 https://doi.org/10.1051/e3sconf/202456906003

Parameters affecting the development of capillary barriers due to conventional geotextiles

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Abstract. The objective of this study is to assess the formation of capillary barriers on unsaturated soils in contact with geotextiles that have been placed with the primary function of acting as a separator between soil or drainage layers, including the geotextile component of a geocomposite. A comprehensive experimental program involving soil column infiltration tests was conducted using a variety of material combinations to assess the hydraulic performance of interfaces between unsaturated clay and geotextiles. Soil moisture was recorded using time domain reflectometers. Custom made acrylic soil columns were comparatively small (20 cm diameter and 33 cm tall) in order to facilitate test setup and reduce total testing time. Multiple column tests were conducted, which included woven and nonwoven geotextiles selected to identify which geotextile characteristics may affect the formation of a capillary barrier. Other tests were conducted to assess the effect of varying relative compaction and inflow rate on the hydraulic performance. Based on data from the moisture sensors, all tests were found to clearly show the 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 conventional geotextiles create a capillary barrier and restrict moisture flow into the underlying soil or drainage layer until the overlying fine-grained soil has become essentially saturated. This includes nonwoven geotextiles that are commonly used as the top layer in geocomposite drainage products or as separators between a soil layer and an underlying gravel drainage layer. The strength of the capillary barrier was found to be similar for the multiple conventional polypropylene geotextiles investigated in this study.

1 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

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soils and geosynthetics under unsaturated conditions. Geotextile properties include those needed to define their soil water retention curve (SWRC) and the hydraulic conductivity function (K-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 [1].On the other hand, a capillary barrier could lead to an undesirable and unexpected delay and reduction of drainage.

1.1 Capillary Barrier Formation in Unsaturated Soils

Under unsaturated conditions, a capillary break can form and restrict water flow when two unsaturated 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 of the overlying soil by forming a temporary barrier at the interface of the two materials [2]. A capillary break develops due to a difference in hydraulic conductivity between the small pores of a fine-grained soil compared to the larger pores of a coarse-grained soil. This difference restricts moisture in the small pores from entering the larger pores. Until there is enough energy to decrease the suction so the hydraulic conductivity of the two adjacent soils are the same, moisture accumulation will continue in the fine-grained soil. When the suction has decreased enough to allow moisture to break into the larger pores, termed the breakthrough suction, or simply, breakthrough, moisture buildup will be halted and flow will proceed into the coarse-grained soil. The strength of a capillary barrier can be quantified by the amount of additional moisture storage induced in a soil. However, the moisture storage will not increase past the saturated moisture content of the soil [3].

K-functions can be utilized to predict the capillary barrier performance between two geomaterials. Figure 1 compares the K-functions of a nonwoven geotextiles and a lean clay. The saturated hydraulic conductivity corresponds to the y-axis intercept and varies by several orders of magnitudes depending on soil or material type. Coarse-grained soils have higher hydraulic conductivity than fine-grained soils when moisture contents are high. However, the hydraulic conductivity decreases at a faster rate than fine-grained soils as moisture content decreases. Therefore, when water content is comparatively low, the hydraulic conductivity of a fine-grained soil is actually higher than that of a coarse-grained soil or geotextile. While counterintuitive, this occurrence is due to the reduction in available pathways for water flow in the coarse-grained soils with increased suction.

The intersection of two K-functions can be used to predict the breakthrough suction value at which the capillary break will no longer be maintained at the interface of two materials. Capillary barriers are generally considered “stronger” when the breakthrough suction is comparatively low, since the barrier will be maintained across a wide suction range.

1.2 Study Objectives

The main objective of this study is to identify the important parameters affecting the formation of a capillary barrier. Geotextile unsaturated hydraulic behavior will be verified via a soil column specifically designed for this study. The several parameters considered in this study included geotextile product (different nonwoven products), geotextile type (woven versus nonwoven), soil relative compaction (60 to 100%), soil column base material underlying the geotextile (fine or coarse-grained), and infiltration rate.

2 Materials and Properties

2.1 Soil Properties

The soil used in this testing program was obtained from a borrow pit at the site of the Rocky Mountain Arsenal (RMA) in Denver, CO. A characterization of the soil was conducted at UT Austin following ASTM procedures. The soil was classified as a lean clay (CL) by the Unified Soil Classification System. Atterberg Limit tests indicated a liquid limit (LL) of 32, a plastic limit (PL) of 12, 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 ($\gamma_{d,max}$) was found to be 1.905 g/cm^3 (119 pcf) with an optimum water content (w_{opt}) of 15%. The saturated hydraulic conductivity (K_{sat}) of the RMA soil at 80% relative compaction determined from a flexible wall permeameter test was approximately 8.2x10^{-5} cm/s (equivalent to a volumetric flow rate of 1.50 mL/min). A summary of the soil properties is provided in Table 1.

Table 1. Summary of RMA soil properties.

Property	**LL**	**PL**	**PI**	**Gs**	$\gamma_{d,max}$	w_{opt}	K_{sat}
Value	32	12	20	2.71	1.905 g/cm^3 (119 pcf)	15%	1.50 mL/min

2.2 Geotextile Properties

Most of 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 nonwoven 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. The geotextile permittivity was reported by the manufacturer per ASTM D4491. Geotextile cross-plane hydraulic conductivity was calculated by multiplying the permittivity by the geotextile thickness. Finally, the geotextile porosity was calculated considering the geotextile thickness, mass per unit area, and fiber density [4].

Table 2. Measured nonwoven geotextile properties.

Value	**Unit**	**GT1**	**GT2**	**GT3**	**GT4**
Unit 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

A few tests were also conducted on conventional woven PP geotextiles to compare to the behavior of nonwoven geotextiles. Four different woven products were used, which are all conventional separation and reinforcement products.

2.3 Unsaturated Material Properties

The SWRC for the RMA soil and each geotextile were obtained to characterize their unsaturated properties. For the RMA soil, the SWRC was obtained at various relative compactions (70%, 80%, and 90% Standard Proctor) by conducting a series of filter paper tests. The SWRC for each of the geotextiles listed in Table 2 was determined by conducting modified hanging column tests in an apparatus similar to the one described in [5].

The van Genuchten-Maulem k-function model [6] uses the van Genuchten SWRC fitting parameters developed for the drying paths of the obtained SWRCs to define the K-function for the RMA soil and the four nonwoven geotextiles. The K-functions for the RMA soil and GT1 to GT4 are shown in Figure 1. An arrow at the intersection of the RMA soil and GT1 K-functions points to the expected breakthrough suction for those materials at the soil-geotextile interface for a specific column test. The moisture content at breakthrough can also be estimated from the SWRC for the RMA soil by using the breakthrough suction predicted from the K-function.

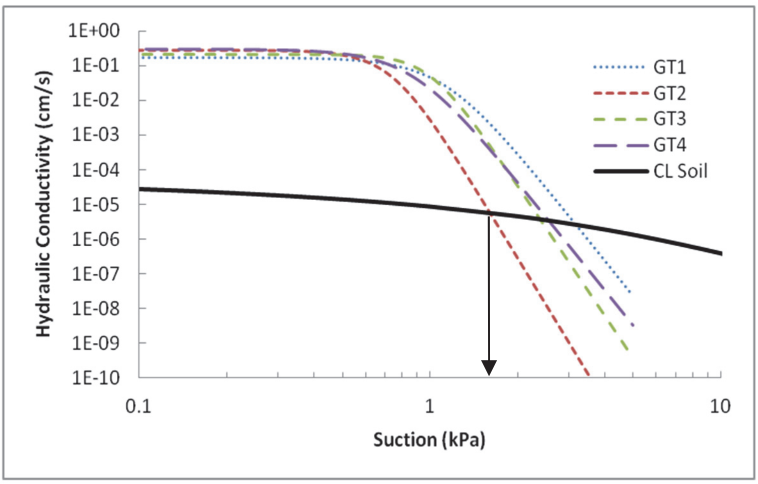

Fig. 1. K-functions estimated for geotextiles and soil

3 Methodology

An experimental small soil column setup was developed at UT Austin to monitor the formation of capillary barriers created by geotextiles. The column model allows for relatively quick setup times as well as allowing breakthrough to occur within a couple days from the initiation of a test. The minimal instrumentation required for this test means that analysis of test results is relatively simple and not time consuming. With test results available within days, this model is ideal for observing the moisture accumulation created by a capillary barrier.

A diagram of the test setup is shown in Figure 2. The setup consisted of a 19.7 cm diameter clear acrylic column with of RMA soil compacted in multiple lifts of 3 cm. The column was instrumented with three time-domain reflectometer (TDR) probes to monitor water content located 2 cm, 8 cm, and 13 cm above the soil-geotextile interface. An additional TDR probe is located 2 cm below the geotextile to provide an indication of when breakthrough occurs. The soil below the geotextile in the column was varied throughout the testing program to be composed of RMA soil and clean, uniformly graded, pea-size gravel.

Flow is supplied to the column from above with a low flow pump at a constant rate of approximately 0.40 mL/min. The moisture supplied by the pump was evenly distributed at the top of the soil column using a large piece of filter paper. 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 plate was placed at the base of the column 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 will indicate when water has penetrated through the entire column. Finally, there was also a sheet of plastic wrap stretched on top of the column to minimize soil moisture loss from evaporation.

In this setup, a Campbell Scientific TDR100 reflectometer was used as a pulse generator. The TDR100 was powered by a PS100. Multiple TDR probes were attached to the TDR100 with the addition of an SDMX50 multiplexer. The TDRs used in the setup are CS645 probes manufactured by Campbell Scientific, which have a radius of influence of 0.8 cm. The probe locations in the column were chosen to be at least 2 cm away from any interface (air-soil or geotextile-soil) so that the entire probe influence volume would be within the soil to ensure accurate moisture content readings.

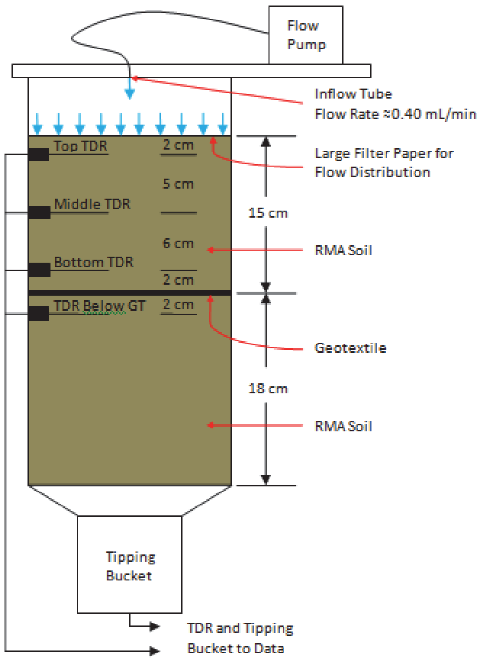

Fig. 2. Diagram of medium soil column capillary barrier model setup.

4 Results

The results from a standard test are presented in Figure 3. Results from tests are presented as volumetric water content versus inflow to account for the slightly different flow rates (± 0.02 ml/min) between tests and allow a comparison of the breakthrough times among multiple tests.

The capillary barrier formation in the standard test was observed with the moisture sensors that were installed throughout the soil column. Initially, the entire column was at a volumetric moisture content of approximately 0.15. When the pump was turned on, the wetting front proceeded down the column, but the probes still recorded a moisture content of 0.15 because the moisture front had not yet reached the probe elevation. Eventually, the top probe experienced an increase in water content once the wetting front reached the probe elevation and remained constant at about 0.28 as the moisture front progressed downward into the column. The other probes experienced a similar increase in water content as the moisture front reached their locations. If a geotextile were not present, then the moisture content would have remained at approximately 0.28 for all moisture sensors after the passing of the moisture front since there would have not been a barrier to retard moisture flow. However, the presence of the geotextile induced the development of a capillary barrier, as observed in Figure 3.

As additional flow is applied to the soil column, the development of a capillary barrier is observed at the soil-geotextile interface, which causes moisture buildup in the column. Moisture keeps building up above the geotextile until the soil suction decreased to a comparatively small value (i.e., the breakthrough suction), at which point breakthrough is achieved and there is finally flow through the geotextile into the underlying soil layer, as recorded by the TDR underlying the geotextile.

A total of thirty-three column tests were completed during the course of this study while varying relative compaction, geotextile types, column base material, and infiltration rate.

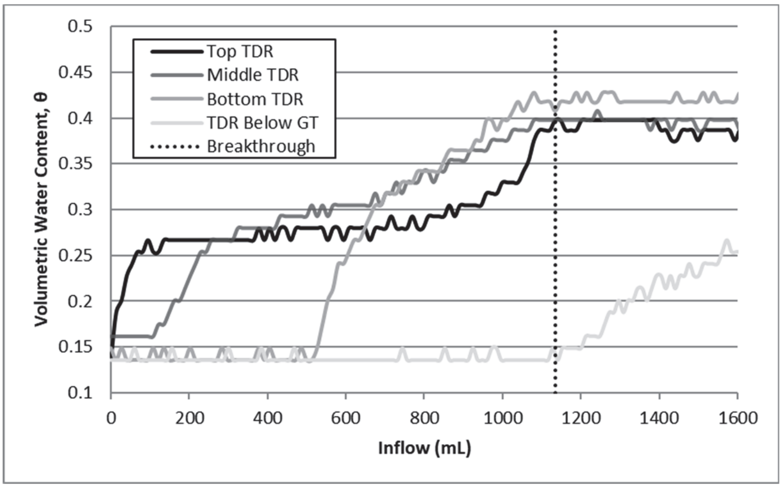

Fig. 3. Standard column test results shown as volumetric moisture content versus inflow.

5 Discussion

5.1 Effect of Geotextiles

A series of column tests were conducted as part of this study to assess the development of capillary barriers for various soil-geotextile interfaces. All parameters between tests were kept constant (80% relative compaction, 15% initial volumetric water content, and 0.40 ml/min inflow rate), other than the actual geotextile utilized in the column tests. A duplicate test was conducted on each of the four nonwoven geotextiles to ensure repeatability of the test results.

Table 3 summarizes the volumetric moisture content values at breakthrough for column tests that were conducted on multiple nonwoven geotextiles. Also presented in Table 3 is a comparison of the predicted suction and moisture content at breakthrough for the four considered geotextiles based on the predictive method outlined earlier utilizing the material K-functions and SWRCs.

Four additional tests were conducted on conventional woven geotextiles under the same testing conditions as the nonwoven geotextiles. Observed breakthrough moisture contents for woven geotextiles varied from 0.37 to 0.41, with an average value of 0.39.

Table 3. Observed breakthrough moisture content for nonwoven geotextiles.

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

These column tests that were conducted while varying geotextiles indicate that a consistent capillary barrier formed in every test, regardless of the geotextile used in this evaluation. 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 moisture content at breakthrough right above the soil-geotextile interface was near saturation (between 80 to 90%), highlighting that a capillary barrier can significantly increase the moisture storage of an overlying fine-grained soil. The applied inflow during these tests corresponded to an equilibrium inflow volumetric moisture content of around 0.28, which correlates to a saturation level of 60%. Therefore, the geotextiles increased the saturation level in the overlying soil by 20 to 30% before breakthrough is observed.

5.2 Effect of Relative Compaction and Column Base

The effects of a gravel or soil base, and relative compaction of the overlying fine-grained soil on the formation of a capillary barrier were tested concurrently. All tests employed a flow rate of 0.4 ml/min, 15% initial volumetric moisture content, and used the same geotextile GT2. The saturation level right above the geotextile is plotted against the relative compaction, which was varied from 60 to 100%, for various tests in Figure 4.

It is apparent that the column base material has no observable effect on the capillary barrier moisture content buildup based on Figure 4. This is important for two main reasons. The first is that it demonstrates the potential issue inherent with an installed drainage layer. If an engineer or designer assumes that once moisture reaches the drain, that it will drain instantly, then this may not likely be true for unsaturated soils. In the case of the geotextile and gravel base, which simulates a geocomposite drainage net, drainage does not begin until the soil is essentially saturated. The same situation applies for a simple conventional geotextile separator in contact with only soil.

The next important conclusion from these two figures is that as the compactive effort in the soil overlying the geotextile increases, then a capillary barrier will cause increasingly higher saturation levels before breakthrough occurs. This finding has implications regarding the interface shear strength. Various direct shear tests on were conducted on soils [7] while varying the degree of saturation to observe the effect on the interface shear strength. It was observed that in most cases, the soil shear strength parameters decreased as the soil was inundated. In the case of this study, this could mean that the additional moisture buildup from a capillary barrier could reduce the interface shear strength of soils with a high degree of compaction. The lower interface shear strength could be problematic in slopes inducing a sliding failure along the geotextile or a pullout failure in pavements.

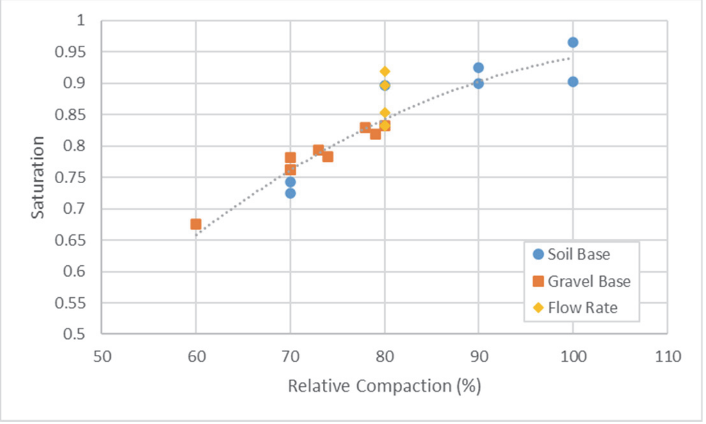

Fig. 4. Saturation level above geotextile for varying compaction, base soil, and flow rates.

It is also important to note that the soils with lower relative compactions store a much greater amount of moisture than the soils with higher compaction levels. This behavior is in spite of the fact that the soil columns with higher compaction have higher final saturation values than the tests with lower compaction. The higher porosity of the less compacted soils accounts for the larger storage. The less compacted columns have a lower saturation level at breakthrough, but there is more moisture spread out throughout the column. On the other hand, the higher compacted soils are almost completely saturated throughout the entire column in such a way that there is no room for any additional moisture in the column.

5.3 Effect of Flow Rate

A series of tests in this study were purposely conducted using very slow or very fast flow rate in order to examine the effect on a capillary barrier. These tests were conducted with the same initial volumetric moisture content of 15%, a relative compaction of 80%, and used the same geotextile GT2.

The low flow rate selected for the first lower flow rate test was 0.014 mL/min, which corresponds to a flux rate of 7.6 x 10^{-7} cm/s. This flow rate is two orders of magnitude smaller than the saturated hydraulic conductivity of the RMA soil at 80% relative compaction. In addition to tests with a low flow rate, tests were conducted with the maximum possible flow rate. These tests were achieved by ponding approximately 2 cm of water above the soil column (constant head) and allowing it to freely infiltrate the soil. This method would provide the maximum saturation possible in a practical sense with gravity driven flow.

By comparing the results from tests with low flow rates, high flow rates, and the baseline flow rate, it is clear that the flow rate does not have an effect on the maximum moisture content at breakthrough due to a capillary barrier. All tests, regardless of the flow rate, had a maximum moisture content of approximately 0.40 and achieved a saturation level between 80 to 90% above the geotextile. Figure 4 plots the results of the varying flow rate tests with the tests conducted while varying relative compaction, which were conducted at the baseline flow rate. The varying flow rate test data falls in line with all of the other tests. The main difference between the tests with low or high flow rates was the duration of the test. The low flow tests took approximately a month to complete, which is too long for a column test where the goal is to produce results relatively expeditiously. On the other hand, the high flow rate tests were completed within 1 to 2 hours, but the formation of the capillary barrier was less obvious. Both the low and high flow tests are not practical to run for these reasons and it is recommended to conduct tests at the baseline flow rate of 0.40 mL/min for the soil used in this study. For other soils, the baseline flow rate should be fixed fraction of the saturated hydraulic conductivity of the soil being tested.

6 Conclusions

A series of soil columns 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 soil column models allowed comparatively expeditious assessment of the susceptibility of combinations of two geomaterials to create a capillary barrier. The columns are instrumented with TDR sensors, which provided reliable moisture content data throughout each test. Duplicate tests showed excellent repeatability of the testing approach to simulate a capillary barrier.

Multiple column tests were conducted in this testing program using different geotextiles with an overlying clay soil. A parametric sensitivity analysis was conducted, which involved multiple parameters that could influence the formation of a capillary barrier. These parameters included the type of geotextile, the applied flow rate, the soil relative compaction, and whether the geotextile was underlain by a coarse-grained or fine-grained soil. All of the geotextiles used in this study were conventional products commonly used for separation, filtration, or reinforcement functions. Both nonwoven and woven polypropylene products were involved in the study.

The results of the tests indicated that a capillary barrier developed consistently, regardless of the geotextile used in this evaluation. Furthermore, the K-function approach utilized to predict the breakthrough moisture content was found to match well with the experimental results. The relative compaction of the overlying fine grained soil was varied from 60 to 100% (in relation to Standard Proctor maximum dry unit weight), with results showing that increasing relative compaction leads to increasingly higher levels of saturation in a soil before breakthrough occurs. 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. Calculations revealed that the increases in moisture storage capacity ranged from 20 to 180% in relation to the amount that would be expected if no capillary barrier were formed. Varying flux rates were found not to influence the final moisture content needed to break through the capillary barrier.

The results of this testing program demonstrate that conventional nonwoven and woven polypropylene geotextiles, which are commonly used in geotechnical applications, should be anticipated to develop capillary barriers depending on the soil type overlying the geotextile. A capillary barrier will cause a temporary delay in drainage and accumulation of moisture in the overlying 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 layers.

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