Technical Note by J.C. Stormont, K.S. Henry and T.M. Evans

WATER RETENTION FUNCTIONS OF FOUR NONWOVEN POLYPROPYLENE GEOTEXTILES

ABSTRACT: The water retention functions of four nonwoven polypropylene geotextiles were measured. Each of the four geotextile types were tested in two conditions: new and cleaned. The water retention functions of each geotextile specimen were found to be hysteretic. The new geotextile specimens always contained more water at comparable suction heads than the cleaned geotextile specimens. At zero suction head, the new specimens approached saturation, whereas the cleaned specimens were less than 20% saturated.

KEYWORDS: Geotextile, Water entry suction, Water retention function, Capillary rise, Capillary barrier.

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PUBLICATION: *Geosynthetics International* is published by the Industrial Fabrics Association International, 1801 County Road B West, Roseville, Minnesota 55113-4061, USA, Telephone: 1/612-222-2508, Telefax: 1/612-631-9334. *Geosynthetics International* is registered under ISSN 1072-6349.

DATES: Original manuscript received 6 August 1997, revised version received 21 November 1997 and accepted 27 November 1997. Discussion open until 1 July 1998.

REFERENCE: Stormont, J.C., Henry, K.S. and Evans, T.M., 1997, “Water Retention Functions of Four Nonwoven Polypropylene Geotextiles”, *Geosynthetics International*, Vol. 4, No. 6, pp. 661-672.

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1 INTRODUCTION

Geotextiles are often placed in soils that are unsaturated for long periods of time, even though the effect of a geotextile on the retention and movement of water within an unsaturated environment is largely unknown. Recent efforts to characterize the unsaturated behavior of nonwoven geotextiles have utilized water capillary rise measurements. These measurements are performed by submerging one end of a geotextile specimen strip in water and measuring the height above the water surface that the water rises due to capillary action (Henry and Holtz 1997). The height of capillary rise approximates the water entry suction head of a material, which is defined as the negative pressure head at which an initially dry material initially conducts water. For hydrophobic (water repelling) geotextiles, a capillary depression occurs.

A more complete characterization of the unsaturated behavior of a porous material is given by the relationship between water content (or saturation) and suction head (or negative water pressure), known as the water retention function or the soil moisture retention function. The standard test method ASTM D 3152 is used to measure the moisture retention functions of soils, which are required parameters for modeling unsaturated flow in soils. The water retention functions are found by establishing a series of equilibria between the soil pore water and a body of water at a known suction (Klute 1986). The water retention functions are hysteretic for almost all soils, therefore, the water content at a particular value of suction head is lower during wetting than during drying.

To the authors' knowledge, no water retention functions have been published for geotextiles. Thus, tests were conducted to: (i) apply an existing experimental technique used for soils to measure the water retention functions of geotextile specimens; and (ii) understand unsaturated water flow in geotextiles. A description of the technique used and the experimental test results are provided in this technical note.

2 MATERIALS AND METHODS

2.1 Geotextiles Tested

The physical properties of the geotextiles tested are given in Table 1. Specimen A1 and A2 were obtained from one manufacturer, and Specimen B1 and B2 were obtained from a different manufacturer. Each geotextile type was tested in two conditions: "new" (as received from the manufacturer) and "cleaned". Replicate tests were conducted for each geotextile and condition. The geotextile specimens were cleaned because it is widely believed that the surfactants used in geotextile manufacturing can change geotextile wetting behavior. Indeed, work by Henry and Patton (to be published) has shown a difference in fiber wetting due to such cleaning, and Henry and Holtz (1997) also demonstrated a change in water capillary rise due to cleaning. The specimens were cleaned by immersing the specimens in tap water, squeezing water through them by hand, repeating the procedure, and then air drying the specimen (Henry and Holtz 1997).

Table 1. Physical properties of the nonwoven, needle-punched, polypropylene geotextiles tested in the current study (data supplied by the manufacturers).

Product designation	Manufacturing process	Mass per unit area (g/m^2)	Apparent opening size* (mm)
A1	Staple fibers	339	0.15
A2	Staple fibers	543	0.15
B1	Continuous filament	340	0.18
B2	Continuous filament	540	0.15

Note: * ASTM D 4751

2.2 Experimental Test Apparatus

The test apparatus commonly used to measure the water retention functions of soils (Klute 1986) was used to measure the water retention functions of geotextile specimens. The apparatus consists of a filter funnel fitted with a porous plate, a bottle which serves as a water reservoir, tubing between the bottom of the funnel and the bottom of the bottle, and tubing to connect the top of the funnel to the top of the bottle (Figure 1). The tubing between the top of the funnel and the bottle is filled with air and reduces evaporative losses from the specimen. The 90 mm-diameter ceramic porous plate has a maxi-

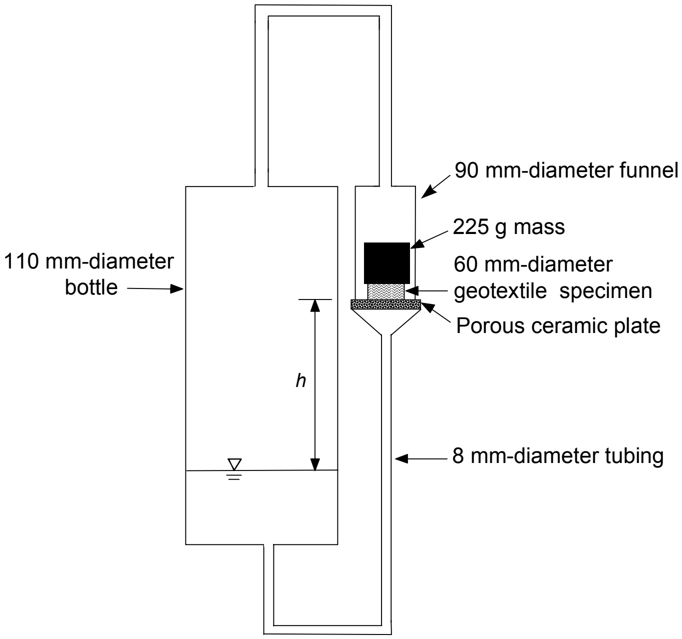

Figure 1. The experimental test apparatus used to measure the water retention functions of geotextile specimens.

mum pore size of 15 μm and an air entry head of approximately 2 m. Initially, a 20 mm-diameter burette was used as the water reservoir rather than the 110 mm-diameter bottle. However, it was necessary to replace the burette with the bottle to accommodate the relatively large amounts of water absorbed by the geotextile specimen without changing the water level in the reservoir.

With the saturated porous plate and the tubing beneath it filled with water, a continuous column of water extends from the porous plate to the bottle. When a geotextile specimen is placed on the porous plate, a hydraulic equilibrium is established between the two materials. The water in the porous plate is at a suction head h when the water level in the bottle is a distance h below the porous plate. The geotextile specimen either absorbs or exsorbs water to equilibrate with the water in the porous plate. The water retention functions are determined by systematically raising or lowering the bottle to change the suction head. This allows the water in the geotextile specimen to equilibrate with the water in the porous plate, and the water content of the specimen can be measured.

A scale with an accuracy of ± 0.01 g was used to weigh the geotextile specimens. Tap water was used for all of the tests.

2.3 Experimental Method

A circular geotextile specimen (60 mm diameter, typically weighing between 1.5 and 2.0 g) was placed on top of the porous plate and a 225 g mass was placed on top of it to maintain hydraulic contact between the geotextile specimen and the porous plate. The first measurement was made at 600 mm of suction head. Subsequent measurements were made at increments of 150 mm until the specimens absorbed an appreciable amount of water. Thereafter, the measurement increments were decreased to as little as 20 mm near 0 mm of suction. After the water in the specimen was equilibrated with the water in the porous plate at zero suction head, the procedure was reversed and the suction heads were increased to 600 mm. At each value of suction head on both the wetting and drying path, the specimens were allowed to equilibrate for at least 24 hours, and often in excess of 48 hours. The specimen was then removed from the funnel, weighed, returned to the funnel, and the suction head was adjusted to the next value. Weighing took less than 1 minute, resulting in negligible evaporative losses from the specimen. On occasion, a small amount of water from the specimen (on the order of 0.01 g) was left on the scale.

The minimum equilibrium period of 24 hours was chosen after performing preliminary tests which were used to refine the experimental procedure. Typical preliminary test results for a cleaned A1 specimen are shown in Figure 2. Figure 2 is a graph of gravimetric water content (ratio of mass of water to dried mass of geotextile), w, versus time which represents the response to the suction head being increased from 100 to 150 mm. To further evaluate time dependency, other specimens were held at the same suction head for several days. The new specimens typically equilibrated within 24 hours. A few cleaned specimens, however, continued to take up small amounts of water beyond 24 hours along the wetting path at low suction heads, and particularly at zero suction head. Therefore, to increase the opportunity for the geotextile specimens to absorb water over time at zero suction head, the specimens were held at zero suction head for at least two days when transitioning from wetting to drying.

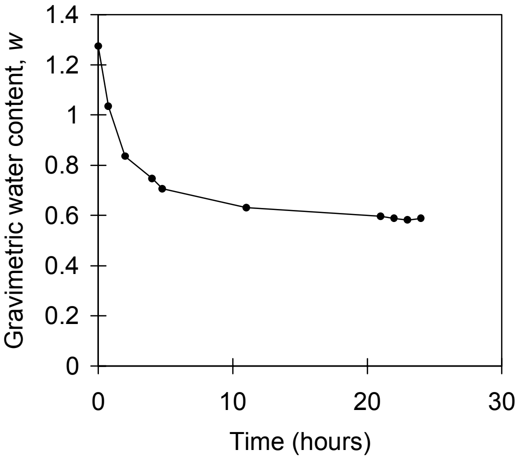

Figure 2. Gravimetric water content versus time for a cleaned A1 specimen in response to the suction head being changed from 100 to 150 mm.

The laboratory was maintained at a mean temperature of 23°C, although diurnal variations of ± 2°C were common. Specimen weighing and suction head adjustments were conducted at the same time every day to minimize the effects of temperature variations. The relative humidity of the laboratory was maintained in excess of 50% using evaporative coolers.

To express the measured gravimetric water content as a saturation value (i.e. volume of water per volume of voids in the specimen), the specimen porosity value was required. The porosity, n, of the specimen was calculated as follows (Koerner 1994):

$$n = 1 - \frac{\mu}{\varrho_f \, t} \tag{1}$$

where: μ = mass per unit area, ϱ_f = fiber density (assumed to be 0.91 g/cm^3 for polypropylene); and t = specimen thickness measured while the specimen was subjected to the same vertical pressure used during the water retention test. The saturation, S, is obtained from the gravimetric water content, w, using the following relationship:

$$S = \frac{w \, \mu}{t \, \varrho_w \, n} \tag{2}$$

where ϱ_w is the density of water.

3 RESULTS AND DISCUSSION

3.1 Overview

Wetting and drying water retention functions for replicate tests on new and cleaned geotextile specimens are shown in Figures 3 and 4, respectively. Note that the water

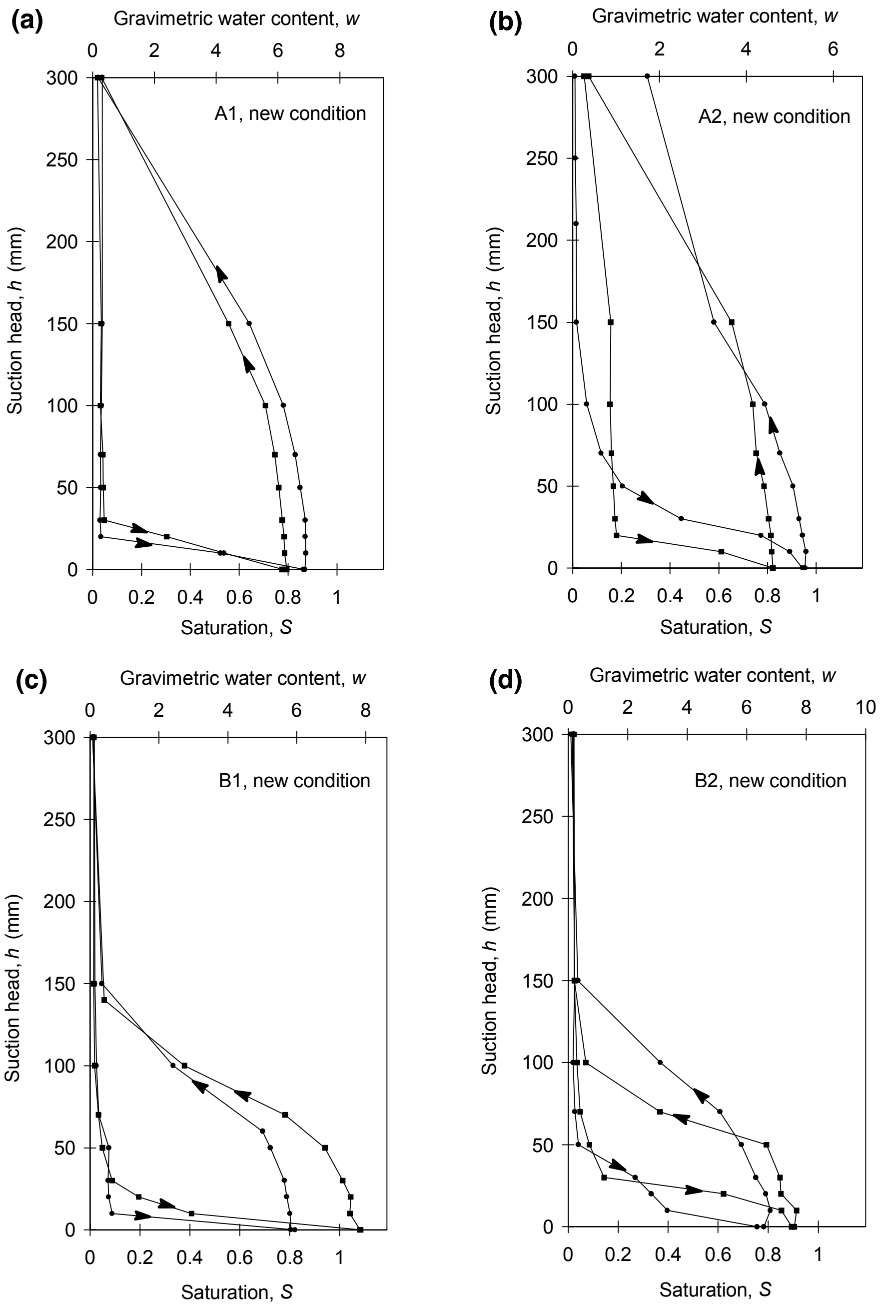

Figure 3. The wetting and drying water retention functions of new geotextile specimens: (a) A1 (b) A2 (c) B1; (d) B2.

Notes: The test results for two specimens from each geotextile type are shown. The arrows denote wetting and drying paths.

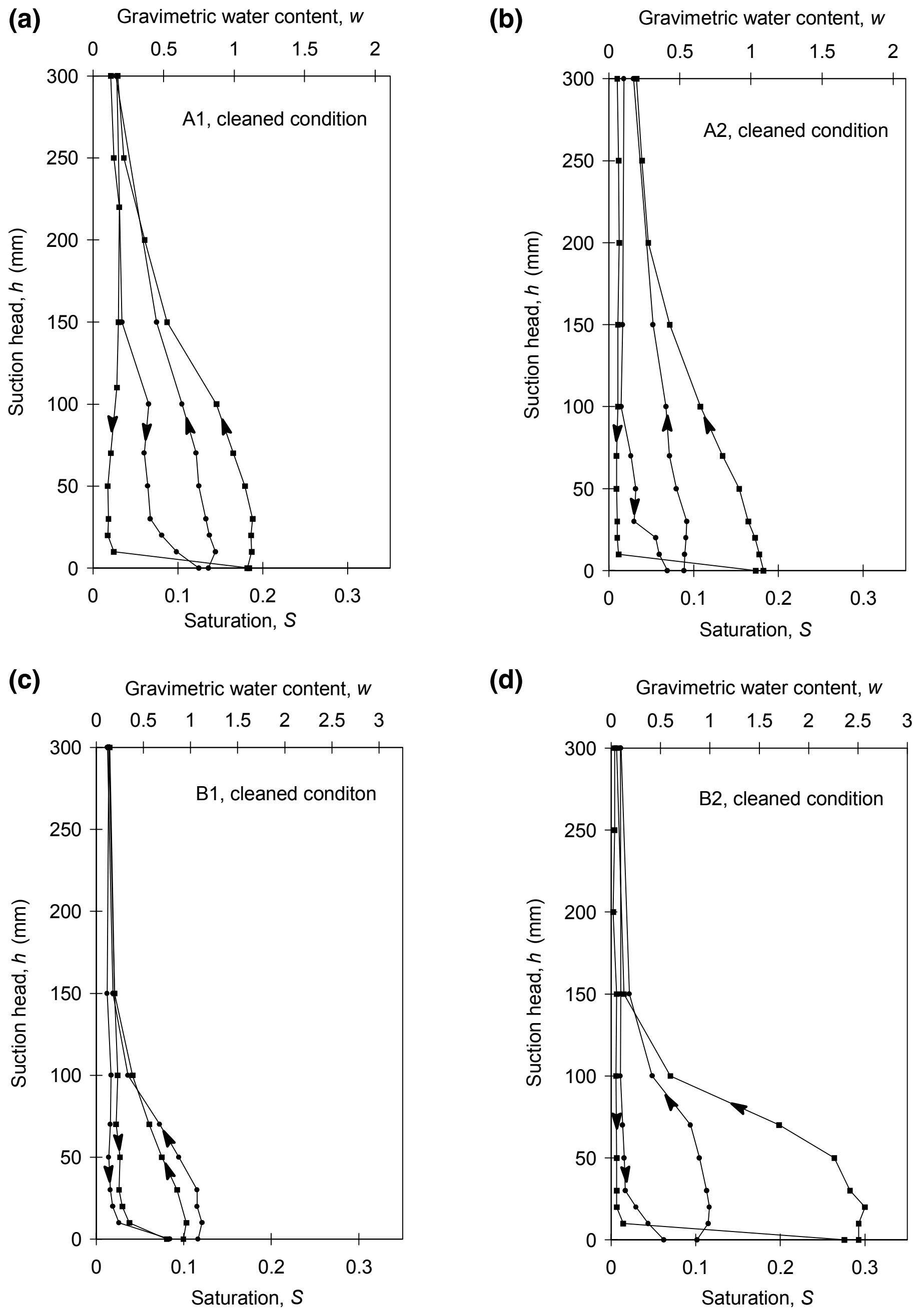

Figure 4. The wetting and drying water retention functions of cleaned geotextile specimens: (a) A1; (b) A2; (c) B1; (d) B2.

Notes: The test results for two specimens from each geotextile type are shown. The arrows denote the wetting and drying paths.

content and saturation scales for the new specimens and the cleaned specimens are different. A small amount of water was absorbed by the geotextile specimens when they were taken from the air-dry condition and equilibrated at the initial suction head of 600 mm. In one test (B1, new condition, Figure 3c), a saturation of 1.1 is reported at zero suction head; this is believed to be due to a small amount of surface water observed on top of the specimen.

The sharp uptake of water during specimen wetting suggests that the geotextiles have a definable water entry suction head, which is the suction head associated with the movement of water into the smallest continuous network of pores in an initially dry geotextile specimen. The suction entry head represents the transition of a material from a hydraulically nonconductive state to a conductive state. Thus, if water in contact with the geotextile specimen is at a suction head in excess of the water entry suction head of the geotextile, it will not enter the geotextile specimen.

The change in water content for most soils is a significantly more gradual process than that for the geotextile specimens tested during both wetting and drying. The specimens contained essentially no water at suction heads greater than a few hundred millimeters; however, most soils have appreciable water contents at hundreds of meters of suction head. The water retention functions for three soils are shown in Figure 5. Very coarse, uniform soils, such as pea gravel, are the only soils that have water retention functions during wetting which resemble the water retention functions of geotextiles. Pea gravel also exhibits a sharp uptake of water very near zero suction head.

3.2 Hysteresis

The water retention functions of each geotextile specimen exhibit hysteresis (Figures 3 and 4). During wetting, there is a sharp break in the water retention functions when

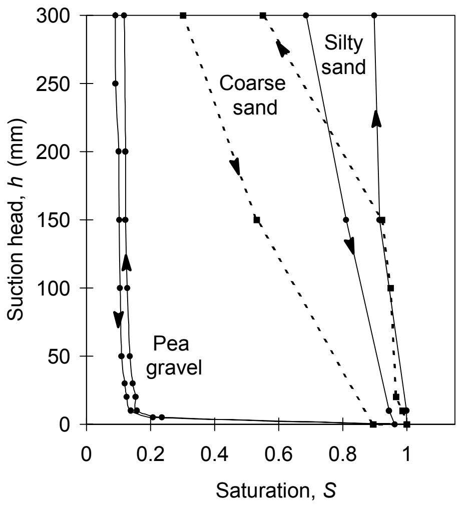

Figure 5. The water retention functions at low suction heads for three soils of varying texture (Stormont and Anderson).

Note: The arrows denote wetting and drying paths.

the specimens first begin to absorb appreciable amounts of water, usually at less than 50 mm of suction head, and often very near zero. During the subsequent drying, the specimens contained more water at each suction head than during wetting. The water content of many specimens did not decrease during the initial portions of the drying path, indicating that once saturated, some geotextiles may remain saturated under small suction heads. Almost all soils exhibit similar wetting/drying hysteresis (e.g. Figure 5) because soil pores are not uniformly cylindrical and there is hysteresis in liquid-solid contact angles (Hillel 1982). The geotextile fiber-water contact angles are also hysteretic (Henry and Patton).

3.3 Differences Between New and Cleaned Geotextile Specimens

New specimens contain more water at comparable suction heads than cleaned specimens of the same product. At zero suction head, the saturation of the new specimens was usually between 0.7 and 1.0. In contrast, the saturation of the cleaned specimens was typically less than 0.2. These results are consistent with previous tests in which the geotextile specimens exhibited either no measurable capillary rise or capillary depression when cleaned in the same manner (Henry and Holtz 1997). The change in the water retention properties of cleaned geotextile specimens is probably caused at least in part to an increase in the contact angles of water on the geotextile fibers making the fibers less wettable with water (Henry and Patton; Henry and Holtz 1997). The removal of a residual surface coating left by the manufacturing process from the fibers could cause such a change. Some physical change in the pore structure, as a result of the squeezing of the geotextile specimen when it was cleaned, may also have occurred.

3.4 Product Differences

The hysteresis loops of the soil moisture retention functions for the new Geotextile A1 and A2 specimens are much larger than those for the new Geotextile B1 and B2 specimens. However, the hysteresis loops for the cleaned Geotextile A1 and A2 and Geotextile B1 and B2 specimens more closely resemble each other. Based on the assumption that the cleaned geotextile specimens had higher water-fiber contact angles, the test results suggest that these contact angles had a greater influence at suction heads in excess of 100 mm for the cleaned Geotextile A1 and A2 specimens than the cleaned Geotextile B1 and B2 specimens.

Fiber wetting properties are affected by a number of factors such as the polymer type, fiber shape, fiber surface roughness, and any surfactants that may have been used in the manufacturing process (Berg 1989). The manufacturing process also affects the pore size distribution of the geotextiles. Therefore, the test results presented in the current paper should not be extrapolated to other geotextile products. However, the authors of the current paper expect that the soil moisture retention functions for nonwoven products made by similar manufacturing processes (which will result in only a limited range of pore size distributions and water-fiber contact angles) will bear a resemblance to those published herein.

Table 2. Estimates of water entry suction heads.

Product designation	Cross-plane water entry suction heads from the water retention functions in current study (mm)	Cross-plane water entry suction heads for geotextiles placed in soil columns (Henry and Holtz 1997) (mm)	In-plane water entry suction heads (mean value) from capillary rise measurements (Henry and Holtz 1997), [standard deviation] (mm)
A1	0 to 20	60 to 69	50 [9]
A2	0 to 20	60 to 70	75 [6]
B1	0 to 10	60 to 70	25 [9]
B2	0 to 30	41 to 48	36 [15]

3.5 Water Entry Suction Heads

The water entry suction head of a soil corresponds to the point on the water retention function where the specific water capacity during wetting ($\mathrm{d}S/\mathrm{d}h$) is maximized (Baker and Hillel 1990). Water entry suction heads for new geotextile specimens are given in Column 2, Table 2 as the interval of suction head for which the value of $\Delta S/\Delta h$ is a maximum. Henry and Holtz (1997) placed specimens of the same geotextile products in an initially dry soil and measured the distance between the water table and the geotextile specimen when water that rose due to capillarity first noticeably moistened soil on the top side of the geotextile specimen. These estimates of water entry suction heads are given in Column 3, Table 2. The height of water capillary rise in geotextile specimen strips is given in Column 4, Table 2.

Regardless of the measurement technique, the water entry suction head values in Table 2 range between 0 and 90 mm; these values fall between those of a gravel (Stormont and Anderson) and a uniform coarse sand (Baker and Hillel 1990). The water entry suction head values estimated from the water retention functions are lower than those from the capillary rise tests (Henry and Holtz 1997), which may have been caused by the different methods used to estimate these values. Soil fines may have entered the geotextile specimen pore spaces, thus increasing the water entry suction head values reported by Henry and Holtz. Also, the geotextile tested may be anisotropic which would explain the differences between the in-plane and cross-plane water entry suction head values reported by Henry and Holtz.

Because the saturation values of cleaned specimens remained significantly low, a water entry suction head value was not interpreted from these test data. In fact, the water entry head values of the cleaned specimens are likely positive.

3.6 Unsaturated Water Flow in Geotextiles

Saturation values substantially less than one at zero suction head, for the cleaned geotextile specimens, suggest that these specimens would require positive water pressures to become saturated. It would have been informative if the tests were prolonged allowing the wetting path to continue into positive pressures until the specimens became completely saturated. If sustainable, such hydrophobic behavior, or a portion thereof, would contribute to the performance of the geotextile as a capillary barrier to limit unsaturated water movement in soils (Stormont 1995). However, when geotextiles are placed in soil, soil particles may adhere to geotextile fibers and mitigate this effect. Henry and Holtz (1997) found that dirty geotextiles had larger capillary rises than cleaned or new specimens because soil fines coated the fibers and thereby increased the wettability of the fibers.

Very little is known about the unsaturated flow properties of geotextiles and the changes that occur in them once placed in soil and subjected to a range of soil and flow conditions. The question of what combination of geotextile conditions, such as new, cleaned, compressed, or containing soil fines, that best represents in situ conditions is important. This will depend on the particular environment in which the geotextile is placed and the conditions to which it is exposed before placement. Conducting water retention tests on geotextiles before and after field installation (with exposure to water flow in the soil) would provide insight into in situ unsaturated behavior of geotextiles. The effect of overburden pressure, which will compress the geotextile and hence influence the unsaturated behavior, should also be considered.

In addition to investigating the effect of in situ conditions on geotextile water retention, a more complete understanding of the influence of geotextiles placed in unsaturated environments is necessary. This will require a characterization of geotextile unsaturated hydraulic conductivities. The unsaturated hydraulic conductivity of the geotextile could then be modeled as a function, which is derived from the water retention functions, as is done with soils.

4 SUMMARY AND CONCLUSIONS

The water retention functions of four nonwoven polypropylene geotextiles were measured with equipment that is typically used for measuring the water retention functions of soils. Each geotextile specimen was tested in two conditions: new (as-received) and cleaned (water-rinsed and air-dried).

The water retention functions for each specimen were hysteretic, as are those for soils, and the specimens contained more water during drying than wetting for the same suction head. New specimens contained more water at comparable suction heads than cleaned specimens of the same geotextile. At zero suction head, the saturation value of the new specimens was typically between 0.7 and 1.0, whereas the saturation value of the cleaned specimens was typically less than 0.2.

The soil moisture retention functions were influenced both by pore size and geotextile fiber-water contact angle, and the relative influence of each factor varies among products. Other nonwoven geotextile products that were not tested in the current study, but manufactured using a similar process to those geotextiles analyzed in the current study, are expected to have similar soil moisture retention functions to those reported herein. The estimated water entry head of the geotextiles is comparable to that of a uniform, coarse soil such as a pea gravel or uniform coarse sand (10 to 20 mm).

The results presented in the current paper suggest that additional testing is required. Conducting the same tests on geotextiles before and after field installation would provide insight into how to simulate in situ behavior. The effect of overburden pressure, which compresses the geotextile and hence would influence the unsaturated behavior, should also be investigated. The significance of the direction of measurement, i.e. in-plane versus cross-plane, is also largely unknown. Finally, a complete understanding of the influence of geotextiles placed in unsaturated environments will require characterization of the unsaturated hydraulic conductivity of the geotextiles in addition to the water retention functions.

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