Nonwoven Geotextiles as Hydraulic Barriers to Capillary Rise

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ABSTRACT
This study focuses on the use of nonwoven geotextiles and geocomposite drainage layers as moisture barriers in geotechnical applications where capillary flow is expected. Capillary rise can lead to a decrease in suction and degradation in performance of compacted fill, such as in flexible pavements and house foundations. This study includes an evaluation of the material properties governing the hydraulic behavior of soils and geosynthetics in these applications, as well as an investigation of capillary rise using physical models of layered soil-geosynthetic systems. Capillary rise was observed to occur rapidly in a control model containing only soil, while capillary rise occurred more slowly when a nonwoven geotextile was placed between two soil layers. This is attributed to the low hydraulic conductivity of the geotextile when unsaturated. Capillary rise was prevented when using a geocomposite between two soil layers, due to the presence of an air gap in the geonet between the two geotextiles. Filter paper measurements indicate that negative water pressure is transmitted from the soil through the nonwoven geotextile, but not across the geocomposite.

1. INTRODUCTION

1.1 Motivation

Nonwoven geotextiles and drainage geocomposites (consisting of nonwoven geotextiles sandwiched around a geonet core) have been used in geotechnical engineering applications to fulfill a wide array of purposes. They have been used to separate different soil layers, protect geomembranes or other sensitive geosynthetics from puncture, provide drainage from surrounding soil, and reinforce poorly draining backfill (Koerner 2005; Zornberg and Mitchell 1994). Geotextiles are able to meet these requirements despite their small thickness (~2.5 mm) due to their high porosity (~0.8 to 0.9), which is greater than most soils used in engineering applications (~0.3 to 0.5). Geotextiles also have a relatively uniform pore size compared to most soils (Aydilek *et al.* 2007). The high porosity of geotextiles not only implies high hydraulic conductivity when saturated, but also the capability to act as a cushion when used for separation or protection purposes.

There has been recent interest in the use of nonwoven geotextiles and geocomposites as hydraulic barriers in unsaturated soils. Richardson (1997) observed that nonwoven geotextiles used as slope underdrains did not drain water readily until the overlying soil is nearly saturated. Early experimental research focused on characterization of the water retention properties of nonwoven geotextiles, and found that geotextiles retain water by capillarity similar to soils (Stormont *et al.* 1997; Knight and Kotha 2001). These studies found that water drains completely from a geotextile upon application of a small matric suction (ψ), equal to the difference between the pore air pressure (u_a) and pore water pressure (u_w). Morris (2000) found that the hydraulic conductivity of geotextiles when unsaturated can be lower than that of most soils. The behavior noted in the laboratory has been employed in several engineering applications. Fiberglass nonwoven geotextiles have been used as wick drains to remove water from unsaturated soils (Stormont and Ramos 2004), and drainage geocomposites have been used to limit frost heave (Henry and Holtz 2001) and to increase the moisture storage capacity of surficial soils (McCartney *et al.* 2005). The behavior of geotextiles in unsaturated soils also may have undesired implications on the performance of earthen structures, such as lysimeters (McCartney and Zornberg 2007), slopes (Richardson 1997), and soil structures reinforced with nonwoven geotextiles (Iryo and Rowe 2006).

This paper focuses on observations of capillary rise in unsaturated, compacted soils containing nonwoven geotextiles and drainage geocomposites. Compacted soils are used in many geotechnical applications due to their high stiffness and shear strength, both of which are partially related to the matric suction after compaction. Flow of water into compacted soil will cause decreases in suction and its stiffness, as well as an increased susceptibility to liquefaction and piping due to vibration or traffic loading. As compacted fills are frequently used in flexible pavements and foundations for structures (walls, footings), a decrease in suction due to capillary rise may compromise performance of the system. A nonwoven geotextile used in a flexible pavement system as a hydraulic barrier to capillary rise (from a water table or drainage ditch) is shown in Figure 1. In this case, the geotextile also serves as a separation layer and lateral drain.

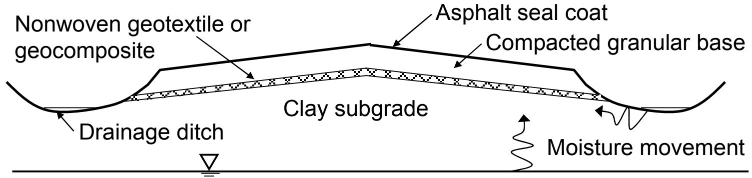

Figure 1. Nonwoven geotextile used as a hydraulic barrier in a flexible pavement

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Nonwoven geotextiles are effective as hydraulic barriers in unsaturated soils for the same reason they are effective for separation, protection and drainage: their average pore size is greater than that of most soils. The specific phenomenon that resists the flow of water from an unsaturated soil into a nonwoven geotextile is referred to as the capillary break effect (Henry 1995). The capillary break effect is encountered in everyday life with ink bottles, in which ink will not drip from the small hole of an inverted ink bottle. The capillary break effect is observed at the interface between fine-grained materials having relatively small pores and coarse-grained materials having relatively large pores, shown schematically in Figure 2(a). The air-water meniscus at the interface between the small and large pores must overcome the shift in radius from r_1 to r_2 in order to force air from the large pore. In other words, the energy in the pore water has to be sufficient to permit it to break into the large pore. Movement of water from the soil into the geotextile is also affected by the polymer type of the geotextile. Polypropylene, a polymer commonly used in nonwoven geotextiles, is hydrophobic and repels water (Henry and Patton 1998). Macroscopically, the capillary break effect prevents a measurable amount of water from flowing from the soil into the nonwoven geotextile until reaching a critical suction close to zero (saturation). At this point, water is capable of "breaking" into the large pore from the small pore. This critical suction, referred to as the breakthrough suction, often occurs when the hydraulic conductivities of the two unsaturated materials are similar.

Downward infiltration of water through an unsaturated soil toward an interface with a nonwoven geotextile has been investigated by several authors (McCartney *et al.* 2005; Iryo and Rowe 2006). Although not the focus of this paper, the lessons learned from investigation of this topic help predict the behavior of a soil-geotextile system encountered during upward capillary flow. A schematic representation of suction profiles in an unsaturated soil-nonwoven geotextile system during infiltration is shown in Figure 2. If the soil is initially dry (*i.e.*, with a uniform, high suction), a "wetting front" will be observed as water passes through the soil. If the infiltration rate is less than the saturated hydraulic conductivity of the soil, the suction at the wetting front will be greater than zero (*i.e.*, still unsaturated). The suction profiles at times t_1, t_2, and t_3 show the progression of the wetting front downward through the soil. After time t_3, the wetting front has reached the nonwoven geotextile. However, the capillary break prevents water from entering the nonwoven geotextile until the energy in the water is great enough to permit water to move from the small to large pores. A smaller suction at the interface implies higher energy. Accordingly, at time t_4, although the suction at the interface is lower (and the soil is wetter), the nonwoven geotextile is still as dry as it was at the beginning of infiltration. After time t_5, the suction at the interface is enough that water is capable of "breaking" into the nonwoven geotextile. At this point, water moves through the soil-geotextile system uniformly at a rate equal to the infiltration rate. This schematic indicates that the soil must be nearly saturated for the geotextile to act effectively as a lateral drain. If the moisture content were plotted instead of suction in Figure 2(b), the soil closer to the interface will be wetter. Accordingly, the capillary break effect leads to an increase in moisture storage of the soil in excess of that expected to be stored against the pull of gravity.

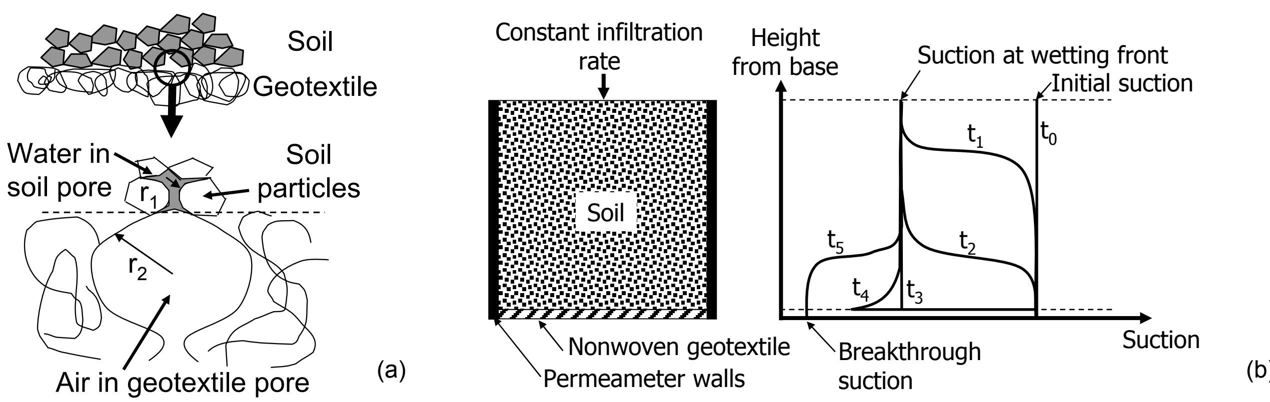


Figure 2. (a) Schematic of capillary break effect at soil-geotextile interface; (b) Schematic of suction profiles at different times during downward infiltration of moisture toward a capillary break

Capillary rise differs from infiltration in that it is associated with spatial equilibration of suction in a soil in response to a boundary having constant suction. For example, if fill is placed atop another soil that is water saturated (i.e., a water table at the surface), water will rise into the fill by capillarity. Flow will stop after reaching an equilibrium suction profile having a slope equal to $1{:}\rho_w g$ (the same slope as the water pressure with depth beneath the water table). The water content above the water table is related to the water retention properties of the soil, as shown in Figure 3(a) (Lu and Likos 2004). Profiles of suction in an unsaturated soil profile during upward capillary flow from a lower water table are shown in Figure 3(b). If the soil is initially dry with a uniform, high suction, the suction will first decrease to zero at the base of the profile, and will gradually decrease with time (t_1, t_2, t_3). At time t_3, capillary flow has reached the geotextile layer atop the soil. Due to the capillary break effect, water will not enter the geotextile until the breakthrough suction is reached at time t_4. After this, the suction in the system continues to decrease until reaching the equilibrium suction profile, during which water is transmitted through the geotextile by capillary rise. However, the nonwoven geotextile is expected to slow the rate of capillary rise through the system.

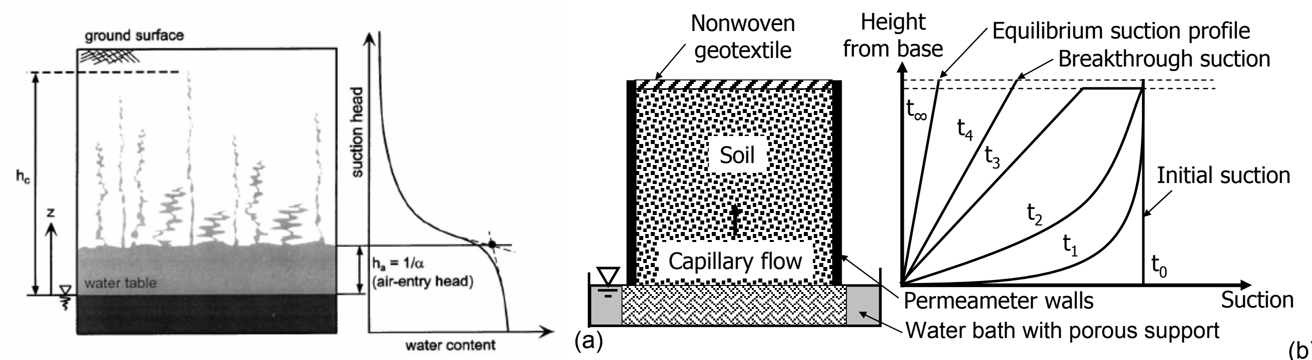


Figure 3. (a) Equilibrium suction profile due to capillary rise (from Lu and Likos 2004); (b) Schematic of suction profiles at different times during capillary rise toward a nonwoven geotextile

1.2 Approach

This study includes an in-depth investigation into the hydraulic characteristics of unsaturated soils and nonwoven geotextiles and evaluation of a physical model of capillary rise in layered soil-geosynthetic systems in order to investigate the use of nonwoven geotextiles and geocomposites as hydraulic barriers to capillary rise. The important hydraulic characteristics of unsaturated soils and nonwoven geotextiles include the water retention curve (WRC), which is the relationship between suction and volumetric moisture content (θ), and the hydraulic conductivity function (K-function), which is the relationship between suction and the hydraulic conductivity. The hydraulic conductivity of soils and geosynthetics is lower when they are unsaturated than when saturated because the presence of air implies that there are less pathways for water flow. A simple physical model was developed to show how nonwoven geotextiles can slow the rate of capillary rise in unsaturated soils, and how geocomposites can halt capillary rise. The physical model consists of a layered soil-geosynthetic system in which a water table is imposed at the base, similar to Figure 3(b). The mass of the system and the interface suction are measured with time to evaluate the rate of capillary rise. The results of the physical model allow investigation of the suction distribution across different soil-geosynthetic interfaces during capillary flow, which will help improve our understanding of the fundamental aspects of the capillary break effect. It is typically easier to obtain the hydraulic characteristics of the components of a layered soil-geosynthetic system than performing a physical model, so the hydraulic characterization results are then used to interpret the results of the physical models.

2. MATERIALS

The nonwoven geotextile used in this study is the NW6 geotextile manufactured by GSE, inc. The geotextile has a thickness (t) of 2.54 mm, a mass per unit area (μ) of 0.2 kg/m^2 (6 oz/yd^2), and a fiber density ρ_f of 910 kg/m^3. The porosity of a nonwoven geotextile is necessary to calculate its degree of saturation from measured values of volumetric moisture content (Stormont *et al.* 1997). The porosity is calculated as (Koerner 2005):

$$\eta = 1 - \frac{\mu}{t\rho_f} \tag{1}$$

The porosity of the nonwoven geotextiles was calculated to be 0.913. The geocomposite used in this study is the GSE Fabrinet®, which consists of two NW6 nonwoven geotextiles heat-bonded to either side of a geonet core. The thickness of the geocomposite is 12.5 mm. The soil used in this study classifies according to the USCS system as a clay of low plasticity (CL), and has a specific gravity of 2.71, a liquid limit of 27, and a plasticity index of 12.

3. EQUIPMENT AND EXPERIMENTAL APPROACHES

3.1 Hydraulic Characterization Equipment

The hanging column apparatus shown in Figure 4 was developed to define the water retention curve and K-function for the nonwoven geotextile. Similar to a conventional hanging column setup, an increment of suction can be applied to the base of a soil specimen placed atop a fritted glass disc inside a Büchner funnel by lowering the water level in a manometer tube connected to the base of the glass disc. Different from a conventional hanging column setup, the system was implemented to measure outflow from the geotextile with time during a given increment of applied suction by attaching the Büchner funnel to a constant-head Mariotte bottle. The Mariotte bottle consists of a thin glass pipette passed though a rubber stopper into a burette, extending far enough into the burette that its end is always beneath the water level. In the case that water flows out of the burette (*i.e.*, the geotextile is absorbing water), a vacuum will develop in the air within the burette and air will be drawn through the glass pipette. Accordingly, while bubbles are coming out of the end of the pipette, the pressure at this point is atmospheric. Accordingly, water can flow out of the burette while the pressure at the end of the pipette remains constant. For a water level difference of H from the specimen base to the end of the pipette, the suction applied to the specimen is equal to $\rho_w gH$. In the case that water is flowing into the burette (*i.e.*, the geotextile is being drained), a vacuum gauge must be used to maintain bubbling during outflow from the specimen. The geotextile was initially saturated by placing it in boiling water, then placing it under vacuum in the hanging column for at least 24 hrs. The geotextile was confined under a non-porous seating weight (a normal stress of 3.0 kPa).

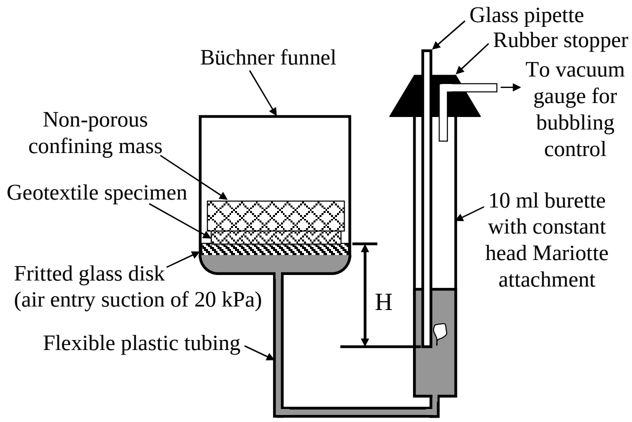


Figure 4. Hanging column apparatus

A centrifuge permeameter was used to determine the WRC and K-function for the clay used in this study. This approach allows concurrent determination of both hydraulic characteristics by supplying a steady flow rate to the top of a specimen and measuring the outflow from the base with time. The schematic in Figure 5 highlights the major components of the centrifuge permeameter, and more details about the setup can be found in McCartney (2007). Time domain reflectometry (TDR) is used to measure the average volumetric moisture content in the specimen, and tensiometers are used to measure the suction distribution with height of the specimen. The WRC can be defined by correlating the measured suction and moisture content values during water flow. At steady-state water flow (when inflow equals outflow), the hydraulic conductivity can be calculated as follows:

$$K(\psi) = \left. \frac{q}{\left(\frac{\omega^2}{g}(r_0 - z) - \frac{1}{\rho_w g}\frac{d\psi}{dz} \right)} \right|_{z=87\,mm} \quad (2)$$

where q is the imposed inflow velocity, ω is the angular velocity of the centrifuge, r_0 is the outside radius of the specimen, z is the height from the base of the specimen, ρ_w is the density of water, and g is gravitational constant. The equation is evaluated at value of z = 87 mm, which is the height of the mid-point of the TDR waveguide from the specimen base. This value of hydraulic conductivity can be correlated with the suction and moisture content to define the K-function.

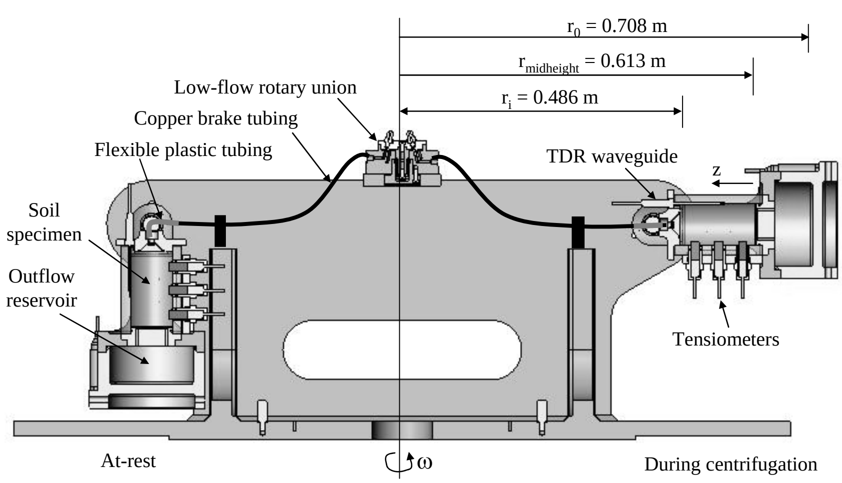
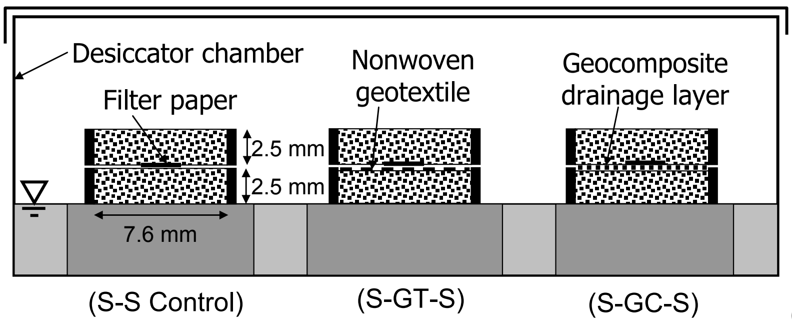


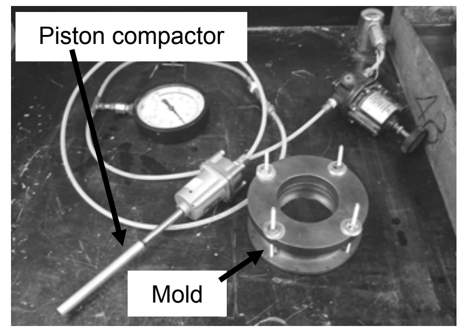
Figure 5. Schematic of centrifuge permeameter: (a) Spinning environment; (b) Permeameter with instrumentation setup

3.2 Equipment for Physical Modeling of Interface Flow

Layered soil-geosynthetic models were used to investigate the flow of water across a geosynthetic interface due to capillary rise. Three systems are investigated in this study. The first is a control system referred to as System (S-S), which consists of two discs of soil retained within acrylic rings. The lower disc of soil is placed atop a saturated porous stone resting within a water bath, and the other disc of soil is placed atop the first. A piece of filter paper is placed between the discs to measure the suction at the mid-height of the system. The top soil disc can also be removed periodically to measure the increase in mass due to capillary rise, and the filter paper can also be removed to infer the suction at the interface. The second is referred to as System (S-GT-S), which consists of two soil discs sandwiched around a nonwoven geotextile. The third is referred to as System (S-GC-S), which consists of two soil discs sandwiched around a geocomposite. Similar to the control system, the top disc of soil in these two systems can be removed for weighing, and a piece of filter paper is placed atop the geosynthetic to infer the suction at mid-height.



(a)



(b)

Figure 6. Schematic of the experimental setup for investigation of interface flow Soil – Soil Control (S-S), Soil – Geotextile – Soil (S-GT-S), Soil – Geocomposite – Soil (S-GC-S); (b) Setup for preparation of the specimens

The soil discs were prepared by compacting clay into Perspex rings having a height of 25 mm, an inside diameter of 76 mm, and a wall thickness of 6 mm. A piston compactor, shown in Figure 6(b), was used to prepare soil specimens with a dry density of 1620 kg/m^3, which corresponds to 85% of the maximum dry density obtained using the standard Proctor effort. The clay was compacted at the optimum gravimetric water content for this effort (12%), and had a porosity of approximately 0.40. A special mold was developed to hold the acrylic ring while soil was being compacted. For the systems containing the geotextile or geocomposite, the geosynthetic was placed at the bottom of the ring, and soil was compacted atop the geosynthetic. This was done to ensure good contact between the geotextile and the soil.

The filter paper technique was used to measure the suction at the base of the top soil disc (*i.e.*, at the top of the geotextile and geocomposite in Systems S-GT-S and S-GS-S). The filter paper technique can be used to measure the entire range of soil suction (Houston *et al.* 1994; Woodburn and Lucas 1995; Villar & de Campos 2002) but some researchers consider that the method impractical for suction values lower than 100kPa (Marinho & Oliveira 2006). When two porous materials are placed together within a hermetic environment, they will change in moisture until the suction at the interface between the two materials reaches equilibrium. This moisture change will occur in vapor form when the materials are not in contact in and liquid form when they are in contact. Accordingly, to measure suction, filter paper is used as a standard, calibrated porous material. Whatman #42 paper was used in this study. The moisture adsorbed by the filter paper can be used as an indicative of the suction level of the other porous material. The determination of suction from filter paper moisture measurements must be done using a calibration curve, such as that in Figure 7. ASTM D 5298 prescribes procedures used to obtain the calibration curve of the filter paper, while Leong *et al* (2002) and Marinho & Oliveira (2006) present extensive discussions on the calibration curve.

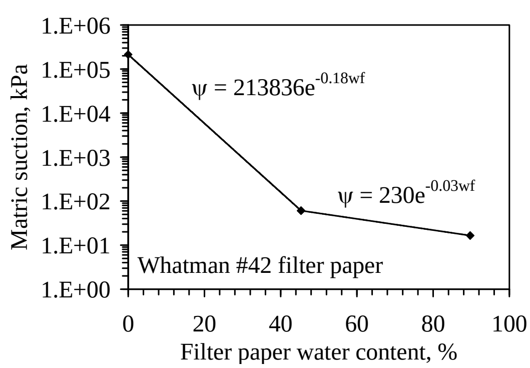


Figure 7. Calibration equation for the filter paper technique (ASTM D 5298)

Further, the filter paper technique was used to compliment the WRC of the clay determined using the centrifuge permeameter. A special container was developed in order to guarantee a good contact between the sample and the filter paper. The container was made of acrylic, and consists of a cylinder with “o”-ring groove in its upper and lower faces. The sample was compacted inside the cylinder, using the same compaction energy and initial moisture content as the physical models. Several compacted clay specimens were saturated within the cylinders by placing them atop the porous stones used in the physical model, and were then exposed to the atmosphere for different periods of time to dry to different moisture contents. After reaching the target moisture content, a filter paper was placed firmly against the soil, and two end caps were attached to the cylinder to provide a hermetic seal. The system was then maintained at an ambient temperature of 21^{o}C until equilibrium was achieved (~1 week). The system was then disassembled, and the filter paper was removed using tweezers. Its mass was measured on a balance with a precision of 10^{-4} grams for a period of 3 minutes. The change in mass of the paper with time was then plotted against the square root of time in order to infer the weight of the filter paper at the time at which the cylinder was opened (t = 0). The filter paper was then dried in an oven at 110 ^{o}C to determine its gravimetric water content.

4. RESULTS

4.1 Hydraulic Characteristics

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 use of a 10 ml Marriotte burette permitted accurate measurement of the water flowing in and out of the geotextile. A point on the WRC was determined by applying a suction to an initially saturated specimen and the outflow was recorded with time. After reaching equilibrium (outflow ceased), the total outflow during the increment was calculated, and this process was repeated for higher suctions. The moisture content at each increment was back-calculated from the outflow data at the end of each suction increment using the final moisture content (determined destructively). The outflow data with time for the drying portion of a hanging column test is shown in Figure 8(a). The drying and wetting WRC curves calculated using this data for the nonwoven geotextile are shown in Figure 8(b). Air entered the nonwoven geotextile at a suction of 0.2 kPa, after which it dried quickly to residual (fully dry) conditions after reaching a suction of 1.2 kPa. Subsequent rewetting of the geotextile allowed measurement of a water-entry suction of 0.4 kPa.

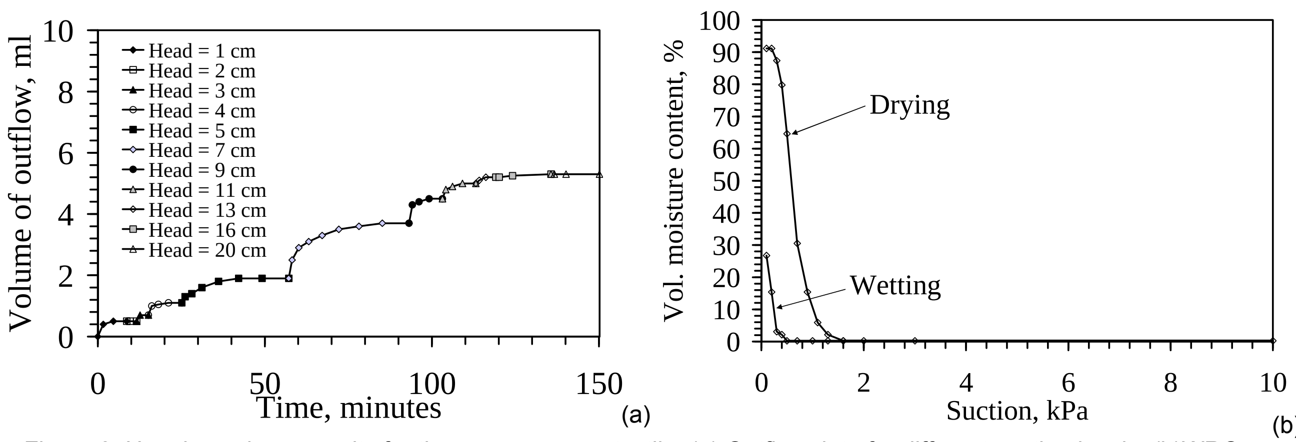


Figure 8. Hanging column results for the nonwoven geotextile: (a) Outflow data for different suction levels; (b)WRC

The outflow data from the hanging column test can be used to determine the K-function for the geotextile using the multi-step outflow method (Gardner 1956). The hydraulic conductivity is obtained using a solution to Fick’s second law:

$$\frac{\partial \psi}{\partial t} = D\frac{\partial^2 \psi}{\partial z^2} \quad (3)$$

where D is the diffusivity, and is assumed constant and equal to:

$$D = K\frac{d\psi}{d\theta} \quad (4)$$

Gardner (1956) obtained an analytical solution to Equation (5) in terms of outflow with time for a hanging column test:

$$\ln\left(\frac{V_\infty - V}{V_\infty}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{D\pi^2 t}{4L^2} \quad (5)$$

where V_∞ is the volume of outflow at the end of a given suction interval, V is the outflow volume at a given time, and L is equal to the thickness of the specimen. D is calculated as the slope of Equation (5). The K-function calculated from D and the slope of the retention curve ($d\psi/d\theta$) using Equation (4) is shown in Figure 9. Only 6 of the suction increments shown in Figure 8(a) resulted in a significant enough change in outflow volume with time to calculate points on the K-function. Nonetheless, a log-linear trend with increasing suction is observed, with a significant decrease in hydraulic conductivity (five orders of magnitude) over a suction range of 2 kPa.

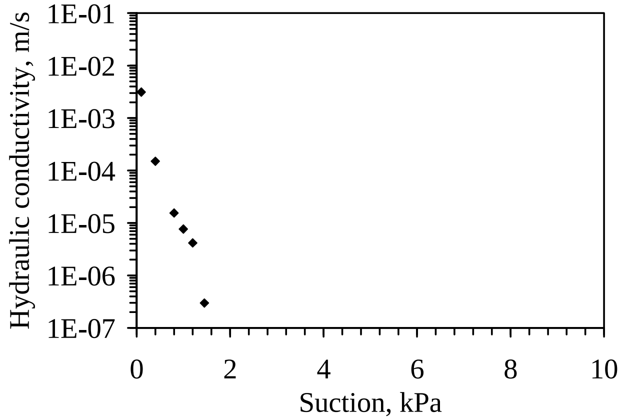


Figure 9: K-function results for the non-woven geotextile obtained from the outflow data

The retention curve for the clay obtained using the centrifuge permeameter is shown in Figure 10(a). The range of suction is relatively small, due to the fact that steady-state water flow was used to define each of the points on the WRC. The K-function defined using the centrifuge permeameter is shown in Figure 10(b). This figure indicates that a decrease in hydraulic conductivity of approximately 3 orders of magnitude occurs over suctions from 0 to 50 kPa. The advantage of using the centrifuge permeameter is that only 3 days were required to obtain this data using steady-state water flow, which is approximately the same as that needed to perform a hanging column test.

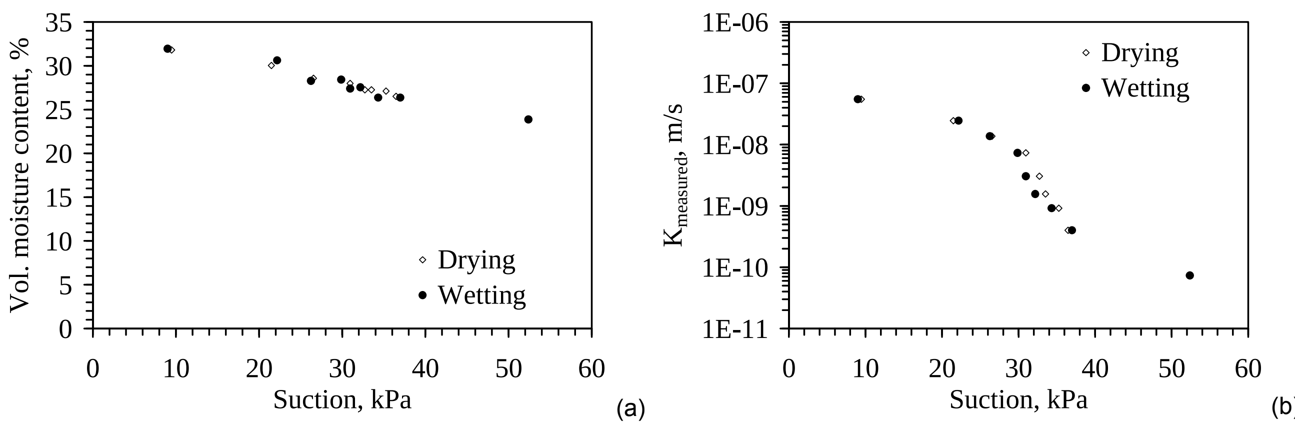


Figure 10. Hydraulic characteristics for the clay of low plasticity from centrifuge permeameter: (a) WRC; (b) K-function

A comparison of the WRC for the geotextile and clay is shown in Figure 11(a) in terms of the degree of saturation, with the suction on a logarithmic scale. Data for the clay obtained using the hanging column and filter paper techniques are also shown in this figure. The data indicates that for suctions less than 100 kPa, the clay has a much greater degree of saturation than the geotextile. A comparison between the K-functions of the geotextile and clay is shown in Figure 11(b) on a log-log plot. Fitted K-functions are also shown in this figure, using a model developed by Gardner (1958), given by:

$$K(\psi) = K_s e^{-\alpha\psi} \qquad (6)$$

where K_s is the hydraulic conductivity of a saturated soil/geotextile and α is a fitting parameter. The data indicates that the measured values of hydraulic conductivity of the geotextile are greater than the clay. However, the shape of the K-function indicates that the geotextile is less permeable than the clay for suctions greater than 2 kPa. As compacted clays generally have an initial suction much greater than 2 kPa, and because the suction at the interface between the clay and geotextile must be equal, the geotextiles used in the physical models have a small initial K (< 10^{-11} m/s).

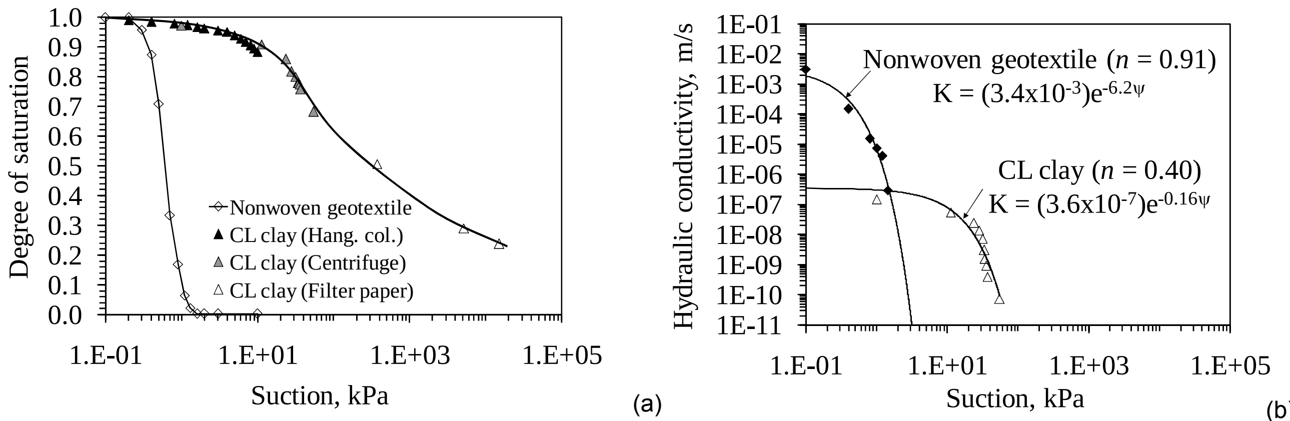


Figure 11. Hydraulic characteristics for clay and nonwoven geotextile: (a) WRC; (b) K-function

4.2 Physical Modeling Results

The cumulative change in mass of the upper disc of soil after placement on the saturated porous stone is shown in Figure 12(a). This figure indicates that the control system with two discs of soil showed a rapid increase in mass during the first 10 hours of testing. The system with a nonwoven geotextile layer between the two soil discs also showed an increase in mass of the upper soil disc, but the increase in mass occurred about 48 hours later than the control system. The geotextile was only able to transmit water by capillary rise because the thickness of the lower soil disc was small enough that the suction at the interface was less than that corresponding to capillary breakthrough (approximately 1 kPa or 100 mm of soil). The a value for the geotextile is about 4 times larger for the nonwoven geotextile, which indicates that it will absorb water by capillary rise about 4 times slower than the soil, so the delay in capillary rise makes sense. No increase in mass of the upper soil disc was observed for the system with a geocomposite between the two soil discs. This was observed because suction was not able to equilibrate across the air gap in the geocomposite. Water was likely able to break into the lower nonwoven geotextile of the drainage geocomposite, but water must fill the air space within the geonet drainage layer in order for water to pass by capillarity into the upper geotextile and overlying soil. The volumetric moisture content of the upper soil disc is shown in Figure 12(b). This figure shows similar results, with the control system rapidly approaching saturation (θ = 36%) and the soil-geotextile-soil system reaching a moisture content of about 35%. The upper bound on the average moisture content is associated with the thicknesses of the soil discs. The soil-geocomposite-soil system actually showed a slight decrease in moisture content, likely due to evaporation.

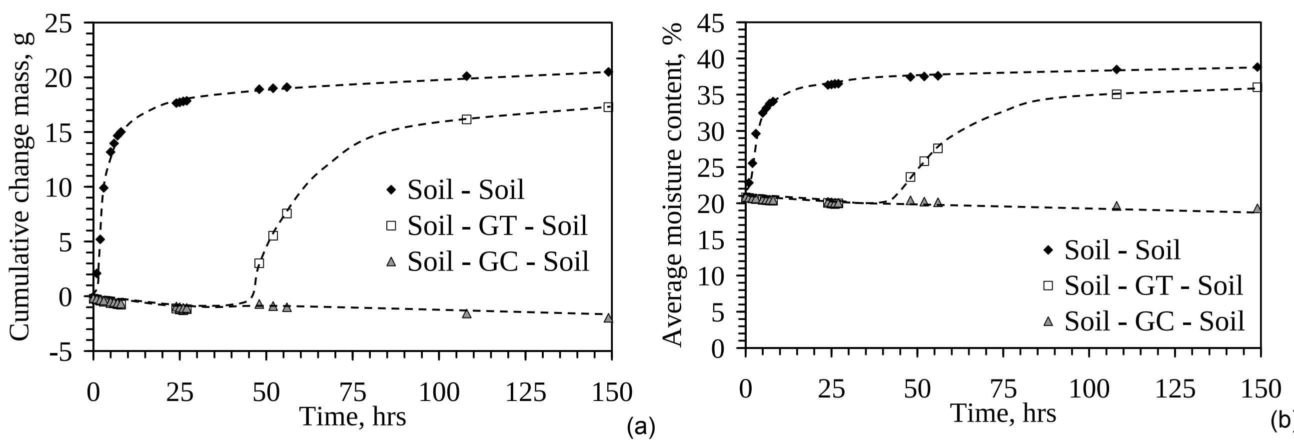


Figure 12. (a) Change in mass of upper soil ring with time; (b) Change in average moisture content with time

The moisture contents of different pieces of filter paper placed at the interface between the upper soil disc and the interface (soil for the control system and a geosynthetic for the other two systems) are shown in Figure 13(a). This figure shows that the trend in the moisture content of the filter papers with time mimics the change in volumetric moisture content of the soil observed in Figure 12(b). The suction at the interface was calculated using the calibration equation shown in Figure 6, and is shown in Figure 13(b). The suction at the interface is initially about 150 kPa, while the suction at the interface is practically zero for the control system and the soil-geotextile-soil system after equilibration of capillary flow. The expected suction at mid-height of the control section is 0.025 m from equilibrium. Consistent with the moisture content, the suction at the interface for the soil-geocomposite-soil system does not change from the initial suction.

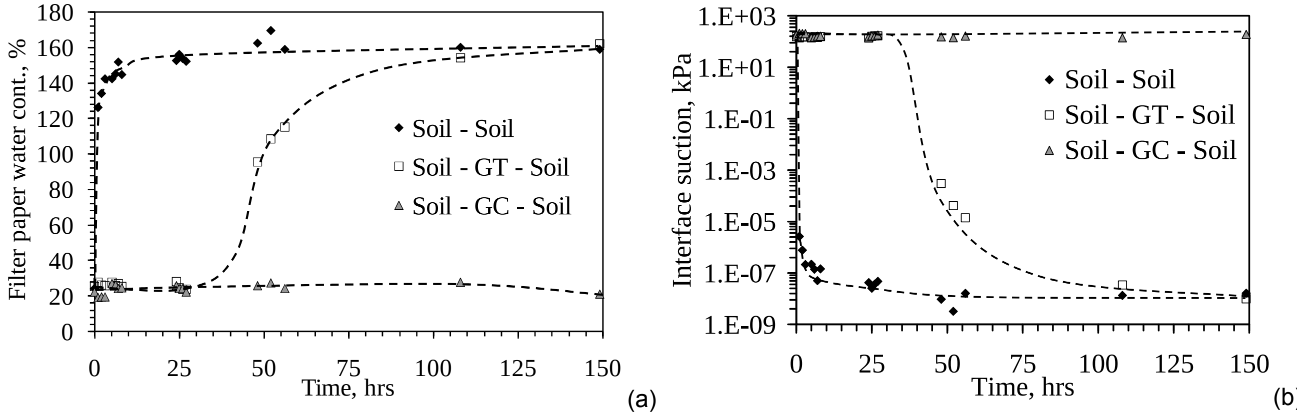


Figure 13. (a) Variation in filter paper moisture content with time; (b) Interface suction with time

5. DISCUSSION OF RESULTS

5.1 Transmission of Suction

Due to the small thickness of the physical models, the suction at the base of the geotextiles predicted from the equilibrium suction profile of the soil is approximately 0.25 kPa, which is close to the water entry value of an unsaturated geotextile. Accordingly, the WRC of the geotextile indicates that water should be able to enter the geotextile. However, water is not transmitted across the geotextile interface after the suction at the interface reaches the breakthrough suction for the geotextile, as indicated by the delay in capillary rise. The suction measured at the top of the geotextile is close to zero after breakthrough, which indicates that once capillary breakthrough occurs, the geotextile is able to transmit water upwards by capillarity rise at a rate consistent with soil alone. The system is then able to approach the expected equilibrium moisture content profile. The geocomposite is more effective as a hydraulic barrier due to the presence of an air gap between the upper and lower geotextiles, and although the lower soil layer likely has a suction profile close to the equilibrium suction profile, the upper soil disc remains at its initial suction. The low normal stress in a pavement system should imply that the geonet will maintain its structure during construction, so the upper and lower geotextiles should not come into contact. Higher stress applications may lead to bridging of the air gap by compression of the geotextiles into each other, in which case capillary rise will occur through the drainage geocomposite.

5.2 Rate of Moisture Absorption

Although the nonwoven geotextile was not effective as a hydraulic barrier to capillary flow, it did slow the rate of capillary rise. This is due to the shape of the geotextile's K-function over the range of suctions expected in compacted, unsaturated soils (an α value 4 times greater than that of the soil). The α values for the soil and geotextile can be incorporated into a model such as that proposed by Lu and Likos (2004) to predict the rate of capillary rise through the geotextile. Further research is necessary to identify the particular contrast in α values between soil and geosynthetics that will optimize the time delay in capillary rise. In an engineering design, this delay in capillary rise can be coupled with projected fluctuations in the water table, or in the required depth of the water table. It is important to note that after water enters the geotextile, its hydraulic conductivity is greater than that of the soil so it can act as a drain. Accordingly if the geotextile is installed on a slope as shown in Figure 1, the geotextile may be able to redirect water from the underlying soil laterally before the water has time to pass into the overlying compacted fill by capillary rise.

6. CONCLUSIONS

This study uses the hydraulic characteristics of unsaturated soil and porous geosynthetics along with physical modeling tests to interpret the transmission of moisture by capillary rise across geosynthetic interfaces. Capillary rise was observed to occur rapidly in a control model containing only soil, while capillary rise was delayed by several days when a nonwoven geotextile was placed between two soil layers. This is attributed to the low hydraulic conductivity of the geotextile when unsaturated. Capillary rise was prevented when using a geosynthetics drainage layer between two soil layers due to the air gap within its geonet core.

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REFERENCES

ASTM D 5298. Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. The American Society for Testing and Materials. West Conshohoken, PA.

Aydilek, A.H., D'Hondt, D., and Holtz, R.D. (2007). "Comparative Evaluation of Geotextile Pore Sizes Using Bubble Point Test and Image Analysis", *Geotechnical Testing Journal,* ASTM, Vol. 30, No. 3,pp. 173-181.

Gardner, W. 1956. "Calculation of capillary conductivity from pressure plate outflow data." SSSA. 20, 317-320.

Gardner, W. (1958). "Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table." Soil Science, 85:223–232.

Henry, K. (1995). "The use of geosynthetics capillary barriers to reduce moisture migration in soils." G.I. 2(5), 883–888.

Henry, K. and Holtz, R. (2001). "Geocomposite capillary barriers to reduce frost heave in soils." Can. Geo. J. 28:678-694.

Henry, K. and Patton, S. (1998). "Measurements of the contact angle of water on geotextile fibers." Geot. Test. J. 21(1), 11–17.

Houston, S. Houston, W. and Wagner, A. (1994). "Laboratory filter paper suction measurements." Geot. Test. J. ASTM. 17(2):185-194.

Iryo, T. and Rowe, R.K. (2006). "Infiltration into an embankment reinforced with Nonwoven Geotextiles." Can. Geo. J. 42:1145-115

Knight, M., and Kotha, S. (2001). "Measurement of geotextile-water characteristic curves using a controlled outflow capillary pressure cell." Geosyn. Int.. 8(3):271-282.

Koerner, R. (2005). Designing With Geosynthetics. 5th Edition. Prentice Hall, NJ.

Leong, E. He, L. Rahardjo, H. (2002). "Factors affecting the filter paper method for total and matric suction measurements". Geot. Test. J. 25(3):321-332.

Lu, N. and Likos, W. (2004). "Rate of capillary rise in soils." J. of Geot. and Geoenv. Eng. 130(6):646-650.

Marinho, F. and Oliveira, O. (2006). "The filter paper method revisited." Geot. Test. J. 29(3): 9pp.

McCartney, J., Kuhn, J., and Zornberg J. (2005). "Geosynthetic drainage layers in contact with unsaturated soils." 16th ISSMGE. 12-16 Sept. 2005. Osaka, Japan.

McCartney, J., and Zornberg, J. (2007). "Effect of wet-dry cycles on capillary break formation in geosynthetic drainage layers." Geosynthetics 2007. Washington, DC. January 16-19, 2007.

McCartney, J. (2007). Determination of the hydraulic characteristics of unsaturated soils using a centrifuge permeameter. PhD Dissertation. The University of Texas at Austin.

Morris, C. (2000). "Unsaturated flow in nonwoven geotextiles," GeoEng 2000, Melbourne, Australia.

Richardson, G. (1997). "Fundamental mistakes in slope design." Geotechnical Fabrics Report 15(2), 15–17.

Stormont, J., Henry, K., and Evans, T. (1997). "Water retention functions of four nonwoven polypropylene geotextiles." G.I. 4(6):661-672.

Villar, L.F.S. and de Campos, T. (2002). "Obtaining the soil moisture characteristic curve of a highly compressible waste submitted to drying." UNSAT 2002. Recife, Brasil. pp. 339 – 345.

Woodburn, J. and Lucas, B. (1995). "New approaches to the laboratory and field measurement of soil suction." Proc. 1st Int. Conf. on Unsaturated Soils. Paris. pp. 667-671.

Zornberg, J.G., and Mitchell, J.K. (1994). "Reinforced Soil Structures with Poorly Draining Backfills. Part I: Reinforcement Interactions and Functions." G.I. 1(2), 103-148.