DETERMINATION OF THE UNSATURATED PROPERTIES OF A NONWOVEN POLYPROPYLENE GEOTEXTILE FOR USE AS PART OF A GEOCOMPOSITE CAPILLARY BARRIER

Kevin D. Park, Graduate Student, University of Saskatchewan, Canada
Ian R. Fleming, Associate Professor, University of Saskatchewan, Canada

ABSTRACT
Geotextiles have most often been used in soil structures for reinforcement, filtration, separation, and drainage. However, in most of these cases the geotextile is designed to behave under saturated conditions. A geotextile's behaviour under unsaturated conditions, as in soils, is much different than in its saturated condition. In this study a nonwoven, polypropylene geotextile was tested in order to determine its water characteristic curve. Two testing methods were used and compared in order to determine which method determined the unsaturated behaviour more accurately. It was found that the water retention function for this geotextile is similar to that of a uniform sand. Therefore, when used in conjunction with a fine-grained, rock flour, a geocomposite capillary barrier can be developed. The van Genuchten, as well as the Fredlund and Xing closed form equations for the water characteristic curves were used to fit the functions for the materials. Finally, these equations were used to estimate the hydraulic conductivity functions of both materials and to evaluate their performance as a geocomposite capillary barrier.

RÉSUMÉ
Détermination des propriétés non-saturées d'un géotextile en polypropylène non-tissé pour son utilisation comme composante d'une barrière capillaire géo-composite.

1. INTRODUCTION

Nonwoven geotextiles are often used in engineering practice as a drainage layer or to enhance the rate of dissipation of excess pore-water pressures due to increasing overburden stress. Due to their high in-plane hydraulic conductivity, they perform quite well in supplying horizontal drainage.

However, studies have shown that geotextiles do not always behave as desirable drainage materials (Iryo and Rowe, 2003). After heavy rainfalls, water has been known to pond to depths of 10 cm above a geotextile, increasing the pore water pressures in the soil (Dierickx, 1996 and Richardson, 1997). Therefore, we must look at the underlying mechanisms of drainage with respect to nonwoven geotextiles. To do this we will evaluate both the water retention and hydraulic conductivity functions for the geotextile.

Perhaps the most important information we can learn about a material when trying to model its drainage characteristics is its water-characteristic curve (Fredlund, 2000). From the water-characteristic curve we have developed estimation techniques for predicting the materials hydraulic conductivity function. Only once we have accurately predicted the material's hydraulic behaviour in both the saturated and unsaturated phase may we begin to look at its behaviour as part of a capillary barrier.

This paper will focus on the determination of the water-characteristic curve for nonwoven geotextiles as well as the estimation of the hydraulic conductivity functions. The hydraulic behaviour of the geotextile will then be evaluated for use as part of a capillary barrier.

2. PAST RESEARCH

2.1 Geosynthetic Capillary Barriers

There has been limited previous work done to evaluate the use of geosynthetics as capillary barriers. A paper by Henry (1995) evaluated the use of a geotextile coupled with a geonet for reducing the moisture migration beneath roadway embankments. Her work showed that the geonet, which has a high in plane permeability, worked quite well in providing horizontal drainage, and a suitable barrier for the migration of moisture. However, the author found no work, to date, evaluating a fine grained material used in conjunction with a geotextile.

2.2 Unsaturated Geotextiles

As is the case for the use of geosynthetics to form capillary barriers, there has also been limited work done to characterize the unsaturated behaviour of geosynthetics. Stormont et al. (1997) evaluated the water retention functions of four nonwoven, polypropylene geotextiles using the hanging column test (Klute, 1986) as described below. A 60 mm, circular sample of geotextile is placed on a high air-entry ceramic disc. Suction is varied by rising or lowering the level of a water tank connected by a tube to one side of the porous plate. The samples were allowed to equilibrate for approximately 24-48 hours at which time they were weighed to determine their water content. For the drying phase, the samples were initially saturated and suction was increased in small increments. For the wetting phase, an equilibrium suction was applied and then incrementally reduced to zero. Their results showed that the geotextile water characteristic curves (GWCC) were similar to that one might anticipate for uniform sand.

Stormont et al. (1997) also considered the effect of a new geotextile versus a washed geotextile. Considering the possibility that oils and lubricants used in geotextile manufacturing can change geotextile wetting behaviour (Stormont et al., 1997). Their results showed that the washed specimens contained more water at comparable suctions than the new specimens.

Iryo and Rowe (2003) summarized published water retention functions of nonwoven geotextiles. However, Iryo and Rowe also determined the hydraulic conductivity functions for these specimens. The hydraulic conductivity for the geotextiles were measured at various suctions in order to develop the K-suction curve. Once both the WCC and the K-suction curve for a geotextile were determined, Iryo and Rowe showed that the van Genuchten equations were valid for approximating the hydraulic conductivity function for a given geotextile from its WCC. Therefore, for the purpose of this research the hydraulic conductivity functions for the geotextile will be approximated from the GWCC's using the van Genuchten method.

3. RESEARCH OBJECTIVES

Our objectives were to (*i*) develop a reliable method for determining the unsaturated properties of geotextiles for loaded and unloaded, as well as new and washed conditions, (*ii*) evaluate the effectiveness of a geosynthetic capillary barrier based on the unsaturated properties of a rock flour and geotextile determined in the lab, and (*iii*) model the geosynthetic capillary barrier in order to evaluate design alternatives for field-scale lab tests and field trials.

The research involved quantifying the change in unsaturated properties of the geotextile with increasing overburden pressure as well as the degradation of the manufacturing oils in order to better represent actual field conditions.

4. THEORY

4.1 Soil-water Characteristic Curves

The soil water characteristic curve can be defined as the relationship between the volumetric water content of the soil and the soil suction (Fredlund and Rahardjo, 1993). The soil water characteristic curve can be shown to have three distinct stages; (i) pre air-entry stage: soil suctions are too small to overcome the capillary forces holding the water within the largest pores in the soil, the soil does not drain and the volumetric water content remains constant, (*ii*) transition stage: the largest pores begin to drain, allowing air to enter the structure, pores of decreasing size are drained as the suction is increased, and (iii) residual stage: characterized by a very slow decrease in volumetric water content as suctions are considerably increased.

Fredlund et al. (2002) showed a closed form equation to represent the soil-water characteristic curve (SWCC) curve for a given soil.

$$\theta_i = \theta_s \left[1 - \frac{\ln(1+\frac{\psi}{h_r})}{\ln(1+\frac{10^6}{h_r})} \right] \left[\frac{1}{\left\{ \ln\left[e + (\frac{\psi}{\alpha_f})^{n_f} \right] \right\}^{m_f}} \right] \quad [1]$$

where: θ_s = saturated volumetric water content, α_f = fitting parameter corresponding to the inflection point and somewhat related to the air-entry value of the soil, n_f = fitting parameter related to the rate of desaturation of the soil in the transition phase, m_f = fitting parameter related to the curvature of the function in the high suction range, h_r = constant used to represent the soil suction at the residual water content, and ψ = value for suction.

Another closed form solution used to evaluate the SWCC was developed by van Genuchten (1980). He describes the SWCC as:

$$\theta_i = \frac{(\theta_s - \theta_r)}{\left\{1 + (\alpha\psi_i)^q\right\}^p} + \theta_r \quad [2]$$

where: θ_s = saturated volumetric water content, θ_r = residual volumetric water content, α = fitting parameter corresponding to the inflection point on the WCC, q = fitting parameter related to the rate of desaturation of the soil, and p = 1-1/q.

For the purpose of our research Eq.1 and Eq.2 will be used to approximate the WCC for nonwoven geotextiles.

4.2 Hydraulic Conductivity Functions

As the suction applied to a porous media increases, the water content tends to decrease. This decrease in water content leads to discontinuities in the water phase within the soil structure, reducing the effective porosity. This effect reduces the area available for water flow and therefore the hydraulic conductivity of the soil decreases (Rowlett, 2000). An equation to approximate the hydraulic conductivity function for a given soil from its soil-water characteristic curve was developed by van Genuchten (1980).

$$K_i = K_s \frac{\left\{1-\left[(\alpha\psi_i)^{(q-1)}\right]\cdot\left[1+(\alpha\psi_i)^q\right]^{-p}\right\}^2}{\left[1+(\alpha\psi_i)^q\right]^{p/2}} \quad [3]$$

where: K_s = saturated hydraulic conductivity, α = fitting parameter corresponding to the inflection point on the WCC (from equation for WCC), q = fitting parameter related to the rate of desaturation of the soil (from equation for WCC), and p = 1-1/q.

Similar equations have also been proposed by; Childs and Collis George (1950), Gardner (1958), as well as Fredlund et al. (1994) to estimate hydraulic conductivity functions from the water-characteristic curves. However, for the purpose of our research we will use Eq.3.

5. MATERIALS

5.1 Geotextile

The proposed geotextile for use in the capillary barrier is a nonwoven, polypropylene, needle punched, continuous fiber geotextile. The product that is currently being tested on the laboratory is Terrafix 1200R. Table 1 shows additional physical properties of the geotextile reproduced from manufacturer's specifications. This particular product was chosen due to its thickness, low filtration opening size, and higher strength as compared to similar products.

Table 1. Properties of geotextile (Terrafix, 2004)

Mass (g/m^2)	Thickness (mm)	Filtration Opening Size (mm)	K_{sat} (m/s)
550	4.0	0.05 to 0.15	1.5 x10^{-3}

5.2 Fine Grained Material

The fine grained material that will be used to contrast the coarse grained behaviour of the geotextile will be a nepheline syentie rock flour. This product is readily available in Canada and has desirable unsaturated characteristics that will be shown later in this paper. The product used for testing is distributed by L.V. Lomas Chemicals in Ontario, Canada. The product name is Industrial Grade #75. Figure 1 shows the grain size distribution for this product. Other pertinent product information is presented in Table 2.

Table 2. Properties of fine grained material

Property	Value
Specific Gravity	2.61
Melting Point (^oC)	1020
Bulk density (Mg/m^3)	1.33 to 1.52

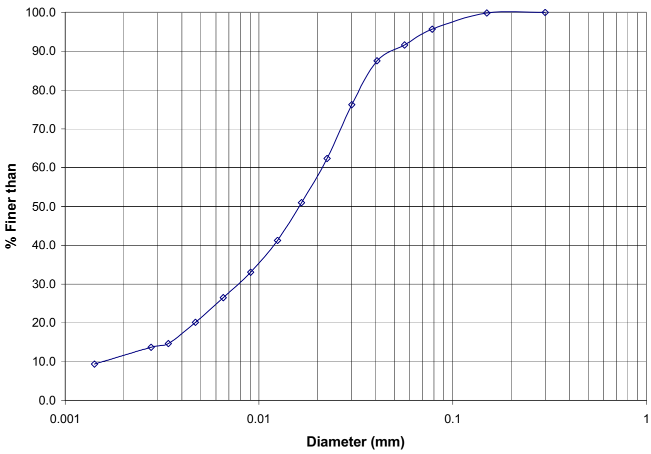

Figure 1. Grain size distribution for fine grained material

6. EXPERIMENTAL PROGRAM

6.1 Hanging Test

A hanging test was initially used to measure the water-characteristic curve for the geotextile. The procedure for determining the drying curve is as described below. A long strip of geotextile with known dimensions (25 x 300 cm) is brought to saturation. The geotextile is then hung with the lower end submerged in water. A protective covering is placed around the textile in order to limit the effect of evaporation. The sample is allowed to come to equilibrium (approx 24 hrs). The geotextile is then cut into thin strips with the height to the midpoint of each strip above the water table being measured. The volumetric water content of each strip is determined. The suction for each strip is calculated using the measured height above the water table.

For determination of the wetting curve, the procedure is identical except that the test starts with a dry geotextile rather than one that is fully saturated. The main advantage of this test is that an entire GWCC can be measured and calculated in a matter of days, rather than weeks which is the case with traditional methods.

6.2 Pressure Plate Cell

The single-specimen pressure plate cell developed at the University of Saskatchewan was used to corroborate the results from the hanging test. This cell is also being used to determine the SWCC for the fine grained material. This type of cell is primarily used for measuring the drying portion of the curve; therefore, the procedure must be modified or another method must be developed in order to measure the wetting portion.

The procedure for the drying curve is as follows. A saturated sample is placed on top of a saturated porous disc with an AEV (air-entry value) greater than the maximum suction that will be applied to the specimen.

Incrementally lowering the elevation of the outlet pipe and recording the elevation below the bottom of the sample varies the suction applied to the base of the disc. The specimen is allowed to equilibrate at each suction increment. If suctions greater than 10 kPa are required, the axis-translation technique is used to increase the suction.

This type of cell was initially developed as testing apparatus for soils; therefore, when testing geotextiles in the same apparatus, careful care must be taken. The sample must be weighed accurately (nearest 0.01 of a gram) in order to determine the precise volume of water that is lost for each suction increment. Also, careful care must be taken in handling the cell to ensure that no water is forced in or out of the sample during the weighing process.

The main advantage of this testing method over the hanging test is that evaporation effects are mitigated. The specimen is entirely enclosed throughout the entire test, limiting the amount of moisture that may escape. Also, the pressure plate cell provides loading capabilities using either a spring or loading ram to consider the effect of overburden on the water-characteristic curve. However, the time to complete as test is considerably higher (in the order of weeks) than the hanging test as previously stated.

7. TESTING RESULTS

7.1 Water Characteristic Curves

7.1.1 Hanging Test

Hanging tests were performed on both washed and unwashed geotextile. During the manufacturing of the geotextile, oils are used to lubricate the needles during the needle-punching process. These oils are hydrophobic and tend to degrade over time. Therefore it was considered appropriate to determine the effect of the degradation of these oils on the geotextile WCC. The samples were washed with detergent in an attempt to remove the oils and then tested. Both the drying and the wetting phases for the geotextiles were determined. Figure 2 shows the measured WCC's for both new and washed specimens under zero load.

Figure 2 shows that for the washed samples, the AEV of the sample is slightly reduced and the water content of the sample, as a whole, is increased for the same suctions.

7.1.2 Pressure Plate Cell

Figure 3 compares the unloaded drying curves for unwashed geotextile determined from the hanging test and the pressure plate cell; a WCC for the silica flour is also included to show the contrast between the two materials.

Figure 3 also shows that when comparing the hanging test to the pressure plate, for the same material, the hanging test produces lower water contents for all values of suction even though the air-entry values for the two testing methods are quite similar. This may be explained due to the fact that during the hanging test, it is impossible to prevent at least small amounts evaporation from occurring. However, for the pressure plate cell, evaporation effects are small.

For design purposes we must be concerned with the effect of overburden pressure on the unsaturated behaviour of the geotextile. Tests were conducted with the geotextiles subjected to pressures of 0, 1, and 5 kPa; with tests of 10, 15 and 20 kPa planned for the future. The results are shown in Figure 4.

Figure 4 shows the effect of overburden on the geotextile WCC. Similar to the effects of washing the geotextile, the AEV (air-entry value) is shifted slightly to the right and the moisture contents are increased for suctions in the transition phase. However, in the residual portion of the curve we see that the water content has been reduced.

7.2 Hydraulic Conductivity Functions

As stated previously, Iryo and Rowe (2003) verified that the van Genuchten equations for estimating hydraulic conductivity functions are valid for geotextiles. The measured data from the WCC for the silica flour and the geotextile loaded at 1 kPa were therefore fit with van Genuchten curves. The curve fit parameters α and q were fit to the data using Eq. 2 and the hydraulic conductivity functions were approximated using Eq.3. The saturated hydraulic conductivities used are 4×10^{-7} m/s (Rowlett, 2000) and 1.5×10^{-3} m/s for the rock flour and geotextile respectively. Figure 5 shows the fitted WCC's, Table 3 shows the determined van Genuchten parameters and Figure 6 shows the estimated hydraulic conductivity functions.

Table 3. van Genuchten Parameters

Material	α	q	p
Rock Flour	0.009	2.90	0.66
Geotextile	0.800	4.70	0.79

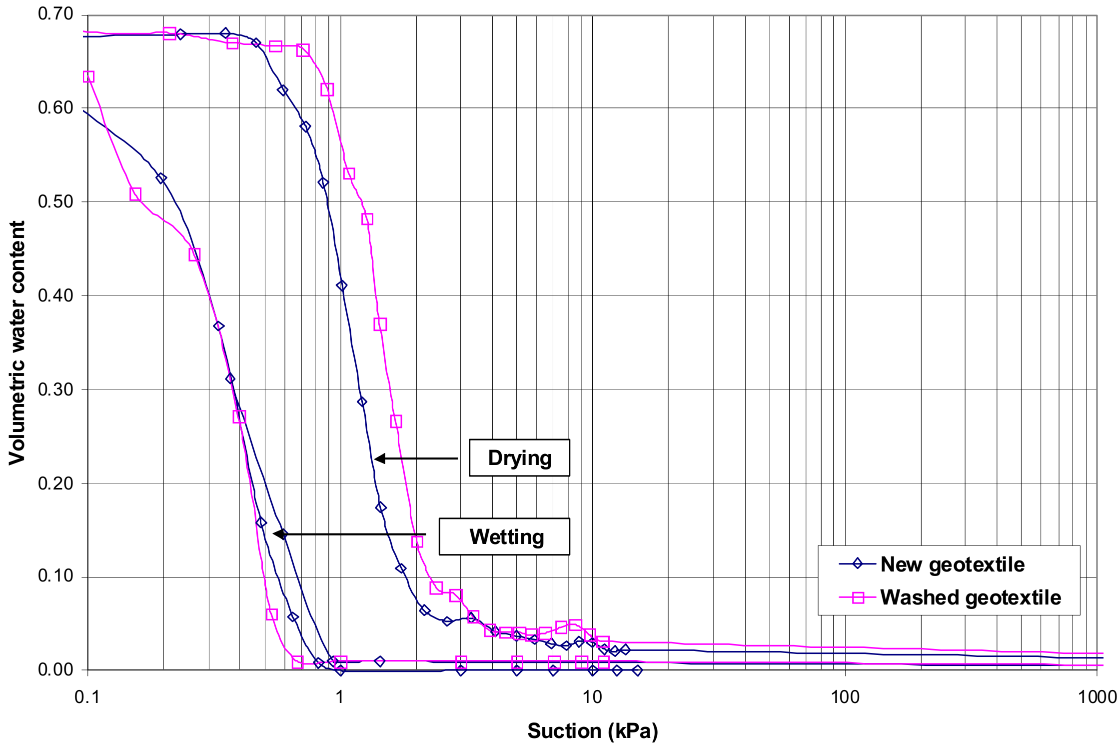

Figure 2. Hanging test water-characteristic curves

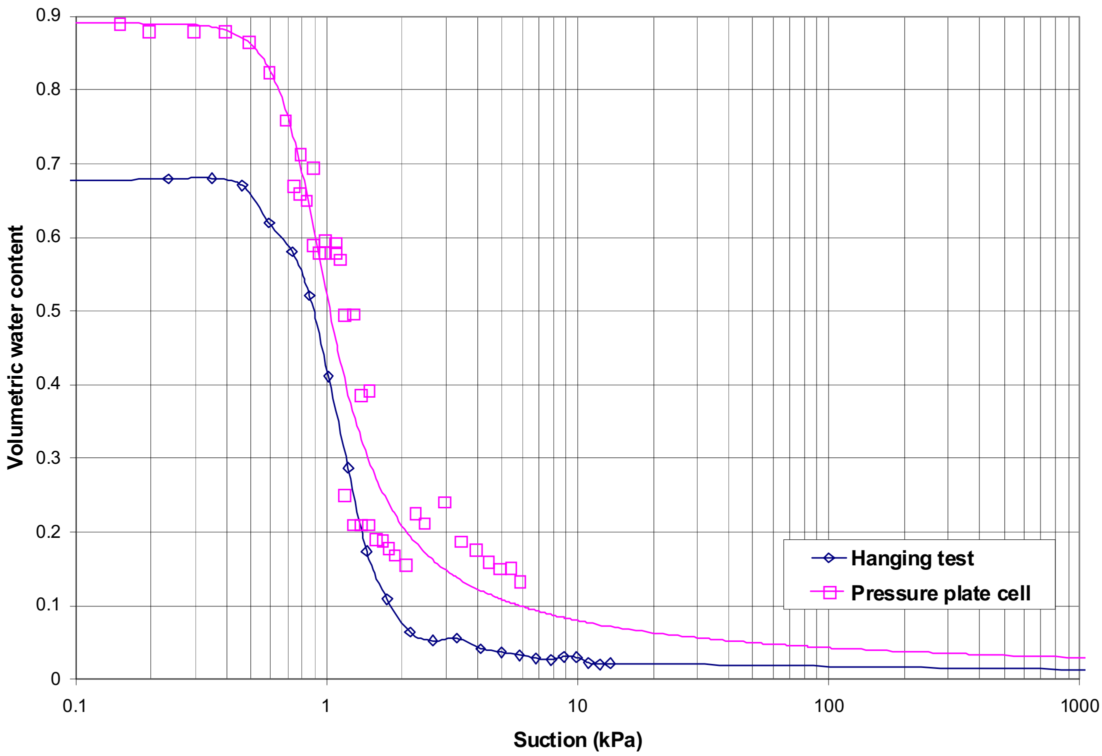

Figure 3. Test method comparison

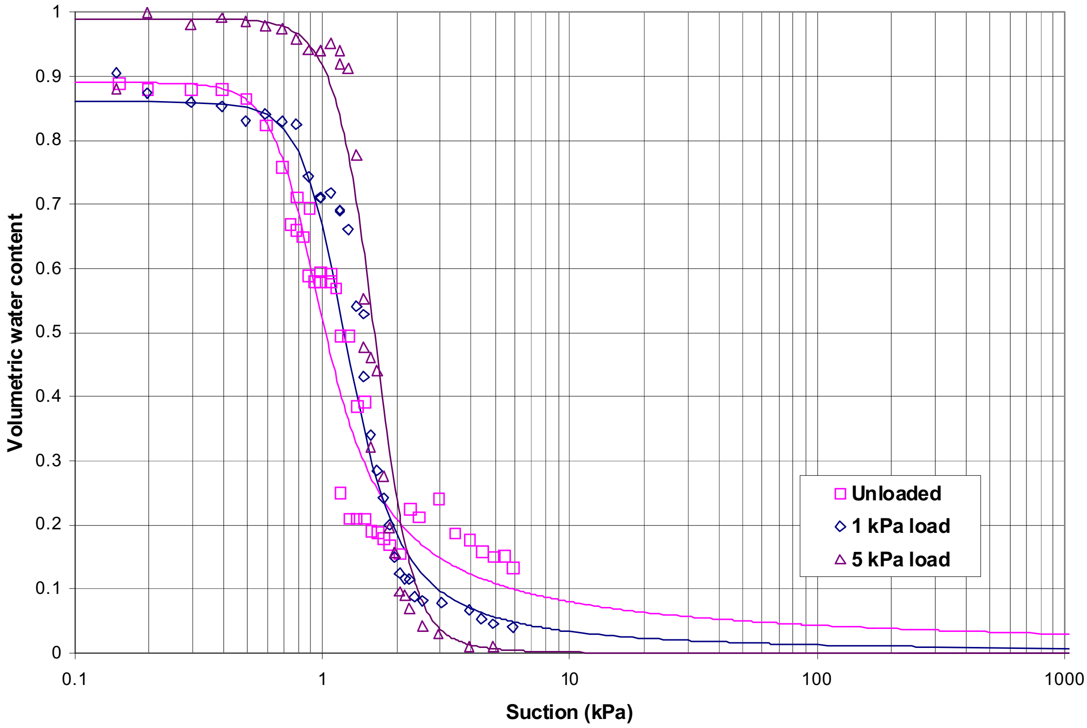

Figure 4. Effect of increasing overburden pressure

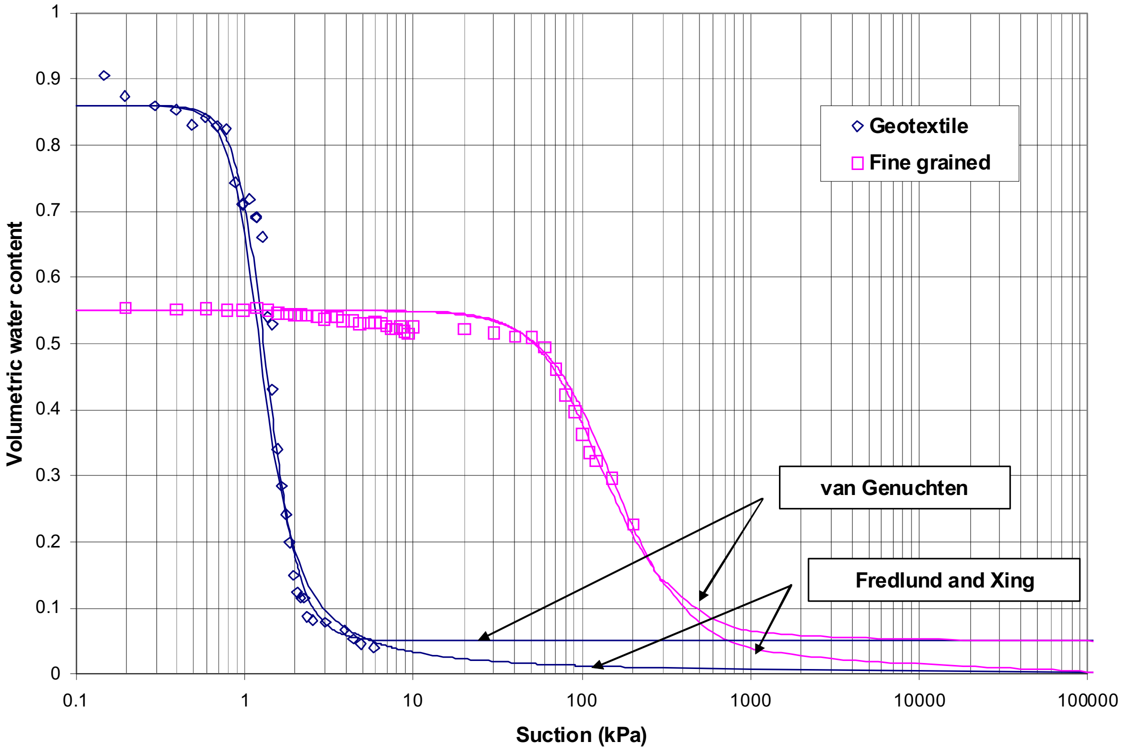

Figure 5. Fitted water-characteristic curves

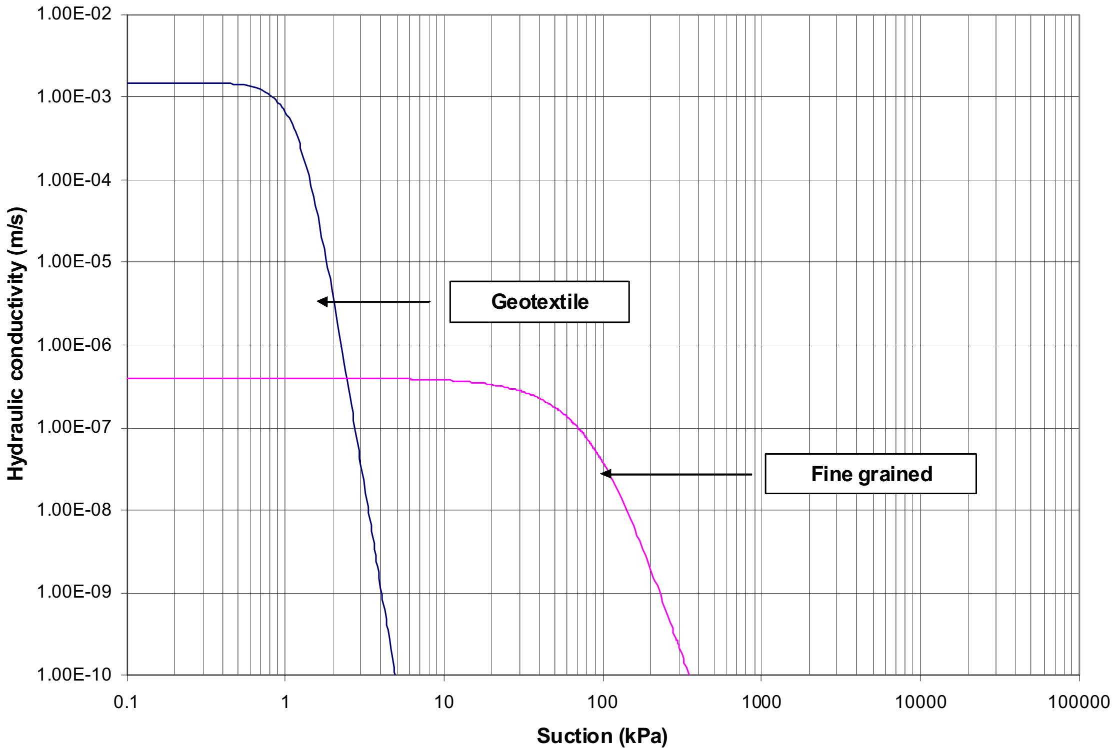

Figure 6. Estimated hydraulic conductivity functions

8. NUMERICAL MODEL

A simple spreadsheet was developed in order develop an initial understanding for the response of the barrier to varying flow rates and suctions. The spreadsheet, also known as a "Kisch" spreadsheet, is based on Darcy's law for flow through a porous media. The cover system is divided into small depth increments in order to calculate the incremental change in suction. The initial suction at the water table is equal to zero and the change in head across each depth increment is calculated using a rearranged form of Darcy's law.

$$\Delta h = \left(\frac{-q}{K_i} - 1\right)(\Delta l) \qquad [4]$$

where: Δh = change in head (m), q = flow rate (m/s), K = permeability (calculated using Eq. 3), and Δl = incremental depth (m)

The new value for suction is used to determine the new volumetric water content as well as the new permeability for the depth increment. The process is repeated until all the increments in the cover system are analyzed. The spreadsheet allows for the flow rate as well as the depth to the water table to be varied.

Preliminary results from the numerical model show that for a steady-state infiltration rate equal to 1.2 $\times 10^{-9}$ m/s (approx 35 mm/year) and a water table depth of 1.0 m below the bottom of the geosynthetic break, we can expect degrees of saturation (S) of 96.3% and 3.6% for the rock flour and geotextile respectively. Also, using the estimated K-functions we find that the unsaturated hydraulic conductivity of the geotextile is 2.5 $\times 10^{-11}$ m/s, whereas the rock flour is 4.0x 10^{-7} m/s. Therefore the geotextile is less permeable than the rock flour under these conditions.

9. DISCUSSION AND CONCLUSIONS

From the preliminary modelling results, we can see that the geotextile-rock flour combination will work to develop a capillary barrier in the cover system. However, in looking at the data obtained from testing the two materials, we can see that over time, or under increasing overburden, the properties of the materials will change. Rigorous testing must continue in order to evaluate these effects.

10. ACKNOWLEDGEMENTS

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