SIGNIFICANCE OF UNSATURATED BEHAVIOUR OF GEOTEXTILES IN EARTHEN STRUCTURES

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ABSTRACT

The unsaturated hydraulic characterisation of nonwoven geotextiles presented in this paper shows that they only require suctions between 0.8 kPa and 1.2 kPa to induce a rapid drop, of several orders of magnitude, in hydraulic conductivity. This implies that the inclusion of geotextiles in unsaturated earthen systems, for drainage or separation/filtration purposes, can potentially impede the flow of water and lead to a redistribution of the water content profile in the system. This latter aspect is the focus of this study. Geosynthetic drainage layers in contact with unsaturated soils were investigated using soil-geosynthetic columns where clay was in contact with a sand drainage material as well as with a drainage geocomposite layer (a geonet sandwiched between nonwoven geotextiles). The unsaturated drainage layers were found to impede downward flow of moisture consistent with the formation of a capillary break at the drainage layer-clay interface. Accumulation of moisture associated with an increase in moisture storage in the clay was observed, which progressed with depth until breakthrough of flow occurred into the drainage layer. Despite having significantly lower thickness than the sand capillary break, the geocomposite capillary break exhibited similar performance to the capillary break.

1 INTRODUCTION

Geosynthetics are thin polymeric materials that are widely used in geotechnical, environmental and hydraulic applications. There are numerous types of geosynthetics available to the design engineer for a diverse range of applications. Geosynthetics functions can be hydraulic (drainage, filtration and waterproofing) or mechanical (protection, reinforcement and separation). Among the different geosynthetic products, geotextiles are porous materials that present the widest range of properties. They can be used to fulfil most of the geosynthetics functions, except waterproofing, for many different geotechnical, environmental, and hydraulic applications. There are two types of geotextiles: woven geotextiles and nonwoven geotextiles. Woven geotextiles are manufactured using traditional weaving methods and are extensively used for reinforcement purposes. Nonwoven geotextiles are manufactured by needle punching or melt bonding and are extensively used for drainage, filtration, protection, and separation purposes (exception is for high tensile nonwoven geotextiles which can be used for reinforcement purposes). They are also used as part of drainage geocomposite materials, which in most cases consist of a geonet sandwiched between nonwoven geotextile filters.

The use of nonwoven geotextiles or geocomposites for filtration or drainage purposes instead of coarse grained soils is very attractive in applications such as paved and unpaved roads, landfill covers and liners, earth dams, embankments and retaining walls because of the relative ease of placement and gain in space. In such applications, the geotextile product must be selected so that: (1) the geotextile has adequate hydraulic conductivity to transmit water in the cross-plane and/or in-plane directions; (2) adjacent soil particles do not migrate across the geotextile layer and (3) the geotextile does not clog internally with soil fines that may be carried by fluid flows during the lifetime of the system. Well established design methods are available to ensure fulfilment of these criteria by assuming that the geotextile and soil are subjected to saturated flow conditions (e.g. Holtz *et al*., 1997, Fannin and Palmeira, 2002, Koerner, 2005). However, in most cases, these products are placed above the groundwater table where soil and geotextiles pores are filled with water and air (i.e. under unsaturated conditions). Therefore, it should be expected that the engineering properties of unsaturated earthen systems combining soils and geotextiles will be significantly influenced by the water storage characteristics of both the soil and the geotextile components. The water storage capacity of porous polymeric materials (e.g. geotextiles) can provide valuable information related to the stability of soil structures including retaining walls, slopes and embankments, flow and movement of water or contaminants through covers and lining systems for waste containment facilities and performance of roads and airport runways. One of the key components governing the behaviour of such structures is the water retention curve of the geotextile. The water retention can be described as the storage capacity of the geotextile as the water content changes when subjected to various values of suction (induced by the presence of negative pore water pressures).

The overall objective of this paper is to assess the hydraulic performance of geosynthetics in contact with unsaturated soils when used as drainage layers, separation layers, protection layers, or hydraulic barriers. In particular, this paper will provide an insight into the unsaturated hydraulic behaviour of non woven geotextiles and its effect on the progress of the wetting front in an earthen structure and the consequent redistribution of the water content profile caused by the presence of geotextiles.

2 UNSATURATED HYDRAULIC CHARACTERISTICS OF GEOTEXTILES

Several techniques are available to measure the geotextile water retention curves. These techniques include hanging column test (Stormont and Morris, 2000, Bouazza *et al.,* 2006, McCartney and Zornberg, 2007); a capillary rise test approach where a geotextile sheet is immersed in water at its base (Lafleur *et al.,* 2000, Bouazza *et al*., 2006); a suction plate apparatus based on the hanging column test procedure (Ho, 2000) and an outflow capillary pressure cell (Knight and Kotha, 2001; Nahlawi *et al*., 2006).

The water retention function plots the relationship between suction and water content. As water flows through the geotextile, the quantity of water entering the porous material may differ from the quantity of water exiting the material. Therefore, the water retention function gives an insight into a material's ability to retain or expel water. Figure 1 shows a typical variation of the volumetric water content against suction, obtained from hanging column tests, for two stand alone needle punched polyester non woven geotextiles (GT1, GT2) and a needle punched polypropylene non woven geotextile (GT3) from a geocomposite material typically used for drainage purposes.

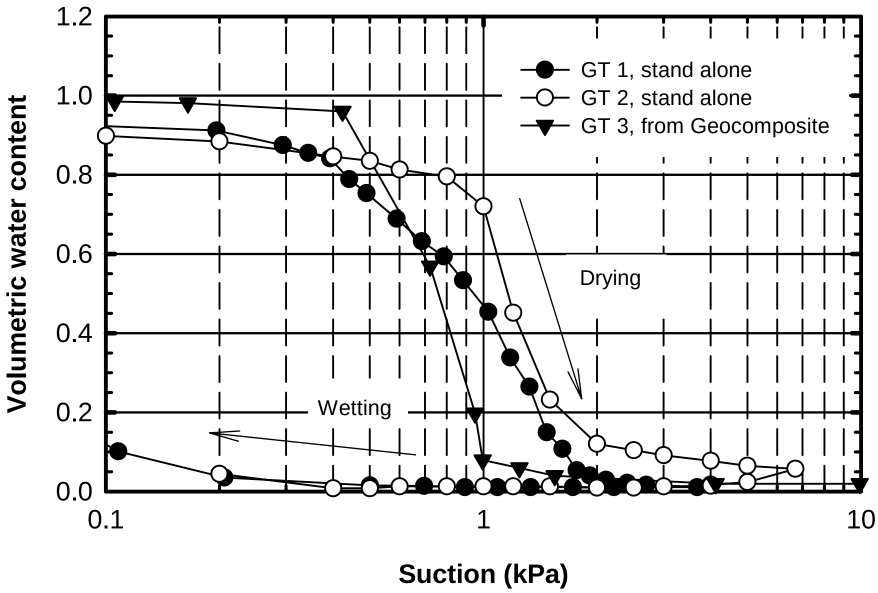

Figure 1: Geotextile water retention curves.

The geotextile retention curves (drying path) are characterized by a nearly constant volumetric water content up to an air entry point beyond which a sharp reduction in volumetric water content occurs. Much of the water held in the large pores of the geotextile can drain at very small suctions, explaining why there is a rapid decrease in volumetric content beyond the air entry value. The drying curve tends to level off at a residual volumetric water content value less than 10%. The air entry value for Geotextiles 1 (GT1) and 3 (GT3) was 0.4 kPa whereas a value of 0.9 kPa was found for Geotextile 2 (GT2). The difference in their entry values is due to their pore size and porosity, Geotextiles 1 and 3 are more porous than Geotextile 2 (porosity = 0.92 and 0.99 for GT1 and GT3, and 0.85 for GT2) and have a higher average pore size (O_{95} = 0.20 mm and 0.21mm for GT1 and GT3, respectively and O_{95}= 0.18 mm for GT2). Therefore, a lower suction pressure was needed to start their desaturation process whereas a higher suction pressure was required to desaturate Geotextile 2 which had a lower porosity and average pore size. The low volumetric water content residual values (less than 10%) indicate that the geotextiles contain very small amount of water when the suction is high (i.e. ≤ 10 kPa for geotextiles). The other primary variable for the geotextiles is the residual suction, which in the present case was found to be about 1 kPa to 1.8 kPa. It is interesting to note that the geotextile air entry values are similar to air entry values reported by Jury and Horton (2004) for coarse sands (0.5 kPa to 1 kPa); consequently their hydraulic behaviour should be expected to be similar to coarse soils. These values are also consistent with the findings of Iryo and Rowe (2003), who reported a variation of 0.4 kPa to 1.2 kPa for geotextile air entry values.

The wetting curve (for GT1 & GT2 only) is characterised by a different shape; it seems to stay almost flat up to a suction level where the water starts to flow through the geotextile. In other words the geotextiles remained impermeable to water until a very low suction (water entry value) where it then experiences an increase in volumetric water content. This means that water can only flow through the geotextile once the suction is lower than the water entry suction. Figure 3 shows that the water entry suction for both geotextiles is in the range of 0.2 kPa-0.3 kPa. These values are consistent with the findings of Iryo and Rowe (2003), who reported a range of water entry values for geotextiles between 0 and 0.8 kPa. Overall, Geotextile 1 seems to be slightly less hydrophobic than Geotextile 2 due to its larger average pore size. Hysteresis is present in both geotextiles, due to air being entrapped in the geotextile voids on the wetting path; this phenomenon is known to happen in other types of porous media (Fredlund and Rahardjo, 1993). At very low suction the volumetric water content due to wetting is only about 10% of full volumetric water content prior to drying. This suggests that for a geotextile to achieve full saturation, positive pore water pressures would be required.

In general, the measurement of water retention is significantly easier than the measurement of unsaturated hydraulic conductivity. For this reason, the common engineering practice is to use parameters resulting from fitting a water retention function, such as the van Genuchten function given by Equation 1 (van Genuchten 1980), to measured water retention data to predict unsaturated hydraulic conductivity relationships. This task can also be accomplished using numerical codes (HYDRUS 1D, RETC, etc.) or other mathematical functions such as the Brook and Corey equation (Brooke and Corey, 1964) among many others.

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left((\alpha\psi)^n\right)\right]^{\left(1-\frac{1}{n}\right)}} \qquad (1)$$

where θ_r and θ_s are the residual and saturated volumetric water contents, respectively, ψ is the pressure head or suction, and α and n are empirical constants determined by nonlinear regression.

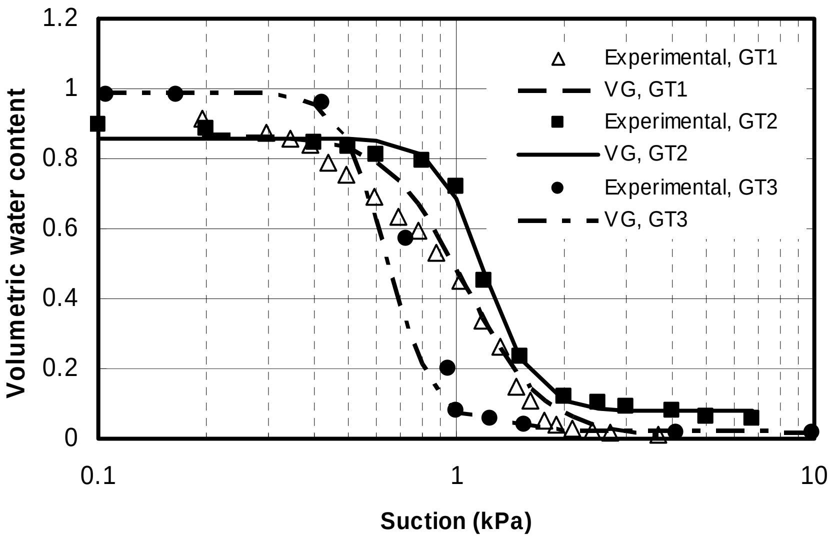

Figure 2: Geotextile, drying path, water retention curves fitting using the van Genuchten (VG) equations.

The above equation was fitted to the measured water retention data, on the drying path, given in Figure 1; the fitted retention curves are shown in Figure 2. There is close agreement between the water retention curve calculated using the van Genuchten equation and the measured retention data indicating that the equation is suitable for geotextiles. A summary of the fitted parameters to the geotextile water retention curves (on the drying path) is presented in Table 1. It should also be highlighted that the same approach can be used to curve fit the retention data on the wetting path and determine the corresponding Van Genuchten parameters.

Table 1: van Genuchten parameters from curve fits (drying path).

Materials	θ_s	θ_r	α (kPa^{-1})	n
Geotextile GT1	0.866	0.004	1.030	4.330
Geotextile GT2	0.857	0.078	0.850	7.01
Geotextile GT3	0.990	0.020	1.569	7.00

The values shown in Table 1 are within the range reported by Stormont and Morris (2000), Iryo and Rowe (2003), and Cartaud *et al.* (2005) for non woven geotextiles. As reported by Stormont and Morris (2000), the large values of θ_s are consistent with the large porosities of non woven geotextiles. The low values of θ_r indicate that the geotextiles contain very small amount of water when the suction is high (i.e. ≤ 10 kPa for geotextiles). The α values are consistent with coarse soils. The large value of n is consistent with the rapid decrease of volumetric content observed over a small variation in suction which is again typical of coarse soils.

Experimental direct determination of the unsaturated hydraulic conductivity function of geotextiles is difficult to conduct and is time consuming. However, it can be obtained indirectly from the water retention curve using a closed form analytical equation proposed by van Genuchten (1980) as follows:

$$k\left(\psi\right) = k_s \frac{\left[1-(\alpha\psi)^{n-1}\left[1+(\alpha\psi)^{n}\right]^{-m}\right]^2}{\left[1+\left(\alpha\psi\right)^{n}\right]^{m/2}} \quad \textbf{(2)}$$

where m = 1-1/n or 1-1/2n and k_s is the saturated hydraulic conductivity.

The *k*-function curves (drying path) obtained by the above equation are shown in Figure 3. It is interesting to note the predictive hydraulic conductivity functions indicate that the three geotextiles require suctions between 0.8 kPa and 1.2 kPa to induce a rapid drop in hydraulic conductivity. This indicates that the geotextiles will be able to drain/filter water at very low suctions (i.e. < 1.2 kPa), whereas an increase in suction will result very rapidly in a much lower water drainage/ filter capacity.

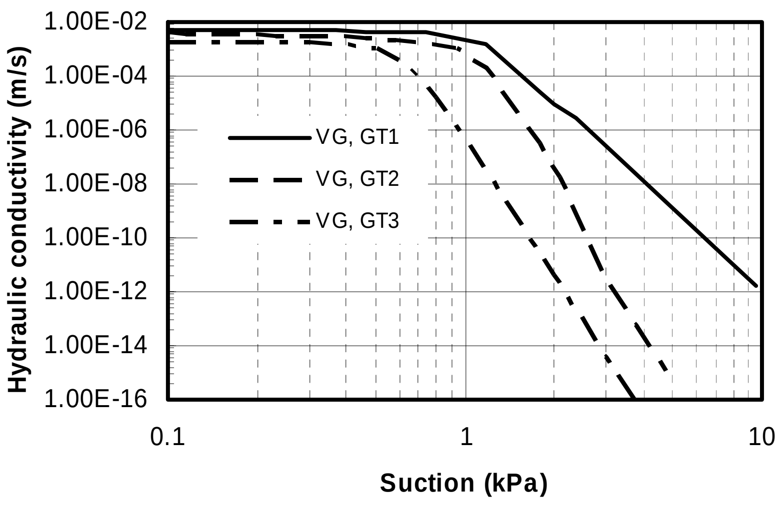

Figure 3: Geotextiles hydraulic functions.

The partially saturated condition of geotextiles under relatively low suction has important implications to the hydraulic performance of geotextiles, as shown earlier. A consequence of low hydraulic conductivity of the geotextile may be ponding (or mounding) of infiltration water and generation of water pressures above the geotextile that could possibly weaken the earth structure. Therefore, if the inclusions of geotextiles reduce the ability for moisture to migrate as planned, they may not be accomplishing their intended purpose and could even worsen rather than improve the earth system performance. This is supported by a case study reported by Richardson (1997) who describes the failure of a side-slope in a landfill cover system due to a capillary break developed over a geotextile. The capillary break impeded moisture movement, leading to an increase in soil pore pressures, loss of soil strength and eventual failure.

3 GEOTEXTILES AND UNSATURATED SOILS

Many design applications involving earth structures have geotextiles placed in contact with unsaturated soils, in some cases for much of their design life. In this respect, quantification of the hydraulic performance of the geotextiles and their interaction with the surrounding soils is crucial to the serviceability and maintenance of a given earthen structure. Equally important is the assessment of the unsaturated hydraulic characteristics of the soils in direct contact with the geotextiles. Considering the differences in both materials, it should be expected that their unsaturated hydraulic properties to affect the overall hydraulic performance of earthen systems because of the possible redistribution of the water content profile.

Two soils were used in the present testing program. A low plasticity clay was used as a relatively low hydraulic conductivity material (k_s= 1.2x10^{-6} m/s). For all tests, the clay was statically compacted to a relative compaction of 75 % in relation to the maximum dry density of 1902 kg/m^3. A coarse sand was used for comparison with geosynthetic drainage layers as it has a high hydraulic conductivity material (k_s= 5.3x10^{-4} m/s), representative of conventional drainage layers. In all tests, the sand was placed at a void ratio corresponding to a relative density of 50% (e_{max} = 0.78, e_{min} = 0.56). Coarse gravel with high hydraulic conductivity (k_s= 1x10^{-4} m/s) was used as a foundation layer. The geocomposite drainage layer used in this study consists of a geonet sandwiched between two nonwoven geotextiles (k_{sGT}=1.9x10^{-3} m/s). The grain size distribution for the clay and sand are shown in Figure 4, along with the apparent opening size (AOS) of the nonwoven geotextile component (GT3) of the geocomposite material. This figure indicates that the clay material has a wide range of particle sizes and should retain significant volume of water even when unsaturated. The sand is poorly graded, with a large fraction of coarse particles, suggesting that it will drain rapidly. According to Carroll's criterion (AOS < 2.5d_{85}), the geotextile is an acceptable filter for both the silt and the sand (Koerner, 2005).

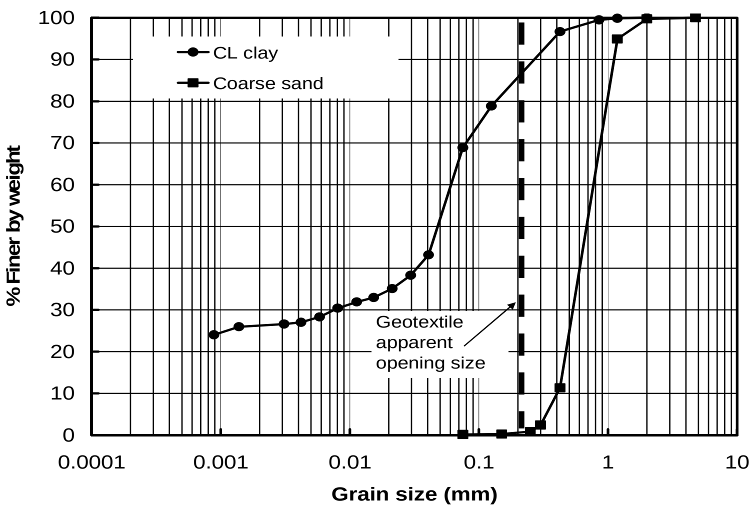

Figure 4: Comparison between the clay and sand grain size distributions and the geotextile apparent opening size.

Although this study involves infiltration into dry soil following the wetting-path of the soil water retention curve, the drying-path defined in this paper can still be used to highlight important hydraulic differences between the materials. Figure 5 shows the water retention data of the three materials along with the best-fit water retention curves defined using the van Genuchten model (van Genuchten, 1980) as discussed in the previous section. The hydraulic conductivity functions shown in Figure 6 were defined using the water retention curve parameters and the saturated hydraulic conductivity (k_s) values obtained from flexible wall permeameter tests for both the clay and the sand. The geotextile saturated hydraulic conductivity was based on the permittivity measurement as supplied by the geocomposite manufacturer. The results in Figure 6 indicate that as suction increases, the hydraulic conductivity values of the three materials decrease at different rates.

The *k*-functions in Figure 6 indicate that a capillary break is likely at the interface between the clay and the nonwoven geotextile, as well as between the sand and the clay. While suction at an interface between two materials is the same, Figure 6 highlights that the three tested materials may have different hydraulic conductivities for a given value of suction, except when their curves intersect. Specifically, in vertical, downward flow through an initially dry (high suction) horizontally layered system, a capillary break will occur when the underlying layer has significantly lower hydraulic conductivity than the overlying layer. Water will not flow into the lower layer until the suction decreases to the value at which the conductivity of both layers is the same. This is the case for the interface between the clay and the sand or between the clay and the geotextile component of the geosynthetic drainage layer. Figure 5 indicates that as suctions increases from 1 kPa to 10 kPa, the geotextile and sand become highly unsaturated while the clay maintains a high degree of saturation. Likewise, Figure 6 indicates that the hydraulic conductivity values of the geotextile and sand decrease sharply with increasing suction, while that of the silt decreases more gently, intersecting the other two curves at suctions of about 1 kPa and 4.5 kPa, respectively.

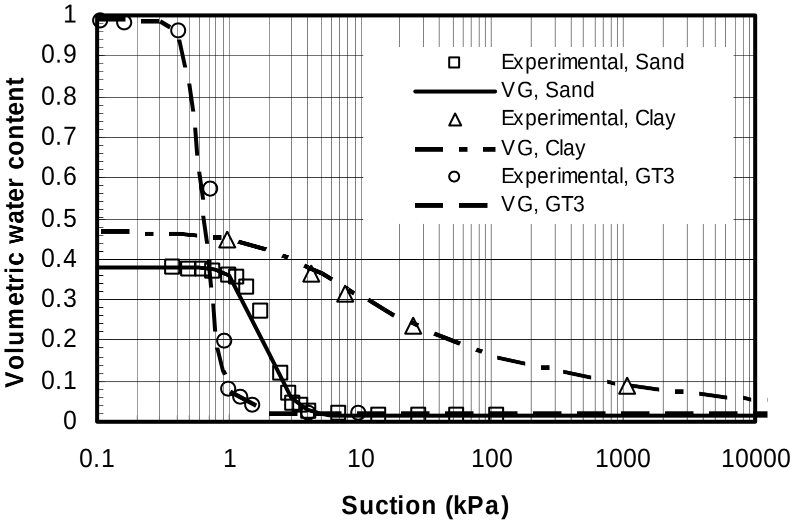

Figure 5: Soil and geocomposite hydraulic characteristics: Water retention curves (VG=van Genuchten equation).

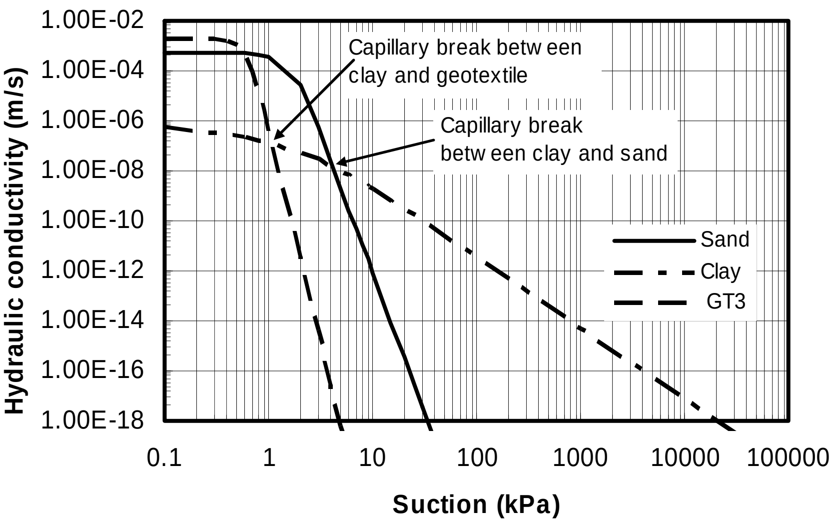

Figure 6: Soil and geocomposite hydraulic characteristics: Hydraulic conductivity functions (*k*-functions).

4 PRACTICAL IMPLICATION: CAPILLARY BREAK PHENOMENON

A typical situation encountered on site is the use of geosynthetic drainage layers. They typically consist of a combination of geosynthetics with the objectives of providing the functions of filtration, in-plane drainage and a separation or protection layer. They are being increasingly used as alternatives to conventional sand or gravel drains in landfills, roadway subgrades, mechanically stabilized walls and dams. The geosynthetic drainage layer configuration consists of a geonet for drainage sandwiched between nonwoven geotextile filters. The in-plane flow through geotextiles and geonets can be reasonably well defined if the soil overlying the geosynthetic drainage layer is saturated (Giroud *et al.*, 2000). However, the overlying soil is often under unsaturated conditions and, in this case, a capillary break may develop within the soil layer, as discussed in the previous section. This can lead to build up of moisture at the interface between the soil and the geosynthetic material. Understanding of this mechanism is relevant in aspects such as quantification of the impinging flow used in the design of drainage layers, performance evaluation of systems used for quantifying percolation through alternative landfill covers, and interpretation of the information gathered in leak detection systems. Consequently, nonwoven geotextiles and drainage geocomposites were evaluated experimentally using infiltration tests involving geosynthetic-soil columns and compared to infiltrations tests in clay-sand columns (McCartney *et al*., 2005).

A capillary break is evidenced as a cease in movement of the wetting front (the depth to which water has infiltrated), and storage in the overlying material of moisture in excess of the amount that would be stored when draining under gravity. When a critical suction is reached, the conductivity of the two materials reaches the same value and water breaks through the interface. This critical suction is referred to as the breakthrough suction. In order to quantify the unsaturated interaction between conventional and geosynthetic drainage layers with low hydraulic conductivity soils, geosynthetic-soil profiles were constructed using different soil and geosynthetic materials horizontally layered in cylindrical tubes with a relatively large diameter (200 mm). Figure 7 shows a schematic view of two profiles that have been tested as part of this study.

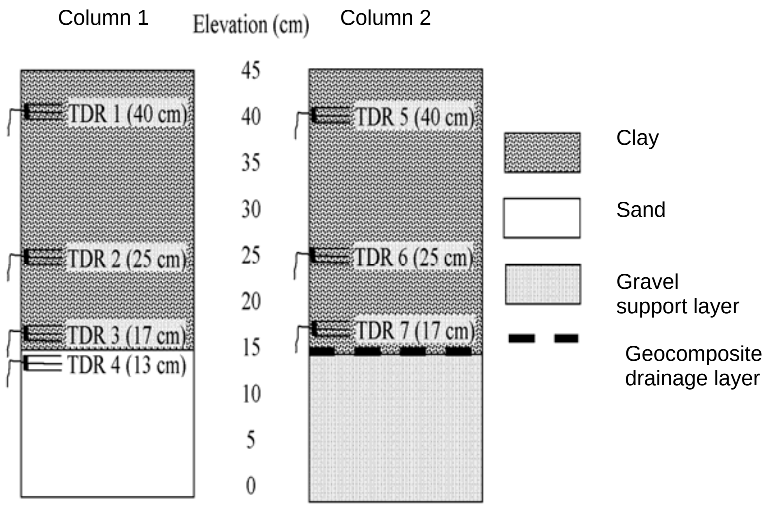

Figure 7: Schematic view of infiltration columns.

Profile 1 (Column 1) includes a conventional drainage layer, consisting of clay placed over a sand layer. A 150 mm layer of sand was pluviated to reach the target relative density of 50%. A 300 mm layer of clay was placed in 50 mm lifts over the sand layer using static compaction to the target dry unit weight of 75% of the maximum dry unit weight based on the standard proctor and a gravimetric moisture content of 8% (volumetric moisture content of 12%). Profile 2 includes a geosynthetic drainage layer involving clay placed over a geocomposite, which in turn rests on a gravel foundation layer. A 300 mm clay layer was placed in 50 mm lifts using the same procedures as for Profile 1. Volumetric moisture content values were continuously measured throughout the vertical soil profiles using time domain reflectometry technology (TDR). Figure 7 shows the location of the TDR probes in both columns. In Column 1 four TDR probes were used. Probes were placed 20 mm above and below the interface between the clay and the sand to measure the behaviour at the interface. In Column 2 three probes were used, including a probe located 20 mm above the geocomposite. A peristaltic pump was used to apply a relatively constant flow rate of 0.4 cm^3/s to the top surface of the clay. This corresponds to a Darcian velocity of 2.06×10^{-7} m/s. The flow rate was selected to be less than the saturated hydraulic conductivity of the clay to ensure unsaturated conditions.

Figure 8 shows the change in water content at four depths in Profile 1 (Column 1). This figure indicates that the sand is initially very dry, at a volumetric moisture content of approximately 5%. At this moisture content, the sand has low hydraulic conductivity. The clay soil is initially at a volumetric moisture content of approximately 12% throughout the entire thickness of the profile. The volumetric moisture content measured by TDR 1 (near the soil surface) increases to approximately 25% as the moisture front advances through the clay. Similarly, the volumetric moisture content measured by TDR 2 increases to 25% after a period of about 5000 minutes. The volumetric moisture content measured by TDR 3 increases to 25%, similar to TDRs 1 and 2. However, TDR 3 shows a continued increase in moisture content to approximately 38%. Also, after approximately 7000 minutes TDR 2 begins to show an increase in a similar fashion as TDR 3. This behaviour suggests that the wetting front reached the sand interface, but moisture accumulated above the interface instead of flowing directly into the sand layer. After the clay reached a volumetric moisture content of 38% at the interface, the volumetric moisture content in the sand layer measured by TDR 4 increased rapidly to 26%. The timing of the increase in volumetric moisture content in the sand layer was consistent with the collection of outflow at the base of the profile, which occurred after approximately 9000 min. The performance of Profile 1 is consistent with the development of a capillary break, and indicates that the clay layer has a volumetric moisture content of approximately 36% at breakthrough. The clay water retention curve shown in Figure 5 indicates that this volumetric water content corresponds to a suction of approximately 5 kPa. This suction is consistent with the breakthrough suction value at which the *k*-functions of the clay and sand intersect, as shown in Figure 6.

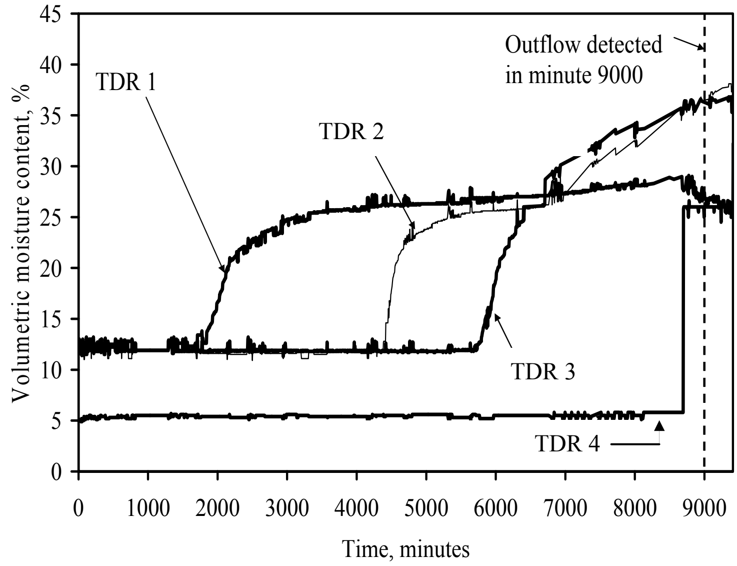

Figure 8: Volumetric moisture content with depth in Column 1.

Figure 9 shows the change in volumetric water content at three depths in the clay in Profile 2 (Column 2). Although similar behaviour as Profile 1 is noted, the wetting front progresses faster through Profile 2. This is because of a clog that was noted in the water supply tube to Profile 1 after the first 300 minutes of testing. However, comparison between the two profiles is still possible. The volumetric moisture content in the clay in Profile 2 is 12% at the beginning of testing. The volumetric moisture content recorded by TDR 5 (near the soil surface) increases to approximately 25% after 2000 minutes. After approximately 3500 minutes, the volumetric moisture content measured by TDR 6 also increases to approximately 25%. Unlike the other two TDRs, the volumetric moisture content measured by TDR 7 (near the geocomposite) shows a continued increase in moisture content to approximately 40%. After TDR 7 shows an increase in volumetric moisture content, the volumetric moisture content recorded by TDRs 5 and 6 also increase from 25% to 40%. This behaviour suggests that a capillary break and storage of water over the geosynthetic interface also occurs in Profile 2. Outflow from Profile 2 was detected after 8180 min, indicating that the breakthrough of the capillary break occurred at a volumetric moisture content of approximately 40%. The clay water retention curve shown in Figure 5 indicates that this corresponds to a suction of about 3 kPa. This suction value is consistent with the intersection of the *k*-functions for the clay and the geotextile given in Figure 6.

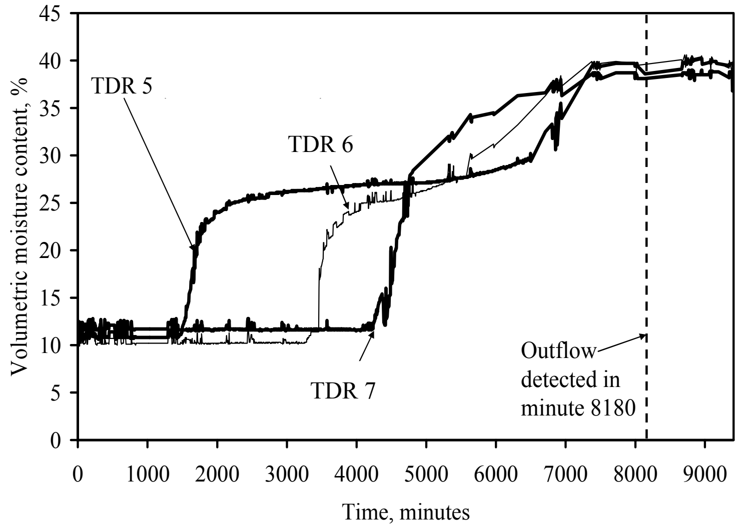

Figure 9: Volumetric moisture content with depth in Column 2.

The results in Figures 8 and 9 indicate that similar behaviour can be expected from both conventional granular drains and geosynthetic drainage layers overlain by unsaturated soil. The moisture front advance was indicated by an increase in volumetric moisture content within the profile to approximately 25% (the moisture content associated with the impinging flow rate). However, as the wetting front reached the interfaces, the unsaturated drainage material created a barrier to flow, and water accumulated above the interfaces as indicated by an increase in volumetric moisture content to values ranging from 35% to 40%. Further, the soil above the interface began to store water to a height of at least 250 mm, indicated by an increase in volumetric moisture content measured by upper TDRs from 25% to approximately 35% to 40%. Although suction was not monitored, the shape of the water retention curve for the clay indicates that the suction can change significantly with small changes in moisture content near saturation. Accordingly, even though moisture remained relatively constant above the interface about 1000 minutes before breakthrough in both profiles, the suction was likely decreasing.

5 CONCLUSIONS

An experimental testing program was conducted on the unsaturated hydraulic behaviour of geotextiles and involved material characterisation and infiltration column tests on geosynthetic and sand drainage layers. The salient conclusions that can be drawn from this study are as follow:

- Nonwoven geotextiles have very low air entry values (0.4 kPa to 0.9 kPa), similar to coarse soils.
- The geotextiles water retention data demonstrates their hydrophobic nature; they are essentially non-conductive to water beyond suction heads of 0.2-0.3 kPa. The low volumetric water content residual values indicate that the geotextiles contain a very small amount of water when the suction is high (i.e. ≤ 10 kPa for geotextiles). Pore size and porosity seem to control both the desaturation and resaturation processes.
- The geotextiles hydraulic conductivity functions indicate that low suctions (0.8 kPa to 1.2 kPa) are needed to induce a rapid drop in hydraulic conductivity. This implies that geotextiles will be able to drain/filter water at very low suctions (i.e. < 1.2 kPa), whereas an increase in suction will result very rapidly in a much lower water drainage/ filter capacity.
- Geosynthetic drainage layers in contact with unsaturated soils behave similarly to conventional sand drainage layers, developing a capillary break that results in a barrier to flow and accumulation of water above the drainage interface.
- The capillary break water breakthrough suction was found to be approximately 3 kPa for the geosynthetic drainage layer and 5 kPa for the conventional sand layer. This is consistent with material hydraulic characterization.
- The unsaturated geosynthetic drainage layer led to an increase in moisture storage through the depth of the soil profile that is well above that expected for freely-draining soils (i.e. field capacity).

The phenomenon of a capillary break occurring between an unsaturated soil and an underlying geosynthetic drainage layer is a good example of the significance of the unsaturated properties of geosynthetics. Their capillary break behaviour has potential implications on the design of landfill leak detection systems, performance evaluation of alternative landfill cover systems, roadway designs using geosynthetic materials as sub-base separators and in mechanically stabilized earth walls constructed using low hydraulic conductivity backfill.

6 ACKNOWLEDGEMENTS

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