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Structural Permeability Law of Geotextiles

Loi structurale de perméabilité pour les géotextiles

The permittivity test is often used for identification and quality control of geotextiles. Many geotextiles are thin and very permeable. Consequently the velocity of flow during the test is very high and Darcy's formula is not applicable, as it is shown using general laws governing flow through porous media. However, a theoretical analysis shows that an approximate value of permittivity can be obtained in the test if the Reynolds'number is kept smaller than a certain value.

The theoretical analysis is used to interpret the results of an experimental study carried out using four permeameters (one with air and three with water). It is confirmed theoretically and experimentally, that air and water lead to consistent values of permittivity and it is concluded that the falling head water permeameter is not satisfactory.

L'essai de permittivité est fréquemment utilisé pour identifier ou contrôler les géotextiles. Mais de nombreux géotextiles présentent une résistance à l'écoulement si faible que les vitesses du fluide dans l'essai sont très fortes. Dans ces conditions, comme nous le montrons à partir des lois générales d'écoulement dans les milieux poreux, la "loi" de Darcy n'est pas vérifiée. On peut cependant garantir une certaine précision sur la valeur de permittivité mesurée à partir du critère proposé qui correspond à une limitation systématique du nombre de Reynolds du fluide en écoulement dans le perméamètre.

L'étude théorique s'appuie sur un travail expérimental comparatif sur quatre perméamètres, l'un utilisant l'air comme fluide et les trois autres l'eau. Cette étude permet de confirmer l'équivalence des résultats obtenus avec les deux fluides et permet aussi de rejeter l'utilisation du perméamètre à eau à charge variable, en raison des erreurs introduites sur la valeur de permittivité.

I. OBJECTIF :

Le test de permittivité sur géotextile non comprimé est un de ceux les plus couramment effectués sur ces produits. Il présente en effet un grand intérêt comme essai de contrôle ou d'identification car la valeur de la perte de charge du fluide s'écoulant normalement au plan de la nappe est très sensible aux variations de structure du géotextile.

A l'instigation du Comité Français des Géotextiles (1), nous avons entrepris une étude sur l'essai de permittivité : il s'agit de définir la relation entre le débit unitaire $V = Q/S$ de fluide (Q débit fluide à la pression atmosphérique et à 20°C, S section du milieu poreux, normalement à l'écoulement) et la perte de charge ΔH (diminution de potentiel à la traversée d'une épaisseur L de milieu poreux, exprimée en hauteur de fluide à la pression atmosphérique).

Il est couramment admis que la loi est linéaire ("loi expérimentale" de Darcy), pour les écoulements à faible nombre de Reynolds (2) :

$V = Q/S = (K/L).\Delta H$ K/L permittivité   (1)

ou $V = Q/S = K.i$ K perméabilité au fluide   (2)
$i = \Delta H/L$ gradient de décharge

Or il apparaît que les géotextiles peuvent présenter des épaisseurs et des porosités très différentes de l'un à l'autre et par conséquent des permittivités très différentes. Comme nous le montrerons ci-dessous, il sera alors difficile de définir un perméamètre à la fois simple et convenable (c.à.d. permettant de vérifier la "loi" de Darcy) pour l'ensemble des géotextiles.

L'étude présentée comprend deux parties, une partie théorique où l'on adapte aux géotextiles la théorie des écoulements en milieu poreux et une partie expérimentale où l'on a comparé les résultats obtenus pour deux géotextiles non tissés avec quatre perméamètres différents.

II. LOI GENERALE D'ECOULEMENT EN MILIEU POREUX :

A. ECOULEMENT DANS UN TUBE :

Pour un tube droit à section circulaire (diamètre d_p) de longueur L_e et un fluide de débit unitaire V_p (viscosité cinématique ν), on a $i_e = \Delta H/L_e$ et on trouve une relation unique entre les paramètres adimensionnels λ^* et R_e^* (3) : (fig. 1)

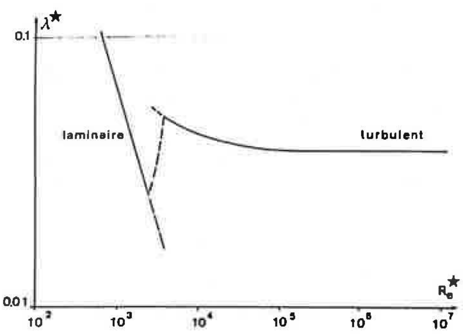

fig. 1 : Ecoulement dans un tube

Even under a very large compression level, the porosity values are higher than the porosity of soils. Also it can be observed that the relative decrease of porosity for the non-woven needle-punched fabrics is lower than the thickness's decrease. This is accordance with Kolb (2) that calculated, from a theoretical analysis, the minimum porosity of non-woven fabrics (to be egual to 45 %).

Because of the importance to understand the hydraulic behavior of geotextiles of different structures under compression, a study was performed to measure permeabilities using two permeameters designed at IRIGM (Grenoble) : normal and lateral permeabilities, K_N and K_P, under pressures ranging from 0 to 2000 kPa. These results are presented in this paper and are completed by a morphologic analysis of the compressed fabrics using the Image Analyser technique developped at Ecole Polytechnique of Montréal. The aim is to develop a correlation between the permeability behavior of fabrics under compression and characteristic structural parameters.

I. PERMEABILITY BEHAVIOR UNDER COMPRESSION

A. TEST APPARATUS

Normal permeability

A permeameter designed to measure the normal permeability, K_N, is shematicaly presented on figure 2. It is constituted of a large number of accessories and measuring instruments. The essential item is an inox cylinder containing a pile of geotextile's samples sanwdwiched between two distributors. A piston is free to move inside the cylinder to compress the installed samples to the compression level.

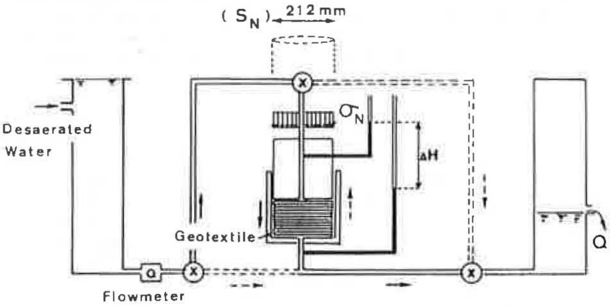

Fig. 2 : Permeameter (N 212) to measure normal permeability of geotextiles.

City water is desaerated in a vacuum tank and then stored in a second tank connected to the cylinder. Rotameters and control valves are installed to regulate the fluid's flow (permanent regime) while manometers are recording the head loss (ΔH) through the samples such that the head loss of the apparatus are not taken in account. Instruments are installed to measure static stress applied on samples (σ_N), the thickness of the pile of N samples (Nb), the water temperature (θ) and the constant fluid flow rate (Q_θ). Each sample of 212 mm in diameter are installed in the cylinder (S_N= 35300 mm^2) to a maximum height of 150 mm. We believe that the total area offer to flow, N S_N, is very representative.

A mechanical set up enables to apply pressure on the samples in a range of values from 0 to 2000 kPa and the flow of water through the samples, Q/S_N, are fixed to values small enough to insure flow conditions at which Darcy's law can be applied (3). Under these fixed water flow rates, the Darcy's velocity can be defined as $V_D = Q/S$ and the permeability coefficient can be calculated from the following equation

$$Q/S_N = K_N . \Delta H/Nb \qquad (2)$$

where Q is the water flow rate at 20°C and can be calculated from the measured flow rate, Q_θ, at θ°C.

Permeability in the plane

A second permeameter was used to measure the permeability within the plane of the fabric (see figure 3). This item is replacing the cylinder in the already described system. The test is performed with a pile of N squared samples, 200 mm x 200 mm, such that two measurements can be performed on the samples in the warp and fill directions (L_1 and L_2). The permeability coefficient, K_P, can be found from the following expression

$$Q/S_P = K_P . \Delta H/L_1 \qquad (3)$$

where S_P = Nb.L_2

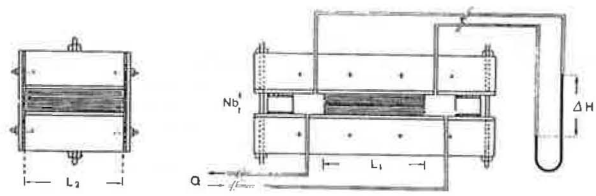

Fig. 3 : Permeameter to measure permeability in the plane of geotextiles.

B. THEORY

Capillary tubings

In this approach, an analysis identical to the well known analysis of granular media (1) will be used for the flow through geotextiles. The velocity, V_P, inside a straight capillary tube of diameter, d, and of length, L, of a fluid when under laminar flow regime (small Reynolds'number) can be expressed as

$$V_P = 1/32.g/\nu.d^2 i \qquad (4)$$

where $i = \Delta H/L$ is the hydraulic gradient and ν is the cinematic viscosity.

The flow of a fluid through a granular medium is analog through flow inside capillary tubings as first pointed out by Kozeny (4). The well known Poiseuille's law, equation (4), was then applied to geotextile even through the cross section as well as the diameter of the intersticial capillaries are not constant.

If L is defined as the distance between two, normal sections, S, of a fabric relatively to the direction of the fluid flow, then the average effective length of a pore size between the fibres should be greater than the distance between these two sections ($L_e > L$). Consequently the effective hydraulic gradient must be defined as

$$i_e = \Delta H/L_e \qquad (5)$$

Following Poiseuille's law but substituting for the effective length, equation (4) becomes

$$V_P = 1/32.g/\nu.d^2.\Delta H/L_e \qquad (6)$$

Unfortunatly the cross section of intersticial pores is not circular such that a correcting factor, r, can be used and an average diameter, $\bar{d}_P$, must be utilized

$$V_P = r/32.g/\nu.(\bar{d}_P)^2 \Delta H/L_e \qquad (7)$$

Because of the difficulty to measure the mean diameter of pores, Kozeny substituted that value by the hydraulic diameter, $\bar{d}_P = d_H$, for the entire granular medium.

$$d_H = 4/A_S . n/(1-n) \qquad (8)$$

where A_S is the specific area defined as

$$A_S = 4/D \text{ for a uni fibre fabric} \qquad (9)$$

for a multi fibres fabric $$A_s = 4\ \frac{\sum_i \frac{P_i}{\rho_s^i\, D_i}}{\sum_i \frac{P_i}{\rho_s^i}} = \frac{4}{D_e} \qquad (10)$$

where D_e is the equivalent diameter, P_i is the percent weight of fibres of diameter D_i and density ρ_s^i and $d_H = D_e.n/1-n$.

Then the velocity of the fluid in a direction parallel to the mean flow path between two fabric sections separate by a distance L is

$$V_n = V_p.\ L/L_e \qquad (11)$$

and $V_n = r/32.g/\nu.(\bar{d}_p)^2.(L/L_e)^2.\Delta H/L$ (12)

where the tortuosity is defined as $t = (L/L_e)^2$

Knowing that $V_D = Q/S = n.\ V_n$ (Darcy Velocity)

then equation (12) can be expressed as

$$Q/S = n.rt/32.g/\nu(\bar{d}p)^2.i \qquad (13)$$

Using Darcy's law, the permeability coefficent can be expressed as

$$K = n.rt/32.g/\nu\ (\bar{d}p)^2 \qquad (14)$$

Following Carman suggestion (4), rt = 2/5 for granular media

$$K = g/\nu.n/80.(\bar{d}p)^2 \qquad (15)$$

or $K = g/\nu.D_e^2/80.n^3/(1-n)^2$ (figure 4) (16)

More, Lord (5) showed, experimentally, that the expression representing flow of fluid through compressed plugs of fibres that had porosities $n > 0,75$, is

$$K = \frac{g}{\nu} \cdot \frac{D_e^2}{17,72} \cdot \frac{n^5}{(1-n)^{1,32}}$$

Single cylinder

Another approach to analyse flow of fluid through synthetic fabric consists in studying the flow around a single cylinder or fibre. This can be applied only if the mean distance between the fibres is large enough such that the fibres are not influencing the flow around each fibre. In another study, Rollin and al (6) have considered the case of bundle of cylinders.

For a flat cross section of geotextile S_N of a mass per unit area, m_s, the total length of a fibre, l, of diameter D and polymer density, ρ_s, is

$$l = m_s.S_N/\rho_s.4/\pi D^2 \qquad (18)$$

For the fibres all enligned in the plane of the fabric and for flow of a fluid normal to that plane

$$V_D = Q/S_N$$

Using the drag coefficient, C_D, around a single cylinder, the drag force, F_D, can be expressed as

$$F_D = C_D.\rho_w/2.(V_D)^2.(l.D) \qquad (19)$$

Knowing that this drag force can be expressed as

$$F_D = \rho_w.g.\Delta H\ S_N \qquad (20)$$

The following expression for the normal permeability can be found

$$K_N = \pi/2.\rho_s.g/m_s\ .\ b.D/C_D V_D \qquad (21)$$

or $$K_N = \frac{g}{\nu} \cdot \frac{\pi}{2} \cdot \frac{D^2}{1-n} \cdot \frac{1}{C_D R_e^g} \qquad (22)$$

where $R_e^g = V_D.D/\nu$

Obtained data are presented on figure 4 for flow regime equivalent to $R_e^g < 1$ $(C_D(R_e^g) = 10)$. It can be observed that the determined permeability coefficients using the capillary tubings and single fibre are in agreement only for the highest porosity values.

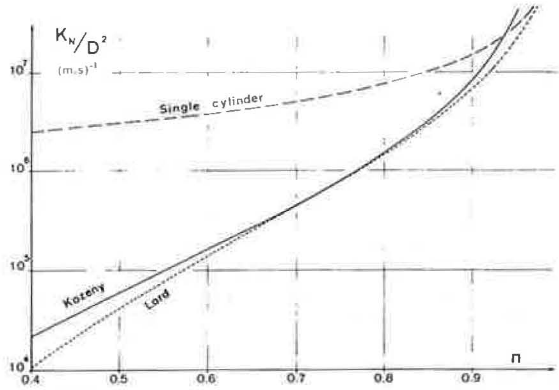

Fig. 4 : Proposed laws of permeability of geotextiles.

C. EXPERIMENTAL

Many different structured geotextiles have been analysed and their normal and lateral permeabilities measured : needle-punched continuous polyester fibres (BD = Bidim ; SDC = Sodoca), needle-punched short polyester fibres (SM : Sommer ; TXL = Texel) and spunbonded fabrics (TP = Typar ; TER = Terram ; LTR = Lutravil) and also woven fabrics (tx = TRI X ; ts = ts26) and multilayers. The mass per unit area of each fabric can be found from the utilized trade name as for example TP = 270 is a Typar product of 270 g/m².

The obtained results presented on figures 5 and 6 are compared with Kozeny's analysis expressed as

$$K/D_e^2 = \frac{1}{80} \cdot \frac{g}{\nu} \cdot \frac{n^3}{(1-n)^2} \qquad (23)$$

to delete the fibre's diameter influence.

Fibre's diameter :

On figure 5 it can be observe that the permeability coefficient varies as a function of D_e^2 for needle-punched geotextiles of equivalent mass per unit area but using different fibre's diameters.

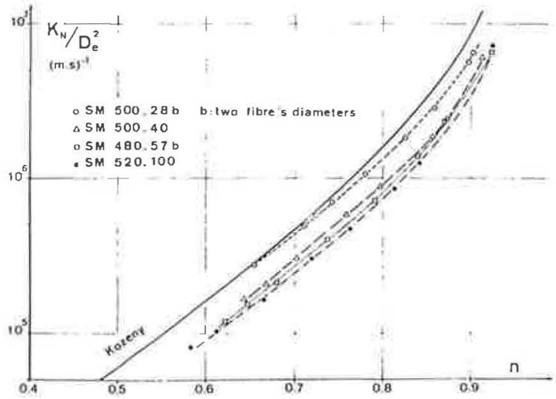

Fig. 5 : Influence of fibres diameter on geotextiles permeability.

Fibre's structure :

Also it can be observed on figure 6 that fabrics with identical structure followed the same analytical model for identical porosity. Needle-punched fabrics permeability measurements are closed to the predicted curve from Kozeny analysis while the woven fabrics are less permeable and the spunbonded more permeable (approximately 2,5 greater than for needle-punched fabrics) for fixed porosity and diameter.

The difference between the spunbonded and the needle-punched fabrics can be explained from the analysis of their structures as already pictured by Rollin et al (7). In fact most of the fibres of spunbonded product are gathered together by group of two or three fibres such that the equivalent diameter D_e must be greater than the used fibre's diameter (photo 1).

Finally it can be observed, from the presented data, that the mass for unit area (refer to TXL-1500 and BD-280) and the fibre's polymer (refer to BD and SDC fabrics) do not influenced the proposed analytical models.

The analysis of needle-punched fabrics manufacture with varying the needle's penetration and also the speed of the machine indicated a change in the thickness and also of the porosity but the measured permeabilites of theses fabrics can be correlated using the same proposed models (1).

Anisotropy :

To learn about the isotropy of fabrics, one should compare on figures 7 and 8 the measured normal and in the plane permeabilities under compression. It can be observed that the permeability in the plane coefficients are greater than the normal permeability coefficients even under large compression levels. On the other hand, the lateral permeability coefficients are decreasing faster with pressure than the normal coefficients indicating an inverse anisotropy when the compression level is increasing.

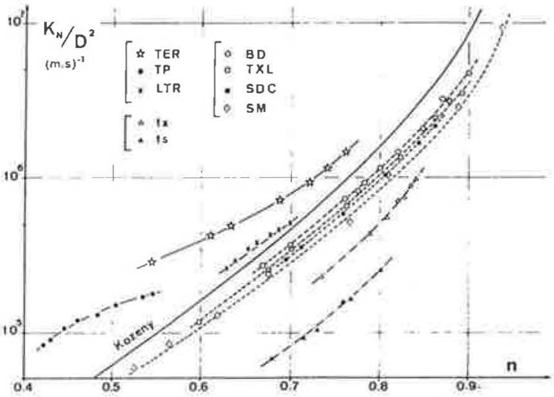

Fig. 6 : Permeability variations with the porosity and the structures of the geotextile

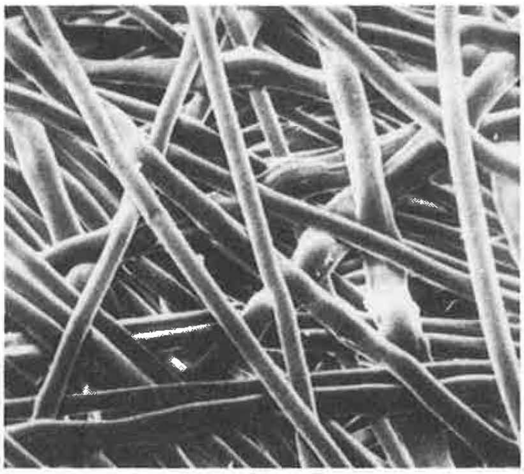

Photo 1 : Macro-photo of a TP270 sample (I.T.F.)

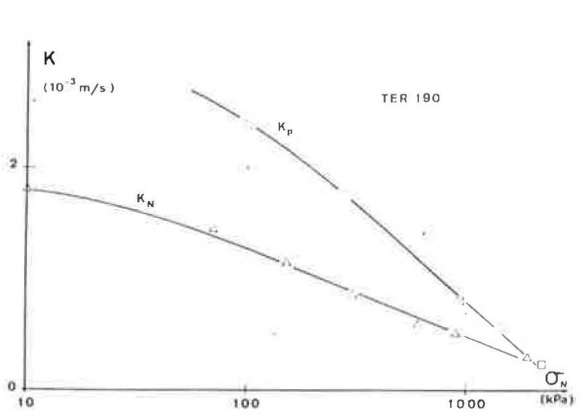

Fig. 7 : Anisotropy of permeability (spunbonded nonwoven TER 190).

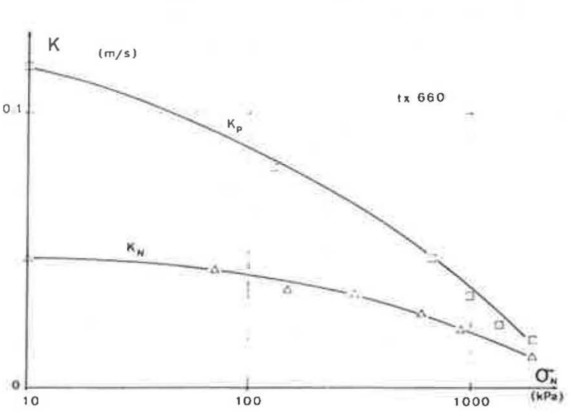

Fig. 8 : Anisotropy of permeability (woven tx 660).

Multilayer's fabric : (fig. 9 and 10) :

A study of the influence on the multilayers' fabrics was done by comparing permeability measurements on individual layer and also on the composite fabric. Comparing results obtained on individual GSM-700 draining layer, on GSM 700 with one filtering layer GSM 300 and also of a fabric constituted of a GSM-700 layer sandwished in between two GSM-300 layers it was found that under manufacturing process each layer's structure is altered by the needle-punching action producing the multi layers's fabric. The correlations to use, if each layer is not altered, are :

transmittivity $K_p\ (\sum_{1}^{3} b_i) = \sum_{1}^{3} (K_p^i\ b_i)$ (24)

permittivity $1/(K_N/\sum_{1}^{3} b_i) = \sum_{1}^{3} (1/K_N/b_i)$ (25)

The result obtained by adding layers is satisfactory for the permittivity but wrong for predicting transmissivity.

The permittivity of the multilayers'fabric is a function of the layers with less permittivity but the transmittivity of the fabric is controled by the layers with greater values. These latest layers are more affected by the needle-punched action of getting together the layers.

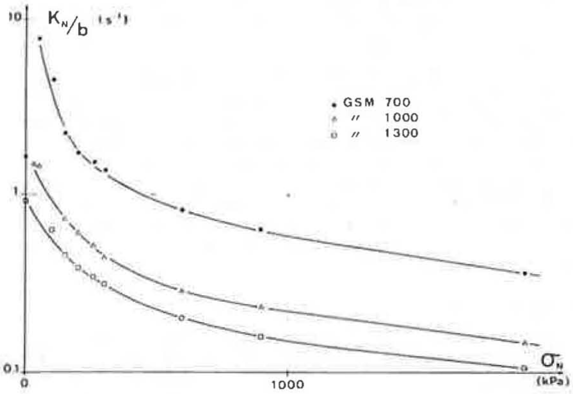

Fig. 9 : Permittivity of multilayer geotextiles under compression

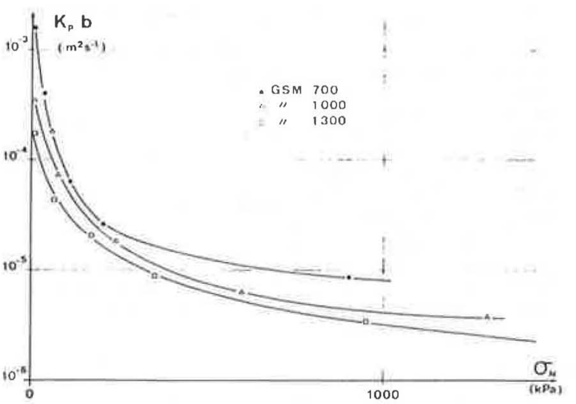

Fig. 10 : Transmissivity of multilayer geotextiles under compression

Summary

The measured normal and lateral permeabilities of geotextiles under compression are of interest to engineers that need to estimate their permeability behavior when installed under a civil engineering work. The permittivity, K_N/b, will vary only slightly with pressure compare to a greater decrease in the transmissivity, $K_p.b$. But it should be keep in mind that the presence of soil particles are surely influencing this behavior in actual applications.

A second interest is to learn about geotextiles' structure under compression and so to learn about their filtration behavior. Using the capillary's tubings analysis, an average pore diameter can be estimated (15) by the following expression

$$\overline{d_p^*} = \sqrt{\nu/g.80/n.K} \qquad (26)$$

In a following step, the morphologic analysis of the fabrics was performed and the measured mean distance between fibres compared to estimated mean pore diameter calculated from permeability coefficients using equation (26).

II. STRUCTURE ANALYSIS

A. IMPREGNATION TECHNIQUE

In order to analyse the structure of choosen geotextiles, each sample must be encapsulated under compression in a resin block. The technique to encapsulate fabric's sample under atmospheric condition was developped by Masounave et al (8) and has already been used extensively. The encapsulation of a sample is more complicated such that a new apparatus was designed at E.P.M.

A sample, impregnated with a very fluid resin, is inserted into a Teflon coated cylinder. The bottom of cylinder and of the piston head are designed to insure evacuation of excess resin as the sample is compressed. A mechanical system insure to lock in place the piston during the cooling period and the resin's recipe is defined to insure transparency of the resin submitted to large static pressures.

Each sample was encapsulated and then analysed with an Image Analyser. The fibre's diameter, the porosity, the thickness and the histogram of the distance between fibres were measured under pressures varying from 0 to 1000 kPa

B. CHOICE OF SAMPLES

For each geotextile, six samples were choosen to be impregnated. As shown on figure 11 the mass per unit area of needle-punched fabrics obtained from 100 samples of 100 cm^3 is varying from a sample to another. In fact the variances of histograms were found to be so large that before choosing the samples to be impregnated the mass per unit area, m_s, histograms were determined. Samples

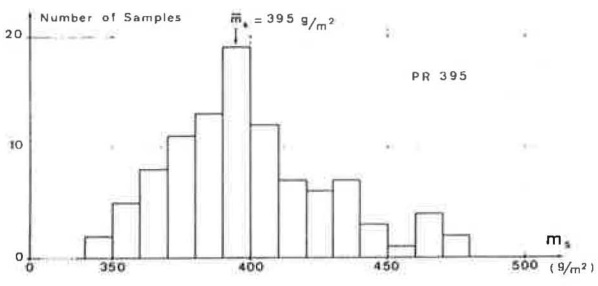

Fig. 11 : Choice of samples to structure analysis.

with identical mass per unit area and corresponding to the mean value were then choosen to insure satisfaction comparison of structure.

The analysis of spunbonded fabrics was achieved by encapsulating a pile of samples to overcome the small thickness of each sample. The analysis of a pile of samples in a manner similar to thick needle-punched non woven fabrics. This is a new technique that will permit to analyse their fabrics and perhaps defined structural parameters responsible for their hydraulic behavior.

C. STRUCTURAL PARAMETERS

For each encapsulated sample under compression the thickness, the porosity and the mean distance between the fibres were measured. As an example, the histograms of the distance between fibres of sample of PR 395 fabric are presented on figure 12. The mean distance between the fibres is greatly affected by the compression level varying from a value of 140 µm at 25 kPa to a value of 38 µm at 800 kPa. As shown on the pore histograms, large holes in the structure are being filled with fibres as the pressure is increased such that smaller and smaller holes are created. This is very important because it points out that under compression the filtration behavior must be different (clogging level, particle size retention...).

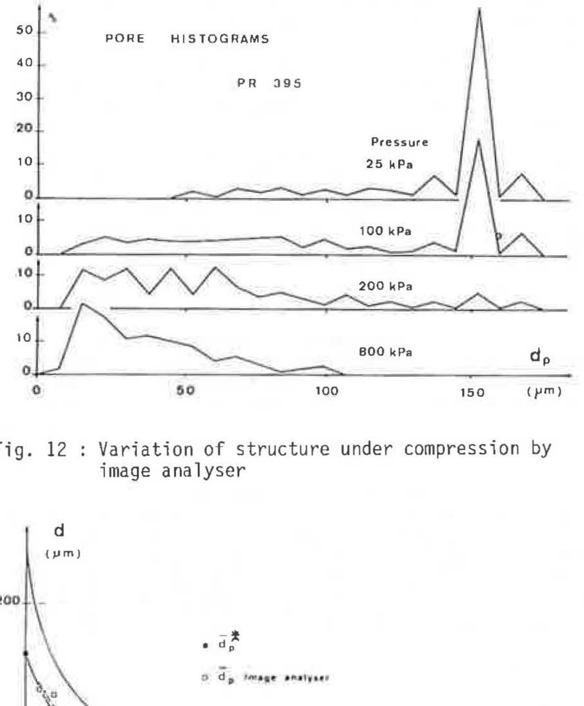

Fig. 12 : Variation of structure under compression by image analyser

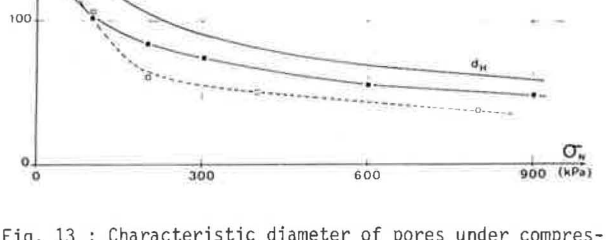

Fig. 13 : Characteristic diameter of pores under compression.

On the other hand the measured porosity of the same samples is equal to 86 % under 25 kPa and 72 % under 800 kPa. This is supporting the permeability measurements because even under large static pressures the porosity of needle-punched fabrics is very large such that under these conditions the permeability is not expected to vary significantly.

As shown on figure 13, estimated mean pore diameter by permeability method, $\bar{d}_p^*$ using equation (26) are compared with the calculated hydraulic diameter and the measured mean distance between the fibres. The three curves are similar in shape indicating a possible correlation between these three parameters. Even though the actual calculated and measured values are different at higher compression levels, a study is presently under way to determine that correlation.

III. CONCLUSION

The analysis of structural parameters of geotextiles under compression coupled to normal and lateral permeabilities' measurements under identical static pressure supported the correlation between the level of compression and the decrease in the permeability coefficients, K_N and K_p, and the porosity of the geotextiles.

The relationship is very important because it enable to estimate the permittivity and transmissivity of fabric under compression by using only measured thickness and mass per unit area.

Finally it was found that, even though the permeability behavior of non-woven geotextiles are not greatly influenced by the compression level, the filtration behavior is expected to be greatly affected. The level of clogging and the soil retention are related to the size of the openings in a geotextile that are found to decrease by approximately three times under pressure varying from 0 to 800 kPa. In fact the structure of needle-punched fabrics is found to be altered in a range of pressure < 200 kPa.

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