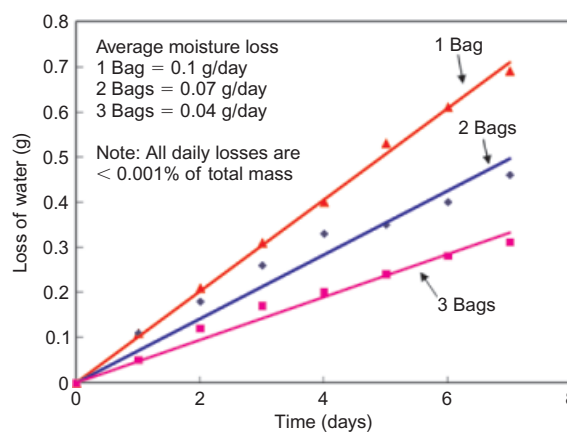
### 3.2. Capacitive relative humidity sensor

The capacitance relative humidity sensor selected for use in the present study is the Vaisala HMP45A relative humidity sensor. The HMP45A probe has a humidity range of 0.8–100% and a temperature range of  $-39.2^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ . The calibration of these sensors was verified in the laboratory by subjecting them to multiple total suction values imposed by salt solutions, and by the vapour equilibrium technique. This validation exercise indicated that an accuracy of  $\pm 1.5\%$  RH could be readily achieved with the sensors and data acquisition configured for use in the present study.

### 3.3. Sensor installation and measurement

During suction measurement, the GCL samples must be placed in a closed environment with little or no moisture loss, so that the sensors can come into equilibrium with the suction in the GCL sample. Several chamber designs were considered, ranging from aluminium test cells and glass desiccators to hard-form plastic cases and flexible plastic bags. The flexible plastic bags were selected for testing for their very low air volume, their flexibility, and their transparency.

Before they were used for suction measurement, various bag configurations were tested to investigate their rate of moisture loss. The plastic bags that were eventually selected were Double Locking Ziploc<sup>®</sup> Freezer Bags. The results of the moisture loss experiments performed on these bags are presented in Figure 5. In each of these tests a known amount of water was placed inside the bags (with the water allowed to touch the inside of the bag), and the loss of moisture was recorded over a period of 1 week as the bags sat on the laboratory bench. These tests were performed both for water placed in a single bag, and for double- and triple-bagged systems. It can be seen that the average loss of a triple-bagged system is approximately 40% that of a single bag. However, even if one bag were used, the small magnitude of moisture loss during the 12 h measurement period represents only a 0.4% change in gravimetric moisture content for the size of GCL samples

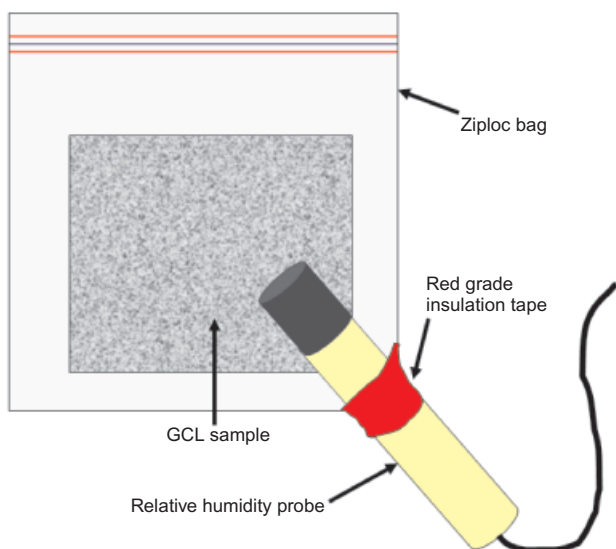


**Figure 5. Bag evaporation test**

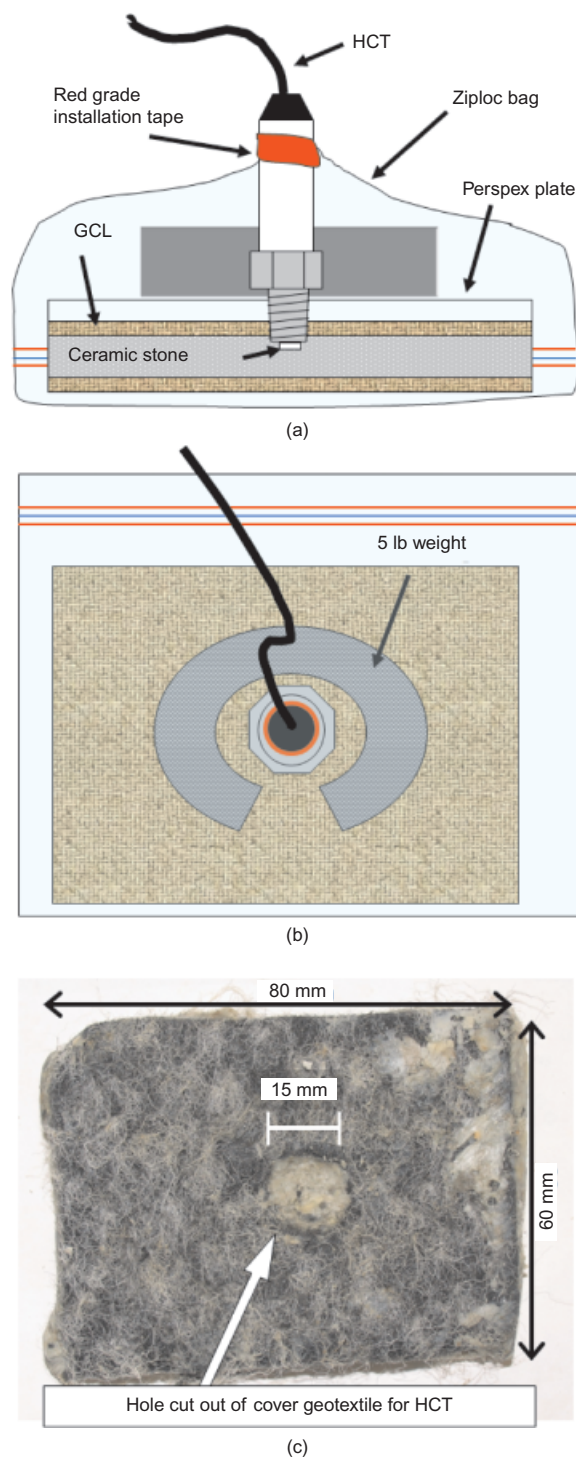
used in the present study. Because of this, a single plastic bag was considered sufficient for the present study.

To measure GCL samples at high suctions, capacitive relative humidity sensors were installed sealed in the corner of the bags opposite to the zipper seal (Figure 6). In this way, the GCL samples could be carefully inserted into and removed from the transparent plastic bag without contacting the sensor or impacting on the zipper seal. During measurement, the sensor rested in the air space above the GCL, but was not touching it. The sample was left in the testing chamber for a minimum of 12 h while the relative humidity and temperature were recorded. At the conclusion of the test the sample was removed, and the relative humidity sensor was allowed to return to the laboratory's relative humidity and temperature. Throughout the duration of GCL testing, the change in temperature of the GCL specimen was held within a range of  $\pm 0.2^{\circ}\text{C}$ .

To measure GCL samples at low suctions it is necessary to ensure that the porous ceramic filter of the HCT maintains contact with the bentonite clay inside the GCL. Therefore, just before the measurement of suction with a HCT began, a small hole was cut in the cover geotextile, exposing the underlying bentonite clay (Figure 7c). Threaded onto the tensiometer was a Perspex plate measuring  $100\text{ mm} \times 100\text{ mm}$ . This held the tensiometer vertical and stationary during testing (Figure 7a). The GCL sample was placed on the underside of the Perspex plate, inside the bag. A small amount of bentonite paste was then harvested from the edge of the GCL and placed as a bead on top of the porous ceramic of the HCT, which was placed in contact with the bentonite core of the GCL. In order for the HCT to maintain good contact with the sample, a 2.25 kg mass was placed on top of the Perspex plate to apply 2 kPa of normal stress (Figure 7b). The objective of this normal stress was to ensure that the HCT maintained contact with the bentonite core of the GCL. The sample was left for a minimum of 12 h while suction was being recorded. At the conclusion of the test the



**Figure 6.** Configuration of capacitance relative humidity probe during testing



**Figure 7.** Configuration of HCT during testing: (a) elevation view; (b) plan view; (c) photograph of sample detailing the incision required in the cover geotextile

sample was removed, and the HCT was quickly returned to water in order to prevent desaturation from occurring.

At the conclusion of every test the sample mass, area and height were recorded. The mass was recorded using a digital scale, to an accuracy of 0.01 g. The linear dimensions of the sample were taken with digital callipers to an accuracy of 0.1 mm. The height of the sample was taken using a laser scanner with an accuracy of  $\pm 0.05\text{ mm}$  (Brachman and Gudina 2008). While the height of the

sample was being measured, a 2 kPa stress was applied to the GCL. This nominal normal stress was added to eliminate deformations in the geotextile material and from the warping of the dried sample. The sample was then placed in a 105°C oven for 24 h before the dry mass was recorded.

### 3.4. GCL sample preparation

Samples of four different types of GCL were selected for testing. The basic characteristics of these products, herein referred to as GCL1 to GCL4, are presented in Table 1. All products were needle-punched. GCL1 and GCL3 both have a nonwoven cover geotextile and a woven slit-film carrier geotextile. GCL1 has also been thermally treated. GCL2 had a nonwoven and scrim-reinforced nonwoven cover and carrier geotextile, respectively, and had been thermally treated, whereas GCL4 had both a nonwoven cover and carrier geotextile. The suitability of tensiometric and capacitance relative humidity sensors to define the WRC of GCLs was investigated by preparing GCL samples along a drying path.

After being taken off the roll, the initial state of the GCL was created by hydrating a 400 mm square piece of GCL under a 2 kPa applied normal stress in submerged conditions. Once the GCL was hydrated, this large piece was subdivided into approximately 100 mm square samples. These samples were then placed on a drying rack in the ambient relative humidity of the temperature-controlled room and dried for different periods of time at an ambient relative humidity ranging between 33% and 40% in order to reach different target moisture contents along the drying curve. These samples were then placed in a sealed plastic bag for a minimum of 24 h before suctions were measured.

## 4. RESULTS AND DISCUSSION

### 4.1. Equilibration time

Once a GCL sample is placed in the sealed environment with the suction sensor, the GCL will gain or lose moisture until equilibrium is reached with the small volume of air within the flexible plastic bag. In addition, the two sensors themselves require a finite amount of time

to reach equilibrium via moisture transfer between the porous ceramic and the bentonite (for the HCT), and between the filter paper cap and the air within the flexible plastic bag (for the RH sensor). As stated earlier in this paper, the anticipated short equilibration time is the primary advantage of the two chosen methods of suction measurement. To develop an experimental method for using these techniques, the equilibration time for both sensor types was investigated for the four GCL types of interest in this study.

The observed relationships between matric suction and time for GCL suctions measured using an HCT are presented in Figure 8 for a range of different GCL moisture contents. As expected, the magnitude of the measured equilibrium matric suction increases with decreasing GCL moisture content. However, two differently shaped curves were observed. The first shows an asymptotic increase in suction to the equilibrium value, typified by the samples at moisture contents of 85% and 153% (Figure 8). The second shape of curve is demonstrated by the sample at moisture contents of 168% and 56%. In this curve, the suction increases rapidly to a maximum value before slowly recovering to a lower equilibrium value. This variation in the suction response curves has also been observed by Ridley *et al.* (2003). They observed that if too much excess moisture on the surface of the ceramic was absorbed or evaporated prior to contact to the soil, then the measured suction would overshoot the actual suction. They noted that after several hours the sensor and soil would reach the true equilibrium, as was observed in these tests (Figure 8). In view of the shape of these curves, a criterion for judging the equilibrium of HCT suction readings was adopted that proposed that a change in suction of less than the accuracy of the device (i.e.  $\pm 1$  kPa) over 1 h was adequate to establish that equilibrium had been reached. This condition was usually reached within 5 h; however, an additional 5 h of measurement time was used as additional assurance that the sample and sensor had come to equilibrium. All test results were individually inspected to assess whether they had reached a satisfactory equilibrium, with a minimum time provided for equilibration being 10 h.

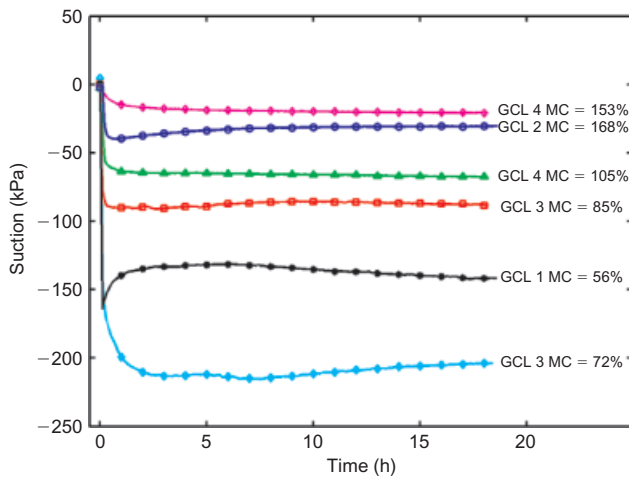
The observed equilibration time of the capacitance relative humidity sensor is presented in Figure 9. These

**Table 1. Geotextile properties as typically found off the roll in the field**

Properties		GCL 1	GCL 2	GCL 3	GCL 4
Avg GCL mass per unit area (g/m <sup>2</sup> )	Measured	4679	4241	5084	4944
	MARV <sup>a</sup>	3965	4060	4008	4097
Carrier	Type	W	NWS	W	NW
	Mass per unit area (g/m <sup>2</sup> )	123	260	125	233
Cover	Type	NW	NW	NW	NW
	Mass per unit area (g/m <sup>2</sup> )	242	232	283	264
Bentonite Structural	As-delivered form	Fine granular	Fine granular	Fine granular	Coarse granular
	Needle-punched	Yes	Yes	Yes	Yes
	Thermally treated	Yes	Yes	No	No

W = woven, NW = nonwoven, NWS = nonwoven scrim reinforced.

<sup>a</sup>Minimum average roll value.

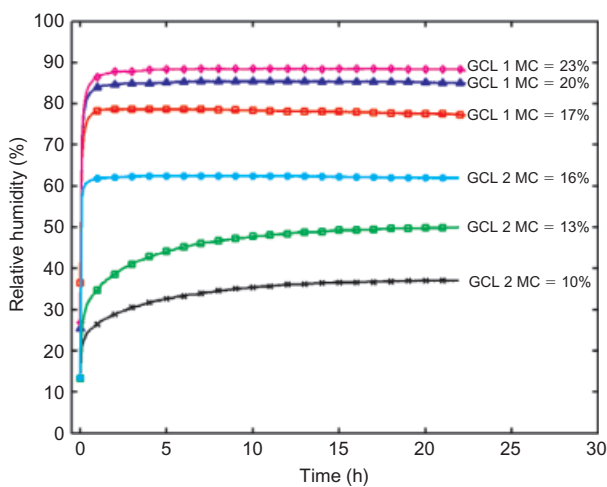


**Figure 8. Equilibration time for HCT measurements for GCL samples of varying moisture content**

results indicate that the length of equilibration time increases with decreasing relative humidity. In order to judge equilibration, a criterion similar to that used with the HCT was adopted, which stated that equilibration was achieved if a change in suction less than the manufacturer’s stated accuracy of the device ( $\pm 1\%$  RH) were to occur over 1 h. For tests with a relative humidity of over 50% this criterion was typically reached after 3 h, but all tests were conducted for a minimum of 10 h to ensure that equilibrium was reached, and for ease of testing in conjunction with the HCT schedule. For tests at a relative humidity less than 50%, up to 20 h was needed for equilibration (Figure 9).

**4.2. Sample homogeneity**

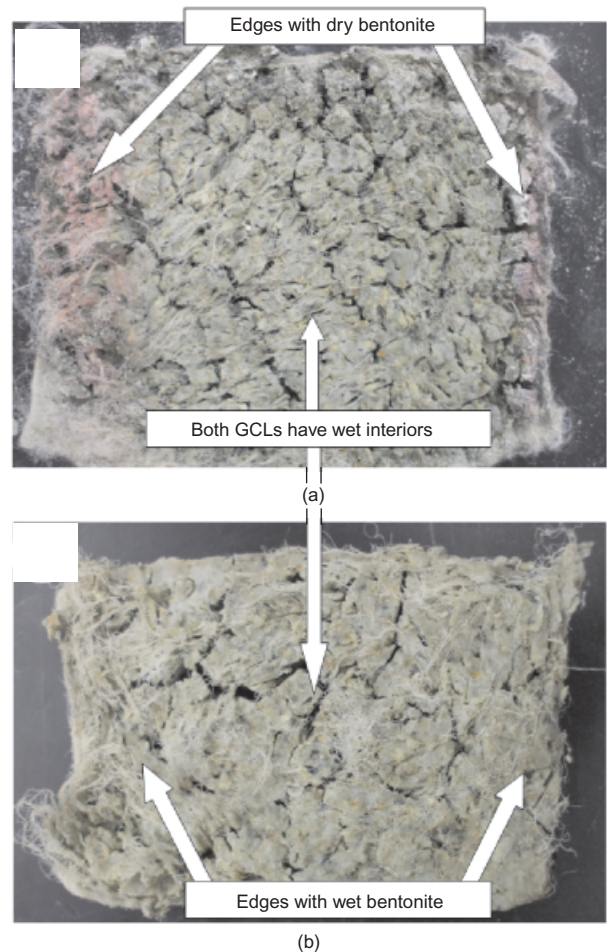
One of the assumptions behind the use of suction measurement techniques to define the WRC of GCLs is uniform spatial distribution of moisture content and suction within the sample. Early in the testing programme it was noted that there was significant initial moisture



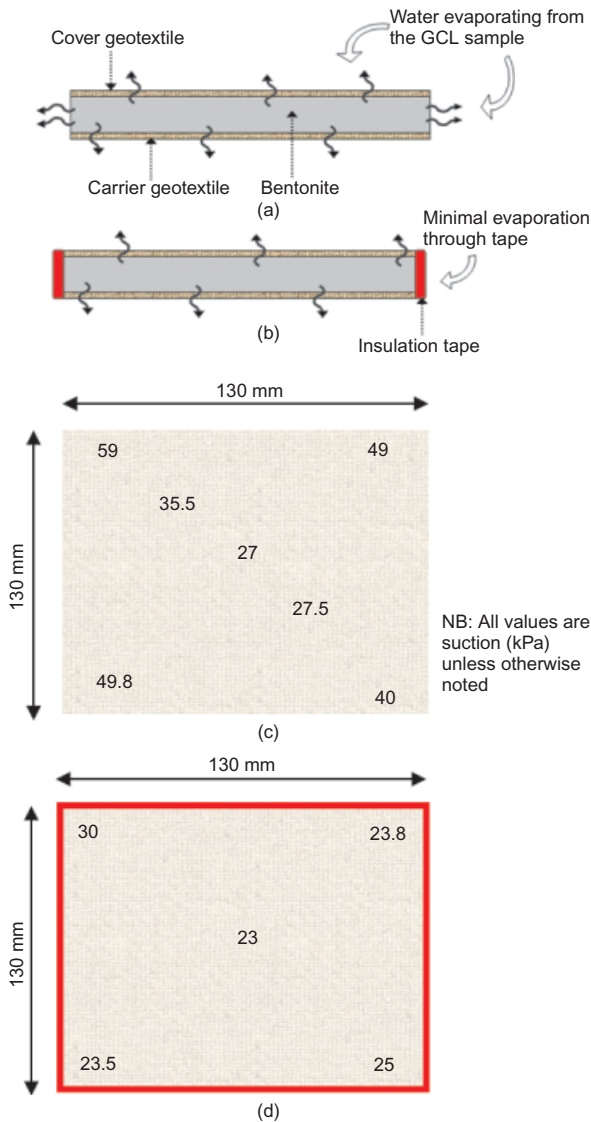
**Figure 9. Equilibration time for capacitive relative humidity measurements for GCL samples of varying moisture content**

content variation in the samples, with the edges of the sample exhibiting a much lower moisture content. To illustrate this problem, a sample of GCL was air-dried in the laboratory, and the cover geotextile carefully removed with a scalpel. An image of this GCL is included as Figure 10a: it clearly demonstrates a wetter inner core with drier edges than was observed when the edges were taped (Figure 10b). Possible hypotheses for this are investigated in Figure 11. As the sample dries, the cover and carrier geotextile quickly lose their moisture to evaporation, and desaturate. As a result, further evaporation of water from the inner bentonite core of the GCL is limited by the unsaturated permeability of the cover and carrier geotextiles while the bentonite at the edges of the GCL still has direct contact with the air. In addition, the edge regions of the GCL are subject to drying in two dimensions, whereas the centre region of the GCL drying is predominately one-dimensional (Figure 11a). As a result, the edges of the GCL were observed to dry at a faster rate than the centre. If these samples were not allowed time to come to moisture equilibrium throughout the sample, the location of suction measurement using the HCT would not correspond to the average moisture content of the sample.

To overcome this issue, the edges of all GCL samples



**Figure 10. GCL edge drying effects: (a) no tape around edges; (b) taped edges during drying**



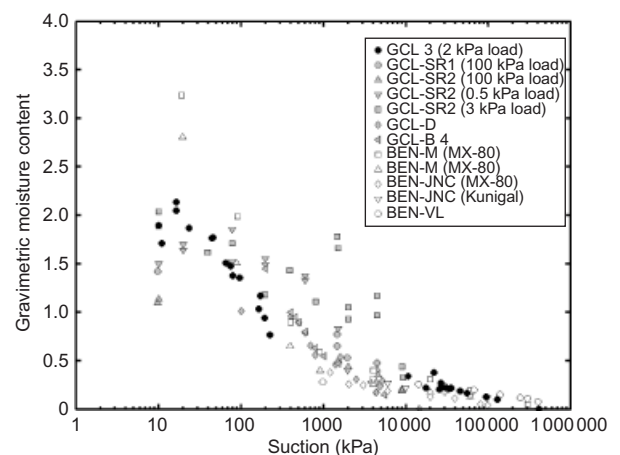
**Figure 11. Evaporation through a GCL sample: (a) without tape; (b) with tape. Resulting spatial variation in observed suction values for these GCL samples: (c) without tape; (d) with tape**

were covered with red insulation tape prior to drying, thus reducing preferential drying in these regions (Figure 11b). A test was conducted to verify this hypothesis, where one sample was left to dry with edges exposed, and one to dry with edges wrapped in insulation tape. The suction results for the untaped and taped GCL samples are shown in Figure 11c and Figure 11d as spot values of measured suction distributed throughout the GCL sample. For the untaped sample (Figure 11c) the spot values of suction range from 27 kPa near the centre of the sample to values up to 59 kPa at one of the corners. This variation in suction across the sample implies that the 24 h time period in a sealed chamber after drying is not sufficient for the sample to homogenise its moisture content. By contrast, spot suction measurements across the sample with taped edges show a much more uniform distribution of suctions. Expressed quantitatively, the provision of tape at the edges lowers the standard deviation of suction measurements across the sample from 12 kPa to 1.8 kPa. However, as

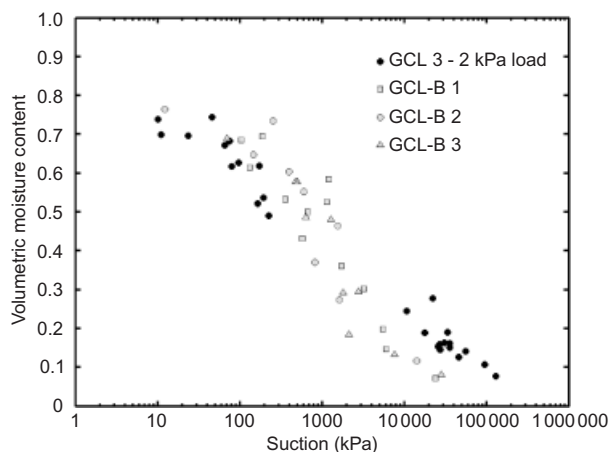
suction measurements are always taken from the centre of the sample, the bias overcome by the taping of the edges is much greater than the 12 kPa suggests. Therefore it was found to be essential to reduce preferential drying at the edges of all samples prepared along the drying curve by providing an adhesive tape moisture barrier.

**4.3. Comparison with published values**

A total of 25 samples of GCL3 were prepared along a drying path to investigate whether the experimental techniques developed in this paper could yield a drying WRC that is consistent with published data. The equilibrium values of suction and moisture content for these samples are presented in Figure 12 in terms of a gravimetric drying curve. These data points are also plotted with the WRC points that have been published for GCLs (solid grey symbols) and pure bentonite (open symbols). These data indicate that the cluster of GCL3 data points measured at the high suction range with the capacitive relative humidity sensor are consistent with published results for pure bentonite. Figure 12 also indicates that the points along the drying curve for GCL3 quantified by the HCT (i.e. between suctions of 10 and 200 kPa) form a tight band of data that is consistent with previous data, but with less scatter. These results are also presented on a volumetric basis in Figure 13 along with published volumetric WRC from Barroso et al. (2006). Although the GCLs tested by Barroso and co-workers were not the same product type as GCL3, the data they obtained from the contact-filter paper technique, when plotted in volumetric terms, show a high degree of similarity to the suction values measured with the HCT. This similarity indicates that the incision made in the geotextile cover (to measure the suction using a HCT) does not significantly change the suction within the GCL. The total suction values measured by the RH sensor are slightly higher than the matric suction values measured by Barroso et al. (2006). This is to be expected, as the RH measurements are total suction, and as such contain the extra osmotic component of suction. However, as the suction axis is logarithmic, this small extra component of suction does not change the fitting parameters appreciably



**Figure 12. Comparison of gravimetric WRC points for GCL 3 (solid black symbols) with published values for GCLs (solid grey symbols) and pure bentonite (open symbols)**



**Figure 13. Comparison of volumetric WRC data for GCL 3 and GCL-B1, B2 and B3 published by Barroso *et al.* (2006)**

for the primary WRC of interest, the gravimetric WRC (i.e. Figure 12)

## 5. CONCLUSIONS

Establishing the WRC of GCLs requires the measurement of a wide range of suction values. To obtain measurements of suction in GCL specimens an experimental strategy was adopted in which two suction measurement techniques were combined. A high-capacity tensiometer and relative humidity sensor were chosen to capture the suction values at the low and high ranges of suction, respectively. Also, during test procedure development for the GCL specimens, it was found that a GCL drying in 2D created an unequal moisture content distribution across the sample. Limiting the specimen drying to evaporation through the cover and carrier geotextiles alone (and not along the edges) greatly reduced the moisture content differences seen across a specimen. During the testing procedure development, it was also found that a minimum of 10 h was an adequate length of time for recording suction tests to allow the sensor and sample to reach equilibrium.

When compared with previously published water retention curves, the results from the dual suction measurement technique showed agreeable results. The high-capacity tensiometer was able to define the low suction range with more accuracy than that available using the axis-translation or filter paper methods. Previous GCL suction data did not extend beyond suctions of 140 000 kPa, but the results from the relative humidity sensor provided suctions of 10 000 kPa to 350 000 kPa. These results were in line with previously published bentonite clay suction results, indicating that, at high suctions, GCL suction is governed by the bentonite clay.

Based on the success of the dual HCT–RH technique method for establishing a drying water retention curve for GCL, the same method could now be applied to investigate the wetting curve of GCLs, and the magnitude of variation between GCL types.

## NOTATIONS

Basic SI units are given in parentheses.

- $s_t$  total suction (Pa)
- $R$  gas constant (J/(kmol K))
- $T$  absolute temperature (K)
- $M_w$  molecular weight of water (kg/mol)
- RH relative humidity (dimensionless)
- $\rho_w$  weight of water (kg/m<sup>3</sup>)

## ACKNOWLEDGEMENTS

The study reported herein was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Ontario Centres of Excellence, and Terrafix Geosynthetics Inc. The authors are grateful to their industrial partners: Terrafix Geosynthetics Inc., Solmax International, Ontario Ministry of Environment, AECOM, AMEC Earth and Environmental, Golder Associates Ltd, and CTT group. The funding for the equipment used, provided by the Canada Foundation for Innovation, the Ontario Innovation Trust and NSERC, is also gratefully acknowledged.

## REFERENCES

- Agus, S. S. & Schanz, T. (2005). Comparison of four methods for measuring total suction. *Vadose Zone Journal*, **4**, No. 4, 1087–1095.
- Agus, S. S. & Schanz, T. (2007). Errors in total suction measurements. *Experimental Unsaturated Soil Mechanics*, Agus, S. S. and Schanz, T. Editors, Springer, pp. 59–70.
- Andrejkovicova, S., Rochab, F., Janotkac, I. & Komadela, P. (2008). An investigation into the use of blends of two bentonites for geosynthetic clay liners. *Geotextiles and Geomembranes*, **26**, No. 5, 436–445.
- ASTM D5298. Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. ASTM International, West Conshohocken, PA, USA.
- Barroso, M., Touze-Foltz, N. & Saidi, F. K. (2006). Validation of the use of filter paper suction measurements for the determination of GCL water retention curves. *Proceedings of the 8th International Conference on Geosynthetics*, Yokohama, pp. 171–174.
- Bouazza, A. (2002). Geosynthetic clay liners. *Geotextiles and Geomembranes*, **20**, No. 1, 3–17.
- Bouazza, A., Vangpaisal, T., Abuel-Naga, H. & Kodikara, J. (2008). Analytical modelling of gas leakage rate through a geosynthetic clay liner–geomembrane composite liner due to a circular defect in the geomembrane. *Geotextile and Geomembranes*, **26**, No. 2, 122–129.
- Bouazza, A., Zornberg, J. G., McCartney, J. S. & Nahlawi, H. (2006). Significance of unsaturated behaviour of geotextiles in earthen structures. *Australian Geomechanics*, **41**, No. 3, 133–142.
- Brachman, R. W. I. & Gudina, S. (2008). Geomembrane strains and wrinkle deformations in a GM/GCL composite liner. *Geotextiles and Geomembranes*, **26**, No. 6, 488–497.
- Daniel, D. E., Shan, H.-Y. & Anderson, J. D. (1993). Effects of partial wetting on the performance of the bentonite component of a geosynthetic clay liner. *Geosynthetics '93*, IFAI, St Paul, MN, Vol. 3, pp. 1482–1496.
- Fredlund, D. G. & Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*, Wiley, New York.
- Gassner, F. (2009). Field observation of GCL shrinkage at a site in Melbourne, Australia. *Geotextiles and Geomembranes*, **27**, No. 5, 406–408.
- Greenspan, L. (1977). Humidity fixed points of binary saturated aqueous

- solutions. *Journal of Research of the National Bureau of Standards. Section AL Physics & Chemistry*, **81A**, No. 1, 89–96.
- Guyonnet, D., Touze-Foltz, N., Norotte, V., Pothier, C., Didier, G., Gailhanou, H., Blanc, P. & Warmont, F. (2009). Performance-based indicators for controlling geosynthetic clay liners in landfill applications. *Geotextiles and Geomembranes*, **27**, No. 5, 321–331.
- JNC (2000). *H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan. Supporting Report 2: Repository Design and Engineering Technology*, JNC TN1410 2000-001. Japanese Nuclear Cycle Development Institute, Ibaraki, Japan.
- Koerner, R. M. & Koerner, G. R. (2005). In-situ separation of GCL panels beneath exposed geomembranes, *Geotechnical Fabrics Report*, **23**, No. 5, 34–39.
- Lake, C. B. & Rowe, K. R. (2000). Swelling characteristics of needlepunched, thermally treated geosynthetic clay liners. *Geotextiles and Geomembranes*, **18**, No. 2–4, 77–101.
- Likos, W. J. & Lu, N. (2003). Automated humidity system for measuring total suction characteristics of clay. *Geotechnical Testing Journal*, **26**, No. 2, 1–12.
- Lu, N. & Likos, W. J. (2004). *Unsaturated Soil Mechanics*. Wiley, New York.
- Marcial, D., Delage, P. & Cui, Y. J. (2002). On the high stress compression of bentonites. *Canadian Geotechnical Journal*, **39**, No. 4, 812–820.
- Marinho, F. A. M., Take, W. A. & Tarantino, A. (2008). Measurement of matric suction using tensiometric and axis translation techniques. *Geotechnical and Geological Engineering*, **26**, No. 6, 615–631.
- Müller, W., Jakob, I., Seeger, S. & Tatzky-Gerth, R. (2008). Long-term shear strength of geosynthetic clay liners. *Geotextiles and Geomembranes*, **26**, No. 2, 130–144.
- Oliveira, O. M. & Marinho, F. A. M. (2008). Suction equilibration time for a high capacity tensiometer. *Geotechnical Testing Journal*, **31**, No. 1, 1–5.
- Rayhani, M. H. T., Rowe, R. K., Brachman, R. W. I., Siemens, G. & Take, W. A. (2008). Closed-system investigation of GCL hydration from subsoil. *61st Canadian Geotechnical Conference*, Edmonton, pp. 324–328.
- Ridley, A. M. (1993). *The Measurement of Soil Moisture Suction*, PhD dissertation, Imperial College, University of London.
- Ridley, A. M. & Wray, W. K. (1996). Suction measurement: a review of current theory and practices. *Proceedings of the 1st International Conference on Unsaturated Soils*, Paris, 1995, Balkema, Rotterdam, pp. 1293–1322.
- Ridley, A. M., Dineen, K., Burland, J. B. & Vaughan, P. R. (2003). Soil matrix suction: some examples of its measurement and application in geotechnical engineering. *Géotechnique*, **53**, No. 2, 241–253.
- Rowe, R. K., Quigley, R. M., Brachman, R. W. I. & Booker, J. R. (2004). *Barrier Systems for Waste Disposal Facilities*, Taylor & Francis (E & FN Spon), London, 587 pp.
- Saidi, F., Touze-Foltz, N. & Goblet, P. (2008). Numerical modelling of advective flow through composite liners in case of two interacting adjacent square defects in the geomembrane. *Geotextiles and Geomembranes*, **26**, No. 2, 196–204.
- Siemens, G. A. & Blatz, J. A. (2005). Soil suction measurement using the Xeritron sensor in two different types of infiltration tests on a swelling soil. *International symposium on advanced experimental unsaturated soil mechanics*, Trento, pp. 23–26.
- Southen, J. M. & Rowe, R. K. (2007). Evaluation of the water retention curve for geosynthetic clay liners. *Geotextiles and Geomembranes*, **25**, No. 1, 2–9.
- Spanner, D. C. (1951). The Peltier effect and its use in the measurement of suction pressure. *Journal of Experimental Botany*, **2**, No. 2, 145–168.
- Stannard, D. I. (1992). Tensiometers-theory, construction and use. *Geotechnical Testing Journal*, **15**, No. 1, 48–58.
- Take, W. A. & Bolton, M. D. (2003). Tensiometer saturation and the reliable measurement of soil suction. *Géotechnique*, **53**, No. 53, 159–172.
- Tang, A. M. & Cui, Y. J. (2005). Controlling suction by the vapour equilibrium technique at different temperatures and its application in determining the water retention properties of mx80 clay. *Canadian Geotechnical Journal*, **42**, No. 1, 287–296.
- Tarantino, A., Romero, E. & Cui, Y. J. (eds). (2009). *Laboratory and Field Testing of Unsaturated Soils*, Springer, New York, NY, USA.
- Thiel, R. & Richardson, G. (2005). *Concern for GCL shrinkage when installed on slopes, JGRI-18 at GeoFrontiers*, GII Publications, Folsom, PA, USA paper 2.31.
- Thiel, R., Giroud, J. P., Erickson, R., Criley, K. & Bryk, J. (2006). Laboratory measurements of GCL shrinkage under cyclic changes in temperature and hydration conditions. *8th International Conference on Geosynthetics*, Yokohama, Japan 1, pp. 21–44.
- Villar, M. V. & Lloret, A. (2004). Influence of temperature on the hydro-mechanical behaviour of a compacted bentonite. *Applied Clay Science*, **26**, Nos 1–4, 337–350.
- Vukelić, A., Szavits-Nossan, A. & Kvasnicka, P. (2008). The influence of bentonite extrusion on shear strength of GCL/geomembrane interface. *Geotextiles and Geomembranes*, **26**, No. 1, 82–90.
- Young, D. F. (1968). Effect of time-dependent stenosis on flow through a tube. *Journal of Engineering for Industry, Transactions of American Society of Mechanical Engineers*, **90**, 248–254.

**The Editor welcomes discussion on all papers published in Geosynthetics International. Please email your contribution to [discussion@geosynthetics-international.com](mailto:discussion@geosynthetics-international.com) by 15 April 2011.**