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Hydraulic Interaction between Geosynthetic Drainage Layers and Unsaturated Low Plasticity Clay

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ABSTRACT

This study focuses on the impact of soil density on the hydraulic interaction between unsaturated, low plasticity clay and geosynthetic drainage layers. The hydraulic interaction was evaluated using the system hydraulic conductivity, moisture retention curves, and moisture and suction profiles obtained during transient infiltration tests. The transient infiltration tests were performed on soil-geosynthetic profiles constructed within 203-mm diameter columns. The results of the infiltration tests indicate that the soil-geosynthetic interface is affected by the capillary break effect. In particular, the results indicate that loosely compacted clays have capillary breakthrough at smaller suctions than highly compacted clays. Also, the increase in moisture storage due to the capillary break was more pronounced for looser clays.

INTRODUCTION

Geosynthetic drainage layers are often used to provide drainage from soil profiles. For instance, geotechnical applications involving geosynthetic drainage layers include leachate collection and leak detection systems in landfills, lysimeters for performance evaluation of alternative landfill cover systems, sub-base drainage systems in roadways, and drainage systems for mechanically stabilized earth walls. For simplicity, designs for these systems assume that the geosynthetics and soil are saturated. This assumption implies that the hydraulic conductivity of the geosynthetic drainage layer is greater than that of the soil (Koerner *et al.* 2005). Water will drain from a saturated soil profile as soon as an infiltration front reaches the geosynthetic drainage layer. Designs for these systems that consider unsaturated behavior are more complex. In this case, hydraulic interaction between soils and geosynthetics depends on their respective relationships between hydraulic conductivity and suction (the K-function) and moisture content and suction (the water retention curve).

Due to the uniform and relatively large pore size of nonwoven geotextiles compared with that of most soils, water will drain from a geotextile more readily than from a soil for a similar suction. In fact, the geotextile will drain to residual saturation at suctions slightly greater than their air-entry value (Stormont *et al.* 1997; McCartney *et al.* 2005). This behavior has an important effect on the hydraulic interaction between unsaturated soils and geosynthetic drainage layers, as the hydraulic conductivity of a geotextile predicted from the shape of its water retention curve is negligible under such conditions. The most important implication of this behavior is that infiltration of water through an unsaturated soil into a nonwoven geotextile is influenced by the capillary break effect (McCartney *et al.* 2005). This effect prevents a measurable amount of water from flowing from the soil into the geotextile until reaching a critical suction. This critical suction, referred to as the water entry or breakthrough suction, occurs when the hydraulic conductivities of the two materials are similar. A capillary break is exhibited as an increase in moisture storage in excess of the volume that can be stored against the pull of gravity.

The goal of this study is to investigate the influence of soil density on the capillary break formed between a geosynthetic drainage layer and a low plasticity clay. To achieve this goal, standard hydraulic tests were conducted to evaluate the contrast in hydraulic properties of the two materials. Further, equipment was developed to measure moisture content and suction profiles during infiltration of water through soil-geosynthetic system. The moisture storage and suction at capillary breakthrough were then compared for systems with varying soil density.

MATERIALS

Geosynthetic Drainage Layer. The geosynthetic drainage layer used in this study is a GSE Fabrinet® geocomposite, which is composed of a 200-mil geonet sandwiched between two 6 oz/yd^2 nonwoven geotextiles (GSE 2004). The thickness of the geocomposite as a whole is 12.5 mm. The porosity of a nonwoven geotextile is necessary to calculate its degree of saturation from measured values of gravimetric moisture content (Stormont *et al.* 1997). The porosity is calculated as (Koerner 2005):

$$\eta = 1 - \frac{\mu}{t\rho_f} \qquad (1)$$

The nonwoven geotextile components of the geocomposite have a thickness t of 2.56 mm, a mass per unit area μ of 20 kg/m^2, and a fiber density ρ_f of 910 kg/m^3. The porosity of the nonwoven geotextiles was calculated to be 0.99.

Clay. The low plasticity clay (CL) used in this study has a specific gravity of 2.71, an average plasticity index of 12, and an average liquid limit of 27. In all tests in this study, the clay was placed at its optimum moisture content of 11.5%. Relative compaction (RC) values of 70, 80, and 90% with respect to the maximum dry density obtained from the standard Proctor test (1902 kg/m^3) were used in this study. These densities correspond to porosities of 0.51, 0.44, and 0.36. The compaction energy was controlled using a piston compactor. By varying the pressure and cross-sectional area of the compaction rod, different compaction energies were obtained. An RC of 70% was obtained using a pressure of 10 psi and a 40-mm diameter rod, an RC of 80% was obtained using a pressure of 15 psi and a 40-mm diameter rod, and an RC of 90% was obtained using a pressure of 15 psi and a 12.5-mm diameter rod.

Saturated Hydraulic Conductivity. The hydraulic conductivities of saturated soil and geosynthetic drainage layer (geocomposite) specimens were assessed using 71 mm-diameter flexible-wall permeameter tests. In addition, the hydraulic conductivities of layered soil-geocomposite systems were also assessed. The soil specimens in each test had a minimum height of 142 mm. Porous stone end platens were not used during measurement of the geocomposite's hydraulic conductivity, but were used for tests on the soil alone and on the soil-geocomposite systems. The specimens were back-pressure saturated with tap water. The soil was considered saturated when a B-value greater than 0.95 was measured. An effective stress of 7 kPa and a hydraulic gradient of 2 were used for all tests.

The results of the hydraulic conductivity testing program are summarized in Figure 1. A series system approach was used to separate the hydraulic conductivity of the porous stones ($3.5x10^{-3}$ m/s) from the hydraulic conductivities of the soil specimens. The hydraulic conductivity of the layered system was observed to be less than that of the individual components. This was not expected from the equivalent hydraulic conductivity calculated assuming a series system, also shown in Figure 1. This may be due to accumulation of fines near the geotextile interface. However, fines migration should not occur under the low gradients used in these tests. Nonetheless, the hydraulic conductivity is on the same order of magnitude as the soil and follows the same trend with relative compaction.

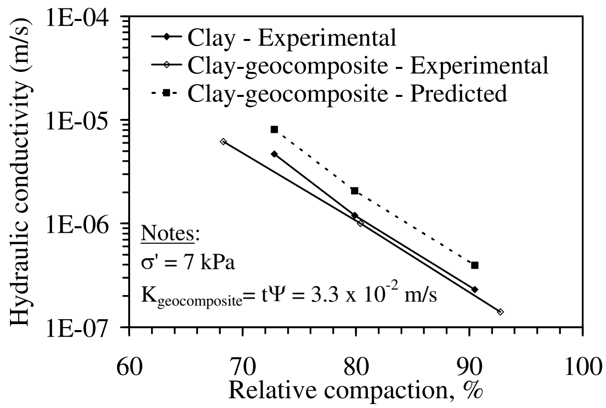


Figure 1: Hydraulic conductivity values of saturated specimens

Retention Curves. A hanging column apparatus was developed to define the water retention curves for specimens of low plasticity clay compacted to different densities and for the nonwoven geotextile component of the geosynthetic drainage layer. The hanging column, shown in Figure 2, consists of a Büchner funnel attached to a constant-head Mariotte bottle. A vacuum gauge was used to maintain bubbling during outflow from the specimen. The specimens were confined in a metal ring under a seating normal stress of 3.0 kPa, and were saturated by providing an upward flow of water to the specimen for at least 24 hours. A point on the WRC was determined by applying a suction to the specimen base via the hanging water column. The outflow was recorded with time. After reaching equilibrium, the total outflow during the increment was calculated, and this process was repeated for suctions. The moisture content at each increment was back-calculated using the final moisture content (determined destructively) and the outflow data.

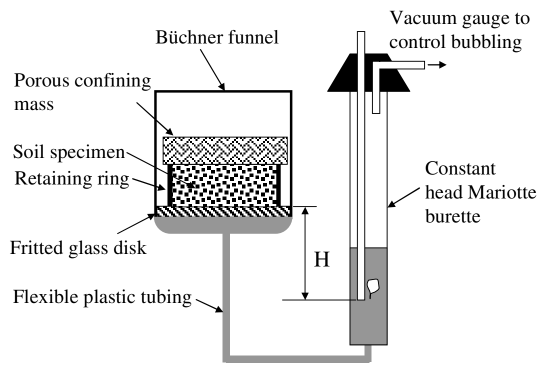


Figure 2: Hanging column apparatus

The hanging column proved useful to define the WRC for the nonwoven geotextile, as the suction range over which changes in moisture content occur is narrow (0 to 10 kPa). The drying and wetting curves for the nonwoven geotextile are shown in Figure 3(a). The nonwoven geotextile drained to residual conditions after reaching its air-entry suction of 0.2 kPa. Subsequent rewetting of the geotextile allowed measurement of a water-entry suction of 0.2 kPa. The drying WRCs for the compacted clays are shown in Figures 3(a) and 3(b). The looser soil has an air-entry suction of approximately 2 kPa, while the denser soils did not reach their air-entry suctions during the test. The K-functions predicted using the van Genuchten-Mualem model (1980) are shown in Figure 3(c). The geotextile is relatively non-conductive for suctions above 0.2 kPa, while the soils show a more gradual decrease in hydraulic conductivity. The density mainly affected the hydraulic conductivity at low suctions.

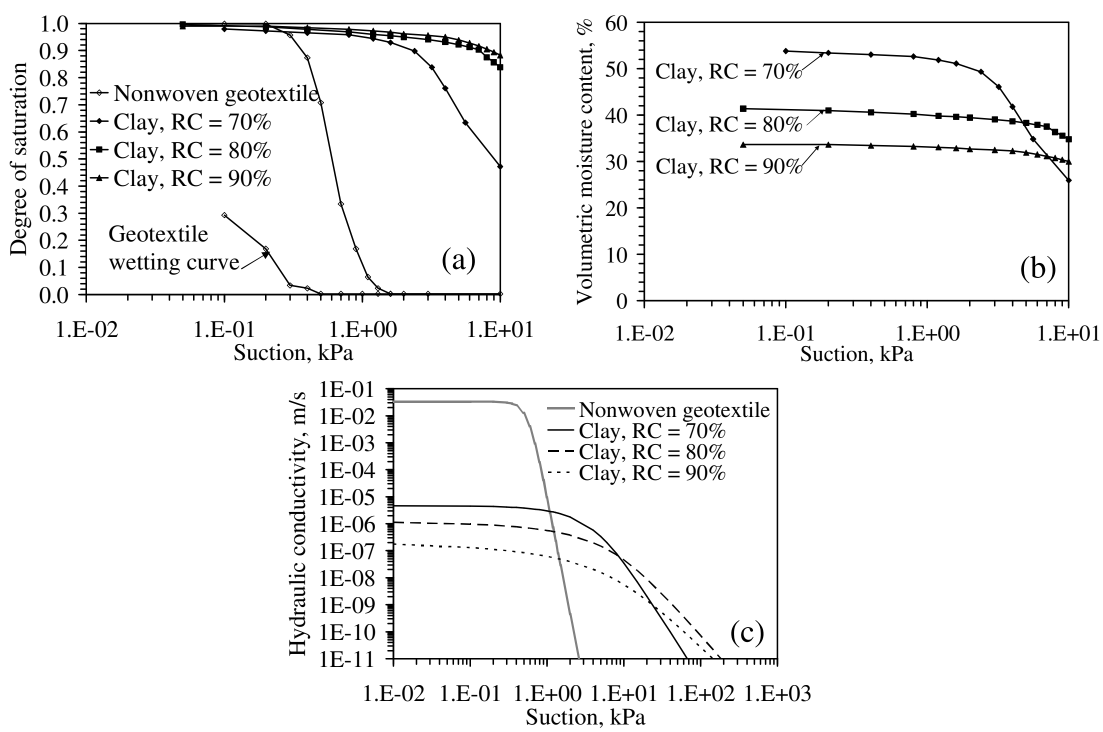


Figure 3: (a) WRC in saturation for geosynthetic drainage layer and clay; (b) WRC in moisture content for clay; (c) Predicted K-functions

EXPERIMENTAL TESTING PROGRAM

Soil Profiles. Three 125-mm tall soil-geosynthetic profiles with different soil densities were constructed in 203-mm cylindrical columns, as summarized in Table 1.

Table 1: Soil conditions in each soil-geosynthetic profile

Profile label	Relative compaction (%)	ρ_d (kg/m^3)	*e*	*n*
A	70.5	1340.0	1.02	0.51
B	79.9	1520.1	0.78	0.44
C	89.2	1696.6	0.60	0.37

A schematic of the testing frame is shown in Figure 4(a). The columns are clear PVC tubes mounted atop perforated acrylic discs, supported on their edges by a wooden platform. Tensioned wires are used to confine the permeameters to the acrylic discs. Outflow is measured using tipping bucket rain gauges mounted below the acrylic discs. A schematic of a profile is shown in Figure 4(b). Inflow is supplied to a reservoir on the surface of the soil profile via a peristaltic pump, and the water is distributed from the reservoir to the soil surface using a system of cotton fiber wicks.

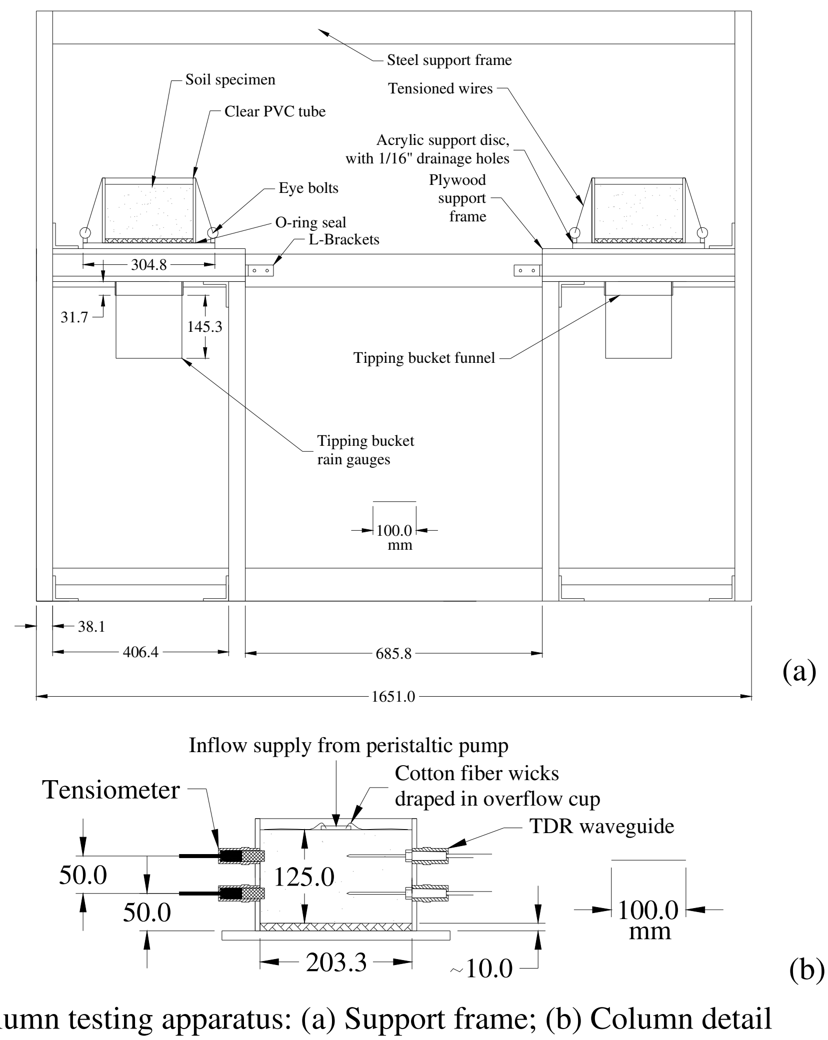


Figure 4: Column testing apparatus: (a) Support frame; (b) Column detail

Monitoring System. Volumetric moisture content was inferred during infiltration using either time domain reflectometry (TDR) or capacitance sensors. The MiniTRASE© TDR system, developed by SoilMoisture, Inc. was used in Profile B. ECH$_2$0-TE© capacitance sensors, developed by Decagon, Inc., were used in Profiles A and C. The two systems are used interchangeably at UT. Both systems were calibrated at three relative compaction values over a range of moisture content, as shown in Figures 5(a) and 5(b). The dielectric constant K_a in Figure 5(a) was calculated from the TDR waveform (SoilMoisture 1996), while the measured moisture content in Figure 5(b) is the raw output from the capacitance sensor. The calibration curves show the same trends with density.

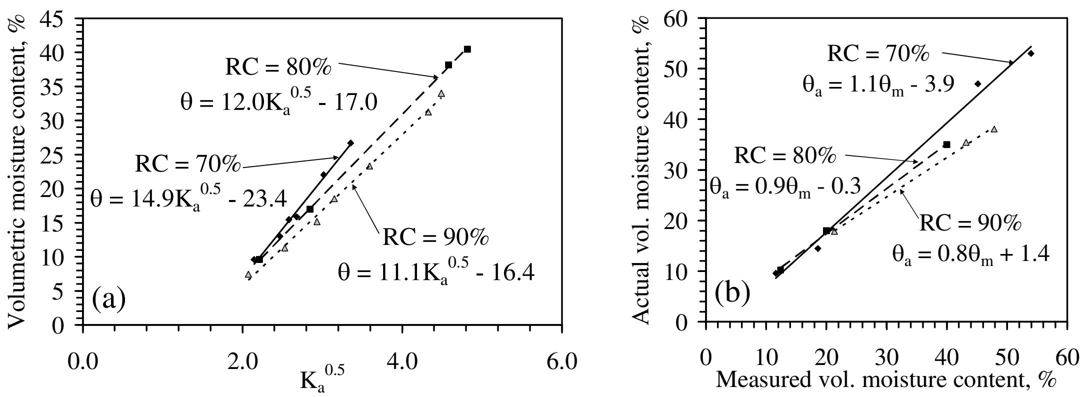


Figure 5: Calibration curves for the (a) TRASE and (b) ECH$_2$O-TE systems

Suction was measured using flushing tensiometers embedded in the walls of the PVC tubes. A schematic of the tensiometer is shown in Figure 6. A Druck PDCR 81 transducer was used to measure the pressure in a 1-ml water reservoir within the brass tensiometer housing. A 5-bar air entry porous stone was used as the interface between the soil and the water reservoir. As the soil in contact with the stone dries, water is drawn through the porous stone from the reservoir, creating a negative pressure. At equilibrium, this water pressure is assumed equal to the matric suction.

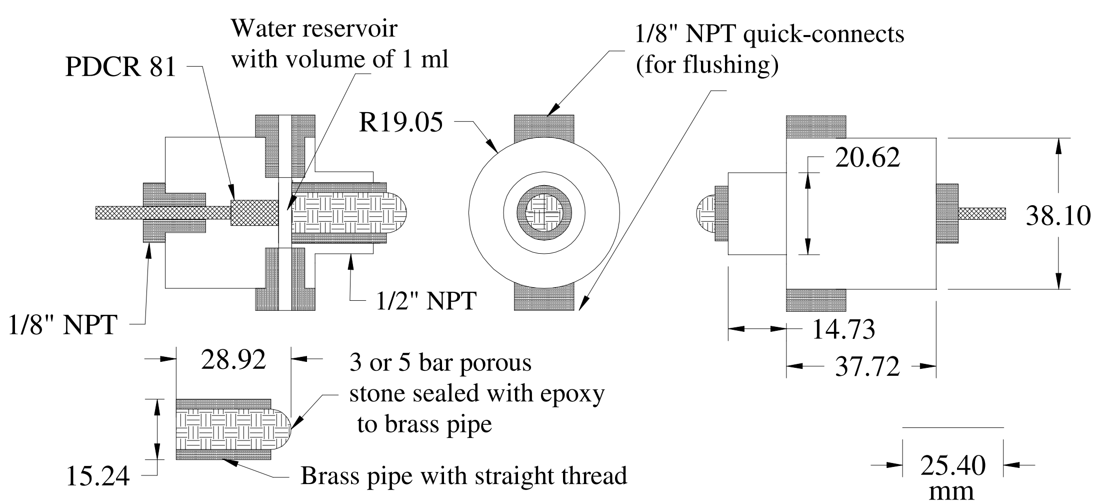
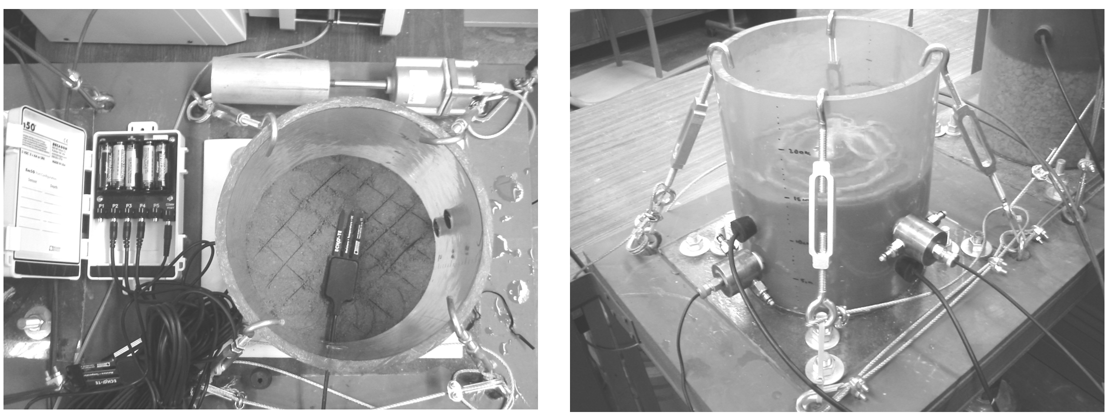


Figure 6: Schematic of the flushing tensiometer

The tensiometers were developed using the concepts described by Ridley and Burland (1995), but were adapted for long-term laboratory testing under low suctions (*i.e.*, less than 150 kPa). Specifically, the tensiometer has a continuous flushing channel that allows removal of air bubbles in the situation that cavitation occurs. The tensiometer has a ½” NPT fitting that allows it to be screwed into the side-wall of the column. The porous stone was sealed to the inside of a threaded brass pipe using epoxy, which allows the porous stones to be interchanged. The porous stones were initially saturated by boiling for 1 hour, after which they were screwed into the tensiometer. The tensiometer was then connected to a pressure cell and the flushing ports were connected to a pressurized, de-aired water tank. The pressure in the cell was increased to 50 psi, while the pressure applied to the flushing ports was maintained at 49 psi. After obtaining a constant hydraulic conductivity of approximately $3x10^{-7}$ m/s (for a 5-bar stone), the flushing ports were disconnected.

The soil was placed into the columns in 25 mm lifts using the piston compactor. The walls of the cylinder were greased to minimize side-wall leakage. The moisture sensors were placed in the middle of the second and fourth lifts, as shown in Figure 7(a). The tensiometers were screwed into the walls of the profile after the soil was compacted, as shown in Figure 7(b). The tensiometer required about 50 hours to equilibrate with the initial suction in the soil due to the low conductivity of the stone.



(a) (b)

Figure 7: (a) Soil profile during compaction; (b) Soil profile after compaction

Test Procedures. The tests involved applying a constant infiltration rate, measuring the volumetric moisture content and suction changes with time as the wetting front progresses through the soil. A peristaltic pump was used to supply a water flow rate of 0.001 cm^3/s to the top surfaces of the profiles. This flow rate corresponds to a Darcian discharge velocity of $3.5x10^{-8}$ m/s. The flow rate was selected to be less than the saturated hydraulic conductivity of the clay, to ensure unsaturated conditions. The profiles were covered with foil to minimize evaporation, but an air gap was left at the surface to allow air escape from the soil during infiltration. Testing was finished when the outflow discharge velocity was the same as the inflow discharge velocity.

RESULTS

The inflow supplied to the columns is shown in Figure 8(a). The pump malfunctioned briefly during testing of Profile A, but was resumed within 10 hours. The outflow from the columns is shown in Figure 8(b). The denser columns (RC = 80 and 90%) both reached capillary breakthrough (outflow from the soil into the geocomposite) in about 210 hours after the beginning of infiltration, while the loosest column (RC = 70%) did not reach breakthrough until 360 hours.

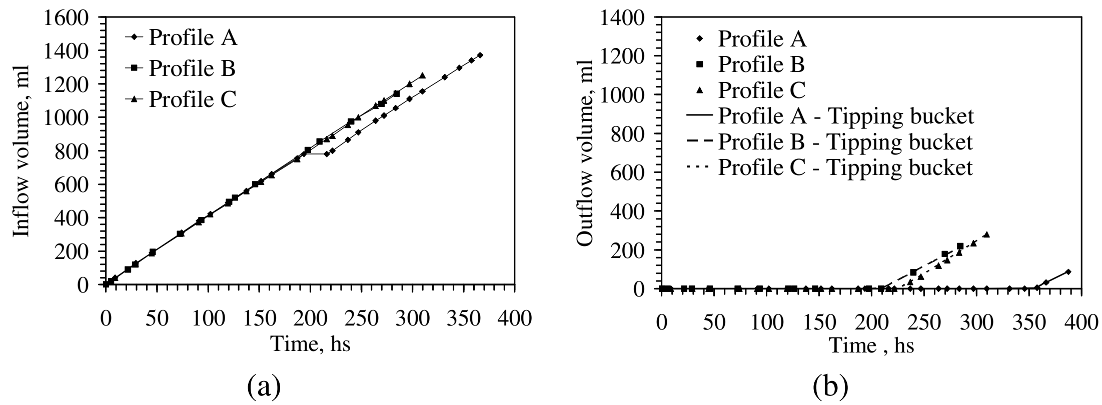


Figure 8: (a) Cumulative inflow; (b) Cumulative outflow

The results obtained from the tensiometer at a height of 50 mm from the base of Profile A are shown in Figure 9(a). It is assumed that the suction at the base of the profile is similar to that at 50 mm. This figure shows a gradual increase in water pressure to the initial suction in the soil (~60 kPa) until the wetting front passes the sensor, after which a drop in suction is observed. The degree of saturation results for Profile A are shown in Figure 9(b). The upper sensor indicates an increase in degree of saturation from 0.3 to 0.4 soon after infiltration started. The lower sensor also shows a similar increase after 45 hs, but afterwards shows a continued increase in moisture content. This increase in saturation at the base of the profile indicates an accumulation of water (*i.e.*, ponding) caused by the capillary break effect. The profiles were constructed only to measure the breakthrough suction, so the height of ponding above the interface could not be determined (ponding affected the entire height of the profile). The degree of saturation increased to 0.97 before breakthrough occurred. Although there is a significant change in the degree of saturation after ponding occurs, the change in suction is not as significant. The results obtained for Profile B are shown in Figures 9(c) and 9(d). Two tensiometers were used in this column, the results of which are consistent with the behavior noted in Profile A. The trends are also consistent with the degree of saturation measured using TDR. Capillary breakthrough occurred at a slightly higher suction, and a lower degree of saturation. The results obtained for Profile C are shown in Figures 9(d) and 9(f). The initial suction and the breakthrough suction were the highest for this profile due to the higher density. Further, the change in degree of saturation was less pronounced than the other profiles. Disassembly of the profiles showed that the clay in Profile A had a soft consistency, while the clays in the other profiles were relatively stiff despite having high moisture content. The moisture content and consistency were relatively uniform throughout the profiles, indicating that flow was relatively homogeneous.

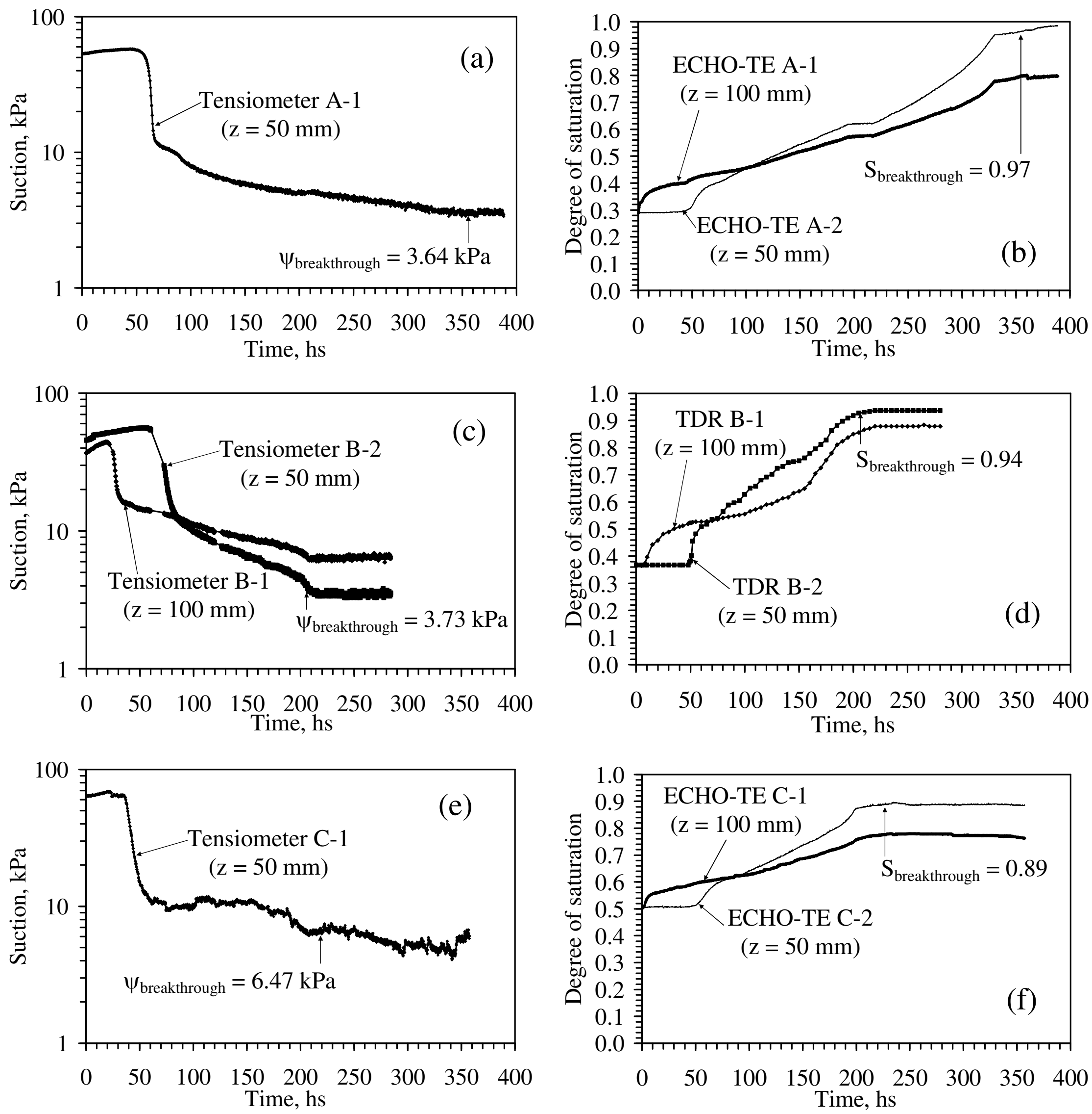


Figure 9: Profile A: (a) Suction; (b) Degree of saturation; Profile B: (c) Suction; Degree of saturation; Profile C: (a) Suction; (b) Degree of saturation

The values of suction at breakthrough summarized in Figure 10(a) indicate an increase in suction with relative compaction. These values are slightly larger than with the suction at which the WCR for the nonwoven geotextile transitions from residual to saturated conditions (0.2 to 0.3 kPa). However, the trend with density is consistent with the fact that the K functions of the soils cross that of the nonwoven geotextile at increasing suction values for increasing relative compactions. The effect of soil density on the moisture storage above the capillary break is shown in Figure 10(b). The loosely compacted soil (RC = 70%) is able to retain two times more water than its initial moisture storage. The moisture storage may govern the design of landfill covers, as water from large precipitation events can be stored in a thinner soil layer. Increased water storage may also affect stability, especially for loose systems.

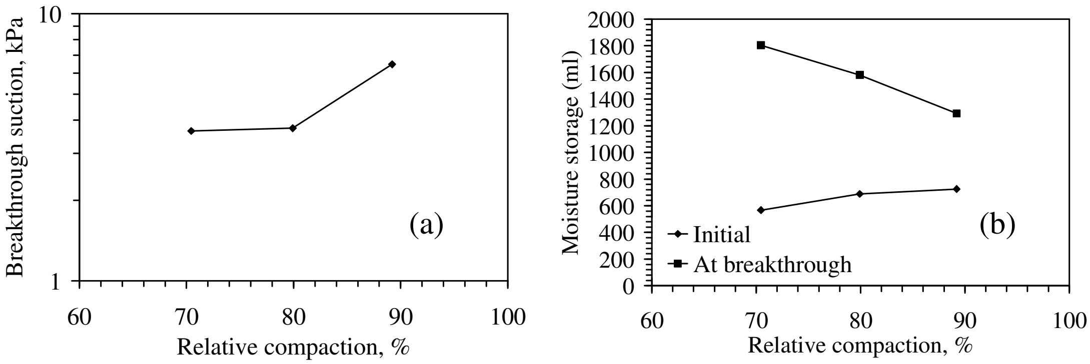


Figure 10: Effect of soil density: (a) Breakthrough suction; (b) Moisture storage

CONCLUSIONS AND DISCUSSION

The capillary break effect was observed during infiltration tests on low plasticity clays placed atop a geosynthetic drainage layer. The capillary break effect was found to be significant in loosely compacted clays. Lower suctions were required to reach capillary breakthrough for looser clays, which implies that the clay must become nearly saturated before measurable flow occurs through the system. Loose clays (*i.e.*, RC = 70%) were also observed to have a high moisture storage induced by the capillary break effect. The results indicate that the soil density may be adjusted to limit or enhance the capillary break effect induced by a geosynthetic drainage layer, depending on the application. The tests presented in this study have the advantage of being fully automated, but a significant time period was required. A centrifuge permeameter will be used to perform additional parametric studies. This approach has the advantage of a shorter testing time.

ACKNOWLEDGEMENTS

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