HYDRAULIC CLASSIFICATION OF UNSATURATED NONWOVEN GEOTEXTILES FOR USE IN CAPILLARY BARRIERS

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ABSTRACT
Significant past research has been conducted in an effort to evaluate the hydraulic properties of porous geosynthetics under unsaturated conditions relevant for geosynthetic capillary barrier design. Additionally, many researchers have concluded that geosynthetic capillary barriers are superior to soil-only capillary barriers, and that the technology is gaining in popular use especially in arid regions. One area relevant to the use of geosynthetic capillary barriers where information is lacking is classification of the wide range of geosynthetic products available based on unsaturated hydraulic properties. This paper provides theoretical background and laboratory data supportive in understanding the correlations between different non-woven geotextile properties and the materials performance under unsaturated conditions in barrier applications. These properties include the water retention curve, and the hydraulic conductivity function. Due to the low water entry suction of all nonwoven geotextiles it was found that when a geotextile and a fine grained soil are placed in contact with each other under unsaturated conditions, the interface of the two materials may create a capillary break that is capable of preventing moisture flow until the soil adjacent to the geotextile is fully saturated. Additionally, the small range of water-entry suctions found in geotextiles makes classification for performance based selection of different geotextiles in capillary barrier systems difficult. Moreover, the classification of different non-woven geotextiles based on unsaturated hydraulic properties has lead to a better understanding of the potential for clogging in the various materials tested.

1. INTRODUCTION

To understand the behavior of a geotextile while in unsaturated conditions the water retention function of the material is extremely helpful. The methods to determine the retention function of geotextiles unfortunately have not yet been standardized. Guidelines for testing methods in this area are also lacking, however, several testing methods have proven to work well in the literature. Two of these methods include the modified hanging column test and the capillary rise test; both were investigated as part of this study. With a greater understanding of the methods used to determine the retention function of geotextiles the materials can be classified based on their unsaturated hydraulic properties.
Nonwoven geotextiles, with a pore structure, in some aspects similar to that of coarse, uniform gravel, have been shown to be effective in creating a capillary barrier (Iryo and Rowe 2003, Bouazza et al. 2006, Krisdani et al. 2006 , McCartney et al. 2005, McCartney et al. 2008). Little progress has been made, however, in identifying the parameters of a soil-geotextile system that most significantly affect capillary barrier performance. The main objective of this research study is to better understand the unsaturated hydraulic properties of nonwoven geotextiles for their use in earthen systems.

1.1 Capillary Barriers

Capillary barriers are becoming an established technology to control water flow in unsaturated soils. Understanding of unsaturated flow concepts has recently gained added relevance in landfill design due to the increased number of alternative covers that have been designed and constructed for waste containment and mine tiling facilities (Zornberg et al. 2009). An example of a structure that acts as a capillary barrier to restrict unsaturated flow is an evapotranspirative cover as used on landfills for waste containment. An evapotranspirative cover uses fine grained soil to act like a sponge that absorb water during a rain event as one of its mechanisms to impede moisture from contacting the waste. After the event, the moisture in the soil evaporates back into the atmosphere. Figure 1.1 shows the components of the water balance in an evapotranspirative cover system. A capillary barrier develops when an unsaturated fine-grained soil layer is underlain by another unsaturated porous material with relatively large-sized pores, such as a coarse grained soil 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 (McCartney et al. 2005). This effect is called a capillary break.

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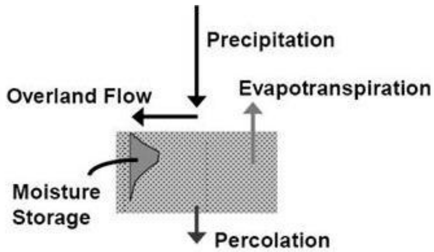


Figure 1.1 - Components of the water balance in an ET cover system (Zornberg et al. 2009)

1.2 Geotextiles

The drainage function refers to the ability of nonwoven geotextiles to provide a path for flow of water within the plane of the geotextile. Drainage capability of the geotextile is quantified by its transmissivity, defined in Equation 1.1.

$$\theta = k_p * t \tag{1.1}$$

$$\psi = \frac{k_n}{t} \tag{1.2}$$

In Equation 1.1 θ is the transmissivity, k_p is the in-plane hydraulic conductivity, and t is the geotextile thickness at a specified normal pressure. The transmissivity of the materials will decrease significantly with decreased saturation.
As the flow of liquid is perpendicular to the plane of the geotextile, filtration refers to the cross plane hydraulic conductivity, or permittivity, defined in Equation 1.2 where ψ is the permittivity, k_n is the cross-plane hydraulic conductivity, and t is the geotextile thickness at a specified normal pressure. The important property for soil retention design is the apparent opening size (AOS), a measure of the pore sizes in a geotextile. More specifically, AOS refers to the opening size at which 95% of all pore spaces are smaller.

1.3 Determine Water Retention Curve of Materials

The water retention curve represents the amount of water retained by the porous material, either a soil or geotextile, at a given suction. Typical results for the water retention curve of soils (SWRC) and geotextiles (GWRC) are presented. The WRC is a measure of the amount of moisture present in the available pore spaces, commonly represented by volumetric moisture content over a desired range in matric suction. The SWRC can be obtained using a number of different methods. Due to the nature of some soils and their ability to retain moisture at high levels of suction different methods must be used for each range of suction. Although alternative methods exist, only one method for each range was used as part of this study. For low suctions, from 0 to approximately 20 kPa, the hanging column method can be used. Pressure plate testing is typically used for suctions ranging from around 5 kPa to nearly 500 kPa. Suctions higher than 500 kPa can be attained using thermodynamic methods. A variety of testing methods used to quantify unsaturated properties of soils have been adapted to use with nonwoven geotextiles along with new testing techniques specific to nonwoven geotextiles. Stormont et. al. (1997) applied an existing experimental technique used for soils to measure the water retention functions of geotextiles. The testing apparatus is similar to the hanging column apparatus used for testing the water retention functions of soils. A test setup similar to that originally presented by Stormont et. al. (1997) was used in this study. Another effort to characterize the water retention function of nonwoven geotextiles by Henry and Holtz (1997) utilizes water capillary rise measurements performed by submerging one end of a strip of geotextile in water and measuring the subsequent height to which the water rises. The height of capillary rise will give a good estimate of the water entry suction of the material. A modification of this technique was presented by Lafleur and Lebeau, (2000) where the in-plane water retention function is measured by submerging one end of a 500 mm long geotextile specimen strip in water and allowed to equilibrate for 72-hours. This technique has been investigated further as part of this study.

1.4 Water Retention Function of Soil and Geotextiles

The water retention function of soils has been studied in depth and is well understood. The water retention function for geotextiles has only been studied for about the last decade and is not as well defined. The amount of moisture in a soil or geotextile at any given time depends on the capillary forces developed in the pores of the material structure. Smaller pore sizes develop higher capillary forces and require higher suctions to remove the same amount of water as in a material with large pore spaces at a lower suction. Due to the manufacturing process, nonwoven geotextiles will experience differences in hydraulic properties between unaltered (as received from the manufacture) and cleaned specimens. It is typical for test results to demonstrate that unaltered test specimens contain more water when subjected to the same suction head than cleaned specimens of the same material. A given mechanical stress condition will also have a significant affect as seen in results presented by Lafleur and Lebeau, (2000).

1.5 Modeling of Hydraulic Conductivity Functions

When relating the water retention characteristics of nonwoven fibrous polypropylene geotextiles to field applications unsaturated hydraulic conductivity is of more significance. The relationship between hydraulic conductivity and suction for a given soil is called the hydraulic conductivity function, or k-function. The common engineering practice is to use parameters from a numerical model, fit to the water retention data, to determine the hydraulic conductivity for a range of suctions. The van Genuchten function has been proven superior when fitting to soils and geotextiles in the literature (Iryo and Rowe 2003, McCartney et al. 2005, Bouazza et. al. 2006, McCartney et al. 2008) and will, therefore, be the model of choice in this study. The van Genuchten function is:

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha_{vG}\psi)^{N_{vG}}]^{-\left(1-\frac{1}{N_{vG}}\right)} \tag{2.3}$$

where $\theta(\psi)$ is the volumetric moisture content at a given suction (ψ), θ_r and θ_s are the residual and saturated volumetric moisture contents, respectively, α_{vG} and N_{vG} are fitting parameters. Most models are a function of the saturated hydraulic conductivity of the soil and the relative percentage of available pore space that is actually filled with water. The general form is as follows (McCartney 2007):

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^b \left(\frac{\int_0^\theta \frac{dx}{\psi^{2-r}(x)}}{\int_0^1 \frac{dx}{\psi^{2-r}(x)}}\right)^m \tag{2.4}$$

where *b*, *r*, and *m* are empirical constants related to the pore structure of the soil and *x* is defined for integration (McCartney 2007). The van Genuchten-Mualem model uses the N_{vG} parameter obtained by fitting the van Genuchten model to the soil water retention data, along with assumptions for *b*, *r* and *m* made by Mualem (1976), to define the K-function:

$$K(\theta) = K_s\sqrt{\frac{\theta - \theta_r}{\theta_s - \theta_r}}\left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1-N_{vG}}\right)^{\frac{1}{1-N_{vG}}}\right]^2 \tag{2.5}$$

1.6 Column Testing

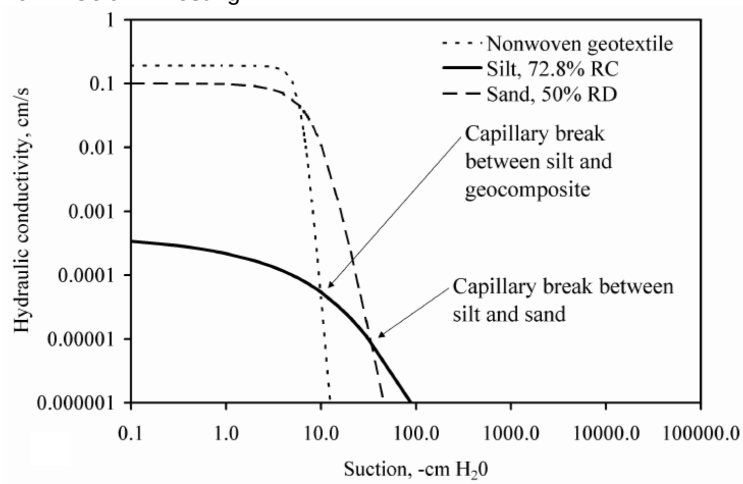


Figure 2.2 – Prediction of capillary break for different materials using K-function (McCartney 2005).

In a study conducted by McCartney et al. (2005) a series of large-scale soil-geosynthetic profiles were constructed using a silt soil in contact with a sand drainage material as well as with a drainage geocomposite. Although the study involved infiltration into dry soil following the wetting-path WRC, the researchers found that the drying path WRC defined in the study can be used to highlight important hydraulic differences between the materials. The K-functions shown above in Figure 2.2 show the predictions made for the performance of the different materials as capillary barriers. The breakthrough suction of the barrier depends on the water retention properties of each material. In the case of vertical flow in a horizontally layered system, e.g. a modeled capillary barrier system, if a coarser material is significantly less conducive to flow than the overlying soil, a capillary break will occur. A comparison of the K-functions between two adjacent materials shows the suction value at which the capillary break effect is expected to occur.

2. EXPERIMENTAL METHODS, MODELS, AND MATERIALS

Four different nonwoven geotextiles provided by two different manufactures were tested as a part of this study. The geotextiles selected varied in properties including: thickness, weight, apparent opening size (AOS), and permittivity. Other relevant properties for this study include the porosity of the geotextile and the saturated hydraulic conductivity. The porosity (n) is calculated using Equation 2.1:

$$n = 1 - \frac{\mu}{\rho_f t} \tag{2.1}$$

$$K_{sat} = \frac{\psi t \rho g}{\mu} \tag{2.2}$$

In where μ = mass per unit area, ρ_f = fiber density (assumed to be 0.91 g/cm^3 for polypropylene), and t = specimen thickness at estimated appropriate confinement stress. The saturated hydraulic conductivity (K_{sat}) can be calculated using Equation 2.2 and the geotextiles permittivity, which was provided by the manufacturer. In Equation 2.2 ψ = permittivity, t = thickness of geotextile, ρ = density of water, g = acceleration of gravity, and μ = viscosity of water. In this study the geotextile property of most interest is the unsaturated hydraulic conductivity for predictions in capillary barrier performance. The geotextile k-function was determined using the van Genuchten-Mualem model with the equations presented above.

The values shown in Table 2.1 are a combination of manufacture reported values and values calculated using equations 2.1 and 2.2. The values from this table are used throughout the study for each geotextile unless otherwise specified. To simplify writing the abbreviations GT1-GT4 were used for the four geotextiles. GT1 is the thinnest, while GT4 is the thickest geotextiles. Other values vary depending on the specific product and are shown in the table.

Table 2.1 – Manufacturer reported and calculated values for geotextile properties.

Geotextile	Thickness (mm)	Weight (g/m^2)	A.O.S. (mm)	Porosity	Permitivity (Sec^{-1})	Hydraulic (cm/s)	Conductivity
ASTM	D 5199	D 5261	D 4751	N/A	D 4491	N/A	
GT-1	1.00	163	0.212	0.821	1.7	0.167	
GT-2	1.80	203	0.180	0.876	1.6	0.283	
GT-3	2.70	414	0.150	0.832	0.8	0.212	
GT-4	3.30	407	0.150	0.864	0.9	0.291	

[1]The values reported for ASTM test results were provided by the manufacturer
[2]Porosity and hydraulic conductivity were calculated based on reported thickness, permittivity and weight
[3]Cross-plane hydraulic conductivity is specified in this table

3. EXPERIMENTAL METHODS AND PROCEDURE

To construct the water retention curve of a geotextile the moisture content at a given suction must be measured. To determine these values for a nonwoven geotextile the material must be subjected, by a various number of methods, to suction, and the corresponding water content is then measured. Each water content and corresponding suction is one point on the water retention curve. Two methods were used to determine the GWRC in this study. The methods include a modified hanging column (MHC) setup as used by Stormont et. al. (1997) and Bouazza et. al. (2006), and a setup similar to the capillary rise experiment used by Henry and Holtz, (1997) and Lafleur and Lebeau, (2000). The capillary rise setup used in this study was modified from those found in the literature to enable cutting of the geotextile without changing the suction conditions. This experimental setup is referred to as the modified capillary rise test (MCR).
For both testing procedures the most inaccuracies are found at low suctions (below 1kPa). This is because the samples are wettest in this range and moisture can be lost from the samples. Additionally, there is the typical error associated with the measurement of the samples volume. For these reasons the porosity, calculated using equation 2.1, is indicated on GWRC plots as a point of reference for the moisture content at zero suction.

3.1 Modified Capillary Rise Test

A modified capillary rise (MCR) test was recently designed as part of this research (at the University of Texas). The new setup is composed of a base and a long cylindrical top tube. Attached to the base is a metal rod with pins spaced 2-6 cm along its length. The MCR test setup can be used as follows. The nonwoven geotextile can easily be pressed onto the pins to suspend the sample in the test apparatus. The base is filled with water to submerge the bottom segment of the sample and the height of water is adjusted to the appropriate level. The sample is then capped with a top tube and left to equilibrate in the sealed environment for 24 hours. The tube is then removed and the sample is cut from the top down into 2 cm segments. The sample will not be removed from its equilibration position while the segments are being cut and weighed for moisture content. The volumetric moisture content can be calculated using the known volume for each segment. The corresponding suction for each segment is calculated based on its average height above the free water in the base of the set up. The water retention curve is plotted with the resulting datum points.

3.2 Effects of Particle Retention on Geotextile Performance

In nearly all applications in which nonwoven geotextiles are used for geotechnical projects the material is in direct contact with soil. To assume that the geotextile will perform as tested, clean in the laboratory, when in contact with soil containing fines is not realistic. In an aid to help quantify the effect the retention of fines will have on the unsaturated performance of geotextiles a simple apparatus was built to impregnate several geotextiles with fines. The setup consists of a large pressure cell with in and outflow lines. Within the cell are two porous stones protected with filter paper. This setup was connected to the laboratory water supply with a pressurized inflow line. Steady flow through the column of soil was reached after about 2 days of infiltration. The setup was left in a steady state flow condition during 22 days. In that amount of time approximately 12 soil volumes of flow were flushed through the soil and geotextiles. The geotextiles where removed from the column and scrapped clean on the surfaces before being tested in a hanging column apparatus to determine the water retention curve. A flexible walled permeameter was used to determine the saturated hydraulic conductivity of the geotextile specimens impregnated with fine soil run in accordance with ASTM D 5084 (ASTM 2003).

3.3 Soil Columns, Pumps, and Instrumentation

Soil column testing has been used in the past to simulate capillary barriers and to help understand capillary barrier performance. Stormont and Anderson (1999) investigated the performance of various soil combinations in creating a capillary barrier. The results of these tests confirmed the reliability of a capillary break. Breakthrough suctions were consistent with those predicted via K-function analysis, independent of applied flow rate, and controlled by the water entry properties of the coarser soil layer. A coarser soil with more uniform pore size was shown to present the best option for capillary barrier performance. Similar conclusions have been made from other column testing on laboratory models of soil capillary barriers (McCartney et al. 2005).
Extensive studies have previously been performed at the University of Texas using small soil columns by Thompson (2009). A large part of the study focused on design of soil columns and instrumentation to provide efficient laboratory testing of capillary barriers with an economical setup. All the column tests run as part of this study followed the setup procedure suggested by Thompson (2009). The tests were kept constant with 80% relative compaction of the soil layer and an average flow rate between 0.35 and 0.42mL/min. The geotextile used to create a capillary barrier was varied between tests. The soil columns designed by Thompson (2009) where used in this study. A schematic diagram along with a photograph of the soil column test setup is shown in Figure 3.1.

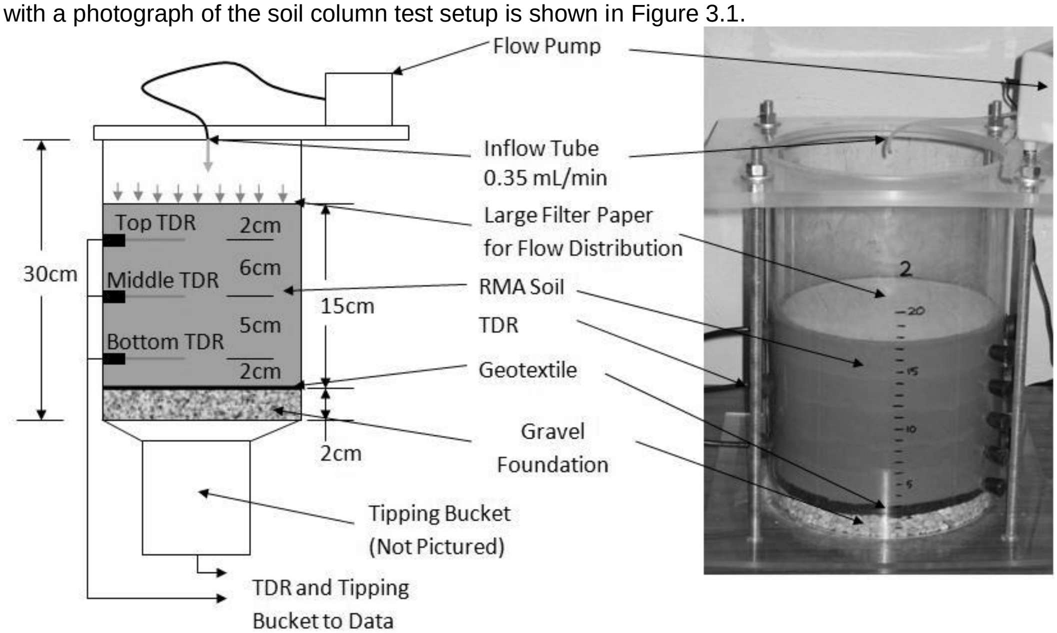


Figure 3.1 – Schematic view and photograph of soil column setup.

4. RESULTS AND DISCUSSION

4.1 Methods for Determining GWRC

Based on the results of this study, there is a clear difference between the water retention curves for geotextiles tested in the in-plane and cross-plane directions. There are several discrepancies between the two test methods and a list of problems with each that make it unclear whether these differences are due to the pore distribution in the material or uncertainties in testing. The difference is likely related to problems with the two test methods, as it is counterintuitive that the same material would be capable of retaining a different percentage of water depending on its orientation. The fibrous nature of the geotextiles, however, may be capable of anisotropic water retention.

Important points about the characteristics of geotextiles that can be established from these test results. Air and water entry values, in general, related to the AOS for the geotextiles. For example, the water entry suctions for geotextiles with larger apparent opening size is lower. This is expected as the larger pores will only draw water into the geotextile at low suctions. Geotextile 2 is an exception and does not appear to draw water into the geotextile until zero or positive suction is applied. This may be attributed to surfactants applied during manufacturing that cannot be removed during washing and or the pore distribution of the material. The air entry values for each geotextile do not correlate well to the apparent opening size. A review of the differences in the two test methods and the results from each test method are presented in the Tables 4.1 and Figure 4.1 below.

Table 4.1 – Differences between MCR and MHC test methods

MCR	MHC
Moisture loss during cutting of the sample	Problems with contact between sample and porous disc
No normal load applied	Normal load applied
No sandwiching surfaces	Sample is sandwiched between seating load and porous disc
In-plane water flow	Cross-plane water flow
	Surfactants applied to cross-plane surface during manufacturing

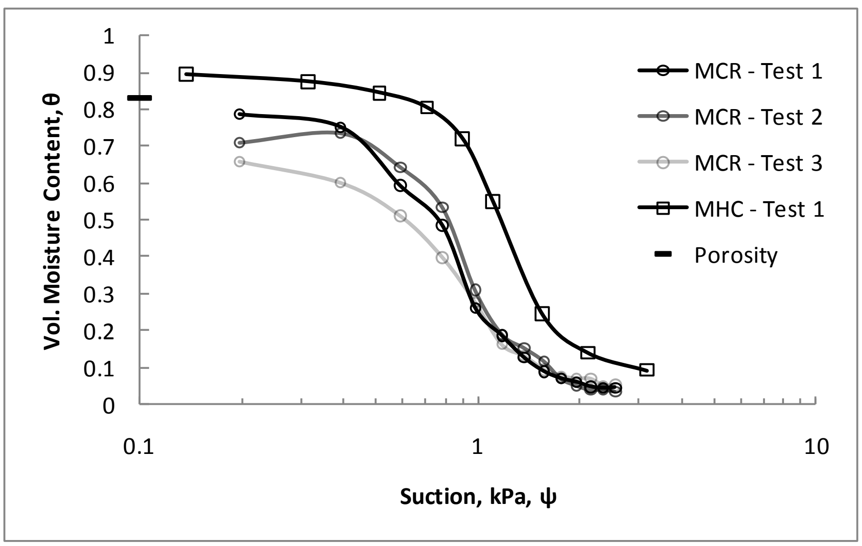


Figure 4.1 – Comparison of MHC and MCR results for GT3.

4.2 Geotextile K-Functions

The water retention functions determined from each series of tests can be used in conjunction with the modified van Genuchten equations to determine the hydraulic conductivity functions for each material. The k-functions for the geotextiles used as a part of this study are presented initially. Secondly, the k-functions for the materials impregnated with fine grained soil are presented. Geotextiles used in capillary barrier applications will be subjected to flow in the cross-plane direction. The retention data from the modified hanging column which tests in the cross plane direction was used in modeling the k-functions for the materials. For this purpose the van Genuchten-Mualem model was used. The van Genuchten model was fit to the data using the method of least squares and is shown in Figure 4.2. The parameters used for the van Genuchten-Mualem model are shown in Table 4.2. The k-functions determined from the water retention curves are presented in Figure 4.3. The resulting k-functions for the non woven geotextiles are similar to those reported in the literature, (McCartney 2005, Bouazza 2006, Thompson 2009).

Table 4.2 – Fitting parameters used in van Genuchten-Mualem model for different geotextiles.

Geotextile	θ_{sat}	θ_{res}	α (cm^{-1})	n	K_{sat} (cm/s)
GT-1	0.821	0.07	0.83	4.95	0.167
GT-2	0.876	0.07	1.32	5.73	0.283
GT-3	0.832	0.07	0.89	5.25	0.212
GT-4	0.864	0.21	1.10	4.37	0.291

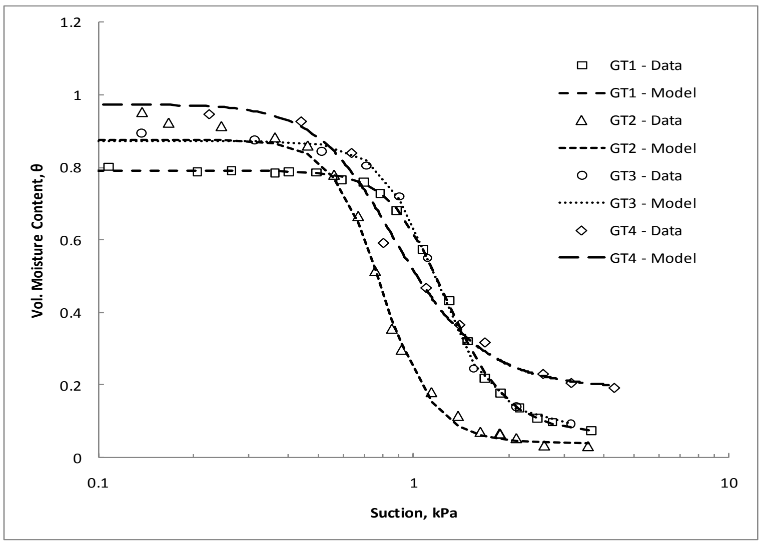
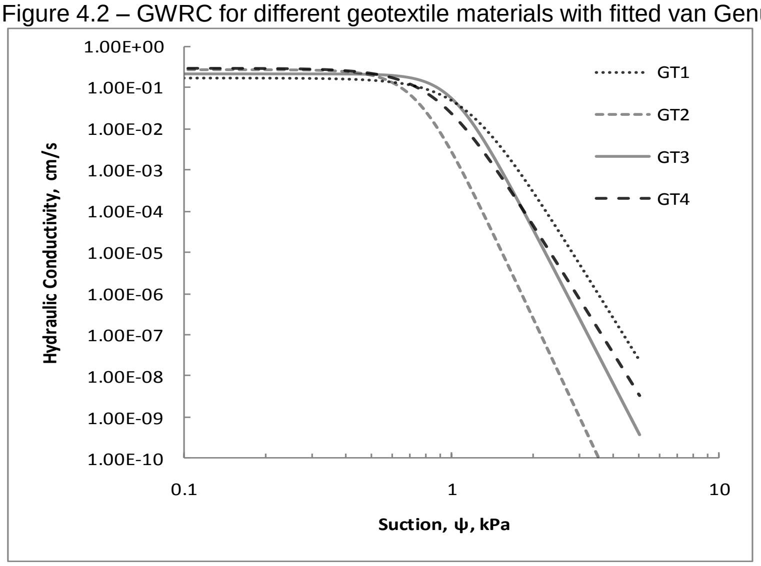


Figure 4.2 – GWRC for different geotextile materials with fitted van Genuchten model



Figrure 4.3 – K-functions for different geotextiles determined using the van Genuchten-Mualem model

4.3 Geotextile Fines Retention

There is a clear difference in the water retention function of geotextiles after the materials become impregnated with fine soil. The results for GT2, which is the material affected the most by impregnation with fines, are shown in Figure 4.4. The results for the clean material (as received from the manufacturer) are shown for comparative purposes. There is a relevant reduction in the materials moisture capacity at low suctions, i.e. the porosity is reduced. This is clearly caused by fine grain soil particles becoming retained within the larger pores of the geotextile and reducing the effective pore size of the material. As the pore size is reduced the moisture capacity of the material also decreases. The hydraulic properties of geotextiles have often been compared with clean coarse sand or gravel; with smaller overall pore sizes after clogging, however, the geotextile begins to act less like gravel and more like fine grained material.

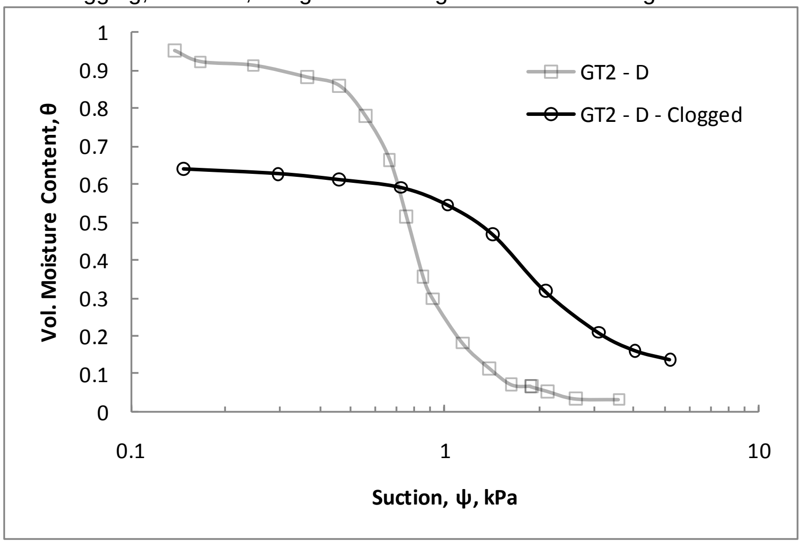


Figure 4.4 – GWRC for GT2 after clogging with fine grained soil

Table 4.3 – Fitting parameters used in van Genuchten-Mualem model for different clogged geotextiles

Clogged Geotextile	θ_{sat}	θ_{res}	α (cm^{-1})	n	K_{sat} (cm/s)
GT-1	0.63	0.16	0.60	4.41	0.101
GT-2	0.63	0.09	0.64	3.09	0.163
GT-4	0.67	0.09	0.89	5.61	0.212

The GWRC for the clogged geotextile specimens are shown in Figure 4.4. Each set of data was also fit with the van Genuchten model; the fitting parameters are shown in Table 4.3 The added thickness of GT4 makes the material more resistant to the effects of clogging. The outer pores of a thick geotextile are expected to become impregnated with fine material; however, the inner pores are expected to remain unchanged. Thin geotextile materials will become almost completely impregnated with fines. During cutting of the thicker geotextiles after clogging it was observed that only the outer edge of the material was discolored by the fine grained soil and showed signs of impregnation. The middle section of the material, however, was clean and seemed unaltered from its original state. The thin geotextiles, on the other hand, were discolored completely through the thickness of the material. The low AOS of GT4 may also have an impact on the materials resistance to clogging. GT2 also has a low AOS when compared with GT1 and the materials seem to have become equally as clogged. The thickness of the material is, therefore, thought to be the controlling factor in resistance to the negative effects of soil impregnation. The k-functions for the clogged geotextile materials are shown in Figure 4.5. The k-functions for the un-clogged materials are also shown for reference. The k-functions are also good evidence to support the idea that the geotextile thickness will increase the materials resistance to clogging. The k-function for GT4 is very similar to that of the material when un-clogged. The k-functions for GT1 and GT2 have shifted significantly. This behavior can be explained by the same reasons attributed to the changes in the GWRC.

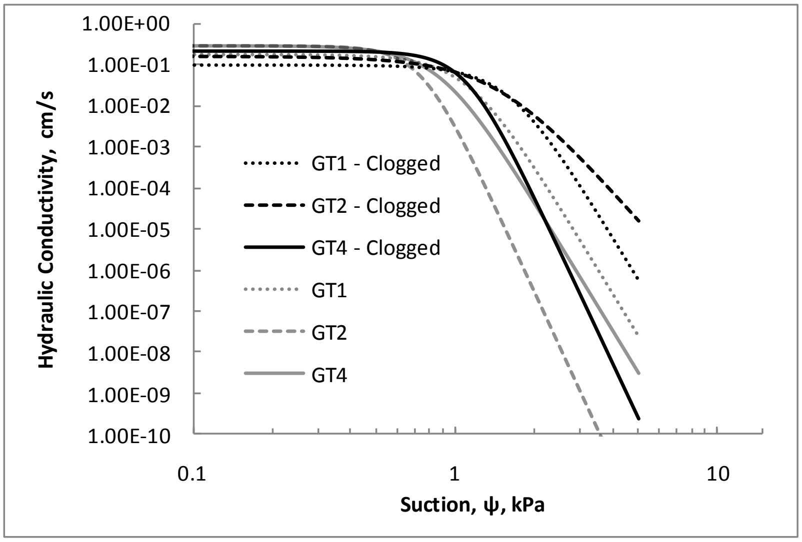


Figure 4.5 – K-functions for different geotextiles determined using the van Genuchten-Mualem model

4.4 Capillary Barrier Predictions

Past researchers (Stormont and Anderson 1999, McCartney et. al. 2005, Thompson 2009, and others) have used the k-functions of different materials, fine soil with coarse soil and fine soil with geotextiles, to make breakthrough predictions of a capillary barrier. With the k-functions for each geotextile material and the lean clay used in this study similar predictions can be made as shown in Figure 4.6 below. The prediction is made by first determining the breakthrough suction, ψ_{bkt}. The suction at which the hydraulic conductivity of each material is the same and a continuity of suction exists across the interface. Next the breakthrough suction is used in conjunction with the water retention function of the fine grained material, in this case the RMA soil, to estimate the moisture content at breakthrough, θ_{bkt}.

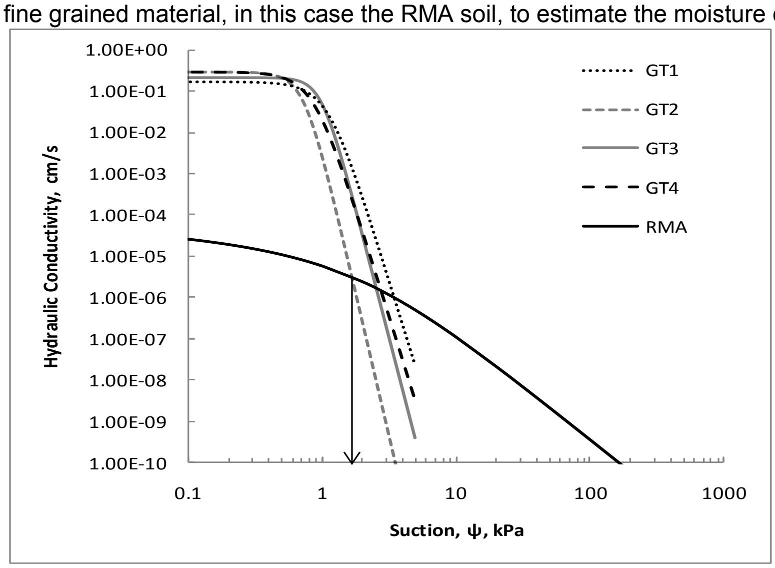


Figure 4.6 – Predictions of capillary break for different materials using K-function

There is a reduction in the predicted θ_{bkt} for the geotextiles which have become clogged. This suggests that a soil-geotextile capillary barrier will degrade with time if water is allowed to pass the geotextile and impregnated the material with fines. Also, although there are differences between the materials the predictions do not suggest that one geotextile will provide a stronger capillary barrier when used at a soil-geotextile interface, i.e. different geotextile materials do not yield significantly different moisture storage nor suction at breakthrough.

4.5 Soil Column Testing

Several small column tests were run as a part of this study to help verify the ability of different geotextiles to form a capillary break at the soil-geotextile interface. Additionally the use of different geotextile materials in the small soil columns allowed for the verification of the predictions made using the k-functions of each material. Figure 4.7 shows typical soil column results and the measured value for θ_{bkt} which is illustrated in the figure by the horizontal arrow indicating the value on the y-axis. The soil columns stored an average of 1291 mL of inflow. The standard deviation between tests is 72.6 mL. The difference in total storage of the capillary barrier is not a result of the geotextile material used. This means that the variations in moisture storage can be attributed to factors other than the specific geotextile material used to create a capillary barrier. These others factors, such as the compaction energy put into the geotextile, the effects of the gravel foundation layer, and the uniformity of the moisture front, will control the breakthrough of the barrier.

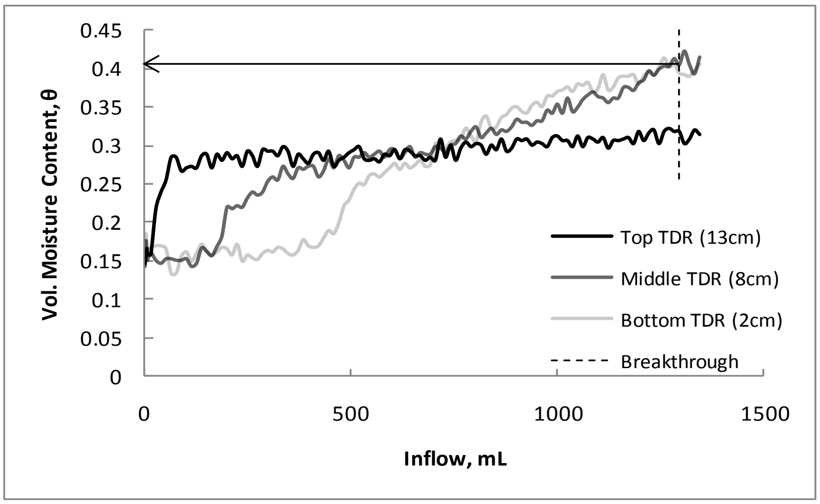


Figure 4.7 – Breakthrough water content from water content vs. inflow for soil column1, test 1, using GT2

4.6 Breakthrough Suction

An assessment of the values of volumetric moisture content at breakthrough will aid in the understanding of soil-geotextile capillary breaks. Soil columns have been used to test a capillary barrier model in the laboratory by various researchers including Stormont and Anderson 1999, McCartney et al. 2005, and Thompson 2009. Although these studies involved infiltration into dry soil following the wetting-path WRC, the researchers involved found that the drying path WRC defined in the study can be used to highlight important hydraulic differences between the materials. Using the k-functions from the drying path for different materials to predict breakthrough of a soil-geotextile capillary barrier did not make accurate predictions for the soil column tests performed in this study. Although the traditional k-function predictions may work fine for soil to soil capillary barriers, the differences between the wetting and drying water retention functions for geotextiles results in an error in the prediction. A prediction based on the water entry suction of the geotextile is more appropriate.

The reason why the k-function predictions work well for soil-soil barriers and not soil-geotextile barriers is due to the difference in the hysteresis behavior of the materials. The retention functions for soils are very similar in shape on the wetting and drying paths, this is however not the case for geotextiles. To support this idea relevant values for predicted and measured moisture contents at breakthrough are presented in Table 4.4.

Table 4.4 – Comparison of predicted versus measured values for θ_{bkt} using various prediction methods.

Test	Column	Material	θ_{BKT} Predicted	θ_{BKT} Measured	θ_{BKT} (Ψ_{WE}) Predicted
Test 1	Column 1	GT - 2	0.38	0.41	0.41
	Column 2	GT - 3	0.37	0.40	0.41
Test 2	Column 1	GT - 4	0.37	0.40	0.40
	Column 2	GT - 1	0.35	0.40	0.41
Test 3	Column 1	GT - 1	0.35	0.39	0.41

Column 2	GT - 4	0.37	0.40	0.40

The results from this study clearly demonstrate that information from the materials wetting curves should be used in making predictions. The water entry suction for nonwoven geotextiles is much lower than the breakthrough suction predicted using k-functions, and, therefore, the water entry suction of the material will govern breakthrough of a soil-geotextile capillary barrier. For the particular materials used in this study use of the drying curves would under predict the soils degree of saturation by more than 15%. This may be important when designing the interface shear strength between the materials.

CONCLUSIONS

The objective of this research study was to gain understanding on the unsaturated hydraulic properties of nonwoven geotextiles for their use in earthen systems. Four nonwoven geotextiles were tested as part of this study. Two test methods for determining the water retention function of the nonwoven geotextiles were studied.

The water retention data was used in conjunction with modeling equations to determine k-functions for different materials. The k-functions were then used for capillary barrier performance predictions. Small soil column tests then helped to further understand the capillary barrier created by a soil-geotextile interface. Additionally, water retention tests were performed to understand the effects of soil retention and an applied mechanical stress on geotextiles in the unsaturated condition. The conclusions of this study are presented below.

Whether a result of differences in the testing methods used, surfactants applied during manufacturing, or anisotropy in geotextiles pore structures, nonwoven geotextiles were found to have variations in air and water entry suctions if tested in the cross-plane or in-plane direction.

The water retention function of nonwoven geotextiles was found to experience increased air-entry suctions when fine grained soil was retained in the material or when subjected to a normal load. Both circumstances will change the geotextiles performance in field applications. Thicker geotextiles provide more resistance to impregnation with fines.

Due to the low water entry suction of nonwoven geotextile when a geotextile and a fine grained soil are placed in contact with each other under unsaturated conditions, the interface of the two materials may create a capillary break that is capable of preventing moisture flow until the soil adjacent to the geotextile is nearly saturated.

The small range of water-entry suctions found in geotextiles makes classification for performance based selection of different geotextiles in a capillary barrier system irrelevant, i.e the geotextiles are very similar and one does not seem to outperform another. The water-entry suction should be used for capillary barrier predictions.

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