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Pressure Drop through Non-Woven Geotextiles: A New Analytical Model

La perte de charge au travers les géotextiles non-tissés: un nouveau modèle

Flow of water through non-woven geotextiles has been associated to the flow of a fluid through granular media such as bed of gravel, sand or soils. The analysis of the hydraulic gradient across capillaries has been used to represent the flow behavior across synthetic fabrics even though the analysis should be applied only to porous media with a porosity equal to or lower than 0.50. As shown, most of the thick non-woven geotextiles contain void fraction greater than 80% such that a new analytical model has been developped to represent the flow of a fluid through fabrics. This model considered the flow of water across a bundle of fibres uniformly distributed throughout the thickness of the fabric. It was found, using data obtained from 6 different permeameters with hydraulic head ranging from values of 450 to 1.5 mm of water and using 40 samples of non-woven geotextiles, that the flow regime was laminar in all the range of flow conditions encountered.

L'écoulement de l'eau au travers de géotextiles non-tissés a été associé à un écoulement au travers d'un milieu poreux tels que les sols. Bien que l'analyse de la perte de charge au travers d'un tube capillaire ne s'applique qu'à des milieux poreux de porosité plus faible que 0.50, elle a été utilisée pour représenter l'écoulement au travers des membranes synthétique. Cependant tel que démontré, les géotextiles non-tissés possèdent une porosité plus grande que 80% de telle sorte qu'un nouveau modèle analytique a été développé pour représenter l'écoulement de l'eau au travers un faisceau de fibres uniformément distribuées dans le géotextile. Les résultats obtenus à l'aide de 6 perméamètres, dont les gradients hydrauliques variaient de 450 à 1.5 mm, et utilisant 40 échantillons de géotextiles non-tissés ont permis de determiner que le régime d'écoulement sous ces conditions est laminaire.

INTRODUCTION

To compare different soils with another, the Darcy's law is used establishing that the permeability coefficient is a function of the type of granular material and its particle size for flow of water at 20°C. The quantity of water flowing through a unit area per unit of time of a layer of soil varies directly with the hydraulic gradient and inversely with the soil's layer thickness (8). This relationship can be applied only when the flow through a porous medium is in laminar regime as it is the case for water travelling through soils. The finer the particle size of a soil, the greater is the resistance to flow such that the permeability coefficient is a useful constant to compare kind of granular material with another.

In recent years, synthetic fabrics have been extensively used in geotechnical work. They offer a way to develop drains with high discharge capacity and good resistance to clogging to protect open-graded drainage aggregates from clogging by adjacent fine soil. Typically many products are non-woven fabrics consisting of a mass of fibres intertangled together. The unloaded thickness of a particular fabric is simply a reflection of the degree of fibre's entanglement that is achieved in manufacturing the fabric (7).

One should not be suprised to learn that even the densest, most compact, needle-punched products contain 75% or more void space in their structure. Usually under no static pressure, the porosity of non-woven geotextiles except spunbonded fabrics, is higher than 90%. More appreciable is the fact that even under a load of 800 kPa, the average porosity of a Polyester needle-punched fabric of 400 g/m^2 is approximately 70% (15).

These very large values of porosity cannot be compared to the porosity of soils that are know to be lower than 50%. One must then be careful in applying to geotextile the flow analysis used for granular materials.

Recently many experimental results have been interpreted to establish the flow regime existing in geotextiles' structure under a wide range of hydraulic heads(5, 12). The growing interest in correlating the hydraulic gradient with the flow parameters of test apparatus emerged from the difficulty of comparing results obtained from different laboratories as well as from an effort to normalize a permeability test method. Until now engineers have been applying the same analytical model for flow through soils and geotextiles, and many permeameters were designed and used (1,14).

In this paper, it will be shown that the approach used until now does not represent the mechanism encountered when water is flowing through non-woven geotextiles. A new approach for the fluid flow through geotextiles is presented and experimental data gathered to support the relationship between the hydraulic gradient and the established flow of a fluid across a bundle of fibres.

FLOW THROUGH SOILS

The flow of a fluid through a porous medium has been extensively studied using the model of flow through capillaries of complex shapes and lengths. The Hagen-Poiseuille formula representing flow through a tube is well known (5,3)

$$V_o = \Delta P \, R_h^2 \, / \, 2 \, \mu L' \qquad (1)$$

where V_o is the mean velocity of the fluid in the tube, ΔP is the pressure drop along a tube lenght L', R_h is the hydraulic radius and μ is the fluid's viscosity.

For a granular medium constituted of soil particles, the mean pore diameter is defined using the equivalent diameter, D_e , related to the hydraulic radius defined as the ratio of the cross section available to flow to the wetted perimeter

$$D_e = 4 \, R_h \qquad (2)$$

Using the porosity, n , and the specific surface, a_v , (the total particle surface to the volume of the particles) equation (2) becomes

$$D_e = n \, / \, a_v \, (1-n) \qquad (3)$$

Supposing that the granular medium is constituted of spherical particles of diameter D_s , then the equivalent diameter can be expressed in term of particle's diameter

$$D_e = \frac{2}{3} D_s \, n \, / \, (1-n) \qquad (4)$$

Because the average velocity in the interstices is not of general interest, the superficial velocity is defined

$$V = V_o \, n \qquad (5)$$

Substituting equations (5) and (4) into the Poiseuille's law, one obtains

$$V = \frac{\Delta \, P \, D_s^2 \, n^3}{L' \, 72 \, \mu \, (1-n)^2} \qquad (6)$$

Using the defined friction factor, λ , and the Reynolds number, R_e , for flow in a tube, the following expressions are found

$$\lambda = \frac{g \, \Delta H \, D_p \, n^3}{V^2 \, L \, (1-n)} \qquad (7)$$

$$R_e = \frac{D_p \, V \, \rho}{\mu \, (1-n)} \qquad (8)$$

where D_p is the particle's diamater, L is the thickness of the soil's layer and ΔH is the hydraulic gradient in height of fluid.

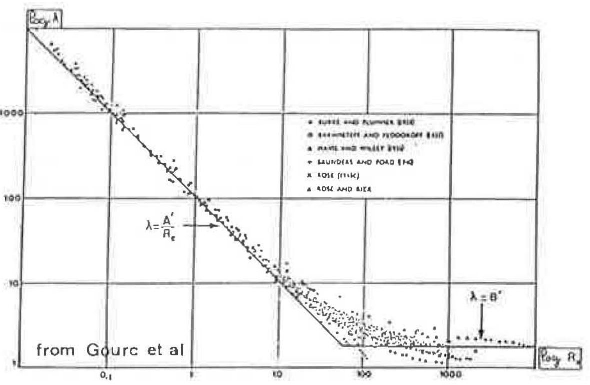

Fig. 1 Pressure drop coefficient for uniform granular media.

Data obtained by several researchers (5,13) for flow through porous media are presented on Figure 1. It can be observed that for $R_e < 10$, a line of slope -1 is obtained resulting in the following expression

$$\lambda = A' \, / \, R_e \qquad (9)$$

This region correspond to a laminar flow regime and can be expressed by the well known Blake-Kozeny equation. It is very important to stress that this analysis is valid for a porosity less than 0.5 .

For a soil, the region of flow for $R_e < 10$ corresponds to a laminar flow regime and Darcy's law can be applied for flow of water at 20°C

$$\frac{Q}{S} = K \, \frac{\Delta H}{L} \qquad (10)$$

where S is the flow area, K the permeability coefficient and Q the fluid flow.

For $R_e > 1000$, the friction factor is no more a function of the Reynolds number and the flow regime is turbulent. Finally a transitional flow regime exists for $10 < R_e < 1000$.

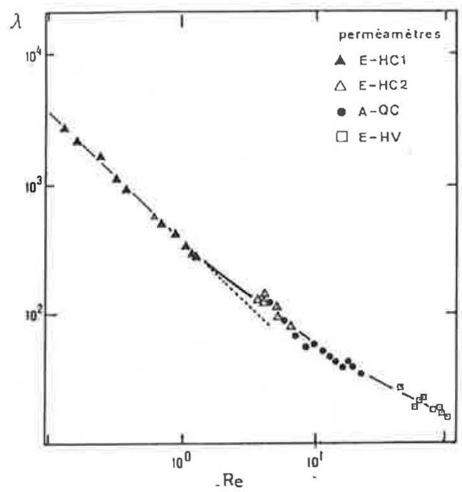

Fig. 2 Pressure drop coefficient for BD geotextile samples (Gourc et al (5))

On Figure 2, the calculated friction factor (5) for samples of Bidim C-34 fabric (BD) and obtained under a range of hydraulic gradients using four different permeameters are plotted versus their Reynolds numbers as defined by equations (7) and (8). It can be observed that, a curve similar in shape to the curve representing the flow across a layer of uniform granular media, is obtained with the difference that the critical Reynolds' number at which Darcy's law cannot be applied is approximately 1.

This would tend to indicate that the transitional flow regime is starting at lower flow rate in a non-woven geotextile than for a granular medium. This cannot be the case as the porosity of this non-woven geotextile is 93% compared to granular media with porosity values less than 50%.

FLOW THROUGH NON-WOVEN GEOTEXTILES

As shown on Figure 3 and as already discussed in a earlier paper (10), thick non-woven fabrics are constituted of a large number of fibres randomly distributed. From the analysis of obtained internal structures of geotextiles, the analytical model that should represent the flow of fluid through non-woven fabrics must be that of flow around a bundle of cylinders, as shown schematically on Figure 4.

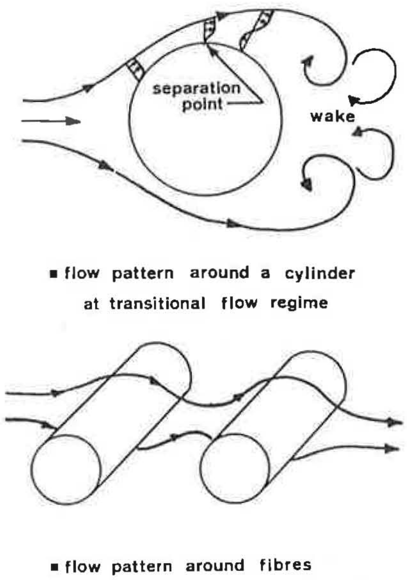

Fig.4 Schematic flow pattern around a cylinder and around two fibres

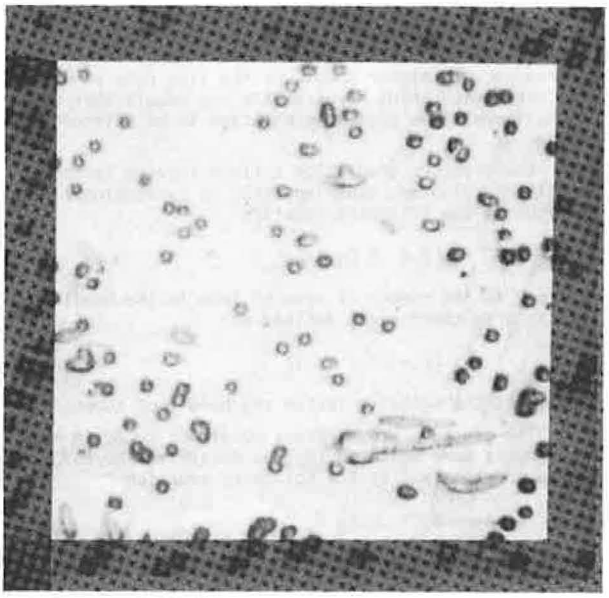

Fig. 3 Cross section of a needle-punched geotextile

As the fluid is flowing around a fibre, a force, in the direction of flow, is exerted by the fluid on the solid and it is defined as "drag". A form drag is related to the pressure and a wall drag is related to the shear stress.

Even though the development of flow around an immersed cylinder is well known (6), unfortunatly the phenomena causing both wall and form drag in actual fluids are complicated and cannot in general be calculated. They are always determined by experiments (11).

The drag coefficient, C_D', is defined by the following equation

$$F_D = C_D' \, S_p \, K_e \tag{11}$$

where F_D is the drag force, S_p is a characteristic area and K_e is a cinetic energy term. For a cylinder of length "l" and of diameter "d", the characteristic area is taken as the projected area (lxd) and the cinetic energy term as

$$K_e = \frac{1}{2} \rho v_\infty^2 \tag{12}$$

where v_∞ is the velocity in the bulk of the fluid. Substituting these expressions in equation (12), the drag coefficient becomes

$$C_D = F_D / (lxd)(\frac{1}{2} \rho v_\infty^2) \tag{13}$$

From a dimensionless analysis, the drag coefficient is found to be a function of the Reynolds number defined as

$$R_e = \rho \, v_\infty \, d / \mu \tag{14}$$

Many experimental works have been conducted in the past to obtained data to correlate the drag coefficient around a single cylinder to the flow conditions. The curve representing collected data is presented on Fig.5.

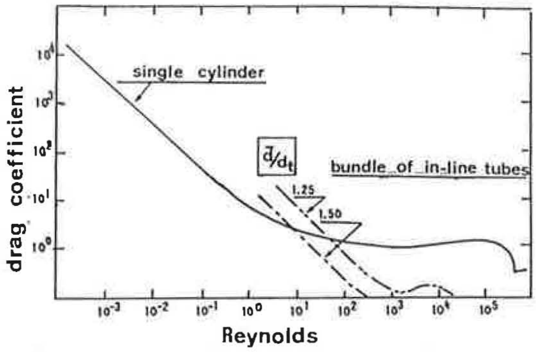

Fig. 5 Drag coefficient around a cylinder and a bundle of tubes.

It can be observed that for low Reynolds' numbers, $R_e < 1$, the data fall on a straight line such that the flow regime is laminar. It is usually called " creeping flow ". As the Reynolds' number is increased, a separation in the boundary layer on the cylinder surface occurs at a point just forward the equatorial plane and a wake, covering the entire rear hemisphere, is formed as schematically shown on Figure 4. A vacuum is then created at the rear of the cylinder resulting in a upward trend of the drag coefficient. As the flow rate is further increased, the separation point moves toward the rear of the body such that finally the wake is dissapearing resulting in a sudden decreased of the drag coefficient.

For the case of a bundle of cylinders or of fibres, the presence of the adjacent cylinders will affect the flow behavior around each cylinder. One can intitutively picture that as the distance between the cylinders is decreased, the higher should be the flow rate at which the separation point appears with the result that the transitional flow regime is expected to be shifted to higher R_e.

The pressure drop which a fluid flowing through a bundle of cylinders experiences(2) is conventionally expressed by the following equation

$$\Delta P = N C_D \rho V_0^2 / 2 \tag{15}$$

where N is the number of rows of tube in the bundle, C_D is the drag coefficient defined as

$$C_D = \Delta P / N \rho V_0^2 \tag{16}$$

and V_0 is the velocity inside the bundle of tubes.

The pressure drops across bundle of tubes in heat exchangers were measured (4) and related to Reynolds' numbers determined by the following equation

$$R_e = \rho V_0 d_t / \mu \tag{17}$$

where d_t is the diameter of the tube.
The empirical curves obtained for in-line tubes' arrangement (2) are presented on Figures 5,7 and 10. As forecast a family of curves exists depending on the ratio of the distance between the tubes to the tube diameter. As the ratio is increased, the influence of the second row of tubes on the preceeding row is less such that the flow is more similar to flow around a single tube. In fact, one can observed on Figure 5, that the critical Reynolds' number at which the laminar flow regime does not exist anymore is greater for flow through a bundle of tubes than for the single cylinder. The smaller the distance between the tube, the greater is the critical Reynolds' number.

Applying the same development to geotextiles and supposing that the fibres arrangement is a serie of rows with square pitch, the following equations can be derived

$$R_e = \rho V_0 d_f / \mu \tag{18}$$

$$C_D = g \Delta H / N V_0^2 \tag{19}$$

where d_f is the fibre's diameter, ΔH is the hydraulic gradient, V_0 is the velocity inside the fabric and N is the the number of rows of fibres. This value can be found from the following equation

$$N = b / (\bar{d} + d_f) \tag{20}$$

where $\bar{d}$ is the mean distance between the fibres and b is the fabric's thickness.

The value of the mean distance between the fibres can be measured using an Image Analyser (10) or can be estimated using the following equations and the curve presented on Figure 6. (9).

$$n = 1 - \frac{m^+}{b \rho_s} \tag{21}$$

$$\nu = 4 (1-n) / \Pi d_f^2 \surd 3 \tag{22}$$

where m^+ is the fabric mass per unit area, ρ_s is the polymer density, ν is the fibres' density per unit area of cross section of fabric.

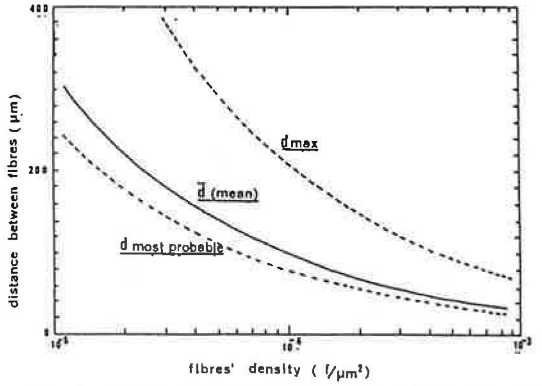

Fig. 6 Distance between fibres as a function of the fibres' density.

Using equations (21) and (22), the number of fibres per unit area of analysed cross section of the geotextile can be calculated. In a following step, the curve representing the mean distance between fibres as a function of the fibres' density is used and the number of rows of fibres can be calculated using equation (20).

EXPERIMENTAL

A) Structure of non-woven fabrics

To confirm that the porosity of thick non-woven geotextiles is greater than 75% and to obtain the structure' parameters of tested geotextiles, twelve non-woven fabrics were analysed using the Image Analyser technique (10). Photographs of cross section of one of these fabrics is shown on Figure 3. As already stated, a cross section of a non-woven fabric should be schematically represented as a porous medium constituted of a large number of fibres randomly distributed. Each dot, representing the cross section of a fibre, is surrounded by void (white area). The experimental testing procedure to obtain picture of cross section of geotextiles has been already discussed in earlier papers (10,14).

The measured structure parameters of the choosen commercial virgin fabrics are discussed. The geotextiles were fabricated with Polyester fibres of diameter equal to 25 µm with a resulting thickness ranging from 2.0 to 7.8 mm. The fibres' density varies appreciably from one fabric to another with results indicating a range of values from 26×10^{-5} to 3.8×10^{-5} fibre/µm^2.

But the most significant parameter for this study is the porosity that was measured for each fabric with values ranging from 80 to 94%. These values are supporting the statement that the Blake-Kozeny equation must not be applied to non-woven geotextiles because of their very high porosity.

The calculation technique using equations (21) and (22) and the curve on Figure 6 was used with a sample of BD fabric to obtain estimated values of the porosity and also of the average distance between the fibres. It was found that the difference between the estimated and the measured porosity was of 1% (92% compare to 91%) and that for the mean distance between fibres was 9% (133 µm compare to 146 µm). This procedure was then accepted and used to calculated the number of rows of fibres for the samples used at Grenoble and at Texel laboratories.

B) Permeability measurement

Experimental work was performed at two laboratories, Ecole Polytechnique de Montréal and Texel Inc., and data published by Gourc et al (5) were used. The data from Gourc et al were obtained with four types of permeameters using samples of BD fabric. In this study two other types of geotextiles were choosen to represent thick non-woven fabrics produced by different manufacturing processes: Texel's fabrics (TE) and Terrafix's fabrics (TR).

A total of twelve samples were analysed with the Image Analyser and permeability measurements through forty-one samples were performed and compared with the data obtained at Grenoble using twenty-two different hydraulic gradients. Also twenty-six fabrics were manufactured on the same machine using identical fibres with the only variable being the mass of fibres per unit area of fabric.

The data obtained from the six permeameters are presented on Figures 7, 8 and 9. The hydrostatic gradients covered a range from 450 to 1.5 mm of water with samples of fabrics' area ranging from 353 to 2.85 cm^2. Also flow through a pile of 15 samples was measured, with varying hydraulic head, in one of the permeameter used in Grenoble (HC-1). These data were choosen to represent a wide range of flow conditions to verify the correlation in a range covering most of the test apparatus used in soil's and producer's laboratories.

For each of the 63 samples, the drag coefficient and the Reynolds' number were calculated. The R_e range from values of 25 to 0.01 with corresponding drag coefficient ranging from values of 0.3 to 624.

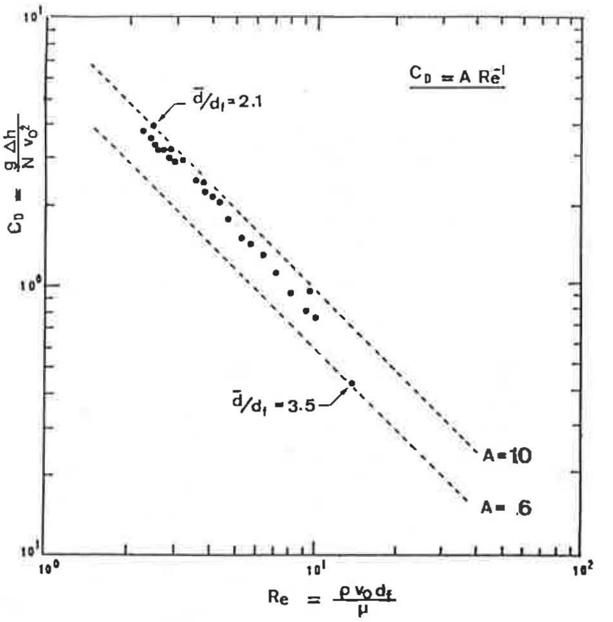

Fig. 7 Drag Coefficient for TE geotextiles

The permeability of the TE samples, varying in mass from a value of 250 g/m^2 to a value of 1450 g/m^2, were measured and the porosity as well as the mean distance between the fibres were estimated. The calculated Reynolds' numbers and the drag coefficients are reported on Figure 7. Because the ratio of the mean distance between the fibres to the fibre's diameter varies from values of 2.1 to 3.5, the data must not fall on a straight line of slope -1. Taking the 250 and 1450 g/m^2 samples as the lower and upper limits of the correlation between the drag coefficient and the Reynolds' number, the value of A in the following expression was found to be ranging from 10 to 6

$$C_D = A / R_e \quad (23)$$

This set of data indicates that as the ratio value, $\bar{d}/d_f$, becomes larger, the flow around each fibre is less disturbed by the presence of the surrounding fibres and consequently the experimental curve fall lower as shown on Figures 8 and 10.

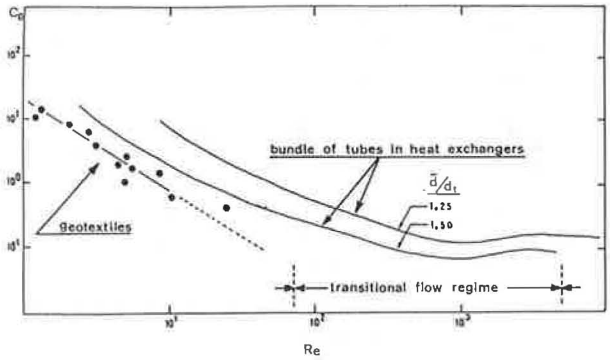

Fig. 8 Drag coefficient for BD,TE and TR geotextiles.

The data obtained for 12 different fabrics using a second permeameter are presented on Figure 8 and compared with two curves representing the pressure drop across a bundle of in-line tubes in heat exchangers. The upper curve was obtained with a ratio $\bar{d}/d_f$ of 1.25 while the lower curve is for a ratio of 1.50. The experimental values for geotextiles are lower suggesting that the ratio for geotextiles should be greater than a value of 1.5. This is the case for most of the analysed fabrics with a characteristic ratio value of 3.

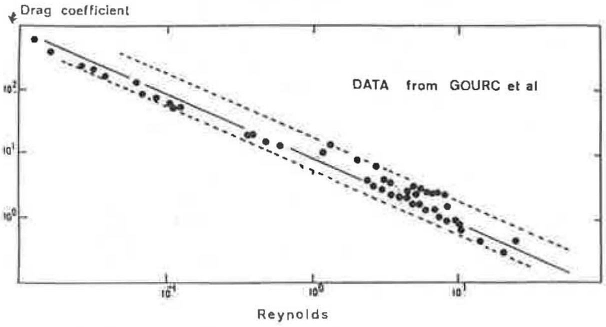

Fig.9 Drag coefficient for BD geotextiles

The data published by Gourc et al are presented on Figure 9. In their work, they have tested BD samples using four permeameters. The ratio of $\bar{d}/d_f$ was estimated at 2.96 and the experimental drag curve should be a straight line of slope -1 with a value of A close to 10. This is the case for most of the data except for the case where the permeability of the pile of samples was measured. The drag coefficient estimated are lower than expected. This can be a result of the overestimation of the real thickness of the pile that was obtained by multiplying by 15 the thickness of the unloaded sample.

As shown on Figure 10, the experimental values can be approximated by a straight line parallel to the curves obtained for bundle of tubes in heat exchangers. The flow rate at which the separation point appears on the fibres are higher from the presence of the other fibres such that a wake do not appear in the rear of the fibre unless the Reynolds' number is very high. Also the greater is the ratio $\bar{d}/d_f$ the greater is the distance between the fibres and the sooner will the transitional flow regime appeared.

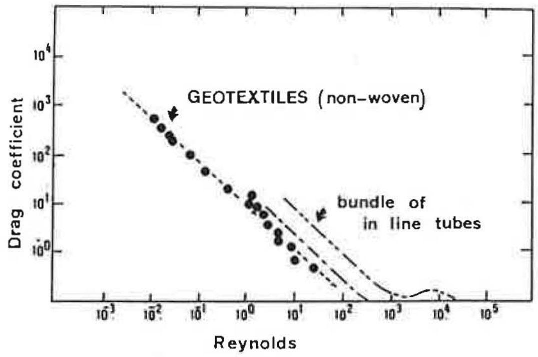

Fig. 10 Drag coefficient for non-woven geotextiles and bundles of in-line tubes.

C) Permeability correlation

From this study, it was confirmed that a relationship exists between the drag coefficient and the Reynolds number supporting the proposed flow model, flow through a bundle of fibres. Even more, from these correlations an expression for the permeability coefficient can be obtained

$$K = \frac{d_f \, (d_f + \bar{d}) \, n \rho \, g}{A} \qquad (24)$$

The permeability coefficient is a function of the geotextile's structure and the fluid's properties. For water at 20°C, both the values of the density and the viscosity are equal to one and the permeability is only a function of the fabric structure. As an exemple, the estimated permeability of a TE sample, using equation (24), is 0.00258 m/s compared to a measured value of 0.00240 m/s.

This expression is also very useful in predicting the permeability coefficient under compression. Under a load, the porosity as well as the distance between the fibres will decrease resulting in a decrease in the value of the permeability coefficient. This is presently being investigated more thoroughly.

CONCLUSION

Permeability measurements through geotextiles, coupled to the analysis of their structure, were used to support the model of flow across a bundle of fibres. It was found that, the data obtained from six different designed test apparatus and using more than 60 samples of fabric can be best represented by a correlation analog to flow across a bundles of tubes in heat exchangers. The resulting empirical correlation is $C_D = A / R_e$ with values of A ranging from 6 to 10 depending on the ratio $\bar{d}/d_f$. For the case of most of the studied geotextiles, the mean distance between the fibres is three times the fibre's diameter. For Reynolds' number as high as 25, the flow regime is still laminar even though hydraulic gradients as high as 450 mm of water were used. This should be keep in mind in determining standard permeability test method.

Secondly, it was established that the estimated values of the porosity and the mean distance between the fibres of thick non-woven fabrics check within less than 10% of the measured values using the Image Analyser. The properties of fabrics can then be easily estimated by engineers using only the known manufacturing data.

Finally the permeability coefficient for flow of water at 20°C through geotextiles was found to be a function of the fabric's structure forecasting their behavior under compression. As a pressure will be applied on fabrics, their permeability coefficient will be affected, decreasing with greater loads. The change of structure and the flow behavior of non-woven geotextiles under compression is presently under investigation.

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