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Capillary barrier dissipation by new wicking geotextile

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ABSTRACT: A capillary barrier will form and restrict water flow when two porous materials with differing porous structures (e.g., a geotextile overlain by a fine-grained soil) are in contact with one another. This can be problematic as the capillary barrier may cause undesirable moisture build-up in the overlying soil. A new geotextile has been manufactured to help dissipate a barrier by "wicking" or laterally draining moisture away from the soil. Research at The University of Texas at Austin investigated the unsaturated properties of various versions of this wicking geotextile, under both woven and non-woven configurations. The testing program includes small soil column infiltration tests with moisture monitored by time domain reflectometers. Also, modified hanging column tests were conducted to define the hydraulic properties of the geotextile. Test results illustrate advantages in lateral drainage of the wicking geotextile when compared to regular geotextiles.

1 INTRODUCTION

In unsaturated conditions, a capillary break can form and restrict water flow when two porous materials with differing hydraulic conductivities are in contact with one another (e.g., a fine-grained soil overlying a coarse-grained soil). Due to the relatively large opening sizes of geotextiles, a geotextile acts similarly to a coarse-grained soil. Capillary breaks will increase the moisture storage in the overlying soil by forming a barrier at the interface of the materials. The cause of the capillary barrier is a difference in hydraulic conductivity between the large pores of a coarse-grained material and the small pores of the overlying fine-grained soil. This difference means that the small pores will restrict water from entering the larger pores. At a certain suction level, termed the breakthrough suction, the hydraulic conductivity of the two materials will be equal to one another and the barrier will fade away. Until there is enough moisture to break into the larger pores, moisture buildup will occur in the fine-grained soil (Zornberg et al., 2010).

The phenomenon of capillary barriers in unsaturated soils has gained increasing attention in recent years. A common application that takes advantage of capillary barriers is evapotranspirative covers for landfills. Alternative covers make use of the fact that moisture will accumulate in the soil cover, minimizing percolation into the waste. The moisture will then dissipate over the dry season due to evapotranspiration. Another beneficial application for capillary barriers is for agriculture. The barrier can be engineered to provide additional moisture to the root zone of crops.

While there are several other applications which may benefit from the development of capillary barriers, there are also many applications where an increase in moisture storage from a capillary barrier can be detrimental. For example, for the case of a geotextile reinforced slope, not accounting for moisture accumulation due to the formation of a capillary barrier at the soil-geotextile interface could be detrimental to its stability. Accordingly, a geotextile has been developed with the objective of minimizing the effect of a capillary barrier by using special wicking fibers. The wicking fibers allow the geotextile to reduce the effect of a capillary barrier through mechanisms such as enhanced lateral drainage.

This geotextile has the potential to perform the functions of separation, filtration, protection, reinforcement, and drainage. These multiple functions achieved by a single geosynthetic product could lead to significant cost savings compared to the use of separate products that perform equivalent functions.

1.1 *Wicking fiber*

The wicking fiber is a nylon fiber with a unique cross-section. The fiber cross-section is deep grooved (4DG) allowing for water to be carried by channels along the longitudinal axis of the nylon fiber. A picture of the cross section of the fiber can be seen in Figure 1.

The nylon fabric is both hydrophilic and hygroscopic. That is, the nylon will pull water from the surrounding soil as well as provide a conduit for the moisture along its channels. Nylon would

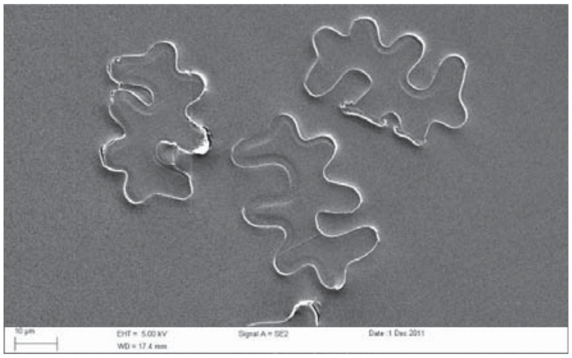

Figure 1. Typical 4DG wicking fiber cross-section.

typically provide these two functions, but an additive enhances them. The additive is not a coating that may diminish with time, but an additive to the nylon formula. The channels will provide some moisture storage as well, but since the channels are not large, their main function is to transport any absorbed water laterally. The channel width between the grooves is approximately 8 µm to prevent clogging from larger particles.

1.2 *Geotextiles*

A total of five different geotextiles were included in the testing program. A brief description of these geotextiles is summarized in Table 1. Each geotextile has been named GT1 through GT5.

GT1 is the control geotextile since it does not have any quantity of wicking fiber. It is commercialized as Mirafi 180 N and is a nonwoven fabric made of standard polypropylene (PP).

All other geotextiles in this study have some amount of wicking fiber. GT2 is commercialized as Mirafi H2Ri and is a woven geotextile composed of standard PP and nylon wicking fiber. The nylon fibers are bundled into strands of approximately 200 fibers. The PP is hydrophobic so it will not absorb water. Instead, the pattern of the weave and the PP itself will help guide the water laterally along with the nylon fibers.

The third geotextile in the study, GT3, is a nonwoven blend of fibers composed of 50% 4DG nylon wicking fibers and 50% standard PP fibers. Similarly, GT4 is a nonwoven blend composed of 50% 4DG nylon wicking fibers and 50% hydrophilic PP fibers. To make the PP hydrophilic, an additive was added to the formula for standard PP. Ideally, the hydrophilic PP will help distribute water to the wicking fibers and increase water movement speed.

The last geotextile in the testing program, GT5, is a nonwoven composed of 100% 4DG nylon wicking fibers. Unfortunately, a woven geotextile made of 100% 4DG nylon wicking fibers could not be created due to challenges in its manufacturing process.

It should be noted that none of the five geotextiles tested in this study had any coating applied to them. While coatings were considered and could provide some benefits to lateral drainage, their use adds a new variable with possible changes with time. Therefore, only additives that were directly included in a polymer's composition were used in this study.

Table 1. List of geotextiles for testing program.

Name	Geotextile description
GT1	Non-woven PP (Mirafi 180 N)
GT2	Woven wicking (Mirafi H2Ri)
GT3	NW 50/50 4DG wicking/PP
GT4	NW 50/50 4DG wicking/Hydrophilic
GT5	NW 100% 4DG wicking

2 WATER RETENTION CURVES (WRC)

A typical WRC for geotextiles is shown in Figure 2 (Bouazza et al., 2006). The WRC shows how the volumetric water content for a material changes with increasing or decreasing suction. The desorption curve (drying path) starts with an initially saturated sample and then increasing suction is applied until the sample reaches residual moisture conditions (going from left to right on the WRC). The initial saturated volumetric water content is the same as the porosity since all the air in the sample has been replaced by water. The final residual water content is due to a small amount of water trapped in the soil pores with no pathway to escape. The air entry value is the value at which the sample first starts to no longer be saturated. The adsorption curve (wetting path) starts out with an initially dry sample and then decreasing suction is applied until the sample becomes saturated (going from right to left on the WRC).

For a geotextile WRC, there is a pronounced hysteresis between wetting and drying paths. An explanation for this hysteresis is that air becomes entrapped in the larger pores, which prevents the geotextile from becoming saturated. The hysteresis for soil WRC is not as prevalent as for geotextiles. Furthermore, geotextile wetting curves obtained via different methods such as hanging column and capillary rise show varying amounts of hysteresis (Krisdani et al., 2006).

Figure 3 shows how the WRC varies for different types of soils (Fredlund et al., 1994). The soils with smaller pore sizes have higher capillary forces and need higher suction to remove water. For coarse-grained soils, the volumetric water content

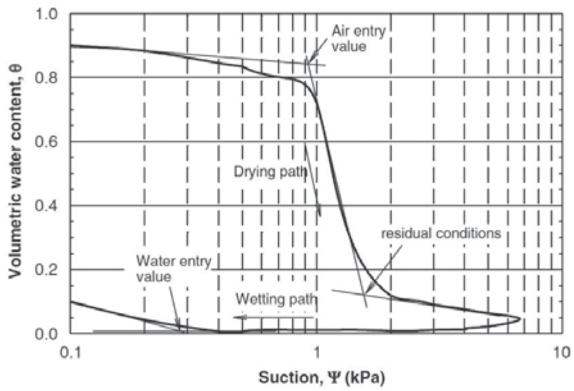

Figure 2. Typical geotextile WRC (Bouazza et al., 2006).

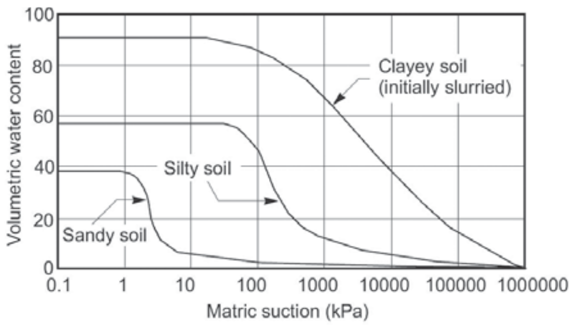

Figure 3. Typical WRCs for different soil types (Fredlund et al., 1994).

decreases sharply over a narrow range of suction. For fine-grained soils, the volumetric water content decreases slowly over a large range of suction. This behavior is explained by the pore size distribution of the soils (McCartney et al., 2005). Coarse-grained soils generally have a uniform pore size, while finer grained soils have a larger distribution of smaller pores. A WRC for a geotextile is similar to that of a coarse-grained soil. Since a geotextile has uniform and comparatively large pores, the WRC shows a steep drying path. The main difference between a soil and geotextile WRC is the wetting path.

2.1 *Modified hanging column test*

The hanging column test commonly used for soils can be modified for geotextiles as shown in the setup by Stormont et al. (1997) in Figure 4. The entire system is sealed to the environment to prevent moisture losses from evaporation. A geotextile specimen is placed into contact with a saturated porous ceramic plate in a Buchner funnel. A seating load is placed on top of the geotextile specimen so that the geotextile remains in contact with the ceramic plate throughout the test. The funnel can be raised or lowered and the head difference between the bottom of the geotextile and the surface of the water reservoir is the applied suction. By raising the funnel to various heights and weighing the geotextile specimen after waiting 24–48 hours at each stage to reach equilibrium, the entire WRC for the geotextile may be obtained.

2.2 *WRC of the wicking geotextile*

The modified hanging column setup in Figure 4 was used to obtain the WRC for the woven wicking geotextile (GT2). Both the drying and wetting curves can be seen in Figure 5. The van Genuchten function was used to fit a curve through the data for the drying path. From the WRC, it is observed that GT2 has a comparatively low porosity, of around 0.2. Also, the volumetric water content does not decrease sharply over a narrow suction range like a regular geotextile. Instead, the water content decreases gradually like a fine-grained soil. However, the WRC is still in a low suction range, which corresponds to a coarse-grained soil.

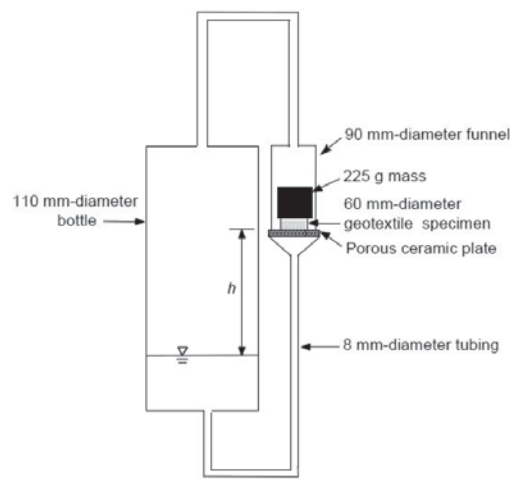

Figure 4. Setup of a modified hanging column test for geotextiles (Stormont et al., 1997).

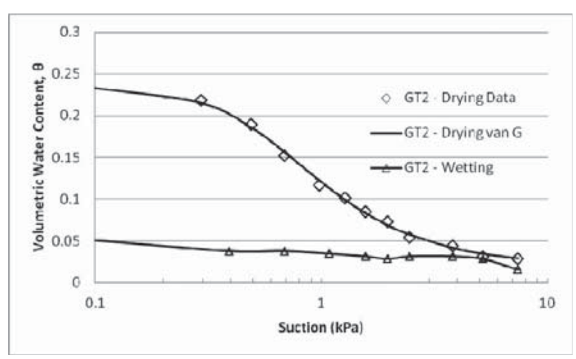

Figure 5. Water retention curve for GT2.

For example, in Figure 3, the suction range for a silty soil goes up to 1,000 kPa. For the sandy soil, the suction range only goes up to 10 kPa, just like for GT2.

Another observation from the wetting curve portion of the WRC is that the wicking geotextile barely absorbed moisture upon wetting. This may just be for the same reasons as other geotextiles which also have minimal absorption upon wetting. It can be noted that this hysteresis may be the result of the wicking fibers not being in contact with the porous stone as shown in Figure 6. The wicking geotextile is composed of black PP fibers and white nylon fibers. Because the geotextile is woven, the surface of the geotextile is uneven and while the PP fibers contact the porous stone, the nylon fibers do not. Since the PP does not absorb moisture and the wicking geotextile depends on the nylon fibers for its moisture capacity, this lack of contact may be why so little water is absorbed during wetting. This may not be an issue in actual soil because the soil should fill in all the pore spaces between the PP fibers.

2.3 *Comparison of mirafi wicking geotextile WRC to other materials*

The WRC of the nonwoven geotextile GT1 is shown in Figure 7. The nonwoven blends of wicking fiber GT3 and GT4 had a WRC very similar to that of GT1. The nonwoven geotextiles behave as expected, with a sharp decrease in water content over a very narrow suction range. The drying curves for the nonwoven geotextiles cover a wider range of moisture content, which differs from the drying curves from GT2. This is expected however, since the nonwoven geotextiles are thicker than GT2 and have more moisture storage capacity. The important difference in the curves of GT1 and GT2 is the water entry suction on the wetting curve. GT2 has a water entry value of 5 kPa while GT1 has a water entry value of 0.2 kPa. This means that GT2 will start absorbing water faster than GT1 and possibly be able to minimize the moisture buildup from a capillary barrier.

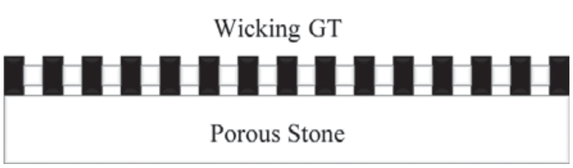

Figure 6. Diagram of GT2 over porous stone.

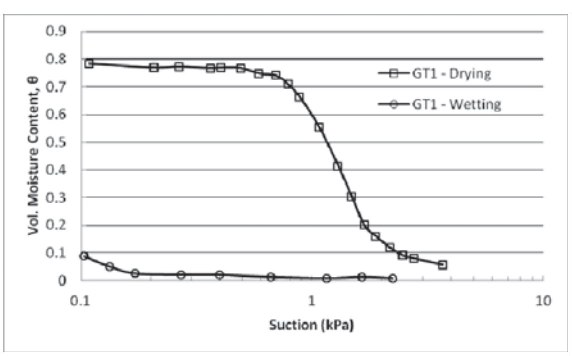

Figure 7. Water retention curve for GT1.

3 SMALL SOIL COLUMN CAPILLARY BARRIER MODEL

The experimental setup to monitor the formation of a capillary barrier is shown in Figure 8. The setup consists of a 19.7 cm diameter column with 15 cm of clay compacted in five lifts of 3 cm. The column is instrumented with three time domain reflectometer (TDR) probes to monitor water content. Flow is supplied to the column from above with a low flow pump at a constant rate of 0.38 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 underlain by 2 cm of clean gravel. The geotextile extends 3 cm from the edge of the column to allow for lateral drainage. There is a base plate underneath the gravel with an array of holes drilled into it to allow water to drain from the column. The water drains into a tipping bucket connected to the bottom of the column which is used to indicate when water has penetrated into the gravel layer.

All column tests used the same clay soil at a relative compaction level of 80%, which corresponds to a porosity (i.e., saturated volumetric moisture

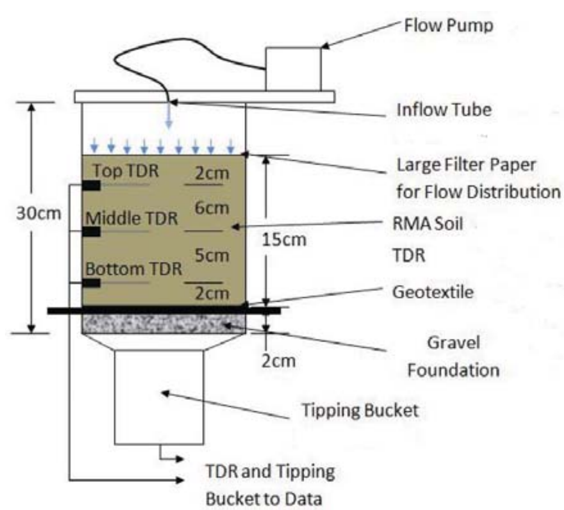

Figure 8. Setup for small soil capillary barrier model (Pickles 2009).

content) of 0.46. Also, all tests had a target initial volumetric water content of 0.15.

The geotextile and the gravel cause the development of a capillary barrier, creating moisture buildup in the column. Moisture keeps building up above the geotextile until a certain point, at which point breakthrough is achieved and there is finally flow through the geotextile into the gravel layer. At this point, there will be minimal storage in the gravel layer before the tipping bucket detects that breakthrough has occurred.

3.1 *Moisture data*

The capillary barrier formation is observed with the TDRs that are installed throughout the soil column. Figure 9 shows an example of volumetric water content with time as measured by the TDRs. Initially, the entire column is at a volumetric moisture content of 0.15. After the pump is turned on, the top TDR sees a jump in water content as it does not take long for the wetting front to reach the top probe. The moisture content for the top TDR remains constant at about 0.25 as the moisture front progresses downward into the column. The other two TDRs see similar jumps in water content as the moisture front reaches their location. If there were no gravel layer or geotextile, then the moisture content would remain at 0.25 for all three TDRs after the passing of the moisture front. However, since there is a gravel layer, a capillary barrier develops at around 2,000 minutes and this is observed in Figure 9. Once the wetting front reaches the geotextile, the wetting front is impeded and moisture increases up the column. The moisture buildup is greatest in the bottom TDR and least in the top TDR since it takes longer for the wetting front to travel back to the top of the column.

Moisture buildup continues until breakthrough suction is reached. The water content recorded by the TDRs remains constant for the entire column

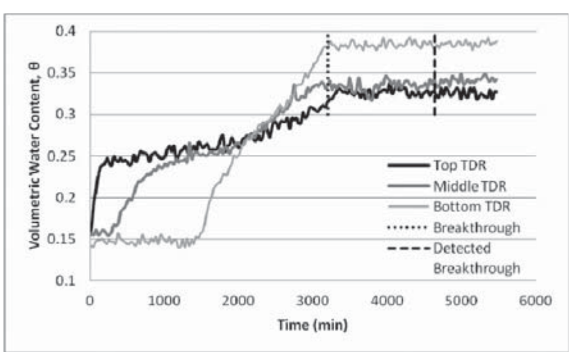

Figure 9. Example water content data from TDRs.

after breakthrough has occurred. If the column did not allow for drainage, then water would immediately flow into the gravel layer upon breakthrough and would be detected by the tipping bucket. This is indicated by the dotted line in Figure 9. However, since the setup allows for drainage, some of the moisture buildup is diverted laterally by the geotextile upon breakthrough and does not immediately flow into the gravel layer. Eventually, however, there will be some moisture that makes it through the geotextile and breakthrough will be detected by the tipping bucket. This delayed breakthrough is indicated by the dashed line in Figure 9.

3.2 *Test results*

A series of small soil column tests were conducted using the five geotextiles listed in Table 1. The goal of testing was to see which geotextile performed the best in terms of lateral drainage as well as possibly minimizing the capillary barrier. All geotextiles were unable to reduce the amount of moisture buildup from the capillary barrier. This is somewhat expected because even though there is a difference in the barrier formed for the various geotextiles, there is still the common gravel layer for every test. This gravel layer forms a second capillary barrier which also needs to be overcome before water can flow into the gravel layer.

In order to quantify the effect of lateral drainage, the percolation rate through the geotextile was calculated. This value was chosen instead of the actual amount of percolation since some tests lasted longer than others and, therefore, were exposed to more flow. The percolation reported here is only the flow that makes it through the base of the column. The idea is that if a geotextile has significant lateral drainage, then most of the moisture buildup will escape through the sides of the column and only a small amount will be left to reach the bottom of the column. Therefore, the smaller the percolation rate, the better the lateral drainage provided by the geotextile.

To calculate the percolation rate, it was first necessary to calculate the time that the geotextile was exposed to flow by subtracting the time it took to reach breakthrough from the total amount of time that the pump was supplying water to the column. To calculate the total outflow at the bottom of the column, the number of tips were multiplied by the volume per tip. The tipping buckets used in this setup have a volume of 8.24 mL per tip. Finally, the percolation rate through the geotextile was calculated by dividing the two previous results. A summary of these calculations can be seen in Table 2.

The percolation rate data in Table 2 provides a comparative assessment of the geotextiles that perform better in terms of lateral drainage. It is

Table 2. Percolation rate calculations.

Test value	Test 1	Test 2	Test 3	Test 4	Test 5
Geotextile	GT1	GT2	GT3	GT4	GT5
Time to brkth.*	3,575	4,640	4,487	4,951	11,622
Total test time*	5,896	5,481	6,665	5,472	12,740
Δ ($T_{bkth} - T_{total}$)*	2,321	841	2,178	521	1,118
Number of tips	79	2	8	7	2
Apprx. outflow†	651	16	66	58	16
Percolation rate‡	0.280	0.020	0.030	0.111	0.015

* minutes † mL ‡ mL/min.

clear that the control, regular nonwoven GT1 performs the worst, as expected. With an inflow rate of 0.38 mL/min, GT1 only minimally reduces the rate that makes it though the geotextile to 0.28 mL/min. Therefore, 74% of the applied flow reaches the gravel layer. The nonwoven 50/50 blend of hydrophilic PP and 4DG wicking fiber (GT4) performed better than GT1, but 29% of the inflow still made it to the gravel layer instead of being redirected laterally. On the other hand, GT2, GT3, and GT5 all performed comparatively much better. The percolation in columns using these geotextiles is reduced to approximately 0.02 mL/min, or an order of magnitude difference from GT1. Only 5% of the inflow makes it into the gravel layer, indicating that these three combinations of wicking fiber create a geotextile that has very good lateral drainage capabilities.

3.3 *Dissipation of capillary barrier*

While a capillary barrier still developed with each of the geotextiles, the lateral drainage function provided by the wicking fibers was able to dissipate the capillary barrier after it formed. Figure 10 shows the dissipation of the capillary barrier by GT5. For that test, the pump was shut off about a day after breakthrough was detected. Up until this point, the moisture in the column had been constant for multiple days after the initial breakthrough (not the detected breakthrough). As soon as the pump was turned off, the geotextile kept laterally wicking away water from the soil immediately above it. This corresponded to a drop in moisture content in the top TDR of the column. Without a continuous supply, the wetting front continued downward until it reached the geotextile where it drained laterally. Eventually, the geotextile was able to reduce the moisture buildup from the capillary barrier in the middle and bottom of the column as well.

The GT5 geotextile saw the greatest moisture buildup dissipation, which can be expected as it has the greatest amount of wicking fibers. Both GT2 and GT3 were able to dissipate moisture as well,

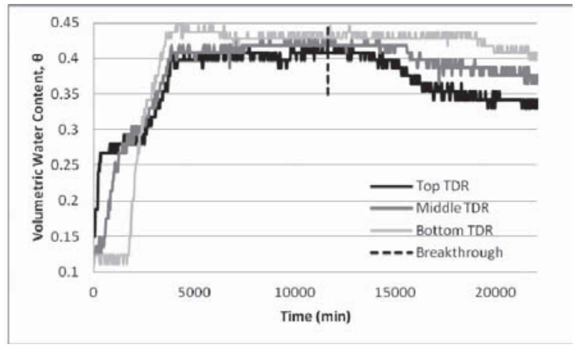

Figure 10. Dissipation of capillary barrier by GT5.

but to a lesser extent than GT5. Those geotextiles saw a decrease in moisture content near the top of the column, but not so much at the bottom of the column.

It is important to note that the decrease in moisture content in the column once the water supply is removed is not attributed to a drying front from evaporation. Tests run with geotextiles with no wicking fibers maintained constant water contents for days after removing the water supply. Only after a few days did the water content near the top of the column begin to slightly decrease. Tests were conducted indoors at room temperature and a low relative humidity of approximately 30%.

4 CONCLUSIONS

Results from infiltration column tests that allow for lateral drainage have shown that various woven and nonwoven configurations of geotextiles with 4DG nylon wicking fiber reduce the moisture buildup formed by a capillary barrier. The moisture dissipation is a direct result of the lateral drainage capabilities of the wicking fiber. Besides drainage, this geotextile has the potential to perform the functions of separation, filtration, protection, and reinforcement. This could lead to an all in one geosynthetic product with significant cost savings. Overall, these features are expected to help prevent common geotechnical problems associated with the use of geotextiles in unsaturated soils.

Ongoing tests are focusing on the conclusion from the WRC for the wicking geotextile which found that the wicking geotextile could minimize moisture buildup from a capillary barrier. New blends of nonwoven fibers will be tested in the same small soil column setup, but no lateral drainage will be allowed. Also, the gravel layer will be replaced with a layer of the same clay that makes up the rest of the column. Therefore, any moisture accumulation will solely be attributed to a capillary barrier from a geotextile and not the gravel layer since it is not present. Hopefully, one of the nonwoven blends will allow for complete passage of water into the base layer, with no additional moisture buildup. Thus creating a geotextile that does not form a capillary barrier.

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