Zornberg, J.G., Azevedo, M.M., and Pickles, C.B. (2016). "Evaluation of the Development of Capillary Barriers at the Interface between Fine-grained Soils and Nonwoven Geotextiles," Geotechnical Special Publication (GSP) 275, *Geosynthetics, Forging a Path to Bona Fide Engineering Materials,* ASCE, Proceedings of the *GeoChicago 2016* Conference, Chicago, IL, 15-17 August, pp. 159-167.

Evaluation of the Development of Capillary Barriers at the Interface between Fine-grained Soils and Nonwoven Geotextiles

Jorge G. Zornberg[1], PhD, PE, Marcelo M. Azevedo[2], MS, and Chris B. Pickles[3], MS

[1]Professor, The University of Texas at Austin, Austin, Texas, USA
[2]PhD Candidate, The University of Texas at Austin, Austin, Texas, USA
[3]Former graduate student, The University of Texas at Austin, Austin, Texas, USA

ABSTRACT: The objective of this paper is to assess the formation of capillary barriers on soils in contact with nonwoven geotextiles that have been placed with the primary function of acting as a separator between clay and gravel. This includes a comprehensive experimental program that involved a number of soil column infiltration tests conducted using a variety of material combinations to assess the hydraulic performance of interfaces between the unsaturated clay and the geotextile. Soil moisture was recorded using time domain reflectometers. The acrylic soil columns custom made for this study were comparatively small (20 cm diameter and 17 cm tall) in order to facilitate test setup and reduce total testing time. Eight column tests were conducted, which included four different nonwoven geotextiles selected to observe the geotextile characteristics that may affect the formation of a capillary barrier. The tests were all performed using the same configuration, soils, relative compaction, initial unsaturated water content, and inflow rate, in order to assess the impact of different geotextiles on the hydraulic performance. Based on data from the moisture sensors, all tests were found to show a clear formation of a capillary barrier, which resulted in additional moisture storage in the overlying fine-grained soil layer. The test results show that currently available standard nonwoven geotextiles will create a capillary barrier and restrict moisture flow into the underlying soil layer until the overlying fine-grained soil has become nearly saturated. The strength of the capillary barrier was found to be similar for the multiple standard polypropylene nonwoven geotextiles investigated in this study.

INTRODUCTION

Geosynthetics have been successfully used in multiple geotechnical and geoenvironmental applications over the years. In particular, they are extensively used in waste containment facilities. However, while significant information has been documented on the mechanical behavior of geosynthetics, the hydraulic behavior of geosynthetics has been investigated primarily under saturated conditions. Theoretical background, laboratory data, and full-scale measurements have become recently available to better understand the interaction between soils and geosynthetics under unsaturated conditions. Geotextile properties include those needed to define their water retention curve and the hydraulic conductivity function. In particular, the mechanisms involved in the development of capillary barriers are relevant to explain the storage of moisture that may develop at the interface between materials with contrasting hydraulic conductivity (e.g., a fine-grained soil and a nonwoven geotextile). Capillary barriers have been considered for closure of waste containment facilities, and the inclusion of nonwoven geotextiles has the potential to significantly increase the moisture storage capabilities of the cover system. On the other hand, a capillary barrier could lead to an undesirable and unexpected delay and reduction of drainage.

MATERIALS AND METHODS

All of the soil used in this testing program involved a low plasticity clay collected in the vicinity of Denver, CO. Specifically, the soils were obtained from borrow sources used as part of the cover construction of the Rocky Mountain Arsenal (RMA) in Denver, CO. A characterization of the soil was conducted at UT Austin following ASTM procedures (Thompson, 2009). The soil is classified as a low plasticity clay (CL) by the United Soil Classification System. Atterberg Limit tests indicate a liquid limit (LL) of 32.3%, a plastic limit (PL) of 11.6%, and a plasticity index (PI) of 20. The specific gravity (G_s) of the clay was determined to be 2.71. Per standard proctor compaction, the maximum dry density ($\gamma_{d,max}$) is 1.84 g/cm^3 with an optimum water content (w_{opt}) of 15%. The saturated hydraulic conductivity (k_{sat}) of the CL soil at 80% relative compaction determined from a flexible wall permeameter test is approximately 8.2×10^{-5} cm/s. This saturated hydraulic conductivity is equivalent to a volumetric flow rate of 1.50 mL/min. A summary of the previously stated soil properties can be seen in Table 1.

Table 1: Summary of RMA soil properties

Property	**LL**	**PL**	**PI**	**G_s**	**$\gamma_{d, max}$**	**w_{opt}**	**K_{sat}**
Value	32	12	20	2.71	1.84 g/cm^3	15%	1.50 mL/min

The soil water retention curve (SWRC) for the CL soil was obtained by conducting a series of filter paper tests. The filter paper procedure involved compacting two 3 cm tall and 7 cm diameter soil samples at 80% relative compaction at a given water content. A Whatman 42 filter paper sandwich (three filter papers with the middle filter paper being a slightly smaller diameter than the outer filter papers) was placed in a sealed glass jar and allowed to equilibrate for a week. After equilibration, the filter papers and soil were removed from the soil jar and their water contents were obtained by utilizing a precision scale (0.0001 g). The Whatman 42 calibration curves provided in ASTM D5298 were used to relate the filter paper water content to soil suction. Data from filter paper tests conducted at various water contents were combined to create the SWRC shown in Figure 1. The van Genuchten (1980) method was used to produce a fitting curve through the data points and create a smooth SWRC.

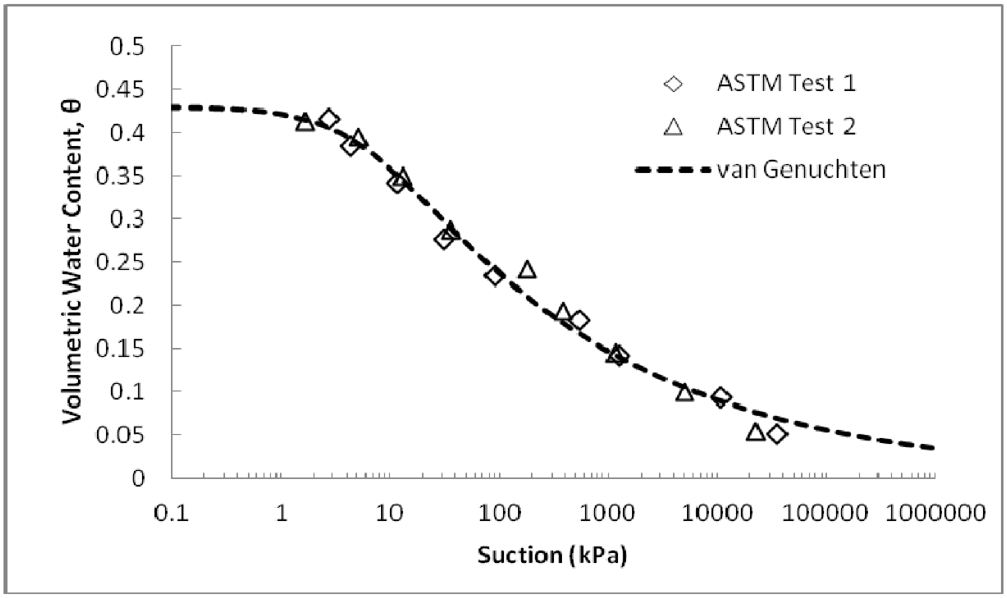

Figure 1: Soil water retention curve at 80% relative compaction

All the geotextiles in this study are nonwoven with polypropylene (PP) fibers, which correspond to commonly available nonwoven geotextile products in the US market. A complete list of all the geotextiles included in the testing program as well as their manufacturer reported properties is provided in Table 2. Each geotextile has been renamed GT1 through GT4 to facilitate references throughout this paper. The weight and thickness of these geotextiles were measured in the laboratory per ASTM D5261 and ASTM D5199, respectively. Geotextile porosity and cross-plane hydraulic conductivity were also calculated. Finally, the geotextile permittivity was reported by the manufacturer per ASTM D4491.

Table 2: Measured nonwoven geotextile properties

Value	Unit	GT1	GT2	GT3	GT4
Weight	g/m^2	163	203	414	407
Thickness	mm	1.00	1.80	2.70	3.30
Porosity	—	0.821	0.876	0.832	0.864
Permittivity	sec^{-1}	1.7	1.6	0.8	0.9
Hydraulic Conductivity	cm/sec	0.167	0.283	0.212	0.291

The SWRC for each geotextile listed in Table 1 was determined by conducting modified hanging column tests in an apparatus similar to the one described in Stormont et al. (1997). A detailed description of the geotextile SWRC characterization procedure is reported by Pickles (2009). A summary of the van Genuchten parameters that best fit the geotextile and soil data are presented in Table 3.

Table 3: van Genuchten model fitting parameters

Material	θ_r	θ_s	α (kPa^{-1})	N	K_s (cm/s)
RMA	0.00	0.430	0.168	1.21	8.2E-05
GT1	0.07	0.821	8.46	4.95	0.167
GT2	0.07	0.876	13.46	5.73	0.283
GT3	0.07	0.832	9.07	5.25	0.212
GT4	0.21	0.864	11.21	4.37	0.291

Hydraulic conductivity functions can be utilized to predict the capillary barrier performance between two geomaterials. The intersection of two K-functions is used to predict the breakthrough suction value at which the capillary break will no longer be maintained at the interface of the two materials. The van Genuchten-Maulem model (van Genuchten 1980) uses the van Genuchten fitting parameters developed for the drying paths of the obtained SWRCs to define the K-function for the CL soil and the four geotextiles. The K-functions for the CL soil and GT1–GT4 determined from the parameters in Table 3 are shown in Figure 2. An arrow at the intersection of the CL soil and GT1 K-functions points to the expected breakthrough suction for those materials at the soil-geotextile interface for a specific column test.

After establishing the breakthrough suction, the moisture content at breakthrough can be estimated from the SWRC for the CL soil shown in Figure 1. The first step is to draw a vertical line from the x-axis to the SWRC at the value of the predicted breakthrough suction. Next, a horizontal line is drawn from the SWRC to the y-axis from wherever the breakthrough suction line intersected the SWRC. The value at which the horizontal line crosses the y-axis is the predicted moisture content at breakthrough for the geotextile.

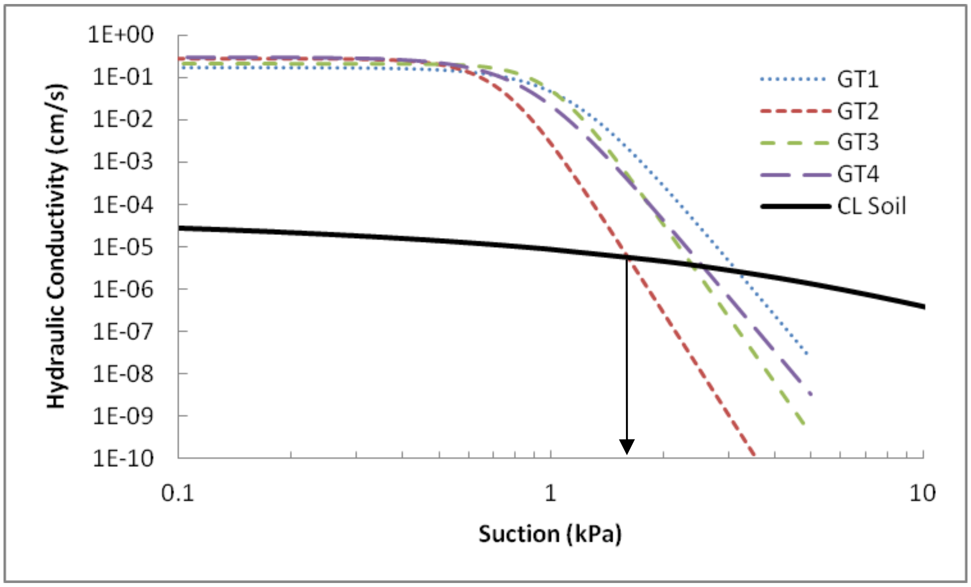

Figure 2: K-functions estimated from van Genuchten-Maulem model

An experimental soil column setup was used in this testing program to monitor the formation of capillary barriers created by geotextiles. The model allows for quick setup times as well as breakthrough occurring within a couple days from the start of a test. The instrumentation required for this test allows for a relatively expeditious analysis of test results. Specifically, the tests were designed so that they could be completed within days, with the specific objective of observing the moisture accumulation created by a capillary barrier.

An extensive investigation was conducted by Thompson (2009) to develop the soil column setup. A diagram of the recommended original test setup is shown in Figure 3. The setup consists of a 19.7 cm diameter clear acrylic column with 15 cm of CL soil compacted in five lifts of 3 cm. The column is instrumented with three time domain reflectometer (TDR) probes to monitor water content 2 cm, 7 cm, and 13 cm above the soil-geotextile interface. Flow is supplied to the column from above with a low flow pump at a constant rate of approximately 0.40 mL/min. The flow is evenly distributed with a large filter paper at the top of the soil column. Beneath the soil is a geotextile, which is in turn underlain by 2 cm of clean, uniformly graded, pea-size gravel. The diameter of the geotextile specimens was about 1 cm larger than the column diameter in order to prevent any side leakage at the interface of the soil and geotextile. A base plate was used underneath the gravel with an array of holes drilled into it to allow water to drain from the column. Water outflow drains into a tipping bucket connected to the bottom of the column which will indicate when water has penetrated into the gravel layer. Finally, a sheet of plastic wrap was used on top of the column to minimize soil moisture loss from evaporation.

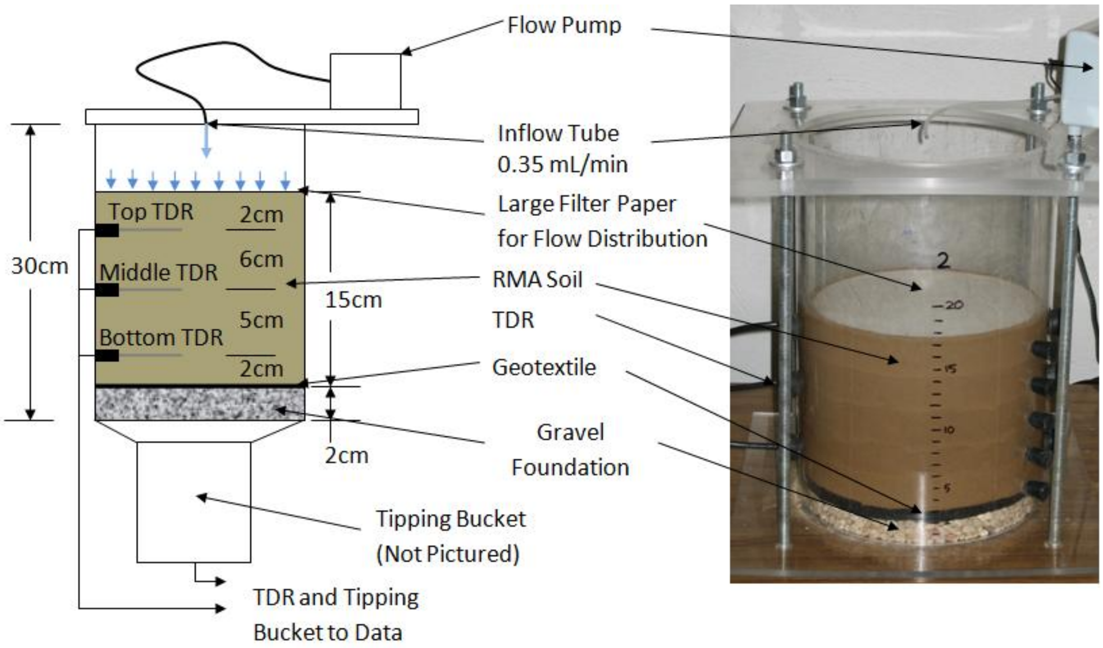

Figure 3: Diagram and photo of small soil column capillary barrier model setup (Pickles, 2009)

The CL soil used in all column tests was prepared using the same target initial conditions. All column tests were run with the CL soil compacted to an 80% relative compaction level. This compaction level was adopted as it is representative of field cover systems, and was observed not to lead to preferential flow paths. An 80% relative compaction of the CL soil corresponds to a dry density of 1.47 g/cm^3 and a porosity of 0.46. The porosity of a soil is also known as the saturated volumetric water content. Accordingly, the maximum amount of moisture accumulation from a capillary barrier will correspond to a volumetric water content of 46%. The initial volumetric water content for all tests was 15%, corresponding to a gravimetric water content of 10.2%. This value was chosen because it is slightly drier than the optimum water content of the CL soil (15% gravimetric). When observing a capillary barrier, it is desirable to have soil initially drier so that any moisture accumulation is clearly visible. If the soil is too wet initially, then the amount of moisture accumulation will be minimized and it will be more difficult to assess capillary barrier behavior. For example, if an initial volumetric water content of 25% was chosen, then moisture contents in a test would vary from 25% to a maximum of 46%. In contrast, the selected 15% initial moisture content allows for a larger range of observation from 15% to 46%. Proper compaction to 80% was achieved by calculating a target weight per each 3 cm lift based on the initial water content and relative compaction level for the soil in the column. An advantage of the testing setup is that the column is composed of clear acrylic so visual observation of the moisture front is possible. Both the large filter paper for proper flow distribution at the top of the column and a careful compaction procedure led to fairly even moisture front progression in all tests.

RESULTS AND ANALYSIS

A series of eight column tests were conducted as part of this study to assess the development of capillary barriers at the soil-geotextile interface. All parameters between tests were kept constant, other than the actual geotextile utilized in the column tests. A repeat test was conducted on each of the four geotextiles to ensure repeatability of the test results.

The results from Test 1 (conducted utilizing GT2) are presented in Figure 4. Recorded data from the probes is in the form of volumetric moisture content versus time for the duration of a test. However, results from all tests will be presented as volumetric water content versus inflow. This is because each test had a slightly different flow rate (± 0.02 ml/min), so this approach facilitates comparison of the breakthrough times among multiple tests. Therefore, using the applied flow rate for each test and multiplying it by the test duration, the cumulative inflow can be plotted instead of time. This approach proved to be effective to accurately enable comparison of breakthrough times between the various geotextiles in this study.

The capillary barrier formation in Test 1 is observed with the moisture sensors that are installed throughout the soil column. Initially, the entire column is at a volumetric moisture content of 0.15. When the pump is turned on, the wetting front starts to proceed down the column, but the probes still record a moisture content of 0.15 because the moisture front has not yet reached the probe elevation. Eventually, the top probe sees a jump in water content once the wetting front reaches the elevation of the top probe. The moisture content for the top probe remains constant at about 0.27 as the moisture front progresses downward into the column. The other probes experience a similar jump in water content as the moisture front reach their locations. If there were no gravel layer or geotextile, then the moisture content would remain at 0.27 for all moisture sensors after the passing of the moisture front since there would be no barrier to retard moisture flow. However, the presence of the geotextile induces the development of a capillary barrier, as observed in Figure 4. Once the wetting front reaches the geotextile, the wetting front is impeded and starts to move back up the column. This is shown in the continued increase in moisture content from 0.27 in both sensors. The moisture buildup is the highest in the bottom probe and least in the top probe since it takes longer for the wetting front to travel back to the top of the column. Moisture buildup continues until the soil suction decreases to a comparatively small value, which corresponds to the breakthrough suction. The water content recorded by the sensors remains constant for the entire column after breakthrough has occurred. There is a slight delay in breakthrough detection due to minimal storage in the gravel layer, but breakthrough as detected by the tipping bucket is indicated by the dotted line in Figure 4.

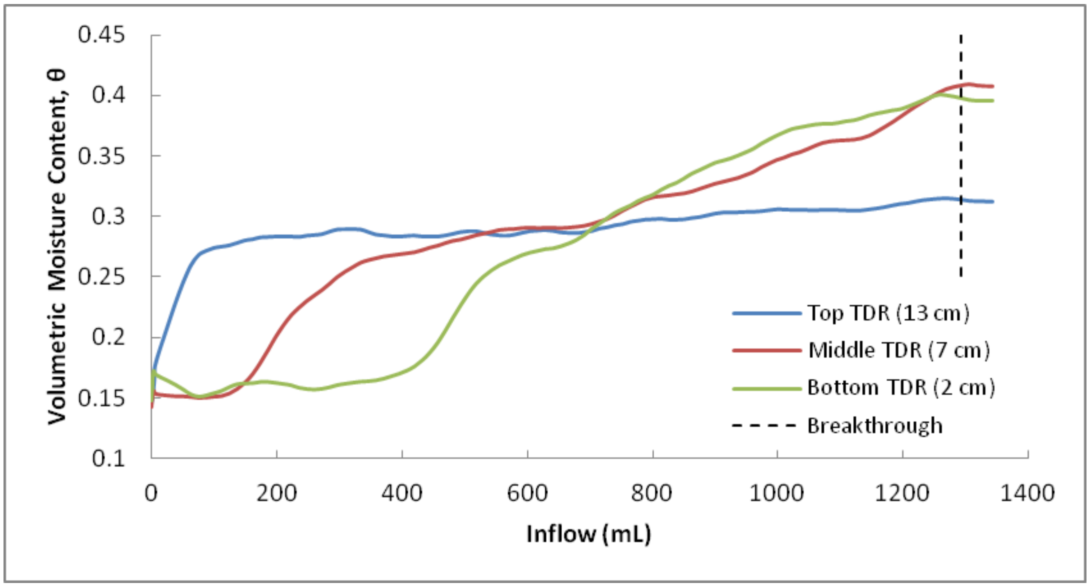

Figure 4: Volumetric moisture content versus inflow for Test 1

The applied flow rate for Test 1 was 0.41 mL/min with breakthrough recorded 3,154 minutes after initially turning on the pump. The breakthrough time corresponds to a cumulative inflow of 1,281 mL to reach breakthrough. The moisture content at the time of breakthrough as recorded by the bottom TDR 2 cm above the geotextile was 0.41. The formation of the capillary break can be observed to start at around 700 mL of inflow in Figure 4, when the moisture content of all the probes start to increase at the same time. Since the bottom probe is closest to the soil-geotextile interface, it is logical that it will experience the highest increase of moisture. The sensors at a higher elevation in the column also experience an increase in moisture content, but at a reduced rate, the greater the distance from the soil-geotextile interface. This behavior shows a clear formation of a capillary barrier at the soil-geotextile interface.

An alternative way to visualize the data from each test is by evaluating the moisture content profiles, at increasing times, along the elevation of the column. Figure 5 shows the moisture content profile created from the Test 1 data. The results shown in Figure 5 indicate that the pre-test moisture content throughout the column was 0.15. As the moisture front passed through the column, the equilibrium water content pertaining to the selected flow rate was about 0.27. However, after the moisture front reached the soil-geotextile interface, the capillary barrier forces moisture to move back up the column, starting from the bottom up.

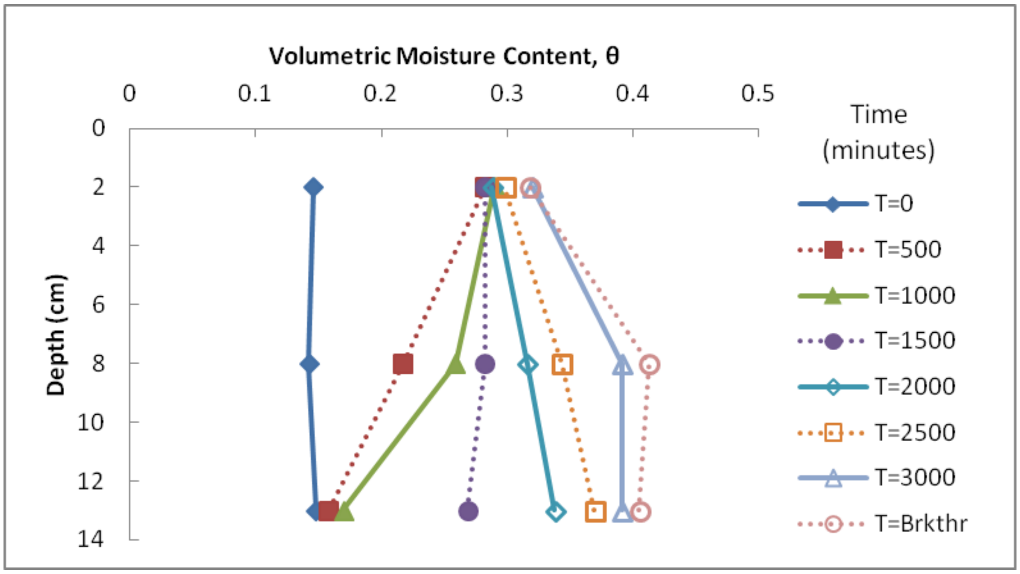

Figure 5: Moisture content profiles for Test 1

Table 4 summarizes the volumetric moisture content values at breakthrough for all eight column tests that were conducted. Also presented in Table 4 is a comparison of the predicted suction and moisture content at breakthrough for the four considered geotextiles based on the predictive method outlined earlier in Figure 2 utilizing K-functions.

Table 4: Predicted and observed breakthrough moisture content

Test #	Geotextile	Suction (kPa)	Predicted θ_{bkth}	Observed θ_{bkth}
1	GT1	3.20	0.402	0.40
2				0.39
3				0.37
4	GT2	1.61	0.415	0.41
5	GT3	2.41	0.409	0.40
6				0.38
7	GT4	2.58	0.408	0.40
8				0.40

CONCLUSIONS

Soil capillary barrier models were tested as part of this study to assess the possible moisture accumulation at a soil-geotextile interface due to the development of a capillary barrier. The models allowed comparatively expeditious evaluation of the susceptibility of combinations of two geomaterials to create a capillary barrier that can be quickly evaluated. The columns are instrumented with TDR sensors, which provide reliable moisture content data throughout each test.

Eight column tests were conducted in this testing program on four different geotextiles with an overlying clay soil. The geotextiles used in this study involved nonwoven, polypropylene products. The results of the tests indicated that a consistent capillary barrier formed in every test, regardless of the geotextile used in this evaluation. The moisture content at breakthrough right above the soil-geotextile interface was near saturation, highlighting that a capillary barrier can significantly increase the moisture storage of an overlying fine-grained soil. Repeat tests on the same geotextiles showed excellent repeatability of the testing approach. Additionally, the K-function method utilized to predict the breakthrough moisture content matched very well with the experimental results.

The results of this testing program demonstrate that standard nonwoven polypropylene geotextiles, which are commonly used in geoenvironmental applications, should be anticipated to develop capillary barriers. The capillary barrier will cause a temporary delay in drainage and additional moisture accumulation in the soil layer. This includes nonwoven geotextiles that are commonly used as the top layer in geocomposite drainage products or as separators between a soil layer and underlying gravel drainage layer.

REFERENCES

ASTM D4491 (2009). Standard Test Methods for Water Permeability of Geotextiles by Permittivity. West Conshohocken, PA: ASTM International.

ASTM D5199 (2012). Standard Test Method for Measuring the Nominal Thickness of Geosynthetics. West Conshohocken, PA: ASTM International.

ASTM D5261 (2010). Standard Test Method for Measuring Mass per Unit Area of Geotextiles. West Conshohocken, PA: ASTM International.

ASTM D5298 (2010). Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. West Conshohocken, PA: ASTM International.

Pickles, C. B. (2009). *Hydraulic classification of unsaturated nonwoven geotextiles for use in soil structures*. Master's thesis. The University of Texas at Austin, Austin, TX.

Stormont, J. C., Henry, K., & Evans, T. (1997). Water retention functions of four nonwoven polypropylene geotextiles. *Geosynthetics International*, 4 (6), 661–72.

Thompson, N. E. (2009). *Small soil column investigation of soil-geotextile capillary barrier systems*. Master's thesis. The University of Texas at Austin, Austin, TX.

van Genuchten, M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44 (5), 892–898.