Technical Paper by J.P. Giroud, A. Zhao, and G.N. Richardson

EFFECT OF THICKNESS REDUCTION ON GEOSYNTHETIC HYDRAULIC TRANSMISSIVITY

ABSTRACT: A new theoretical relationship that quantifies the reduction in hydraulic transmissivity resulting from a reduction in geosynthetic thickness is presented. It is shown that the proposed relationship is in good agreement with experimental data on geotextiles and geonets. This relationship is useful to predict hydraulic transmissivity reduction from the results of compression tests on geosynthetics. This is particularly useful when the thickness reduction is due to creep, because it is impractical to conduct hydraulic transmissivity tests over a long period of time.

KEYWORDS: Geosynthetic, Geonet, Geotextile, Thickness, Hydraulic transmissivity, Hydraulic conductivity, Theoretical, Reduction factor.

AUTHORS: J.P. Giroud, Chairman Emeritus, GeoSyntec Consultants, 621 NW 53rd Street, Suite 650, Boca Raton, Florida 33487, USA, Telephone: 1/561-995-0900, Telefax: 1/561-995-0925, E-mail: jpgiroud@geosyntec.com; A. Zhao, Vice President of Engineering, Tenax Corp., 4800 E. Monument Street, Baltimore, Maryland 21205, USA, Telephone: 1/410-522-7000, Telefax: 1/410-522-7015, E-mail: azhao@us.tenax.com; and G.N. Richardson, Principal, G.N. Richardson and Associates, 425 N. Boylan Avenue, Raleigh, North Carolina 27603, USA, Telephone: 1/919-828-0577, Telefax: 1/919-828-3899, E-mail: greg@gnra.com.

PUBLICATION: *Geosynthetics International* is published by the Industrial Fabrics Association International, 1801 County Road B West, Roseville, Minnesota 55113-4061, USA, Telephone: 1/651-222-2508, Telefax: 1/651-631-9334. *Geosynthetics International* is registered under ISSN 1072-6349.

DATES: Original manuscript received 19 May 2000, revised version received 4 August 2000, and accepted 4 August 2000. Discussion open until 1 June 2001.

REFERENCE: Giroud, J.P., Zhao, A., and Richardson, G.N., 2000, “Effect of Thickness Reduction on Geosynthetic Hydraulic Transmissivity”, Special Issue on Liquid Collection Systems, *Geosynthetics International*, Vol. 7, Nos. 4-6, pp. 433-452.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

1 INTRODUCTION

Hydraulic transmissivity, recognized since the early days of geosynthetic engineering as an essential property of geosynthetics used as drainage layers, is defined as the product of hydraulic conductivity and thickness (Giroud and Perfetti 1977):

$$\theta = k\,t \tag{1}$$

where: θ = hydraulic transmissivity of the geosynthetic; k = hydraulic conductivity of the geosynthetic; and t = thickness of the geosynthetic. Equation 1 can be used with any set of coherent units. The basic SI units are: θ (m^2/s), k (m/s), and t (m).

The thickness of a geosynthetic decreases when the geosynthetic is subjected to a compressive stress. The thickness of a geosynthetic also decreases with time due to creep under a constant compressive stress. A decrease in geosynthetic thickness causes a decrease in hydraulic transmissivity not only because of the presence of the term t in the right-hand side of Equation 1, but also because the hydraulic conductivity of the geosynthetic decreases when the thickness decreases.

The present paper provides a theoretical relationship between hydraulic transmissivity reduction and thickness reduction. This relationship can be used to predict hydraulic transmissivity reduction from the results of compression tests on geosynthetics. This is particularly useful when thickness reduction is due to creep (i.e. when thickness reduction occurs over a long period of time), because it is impractical to conduct hydraulic transmissivity tests over a long period of time. In contrast, compression tests can easily be conducted over a long period of time and can even be accelerated using time-temperature superposition.

2 DEVELOPMENT OF THEORETICAL RELATIONSHIPS

2.1 Relationship Between Hydraulic Conductivity and Porosity

The well-known Kozeny-Carman's equation (Carman 1937) gives a relationship between hydraulic conductivity and porosity of porous media. As indicated by Giroud (1996), this equation can be used for geosynthetics. A demonstration of Kozeny-Carman's equation is provided in the paper by Giroud (1996). The demonstration is based on the assumption that the flow is laminar. Flow is typically laminar if the medium conveying the flow is a geonet, provided that the hydraulic gradient is small (i.e. $i \leq 0.1$), or a needle-punched nonwoven geotextile for a wide range of hydraulic gradient values. Kozeny-Carman's equation can be written as follows:

$$k = \zeta \, \frac{n^3}{(1-n)^2} \tag{2}$$

where: n = porosity of the geosynthetic; and ζ = factor incorporating several parameters (including characteristics of the fluid, such as density and viscosity, and characteristics of the permeable medium, such as shape and specific area of solid elements) that are

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

not relevant to the present study. Equation 2 can be used with any set of coherent units. The basic SI units are: k (m/s) and ζ (m/s); n is dimensionless.

When the thickness of a geosynthetic decreases, its porosity decreases. As a result, its hydraulic conductivity decreases. The relationship between the hydraulic conductivity, k_1, of a geosynthetic when its porosity is n_1, and its hydraulic conductivity, k_2, when its porosity is n_2, is given by the following equation derived from Equation 2:

$$\frac{k_2}{k_1} = \left(\frac{n_2}{n_1}\right)^3 \left(\frac{1-n_1}{1-n_2}\right)^2 \tag{3}$$

2.2 Relationship Between Hydraulic Conductivity and Thickness

The following relationship exists between the porosity of a geosynthetic and its thickness (Giroud and Perfetti 1977):

$$n = 1 - \frac{\mu}{\rho\, t} \tag{4}$$

where: μ = mass per unit area of the considered geosynthetic; and ρ = density of the polymeric compound used to make the geosynthetic.

Combining Equations 3 and 4 (with the subscript *1* or *2*, as appropriate) gives:

$$\frac{k_2}{k_1} = \left(\frac{1-\dfrac{\mu}{\rho\, t_2}}{1-\dfrac{\mu}{\rho\, t_1}}\right)^3 \left(\frac{\dfrac{\mu}{\rho\, t_1}}{\dfrac{\mu}{\rho\, t_2}}\right)^2 \tag{5}$$

hence:

$$\frac{k_2}{k_1} = \left(\frac{t_1}{t_2}\right) \left(\frac{t_2-\dfrac{\mu}{\rho}}{t_1-\dfrac{\mu}{\rho}}\right)^3 \tag{6}$$

Equation 6 gives the ratio between the hydraulic conductivity of a geosynthetic with a thickness t_2 and the hydraulic conductivity of the same geosynthetic with a thickness t_1. The thickness of a geosynthetic is a function of both the compressive stress applied on the geosynthetic and the time duration in which the compressive stress is applied. Therefore, different thicknesses of a geosynthetic can be caused by either different compressive stresses, σ_2 and σ_1, or continued reduction in thickness under a constant compressive stress (i.e. creep). In particular, Equation 6 can be used to derive the hydraulic conductivity after compression from the hydraulic conductivity before compression as a function of the geosynthetic thicknesses before and after compression. It is important to note that μ/ρ is a constant for a given geosynthetic, i.e. μ/ρ is not affected by any change in the geosynthetic thickness.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

Equation 6 is the simplest relationship between k_1, k_2, t_1, and t_2. However, a relationship between k_2/k_1 and t_2/t_1 can be derived from Equation 6 as follows:

$$\frac{k_2}{k_1} = \left(\frac{t_1}{t_2}\right)\left(\frac{\frac{t_2}{t_1} - \frac{\mu}{\rho\, t_1}}{1 - \frac{\mu}{\rho\, t_1}}\right)^3 \tag{7}$$

Combining Equation 4 (with the subscript *1*) and Equation 7 gives:

$$\frac{k_2}{k_1} = \left[1 - \frac{1-(t_2/t_1)}{n_1}\right]^3 \left(\frac{t_1}{t_2}\right) \tag{8}$$

Equation 8 gives the ratio between the hydraulic conductivity of a geosynthetic with a thickness t_2 and the hydraulic conductivity of the same geosynthetic with a thickness t_1 as a function of the ratio of these two thicknesses and the porosity of the geosynthetic corresponding to thickness t_1. In particular, Equation 8 can be used to derive the hydraulic conductivity after compression, k_2, from the hydraulic conductivity before compression, k_1, as a function of the thickness ratio after and before compression, t_2/t_1, and the porosity of the geosynthetic before compression, n_1.

2.3 Relationship Between Hydraulic Transmissivity and Thickness

From Equation 1, the relationship between the hydraulic transmissivity, θ_1, of a geosynthetic when its thickness is t_1, and its hydraulic transmissivity, θ_2, when its thickness is t_2, is given by the following equation derived from Equation 1:

$$\frac{\theta_2}{\theta_1} = \frac{k_2\, t_2}{k_1\, t_1} \tag{9}$$

Combining Equations 6 and 9 gives:

$$\frac{\theta_2}{\theta_1} = \left(\frac{t_2 - \frac{\mu}{\rho}}{t_1 - \frac{\mu}{\rho}}\right)^3 \tag{10}$$

Equation 10 gives the ratio between the hydraulic transmissivity of a geosynthetic with a thickness t_2 and the hydraulic transmissivity of the same geosynthetic with a thickness t_1. In particular, Equation 10 can be used to derive the hydraulic transmissivity after compression from the hydraulic transmissivity before compression as a function of the geosynthetic thicknesses before and after compression. As already mentioned after Equation 6 for hydraulic conductivity, it is important to note that μ/ρ is a constant for a given geosynthetic, i.e. μ/ρ is not affected by any change in the geosynthetic thickness.

Combining Equations 8 and 9 gives:

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

$$\frac{\theta_2}{\theta_1} = \left[\frac{(t_2/t_1)-(1-n_1)}{n_1}\right]^3 = \left[1-\frac{1-(t_2/t_1)}{n_1}\right]^3 \tag{11}$$

Equation 11 gives the ratio between the hydraulic transmissivity of a geosynthetic with a thickness t_2 and the hydraulic transmissivity of the same geosynthetic with a thickness t_1 as a function of the ratio of these two thicknesses and the porosity of the geosynthetic corresponding to thickness t_1 . In particular, Equation 11 can be used to derive the hydraulic transmissivity after compression, θ_2 , from the hydraulic transmissivity before compression, θ_1 , as a function of the thickness ratio after and before compression, t_2/t_1 , and the porosity of the geosynthetic before compression, n_1 .

The graph presented in Figure 1 presents numerical values of the θ_2/θ_1 ratio, due to a thickness reduction from t_1 to t_2 , as a function of the value of the porosity before thickness reduction, n_1 , i.e. the porosity when the thickness is t_1 . It appears that the influence of thickness reduction on hydraulic transmissivity is very large, which is confirmed by experimental data, as shown in Section 3.

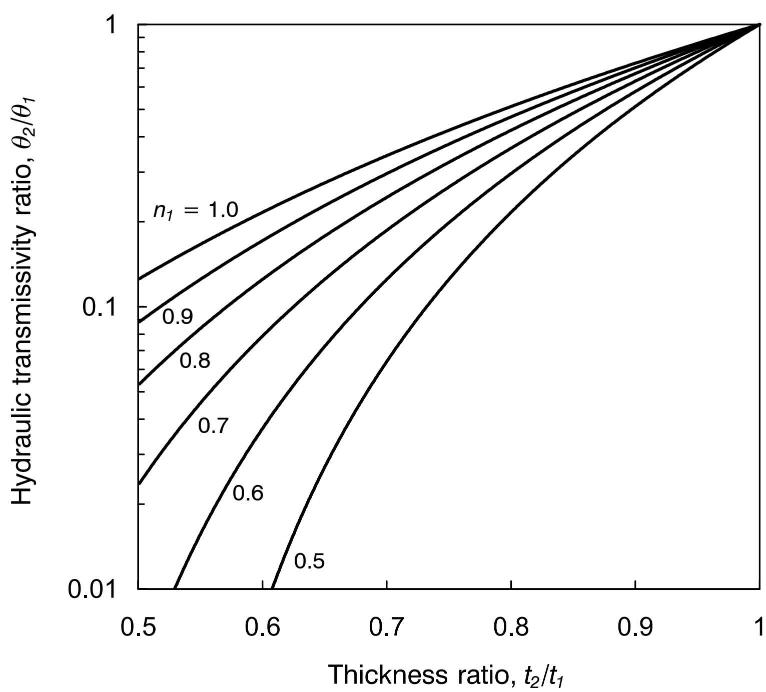


Figure 1. Value of the hydraulic transmissivity ratio, θ_2/θ_1 , as a function of the thickness ratio, t_2/t_1 , and the geosynthetic porosity in the initial state, n_1 .

Notes: The curves were obtained using Equation 11. The case n_1 = 1.0 is a limit case. In reality, the most porous geosynthetics have a porosity that typically does not exceed 0.95.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

3 COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL VALUES

3.1 Comparison Between Experimental and Theoretical Values for Geonets

Table 1 presents a comparison of experimental data and theoretical calculations for a high density polyethylene geonet having a mass per unit area μ = 0.818 kg/m^2 and made with a polymeric compound having a density ρ = 950 kg/m^3, hence μ/ρ = 0.86 × 10^{-3} m = 0.86 mm. The experimental data on geonets were obtained from a testing program prepared by the authors of the present paper. Inspection of Table 1 does not reveal any significant difference between the values of θ/θ_o for the different values of the hydraulic gradient, i (where θ_o is the hydraulic transmissivity value that corresponds to the lowest compressive stress in a series of hydraulic transmissivity tests performed under various compressive stresses). The comparison of experimental data and theoretical calculations presented in Table 1 is illustrated in Figure 2. It appears in Figure 2 that there is a good agreement between the experimental data and theoretical calculations for the considered geonet.

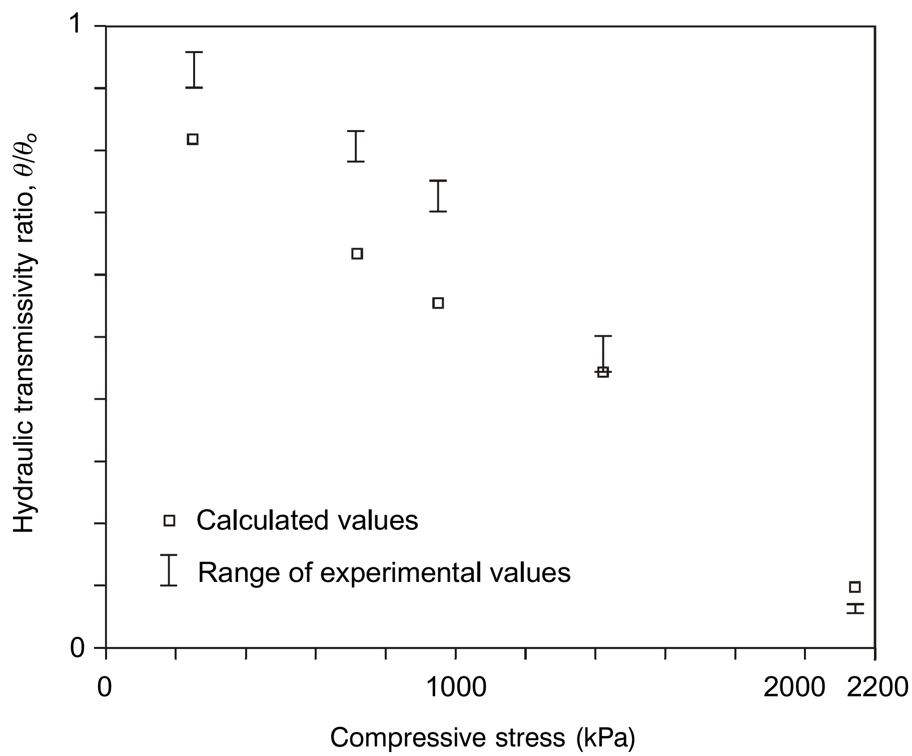


Figure 2. Comparison between theoretical and experimental values of θ/θ_o for a high density polyethylene geonet.

Note: The experimental data and theoretical calculations for Figure 2 are presented in Table 1.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

Table 1. Comparison between theoretical and experimental data for a high density polyethylene geonet.

Experimental values											Theoretical values	
Compressive stress	Thickness	Hydraulic transmissivity for various values of the hydraulic gradient, i									$t - (\mu/\rho)$ (mm)	$\frac{\theta}{\theta_o} = \left(\frac{t - \frac{\mu}{\rho}}{t_o - \frac{\mu}{\rho}}\right)^3$
		$i = 0.1$		$i = 0.25$		$i = 0.50$		$i = 1.00$				
σ (kPa)	t (mm)	θ (m^2/s)	θ/θ_o (-)	θ (m^2/s)	θ/θ_o (-)	θ (m^2/s)	θ/θ_o (-)	θ (m^2/s)	θ/θ_o (-)			
2.4	5.84	4.24×10^{-3}	1.00	2.72×10^{-3}	1.00	2.17×10^{-3}	1.00	1.55×10^{-3}	1.00	4.98	1.00
240	5.53	4.04×10^{-3}	0.95	2.56×10^{-3}	0.94	1.96×10^{-3}	0.90	1.40×10^{-3}	0.90	4.67	0.82
720	5.13	3.53×10^{-3}	0.83	2.20×10^{-3}	0.81	1.68×10^{-3}	0.77	1.25×10^{-3}	0.81	4.27	0.63
960	4.94	3.15×10^{-3}	0.74	1.85×10^{-3}	0.68	1.47×10^{-3}	0.68	1.06×10^{-3}	0.68	4.08	0.55
1,440	4.61	1.96×10^{-3}	0.46	1.23×10^{-3}	0.45	9.35×10^{-4}	0.43	7.55×10^{-4}	0.49	3.75	0.43
2,160	3.07	3.14×10^{-4}	0.07	1.97×10^{-4}	0.07	1.59×10^{-4}	0.07	1.16×10^{-4}	0.07	2.21	0.09

Notes: The hydraulic transmissivity tests, whose results are reported in Table 1, were conducted with the geonet between two steel plates. The high density polyethylene geonet has the following characteristics: $\mu = 0.818$ kg/m^2 and $\rho = 950$ kg/m^3, hence $\mu/\rho = 0.86$ mm. Notations are listed at the end of the present paper. The values of t_o and θ_o used in the equation in the last column are as follows: (i) t_o is the value presented in the first row of the t column, i.e. $t_o = 5.84$ mm; and (ii) θ_o is the value presented in the first row of each of the four θ columns. The comparison between the experimental theoretical values presented in Table 1 is illustrated in Figure 2.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

3.2 Comparison Between Experimental and Theoretical Values for Geotextiles

Extensive comparisons were made between values of θ/θ_o derived from hydraulic transmissivity values measured by Palmeira and Gardoni (2000a, 2000b) on needle-punched nonwoven geotextiles and calculations performed using Equation 10 with the thickness values measured by Palmeira and Gardoni (2000b). It would be too cumbersome to report the comparisons in tabulated form as was done in Section 3.1 for geonets. Instead, the comparisons are reported in one graph (Figure 3). It appears in Figure 3 that there is a good agreement between the experimental data and theoretical calculations for the considered needle-punched nonwoven geotextiles.

3.3 Conclusions Regarding Comparisons Between Experimental and Theoretical Values

Based on the comparisons presented in Sections 3.1 and 3.2, it appears that there is a good agreement between experimental data and theoretical calculations of the hydraulic transmissivity ratio performed using Equation 10. Considering the large dispersion of values typically observed in hydraulic transmissivity test results, the agreement between experimental and theoretical data can even be considered excellent. Therefore,

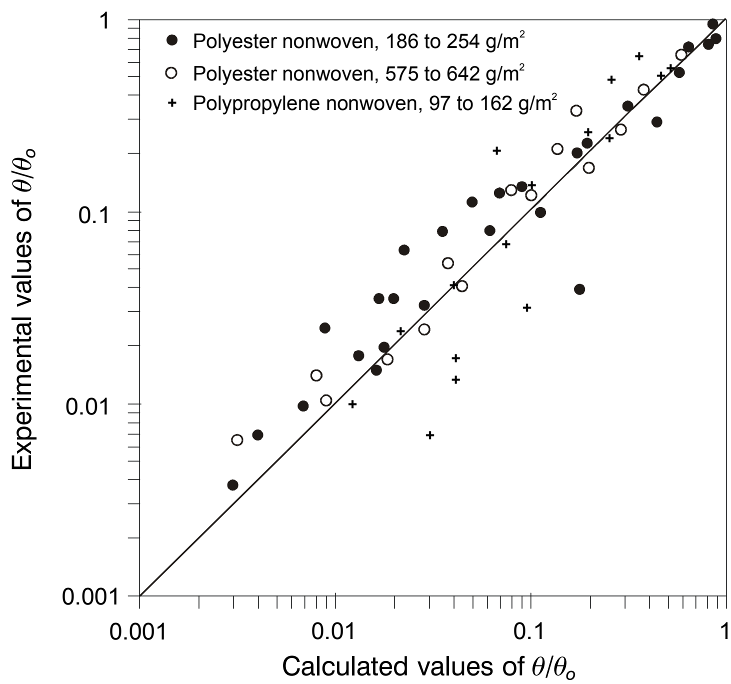


Figure 3. Comparison between theoretical and experimental values of θ/θ_o for needle-punched nonwoven geotextiles.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

the method proposed in the present paper can be recommended for the prediction of the decrease in hydraulic transmissivity of a geosynthetic due to a reduction of its thickness.

4 REDUCTION FACTORS

4.1 General Expression for Transmissivity Reduction Factor due to Thickness Reduction

Decrease in hydraulic transmissivity may be due to a variety of causes and is often expressed using reduction factors (Giroud et al. 2000). Two equivalent expressions are presented below for the hydraulic transmissivity reduction factor, RF_{TR}, due to thickness reduction from t_1 to t_2.

Based on Equation 10, RF_{TR} can be expressed by the following equation, as a function of t_1 and t_2:

$$RF_{TR} = \left(\frac{t_1 - \dfrac{\mu}{\rho}}{t_2 - \dfrac{\mu}{\rho}} \right)^3 \tag{12}$$

Alternatively, based on Equation 11, RF_{TR} can be expressed by the following equation, as a function of t_2 / t_1 and n_1:

$$RF_{TR} = \frac{1}{\left[1 - \dfrac{1 - (t_2 / t_1)}{n_1} \right]^3} = \left[\frac{n_1}{(t_2 / t_1) - (1 - n_1)} \right]^3 \tag{13}$$

The graph in Figure 4 presents numerical values of the reduction factor due to thickness reduction, RF_{TR}. It appears in Figure 4 that hydraulic transmissivity reduction factors can be quite large. For example, for geonets, the porosity under zero or very small compressive stress is typically of the order of 0.8, and the ratio between thickness after and before compression may be 0.7 or even less, under very high compressive stress. Figure 4 shows that, for $n_1 = 0.8$, RF_{TR} is approximately 4 for $t_2/t_1 = 0.7$ and approximately 5 for $t_2/t_1 = 0.67$. As discussed in Section 4.2, part of this reduction factor corresponds to a thickness reduction that occurs immediately after application of a compressive stress, whereas the rest corresponds to a thickness reduction that occurs during a period of time after application of the compressive stress.

4.2 Expression for Transmissivity Reduction Factors due to Compression and Creep

As indicated by Giroud et al. (2000), the reduction in thickness of a geosynthetic due to a compressive load takes place in two stages: an instantaneous thickness reduction due to instantaneous compression and a thickness reduction that takes place over a long period of time due to creep. The geosynthetic thickness, which is t_{virgin} before applica-

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

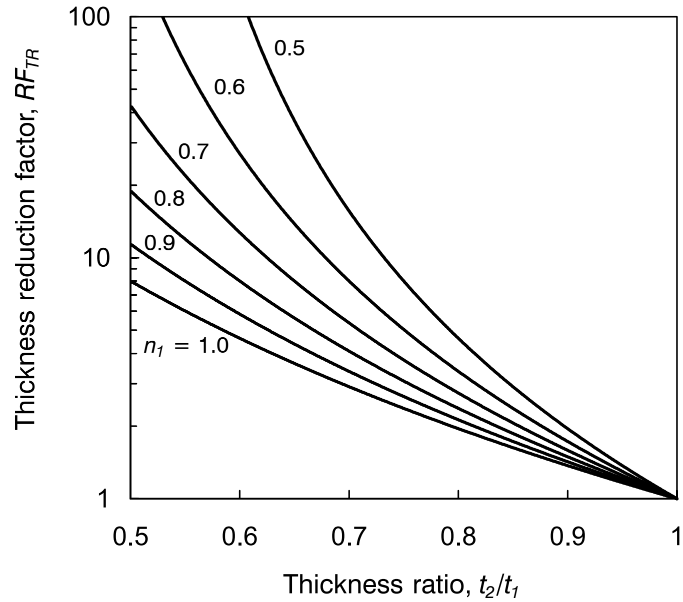


Figure 4. Value of the hydraulic transmissivity reduction factor due to thickness reduction as a function of the thickness ratio, t_2/t_1, and the geosynthetic porosity in the initial state, n_1.

Notes: The curves were obtained using Equation 13. The case n_1 = 1.0 is a limit case. In reality, the most porous geosynthetics have a porosity that typically does not exceed 0.95.

tion of any compressive stress, becomes t_{IMCO} immediately after application of the compressive stress and becomes t_{CR} at the end of the period of time when the effect of creep is to be evaluated. It is important to note that the thickness of a geosynthetic is never measured *immediately* after application of the compressive stress. In fact, a thickness, t_{CO}, is measured a certain time after application of the compressive stress; t_{CO} is less than t_{IMCO} due to the thickness reduction resulting from creep between the time immediately after application of the compressive stress and the time when t_{CO} is measured. The time at which t_{CO} is measured is often specified, e.g. 100 hours.

Based on Equation 12, the hydraulic transmissivity reduction factor due to thickness reduction (resulting from immediate compression and some creep), RF_{CO}, between t_{virgin} and t_{CO} can be expressed as a function of t_{virgin} and t_{CO} as follows:

$$RF_{CO} = \left(\frac{t_{virgin} - \dfrac{\mu}{\rho}}{t_{CO} - \dfrac{\mu}{\rho}} \right)^3 \tag{14}$$

and, based on Equation 13, the same hydraulic transmissivity reduction factor can be expressed as a function of t_{CO}/t_{virgin} and n_{virgin} as follows:

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

$$RF_{CO} = \frac{1}{\left[1 - \frac{1-\left(t_{CO}/t_{virgin}\right)}{n_{virgin}}\right]^3} = \left[\frac{n_{virgin}}{\left(t_{CO}/t_{virgin}\right)-\left(1-n_{virgin}\right)}\right]^3 \tag{15}$$

where n_{virgin} is the porosity of the geosynthetic as manufactured, i.e. before application of any compressive stress. Numerical values of RF_{CO} are given in Figure 4 with $n_1 = n_{virgin}$ and $t_2/t_1 = t_{CO}/t_{virgin}$.

Based on Equation 12, the hydraulic transmissivity reduction factor due to creep, RF_{CR} , can be expressed as a function of t_{CO} and t_{CR} as follows:

$$RF_{CR} = \left(\frac{t_{CO} - \frac{\mu}{\rho}}{t_{CR} - \frac{\mu}{\rho}}\right)^3 \tag{16}$$

and, based on Equation 13, the same hydraulic transmissivity reduction factor can be expressed as a function of t_{CR}/t_{CO} and n_{CO} as follows:

$$RF_{CR} = \frac{1}{\left[1 - \frac{1-\left(t_{CR}/t_{CO}\right)}{n_{CO}}\right]^3} = \left[\frac{n_{CO}}{\left(t_{CR}/t_{CO}\right)-\left(1-n_{CO}\right)}\right]^3 \tag{17}$$

To use Equation 17, it is necessary to know n_{CO} , the value of the geosynthetic porosity that corresponds to the thickness t_{CO} , i.e. the value of the geosynthetic porosity at the beginning of the period where the effect of creep is evaluated. This is not convenient because n_{CO} is not known and would need to be calculated if Equation 17 were to be used. Therefore, it is preferable to replace n_{CO} by its expression as a function of known parameters. From Equation 4:

$$\frac{\mu}{\rho} = t_{virgin}\left(1-n_{virgin}\right) = t_{CO}\left(1-n_{CO}\right) \tag{18}$$

Eliminating n_{CO} between Equations 17 and 18 gives:

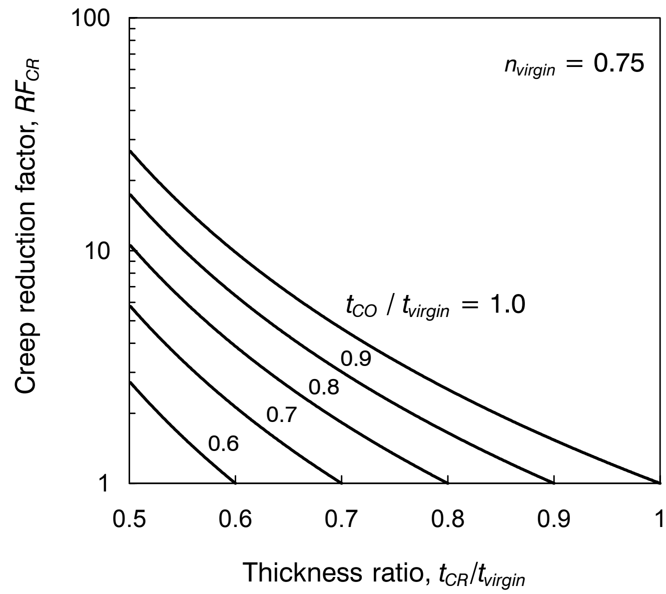
$$RF_{CR} = \left[\frac{\left(t_{CO}/t_{virgin}\right)-\left(1-n_{virgin}\right)}{\left(t_{CR}/t_{virgin}\right)-\left(1-n_{virgin}\right)}\right]^3 \tag{19}$$

It is important to note that the creep reduction factor calculated using Equation 16, 17, or 19 corresponds only to the effect of creep that occurs between the thicknesses t_{CO} and t_{CR} , i.e. during the period where the effect of creep is evaluated.

Values of RF_{CR} for different values of the three parameters, n_{virgin} , t_{CO}/t_{virgin} , and t_{CR}/t_{virgin} , are given in Figure 5. In the graphs presented in Figure 5, t_{CO} is the thickness of the compressed geosynthetic at the time the hydraulic transmissivity is measured, and t_{CR} is the thickness of the geosynthetic after creep, i.e. at the time in the future when

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

(a)



(b)

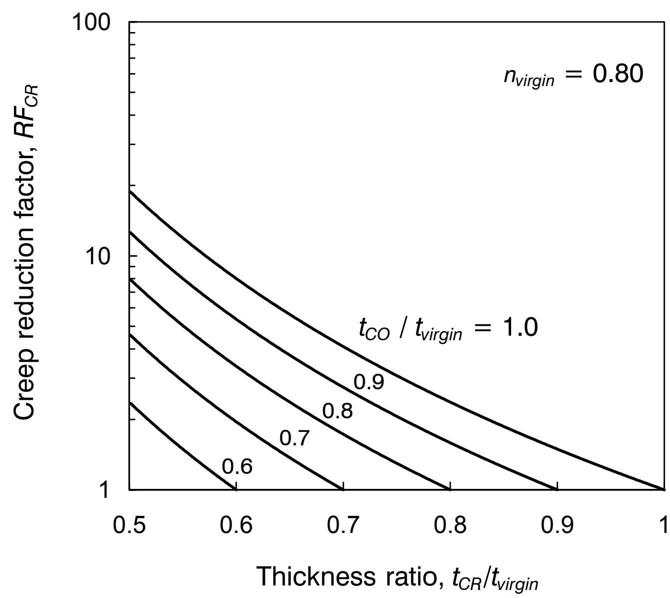
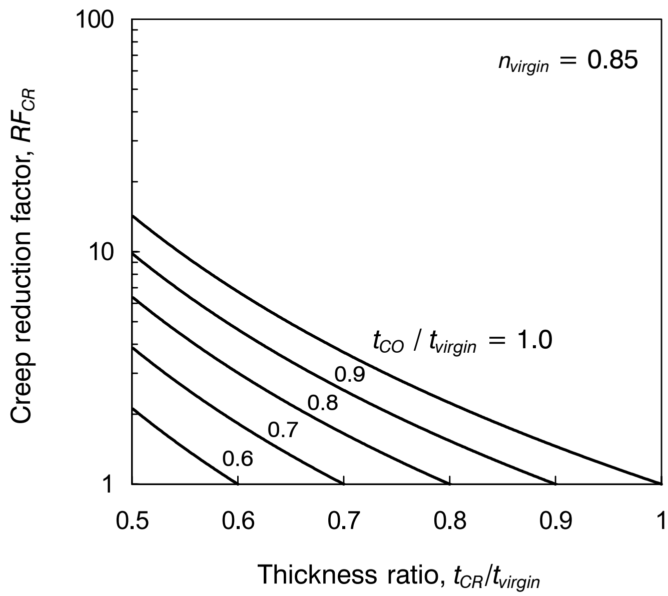


Figure 5. Value of the hydraulic transmissivity reduction factor due to creep ("creep reduction factor") as a function of the thickness ratios, t_{CO}/t_{virgin} and t_{CR}/t_{virgin}, for four values of the initial porosity: (a) n_{virgin} = 0.75; (b) n_{virgin} = 0.80 (Figure 5 continues on the next page).

Note: The curves were obtained using Equation 19.

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

(c)



(d)

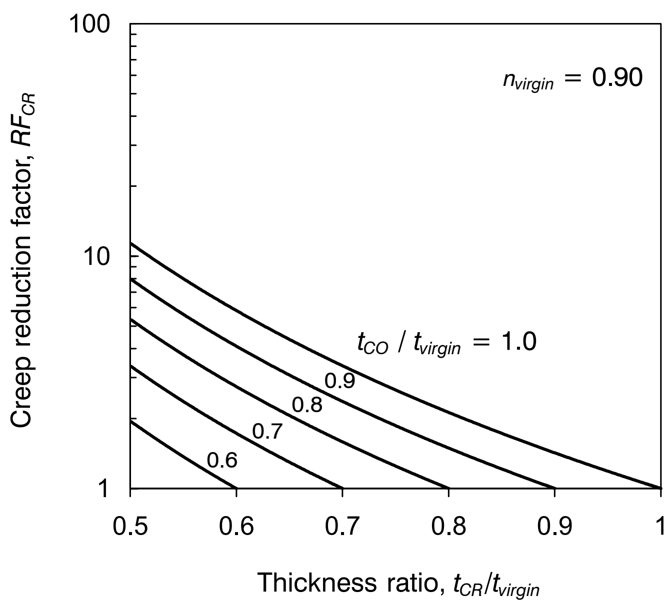


Figure 5 continued. **(c) n_{virgin} = 0.85; (d) n_{virgin} = 0.90.**

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

the predicted hydraulic transmissivity is expected to occur. An example of how Figure 5 can be used is presented in Example 2 (Section 4.4).

It is important to note that, from Equations 14 and 16:

$$RF_{CO} \times RF_{CR} = \left(\frac{t_{virgin} - \dfrac{\mu}{\rho}}{t_{CO} - \dfrac{\mu}{\rho}} \right)^3 \left(\frac{t_{CO} - \dfrac{\mu}{\rho}}{t_{CR} - \dfrac{\mu}{\rho}} \right)^3 \tag{20}$$

and, from Equations 15 and 19:

$$RF_{CO} \times RF_{CR} = \left[\frac{n_{virgin}}{\left(t_{CO} / t_{virgin}\right) - \left(1 - n_{virgin}\right)} \right]^3 \left[\frac{\left(t_{CO} / t_{virgin}\right) - \left(1 - n_{virgin}\right)}{\left(t_{CR} / t_{virgin}\right) - \left(1 - n_{virgin}\right)} \right]^3 \tag{21}$$

hence:

$$RF_{CO} \times RF_{CR} = \left(\frac{t_{virgin} - \dfrac{\mu}{\rho}}{t_{CR} - \dfrac{\mu}{\rho}} \right)^3 = \left[\frac{n_{virgin}}{\left(t_{CR} / t_{virgin}\right) - \left(1 - n_{virgin}\right)} \right]^3 \tag{22}$$

Comparing Equation 22 to Equation 12 or 13 shows that Equation 22 is the expression of the hydraulic transmissivity reduction factor for a geosynthetic whose thickness is reduced from t_{virgin} to t_{CR} . This shows that it is legitimate to multiply RF_{CO} by RF_{CR} when these two reduction factors are used (Giroud et al. 2000).

4.3 Comment on the Use of the Equations

In the United States, more and more frequently, hydraulic transmissivity tests are performed under loads sustained for a long period of time, such as 100 hours, as recommended by some regulatory agencies, or 300 hours, as recommended by Holtz et al. (1997). This eliminates the need for the reduction factor due to compression, RF_{CO} . To be able to use Equation 16 or 19 to predict the reduction factor due to creep, RF_{CR} , it is essential that the geosynthetic thickness be measured at the same time the hydraulic transmissivity is measured. The geosynthetic thickness thus measured is the value of t_{CO} to be used in Equation 16 or 19. This is illustrated in Examples 1 and 2 (Section 4.4).

More generally, it is important to note that, if the thickness t_{CO} is not measured *immediately* after the application of the compressive stress, but hours or days later, some creep would have occurred, and the value of t_{CO} thus measured is smaller than the value that would have been obtained if t_{CO} had been measured *immediately* after the application of the compressive stress. Delaying the measurement of t_{CO} leads to an increase of RF_{CO} (which is only of academic interest since RF_{CO} is not needed as mentioned above) and a decrease of RF_{CR} . This is illustrated in Example 3 (Section 4.4).

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

4.4 Examples

Five examples are presented. These examples illustrate the use of the two types of equations (equations that include the porosity, and equations that do not include the porosity), and illustrate the fact that the times at which the thicknesses t_{CO} and t_{CR} are considered have an impact on the values of the hydraulic transmissivity reduction factors. The first four examples deal with hydraulic transmissivity, and the considered geosynthetics are geonets. The fifth example deals with hydraulic conductivity, and the considered geosynthetic is a geotextile. However, it should be noted that all equations in the present paper apply to all types of geosynthetic drainage media.

Example 1. A high density polyethylene geonet has a mass per unit area of 1,216 g/m^2 and an initial thickness of 8.55 mm. Its hydraulic transmissivity is 3.5×10^{-3} m^2/s, as measured between two steel plates, under the compressive stress of 700 kPa that is expected in the field. In the test, the load was sustained for 100 hours before the hydraulic transmissivity was measured; the geonet thickness measured at the end of the 100 hour period was 7.14 mm. Based on creep tests, a thickness of 6.3 mm has been extrapolated at the end of the design life of the structure where the geonet is to be used. Calculate the hydraulic transmissivity reduction factor due to creep.

To use Equation 16, it is necessary to know the density of the polymeric compound used to make the geonet. For high density polyethylene including a typical amount of carbon black, a density of 950 kg/m^2 can be assumed. Equation 16 can then be used as follows:

$$RF_{CR} = \left(\frac{7.14 - \dfrac{1216}{950}}{6.3 - \dfrac{1216}{950}} \right)^3 = \left(\frac{5.86}{5.02} \right)^3 = 1.59$$

It should be noted that the initial thickness of the geosynthetic was not needed in the above calculations. In contrast, it was essential to know the thickness at the time when the hydraulic transmissivity was measured.

END OF EXAMPLE 1

Example 2. A high density polyethylene geonet has an initial thickness of 8.55 mm and an initial porosity of 0.85. Its hydraulic transmissivity is 3.5×10^{-3} m^2/s, as measured between two steel plates, under the compressive stress of 700 kPa that is expected in the field. In the test, the load was sustained for 100 hours before the hydraulic transmissivity was measured; the geonet thickness measured at the end of the 100 hour period was 7.14 mm. Based on creep tests, a thickness of 6.3 mm has been extrapolated at the end of the design life of the structure where the geonet is to be used. Calculate the hydraulic transmissivity reduction factor due to creep.

Equation 19 can then be used as follows:

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

$$RF_{CR} = \left[\frac{(7.14/8.55)-(1-0.85)}{(6.3/8.55)-(1-0.85)}\right]^3 = \left(\frac{0.685}{0.587}\right)^3 = 1.59$$

The result is the same as in Example 1 because the geosynthetic is the same, which can be checked using Equation 4.

Also, the graph in Figure 5c can be used with n_{virgin} = 0.85 and:

$$\frac{t_{CO}}{t_{virgin}} = \frac{7.14}{8.55} = 0.84 \quad \text{and} \quad \frac{t_{CR}}{t_{virgin}} = \frac{6.3}{8.55} = 0.74$$

END OF EXAMPLE 2

Example 3. A geonet having an initial porosity of 0.79 and an initial thickness of 8.3 mm is subjected to a compressive stress. Its thickness becomes 6.6 mm one minute after application of the compressive stress, 6.2 mm after 100 hours, and 6.0 mm after 10,000 hours. Calculate the values of the hydraulic transmissivity reduction factors.

First, it is assumed that the compression phase is between time zero and time one minute, and the creep phase is between time one minute and time 10,000 hours. In this case, Equation 15 can be written as follows:

$$RF_{CO} = \frac{1}{\left[1 - \frac{1-(6.6/8.3)}{0.79}\right]^3} = 2.46$$

and Equation 19 can be written as follows:

$$RF_{CR} = \left[\frac{(6.6/8.3)-(1-0.79)}{(6.0/8.3)-(1-0.79)}\right]^3 = 1.49$$

Second, it is assumed that the compression phase is between time zero and time 100 hours, and the creep phase is between time 100 hours and time 10,000 hours. In this case, Equation 15 can be written as follows:

$$RF_{CO} = \frac{1}{\left[1 - \frac{1-(6.2/8.3)}{0.79}\right]^3} = 3.18$$

and Equation 19 can be written as follows:

$$RF_{CR} = \left[\frac{(6.2/8.3)-(1-0.79)}{(6.0/8.3)-(1-0.79)}\right]^3 = 1.15$$

It should be noted that:

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

$$2.46 \times 1.49 \;=\; 3.18 \times 1.15 \;=\; 3.65$$

which could have been obtained directly using Equation 22 as follows:

$$RF_{CO} \times RF_{CR} \;=\left[\frac{0.79}{(6.0/8.3)-(1-0.79)}\right]^3 \;=\; 3.65$$

The reduction factor RF_{CO} quantifies the hydraulic transmissivity reduction that results from thickness reduction between t_{virgin} and t_{CO} . As indicated in Section 4.3, the reduction factor RF_{CO} is only of academic interest if the hydraulic transmissivity is measured at the same time as the thickness t_{CO} is measured, which is the usual case. The reduction factor RF_{CO} would be applicable only in the case where the hydraulic transmissivity is measured on the virgin specimen, i.e. before the application of the compressive stress.

The reduction factor RF_{CR} is the only reduction factor to be applied if the hydraulic transmissivity is measured at the same time as the thickness t_{CO} is measured, which is the usual case. The value of RF_{CR} depends on the time at which t_{CO} is measured: the longer the time, the smaller the RF_{CR} value. Two examples, based on the above numerical calculations, are given below:

- if the hydraulic transmissivity had been measured one minute after the application of the compressive stress, the only reduction factor to be applied would be RF_{CR} = 1.49; and
- if the hydraulic transmissivity had been measured 100 hours after the application of the compressive stress, the only reduction factor to be applied would be RF_{CR} = 1.15.

END OF EXAMPLE 3

Example 4. A high density polyethylene geonet has a mass per unit area of 1,254 g/m^2 and an initial thickness of 8.3 mm. Its hydraulic transmissivity, measured between two steel plates, under a compressive stress of 10 kPa, is 9.5 × 10^{-3} m^2/s; its thickness is then 8.16 mm. Under a compressive stress of 1,000 kPa, its thickness is 7.27 mm. What hydraulic transmissivity can be predicted for this geonet between two steel plates under a compressive stress of 1,000 kPa?

To use Equation 10, it is necessary to know the density of the polymeric compound used to make the geonet. For high density polyethylene including a typical amount of carbon black, a density of 950 kg/m^2 can be assumed. Equation 10 can then be used as follows:

$$\frac{\theta_2}{\theta_1} \;=\left(\frac{7.27-\dfrac{1254}{950}}{8.16-\dfrac{1254}{950}}\right)^3 =\left(\frac{5.95}{6.84}\right)^3 \;=\; 0.658$$

hence:

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

$$\theta_2 = (0.658)\left(9.5\times10^{-3}\right) = 6.25\times10^{-3}\ \text{m}^2/\text{s}$$

END OF EXAMPLE 4

Example 5. A polypropylene needle-punched nonwoven geotextile with a mass per unit area of 335 g/m^2 is used as a filter in an earth dam, at a location where the normal stress is expected to be 800 kPa. Under a very small stress (8 kPa), the thickness of the geotextile is 3.1 mm and its hydraulic conductivity is 3.0×10^{-3} m/s. The thickness of the geotextile under a normal stress of 800 kPa sustained for a duration equal to the design life of the dam is estimated to be 1.2 mm, based on extrapolation of creep test results. Calculate the expected hydraulic conductivity of this geotextile filter in the dam.

To use Equation 6, it is necessary to know the density of the polypropylene compound used to make the geotextile. A typical value of 910 kg/m^3 is considered. Then, Equation 6 is used as follows:

$$\frac{k_2}{k_1} = \left(\frac{3.1}{1.2}\right)\left(\frac{1.2-\dfrac{335}{910}}{3.1-\dfrac{335}{910}}\right)^3 = 0.073$$

hence:

$$k_2 = (0.073)\left(3\times10^{-3}\right) = 2.2\times10^{-4}\ \text{m/s}$$

It appears that the hydraulic conductivity of a needle-punched nonwoven geotextile filter in an earth dam is much less than the hydraulic conductivity of the same geotextile measured in the laboratory. This is an important consideration when filter criteria are used.

END OF EXAMPLE 5

5 CONCLUSION

A relationship between the decrease in hydraulic transmissivity of a geosynthetic due to a decrease in thickness was developed (Equations 10 and 11). Hydraulic transmissivity values calculated using this relationship are in good agreement with experimental data for geotextiles and geonets, as shown in Section 3. From the relationship expressed by Equation 10 or 11, reduction factors have been derived. These reduction factors make it possible to predict the decrease in hydraulic transmissivity that results from a decrease in thickness of the considered geosynthetic. The equations proposed in the present paper are a powerful design tool, especially when the thickness reduction is due to creep, because it is impractical to conduct hydraulic transmissivity tests over a period of time that exceeds a few hundred hours, whereas the decrease of geosynthetic thickness during a very long period of time can be evaluated by using compressive creep

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

tests that are performed during a long time and/or accelerated using time-temperature superposition.

ACKNOWLEDGEMENTS

The support of GeoSyntec Consultants is acknowledged. The authors are grateful to E.M. Palmeira for providing data on geotextiles and for his comments, and to C. Babcock for performing geonet tests.

REFERENCES

Carman, P.C., 1937, "Fluid Flow Through Granular Beds", *Transactions of the Institution of Civil Engineers*, Vol. 15, pp. 150-166.

Giroud, J.P., 1996, "Granular Filters and Geotextile Filters", *Proceedings of GeoFilters '96*, Lafleur, J. and Rollin, A.L., Editors, Montréal, Québec, Canada, May 1996, pp. 565-680.

Giroud, J.P. and Perfetti, J., 1977, "Classification des textiles et mesure de leurs propriétés en vue de leur utilisation en géotechnique", *Proceedings of the International Conference on the Use of Fabrics in Geotechnics*, Vol. 2, Paris, France, April 1977, pp. 345-352. (in French)

Giroud, J.P., Zornberg, J.G., and Zhao, A., 2000, "Hydraulic Design of Geosynthetic and Granular Liquid Collection Layers", *Geosynthetic International*, Special Issue on Liquid Collection Systems, Vol. 7, Nos. 4-6, pp. 285-380.

Holtz, R.D., Christopher, B.R., and Berg, R.R., 1997, "*Geosynthetic Engineering*", Bitech Publishers, Vancouver, British Columbia, Canada, 452 p.

Palmeira, E.M. and Gardoni, M.G., 2000a, "The Influence of Partial Clogging and Pressure on the Behaviour of Geotextiles in Drainage Systems", *Geosynthetic International*, Special Issue on Liquid Collection Systems, Vol. 7, Nos. 4-6, pp. 403-431.

Palmeira, E.M. and Gardoni, M.G., 2000b, "*Tabulated Values of Hydraulic Transmissivity and Thickness of Nonwoven Geotextiles Subjected to Compressive Stress*", Personal communication, April 2000.

NOTATIONS

Basic SI units are given in parentheses.

k	=	hydraulic conductivity of geosynthetic (m/s)
k_1	=	hydraulic conductivity of geosynthetic when its thickness is t_1 (m/s)
k_2	=	hydraulic conductivity of geosynthetic when its thickness is t_2 (m/s)
i	=	hydraulic gradient (dimensionless)
n	=	porosity of geosynthetic (dimensionless)

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.

n_1	=	porosity of geosynthetic when its thickness is t_1 (dimensionless)
n_2	=	porosity of geosynthetic when its thickness is t_2 (dimensionless)
n_{CO}	=	porosity of geosynthetic immediately after application of compressive stress (dimensionless)
n_{virgin}	=	porosity of geosynthetic as manufactured, i.e. before application of any compressive stress (dimensionless)
RF_{CO}	=	reduction factor for compression (dimensionless)
RF_{CR}	=	reduction factor for creep (dimensionless)
RF_{TR}	=	reduction factor for thickness reduction (dimensionless)
t	=	thickness of geosynthetic (m)
t_1	=	thickness of geosynthetic that corresponds to hydraulic conductivity k_1 and hydraulic transmissivity θ_1 (m)
t_2	=	thickness of geosynthetic that corresponds to hydraulic conductivity k_2 and hydraulic transmissivity θ_2 (m)
t_{CO}	=	thickness of geosynthetic measured a certain time after application of compressive stress (m)
t_{CR}	=	thickness of geosynthetic after creep (m)
t_{IMCO}	=	thickness of geosynthetic immediately after application of compressive stress (m)
t_o	=	thickness of geosynthetic under zero or quasi-zero compressive stress in a series of tests (m)
t_{virgin}	=	thickness of geosynthetic as manufactured, i.e. before application of any compressive stress (m)
μ	=	mass per unit area of geosynthetic (kg/m^2)
ρ	=	density of polymeric compound used to make geosynthetic (kg/m^3)
θ	=	hydraulic transmissivity of geosynthetic (m^2/s)
θ_1	=	hydraulic transmissivity of geosynthetic when its thickness is t_1 (m^2/s)
θ_2	=	hydraulic transmissivity of geosynthetic when its thickness is t_2 (m^2/s)
θ_o	=	hydraulic transmissivity value that corresponds to lowest compressive stress in a series of hydraulic transmissivity tests performed under various compressive stresses (m^2/s)
σ	=	compressive stress (Pa)
ζ	=	factor used in Equation 2 incorporating several parameters that are not relevant to present study (m/s)

Downloaded by [International Geosynthetics Society] on [22/04/25]. Copyright © ICE Publishing, all rights reserved.