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Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

In-plane hydraulic conductivity and porosity of geotextiles

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ABSTRACT: In the paper the experimental results of hydraulic conductivity of geotextile products in its plane are presented. In the experiments short-term flow capacity for given static load and hydraulic gradient was considered. The experiments were completed by the analysis of the porosity for nonwoven geotextile under normal pressure with the use of probability elements. The attempt was taken to determine most probable, mean and maximum diameters of pores and porosity by means of one dimensional image processing.

1. INTRODUCTION

Recently, on can observe a significant growth of numerous applications of geotextiles which play a function of drainage systems in engineering constructions parallel to its constructional role as the materials interacting with a subsoil and foundations. Consequently there is a need to investigate in-plane flow water capacity of geotextiles together with the design parameters of the normal stress and hydraulic gradient. The in-plane flow through geotextile product is characterised by its transmissivity θ. The transmissivity of the material is defined as volume flow rate of water per unit hydraulic gradient in the direction parallel to the sample plane. Additionally, according to Darcy's empirical law it is assumed that the discharge velocity of flow is proportional to hydraulic gradient corresponding to laminar flow, thus:

$$\theta = \frac{q_{20} \cdot L}{W \cdot h} = \frac{q_{20}}{W \cdot i} \tag{1}$$

$$q_{20} = q_T \cdot R_T = q_T \cdot \left(\frac{\mu_T}{\mu_{20}} \right) \tag{2}$$

where θ = transmissivity of geotextile; q_{20}, q_T = flow rate at 20^0 C and T^0 C respectively; μ_{20}, μ_T = dynamic viscosity coefficient at 20^0 C and T^0 C respectively; L = length of a sample; W = width of a sample, h = hydraulic head; R_T = correction factor.

In nature, the flow through the geotextile being an element of any engineering constructions is of the laminar-turbulent character that means that every particle can move in any direction and drop of pressure head is approximately proportional to the second power of the velocity. Therefore, in order to determine the permeability of the material the term transmissivity in the material plane should be replaced by capacity of flow. It can be described by the following equation:

$$q_{ng} = \frac{q_{20}}{W} \tag{3}$$

where q_{ng} = capacity of flow in the plane of geotextile.

The flow capacity depends either on a given hydraulic gradient or on normal stress acting on the material plane. The flow capacity can not then be identified with one specific value but with a set of values of given distribution and consequently it can not be a material constant.

2. INVESTIGATIONS OF HORIZONTAL FLOW THROUGH GEOTEXTILE

2.1 Laboratory testing equipment

The experiments were carried out by means of a measuring device constructed in Geotechnical Department of Gdańsk Technical University. The scheme of the device is shown in Figure 1.

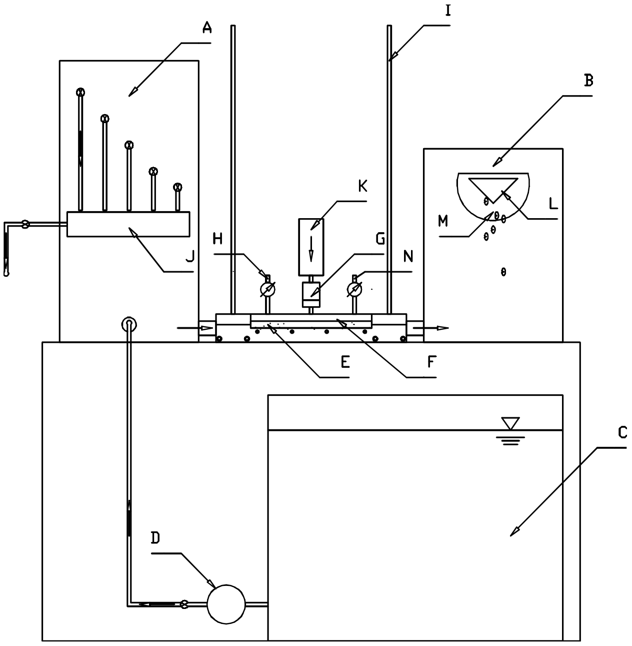

Figure 1. Scheme of the device for measurement of in-plane flow through geotextile A – supply reservoir, B – drainage reservoir, C – mian reservoir, D – pump, E – specimen of geotextile product, F – loading plate, G – force gauge, H – left displacement gauge, I- piezometer, J – excess water reservoir, K – ballast load, L – overflow, M – flow measurement, N – right displacement gauge.

The device allows for the measurement of permeability in the plane of geotextile material at the given normal stress and for the following gradients: 1.0, 0.75, 0.50, 0.25 and 0.10. In order to assure constant pressure acting on the sample during the test the ballast frame system with maximum pressure of 250 kPa has been employed. Such load enables the maintenance of constant pressure acting on a sample during its testing in spite of the changes of the material thickness due to creep of geotextile. In the device the samples of various thickness can be tested. The basic element fo the device is a box which serves for testing the geotextile samples 200 mm wide by 300 mm long. Al joints between individual elements of the box were design to be watertight and enable the flow in horizontal plane of a sample. The measuring box has been connected with plexiglass suply and drainage reservoirs.

Continuous monitoring of both static load and vertical displacements of the sample was made by data acquisition system. The system collects the data from the bridge and transmits it to the PC equipped in analogue-digital PCAD transducer. The system was controlled by the specially elaborated numerical code.

The tests were performed on two types of nonwoven polypropylene geotextiles the basic physical parameters of which are shown in Table 1.

Table 1. Basic physical parameters of tested geotextiles.

Notation	Polymer	Mass per unit area	Thickness	
		g/m^2		mm
A	PP	935	at 2 kPa	8.85
			20 kPa	6.69
			200 kPa	3.99
B	PP	968	at 2 kPa	10.9
			20 kPa	7.70
			200 kPa	4.40

2.2 Test results

The results of tests in the form of capacity of flow versus normal pressure for two different gradients are presented in Figures 2 and 3.

It can be clearly seen that the increase of normal pressure acting on the geotextile material causes the decrease of its flow capacity. It is basically caused by the substantial strain and creep of the material due to load applied. Thus, if we know the change of normal pressure acting on the geotextile material it is possible to predict the reduction of flow capacity through the material in time. Comparing the plots presented in Figures 2 and 3 it can be also seen that the greater mass per unit area of the material the higher flow capacity.

The flow capacity for samples cut out in the machine direction and in cross machine direction for hydraulic gradient 1.0 are shown in Figure 4. The results obtained are almost identical what means that the flow is characterised by significant isotropy.

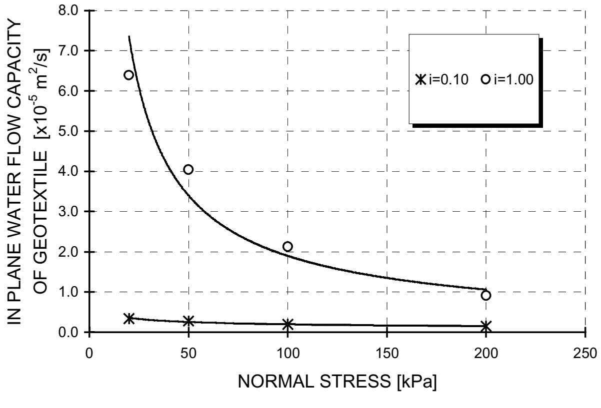

Figure 2. In plane water flow capacity through geotextile A versus normal stress.

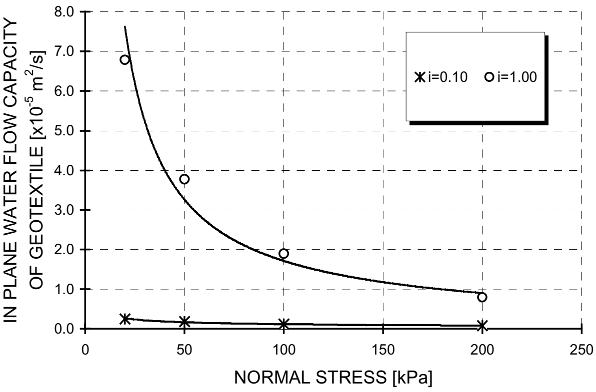

Figure 3. In -plane water flow capacity through geotextile B versus normal stress.

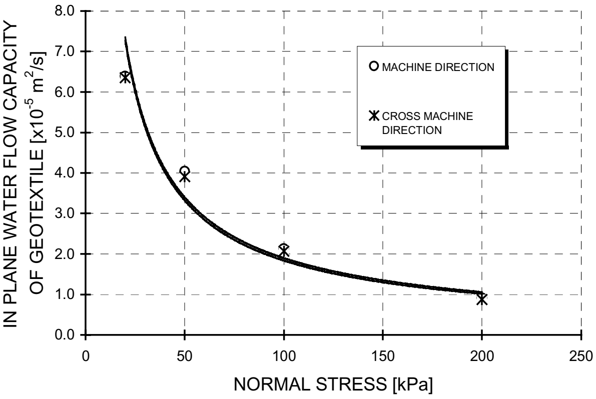

Figure 4. In plane water flow capacity through the plane of geotextile A versus normal pressure for hydraulic gradient 1.0.

3. GEOTEXTILE POROSITY

The flow trough the geotextiles can be treated as the flow through the porous body. Complex geometry of natural porous medium causes that the theoretical description of such medium has to be simplified. The sizes of pores, its shapes and mutual location are of random character and depend on production technology of the material. Distribution of pores and its size can be treated as statistically identical. It allows for the assumption of geotextile material as continuous medium with the same characteristic of an arbitrary small material area as the for whole sample.

In the Figure 5 the scheme of cross-section through the geotextile is shown. For better understanding of the problem the circular shape of fibers and pores was assumed. For the description of the probability of existence of pores in the given geotextile cross-section, probability of its size and distribution the exponential distribution function was employed. The modified form of the function for porous medium is the following:

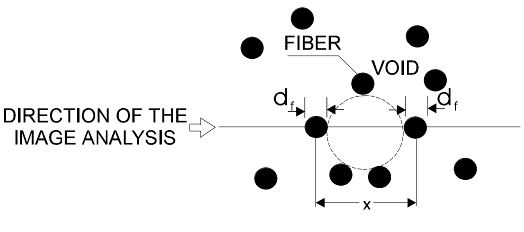

Figure 5. Scheme of cross-section through the geotextile.

$$F_X(x) = 1 - \exp[-\frac{1}{n}(\frac{\pi\nu}{4}x^2 + \frac{2\lambda}{2}x)] \tag{4}$$

where: n = surface porosity; x = distance between centres of fibers; 2λ = perimeter of fiber; ν = fiber density per unit cross-section of geotextile product.

The perimeter of fiber can be expressed in terms of its cross-sectional area by the following relationship:

$$\lambda x = 2\bar{F} \tag{5}$$

Substituting the Equation 5 into Equation 4 the authors propose following form distribution function:

$$F_X(x) = 1 - \exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})] \tag{6}$$

where $\bar{F}$ = average cross-sectional area of fibers.

After differentiating the Equation 6 over x the probability density function takes the following form:

$$f_X(x) = \frac{\pi\nu}{2n}x\exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})] \tag{7}$$

and corresponding second and third derivative:

$$\begin{aligned}\frac{d^2F_X(x)}{dx^2} &= \frac{\pi\nu}{2n}\exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})] \\ &- \frac{\pi^2\nu^2}{4n^2}x^2\exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})]\end{aligned} \tag{8}$$

$$\begin{aligned}\frac{d^3F_X(x)}{dx^3} &= -\frac{3}{4n^2}\pi^2\nu^2x\exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})] \\ &+ \frac{1}{8n^3}\pi^3\nu^3x^3\exp[-\frac{\nu}{n}(\frac{\pi}{4}x^2 + 2\bar{F})]\end{aligned} \tag{9}$$

The graphical interpretation of probability density function is shown in Figure 6

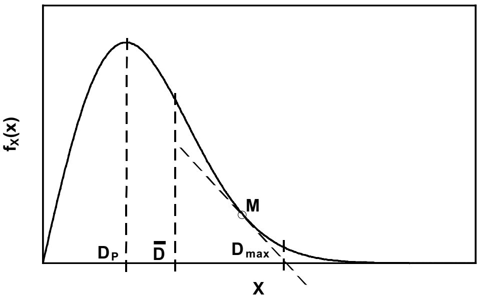

Figure 6. Distribution of probability density function.

In order to simplify the considerations (Masounave et al. 1980) assumed the porous medium with porosity equal to unity. For such assumption the fiber perimeter is equal to zero what leads to the incorrect interpretation of porosity and distribution and size of pores. Calculated values of pores diameters are usually overestimated in this case.

The porosity of geotextile material for given normal pressure is of the order of 70÷90 % (see Table 2). In the considerations the authors of the paper assumed the porosity to be different then 1.0.

The mean pore diameter of pores were determined from the following relationships:

$$\bar{x} = \frac{\int_0^\infty x f_x(x)dx}{\int_0^\infty f_x(x)dx} \tag{10}$$

$$\bar{D} = \bar{x} - d_f = \left(\frac{n}{\nu}\right)^{\frac{1}{2}} - d_f \tag{11}$$

where d_f = mean fiber diameter.

If there is second derivative of distribution function given by Equation 6 and can be equal to zero thus most probable pore diameter of pores are described by the expression:

$$D_p = x - d_f = \left(\frac{2n}{\pi\nu}\right)^{\frac{1}{2}} - d_f \tag{12}$$

Maximum pore diameter D_{max} are described by the following equation:

$$D_{\max} = x_{\max} - d_f = 3.67423\left(\frac{n}{\pi\nu}\right)^{\frac{1}{2}} - d_f \tag{13}$$

4. MICROSCOPIC SCALE IMAGE ANALYSIS

The microscopic scale image analysis was used to determine the porosity of cross-section of polypropylene geotextile A, the basic physical parameters of which are shown in Table 1. The analysis was performed onto five samples randomly cut out from the series of the material. The samples were next placed in the epoxy resin and subject to the following normal pressures: 0, 20, 50, 100 and 200 kPa. After reaching the solid state by resin (approximately after 24 hours) the cylinders of the diameter of 13 mm and the height of 15 mm were cut out. The cylindrical samples were next placed within copper made cylinders of the same inner size as dimension of the sample. In order to remove the fissures and scratches the surface of such sample was being polished by means of the material with gradation of the order of micrometers. Next the cross-section of the sample has been covered by very thing layer of gold silt and scanned by scanning electron

Table 2. Structural parameters and of in-plane water flow capacity through geotextile A (for hydraulic gradient 1.0).

Normal pressure	Fiber diameter	Cross-sectional area of fibers	Porosity	Fiber density per cross-section of a fabric	Pore diameter			Flow capacity
σ_v	d_f	$\bar{F}$	n	ν	D_p	$\bar{D}$	D_{max}	q_{ng}
kPa	μm	μm^2	-	$x10^{-6}\ \mu m^{-2}$	μm	μm	μm	$x10^{-5}\ m^2/s$
0	179	20740	0.89	5.29	148	231	671	-
20	188	25888	0.84	6.08	109	184	583	6.39
50	176	21656	0.82	8.14	77	141	482	4.04
100	204	26154	0.78	10.3	8	62	348	2.13
200	209	27251	0.69	11.2	-	39	306	0.91

microscope. The image obtained was digitised in the BMP graphical form. It allowed for digital processing of the input image. The images of cross-section of the geotextile material for different normal loads are presented in Figures 7 and 8.

Using one dimensional analysis of cross-sectional image of the geotextile and commercial version of the code released by computer scanning system the following parameters have been determined:

- surface porosity n (as the ratio of number of white pixels to the total size of bitmap analysed (in pixels),
- fiber density per unit cross-section ν,
- Feret diameters,
- length and width of fiber diameters projection (number of neighbouring black pixels),
- co-ordinates and orientation of local co-ordinates system of fiber towards global system.

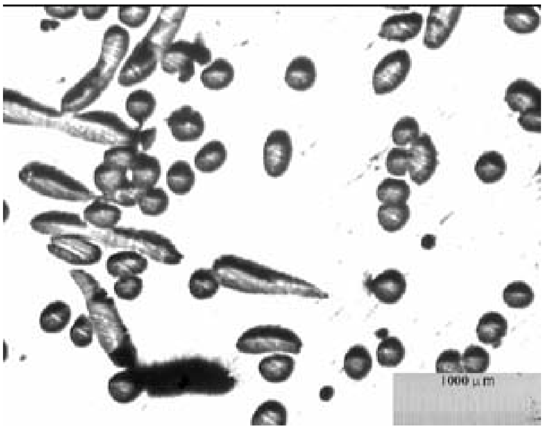

Figure 7. The images of cross-section of the geotextile material for normal pressures: 0 kPa.

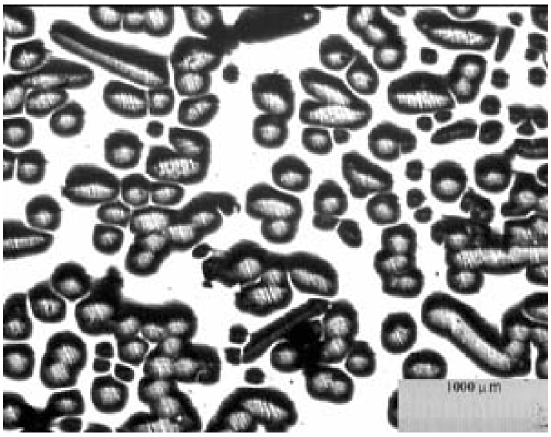

Figure 8. The images of cross-section of the geotextile material for normal pressures: 200 kPa.

The MultiScan code has been applied as an element of computer measurement system serving for monitoring, visualisation, processing and analysis of the microscope images.

The size of bitmap of analysed digital image was 712 x 550 pixels (1 pixel ≈ 5.10 μm). The analysis of the input image has been carried out by morphologic transformation which allows for most complex operations concerning the analysis of fibers, its mutual distribution and for complex processes of image simulation.

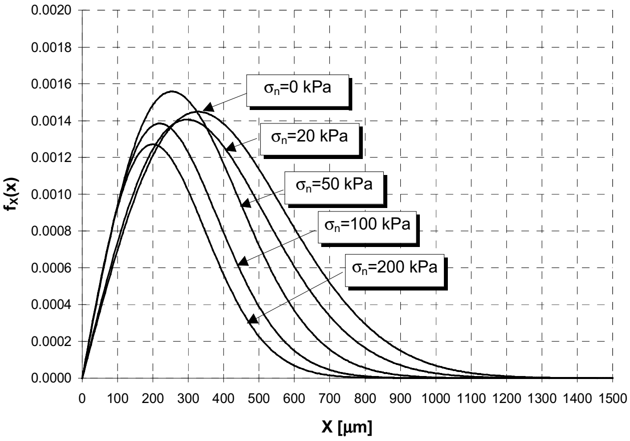

Fig. 9 Distribution of probability density functions -geotextile A.

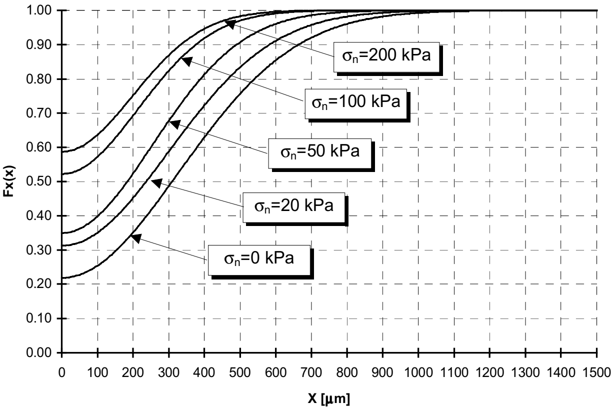

Figure 10. Distribution function of random variable X for geotextile A.

The probability density function of occurrence of pores of the given size for geotextile A which was subject to various normal pressure is presented in Figure 9 whereas in Figure 10 is shown the distribution of random variable *X* which represents the distance between centres of fibers.

5.SUMMARY

The results of hydraulic permeability in plane of geotextile presented in this paper concerned short-term behaviour of the material tested. The experiments have shown that for given value of normal pressure and hydraulic gradient the flow capacity is higher for the geotextile with higher mass per unit area. The flow capacity decreases with the increase of normal pressure. The influence of anisotropy of the material is negligible. It results from the probability distribution of pores. The increase of normal pressure acting on the geotextile causes the decrease of its porosity together with decrease of diameters of pores. The increase of porosity results in the decrease of the fiber density per cross-section of a fabric.

The variety and sometimes contradictory recommendations regarding design methods cause that manufacturers of geotextiles can not properly improve their products to produce the materials of better drainage parameters. Comprehensive studies and investigations on proper determination of hydraulic properties of geotextiles are then now of the great demand.

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