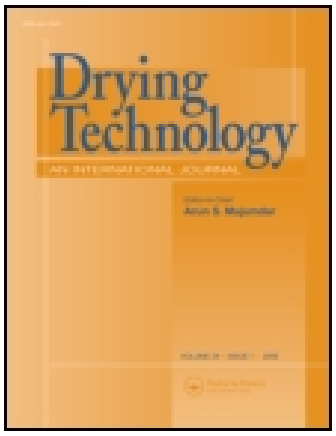

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INVESTIGATION OF THE TRANSVERSE PERMEABILITY OF SATURATED PAPER SHEETS

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ABSTRACT

Papermaking process consists in a succession of unit operations having for main objective the expression of water out of the wet fiber pad. The three main stages are successively, the forming section, the press section and finally the drying section. Pressing combines consolidation of the fiber network (compressibility) and expression of water (permeability). Only permeability properties are on the scope of this paper. This work is dedicated to the description of a new device: the Paper Transversal Permeameter (PTP). This apparatus allows permeability determination of strained wet sheet submitted to both mechanical and hydrostatic pressures. Hydrostatic pressure is applied onto the sample maintained at a strain level; the flow of water through the sheet is then measured. Under static conditions and laminar flow, it is therefore possible to determine the Darcian permeability. Then, results obtained on different samples with the PTP are discussed.

Key Words: Compressible; Experimental; Fibrous network; Liquid flow; Porous material

INTRODUCTION

The permeability evaluation of strained saturated paper sheet is the main goal of this study. This work was motivated by limits encountered during pressing, one of the unit operations in papermaking that consists in removing water out of the wet web while consolidating the fibrous network. Indeed, limits (shadow marking or delamination of the structure) appear when machine speed and temperature in press section are increased in order to increase production.

The knowledge of permeability in saturated web is important to predict the efficiency of pressing. This paper is dedicated to the description of the apparatus designed to measure transverse permeability in strained paper.

Darcy's Law

Whereas the flow through a porous medium is characterized, at the microscopic level, by the Navier-Stokes equations, Darcy's law describes the flow at the macroscopic level. Darcy's law is valid for low Reynolds number, creeping flow and at steady state conditions. Darcy's law (equation (1)) states that, for these conditions of uni-directional flow and for a homogeneous material, the flow rate is proportional to the pressure gradient across the sample:

$$\frac{Q}{A} = \frac{\mathbf{K}}{\mu} \cdot \frac{\Delta P}{e} \tag{1}$$

Thus, the permeability $\mathbf{K}$ (m^2), intrinsic parameter, may be calculated with the measurement of:

- the volumetric flow rate Q ($m^3 \cdot s^{-1}$) passing through the sample area A (m^2);
- the pressure drop ΔP (Pa) across the sample;
- the sheet thickness e (m) at a given level of deformation;
- the liquid temperature T (°C) to determine the value of the viscosity (Pa.s).

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Porosity Evaluation

When submitted to a mechanical compression, the porosity of the paper web varies widely leading to wide changes in permeability. Therefore, permeability is expressed, in this paper, according to absolute porosity. The general expression for absolute porosity, n, is given by equation (2):

$$n = \frac{V_v}{V_{\text{app}}} = \frac{V_{\text{app}} - V_{\text{cell}}}{V_{\text{app}}} = 1 - \frac{V_{\text{cell}}}{V_{\text{app}}} \tag{2}$$

with V_v, void volume or pore volume, V_{app}, apparent or total volume, V_{cell}, volume of cellulose.

Absolute porosity is thus determined from the knowledge of sheet thickness at each level of deformation, and of oven-dry mass of the sheet:

$$n = 1 - \left(\frac{m_{\text{oven}}}{A.e.\rho_c}\right) \tag{3}$$

with m_{oven}, oven-dry mass of the sheet (kg), A, sample area (m^2), e, thickness of the sample (m), ρ_c, density of cellulose ($\rho_c = 1550\,\text{kg}\cdot\text{m}^{-3}$).

The basis weight is defined (equation (4)) as the oven-dry mass (m_{oven}), of the sample divided by its area (A):

$$Gr = \frac{m_{\text{oven}}}{A} \tag{4}$$

LITERATURE REVIEW

A thorough review of the literature helped identify the main characteristics of the previous experimental devices used in measuring liquid permeability. This also helped us avoid problems encountered by earlier researchers.

Apparatuses were first designed to measure the permeability of beds of unconsolidated particles. Researchers used a liquid permeability method essentially to determine the specific surface of cellulose fibers (Robertson–1949, Ingmanson– 1952). Values of the Darcian permeability (K) were then linked to the specific surface of the fibers using Kozeny–Carman equation. Later, White (1962) designed a water permeability apparatus to investigate the capillary behavior of paper. However, this cell did not offer the possibility of compressing the pad mechanically; the compression was only due to the pressure differential across the sample. Lindsay (1988, 1990, 1993) adapted to paper the concept of guard rings used by Macklem (1961) (who designed two apparatus for felt permeability measurement) and also designed an apparatus

to study the lateral permeability of sheets in a compressed state. Kafi (1993) used an oedometer, classically adapted to test soils. By this mean, he measured water permeability of various pulps of paper, with addition of different products, to determine their influence on pulp dewatering. Mulder (1995) designed a transverse permeability cell in which the wet sheet could be mechanically compressed. Silvy (1995) used another approach: he calculated the permeability tensor using a theoretical model from structural analysis of small cross cut slices of paper sheets. Vomhoff (1998) investigated the in-plane permeability of paper in a compressed state. He also designed a permeability cell to measure the transversal permeability of a compressed saturated paper. For the analysis, he reformulated Darcy's law in order to calculate a modified permeability from the knowledge of the sheet basis weight only (because the wet pad was compressed between two rough surfaces, so the thickness could not be measured accurately).

EXPERIMENTAL PROCEDURE

The basic principle of the PTP (see Figure 1) consists in a measurement of water flow across a mechanically strained web pad; the pad is compressed between two permeable surfaces.

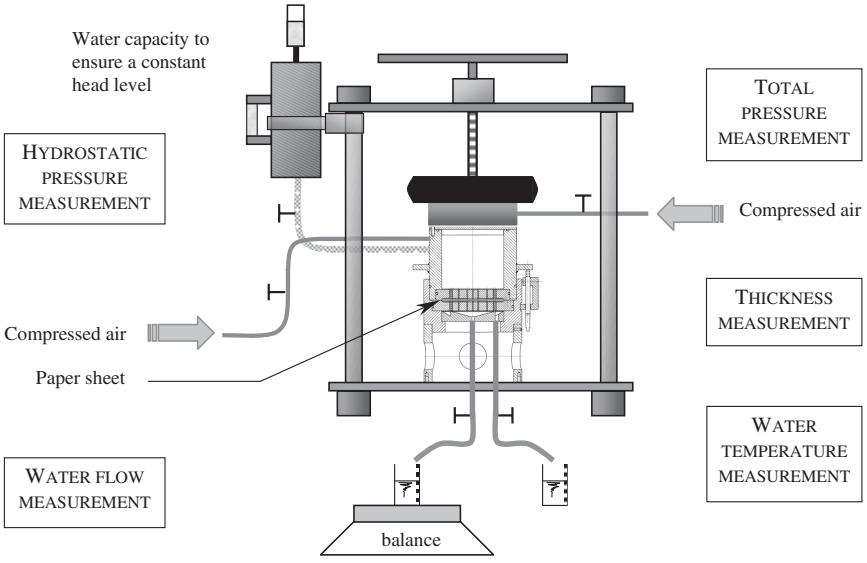

Figure 1. Schematic view of the Paper Transversal Permeability (PTP) device.

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As it is important to evaluate the level of deformation, 3 sensors embedded at 120° were dedicated to the measure of sample thickness (*Sensorex*– SX 8 MM 3). The range was chosen equal to 3 mm because paper thickness may vary from one hundred to a few hundred micrometers. Another particular attention was given to the choice of the porous discs. The material (stainless *Poral* /NFISO5755–3 - class 15) was chosen because of its better aging compared to bronze. As the discs must ensure a compression as uniform as possible, their surfaces should be as smooth as possible. However, the higher the permeability, the lower the smoothness is. The porous discs were chosen in respect of their permeability (up to $10^{-12}\,m^2$) evaluated from parameters given by the manufacturer. This value was estimated high enough, compared to the values given in literature for compressed paper sheets (from 10^{-18} to $10^{-13}\,m^2$). Discs have diameter of 114 mm in order to provide a maximum available area for flow. The principle of guard ring is used in order to avoid edge effects: with this guard ring, it is possible to collect the flow, both in the central and in the outer part of the sample. However, only the central measurement is taken into account for the permeability factor calculation. The compression of the sheet is realized with a pneumatic jack (370 mm in diameter) which maximum extent is 115 mm (*Pneuride*– 9109064). The total pressure that may be reached with this device is 3,5 MPa.

RESULTS

Validation of the Design Choices

The plate permeability predicted by the manufacturer was checked carrying out a trial without any sample in the cell. Measured permeability was found equal to $0{,}5 \cdot 10^{-11}\,m^2$.

Accuracy of sensors was checked by introducing an increasing number of calibrated sheets in the cell. The mean value given by the three sensors was then compared with the measure obtained by a micrometer. Error was found to increase with increasing number of calibrated sheets. For the range studied (500 μm), it was however less than 9 μm.

Uniformity of compression was verified by placing a carbon paper sheet and a white sheet in the cell. When compressed, the paper showed a uniform imprint.

Furthermore, a series of compression was made on different sheets (blotting paper, calibrated sheets and wet fiber pads) in order to check the accuracy of the thickness measurement. The results (presented on Figure 2) exhibit good linear relationships between thickness and number of sheets.

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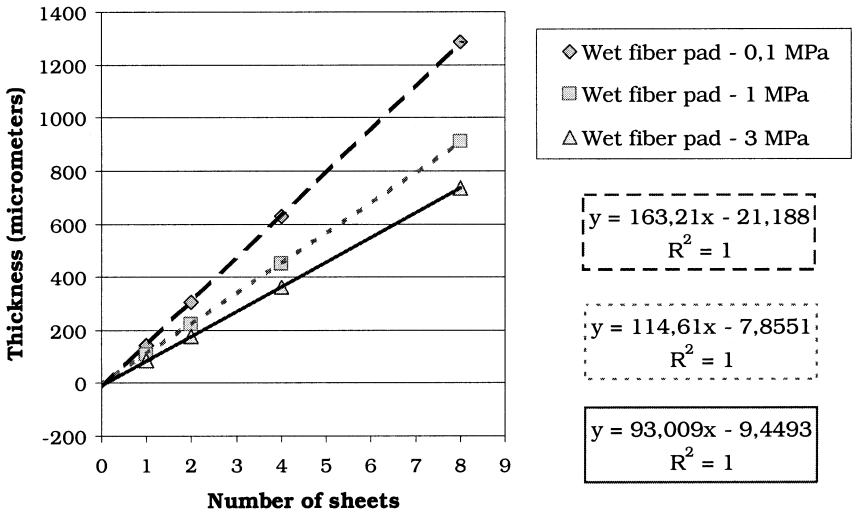

Figure 2. Example of linear relationships between thickness and number of sheets introduced in the cell.

Efficiency of guard ring and repeatability were checked by plotting (Figure 3) water velocity versus pressure gradient across the sheet for the useful zone $(Q/A)_u$ and the guard ring zone $(Q/A)_g$ (where Q is the volumetric flow rate and A, the area available for flow). Test was carried out to evaluate, if any, the interaction between the two zones. An impervious surface was placed in the central part of the sample and a pressure drop was applied; in the case of interactions, a flow in the central zone should have occurred, but it was not the case. The same trial was carried out with an impervious surface in the outer part of the sample, and the flow in this zone has been found negligible.

Experimental Results

On the graph (Figure 4) the permeability factor is plotted versus absolute porosity. The reproducibility is very good for samples having °SR equals to 28 (samples D and Dbis). Further more, in this case, water velocity is low. The association of two sheets (sample C) of global basis weight equal to those of one sheet (sample B) gives the same results, as expected. Indeed, for these unbeaten pulp samples, the gradient of porosity is small (compared to a beaten pulp) and thus the structure of samples B and C is very similar.

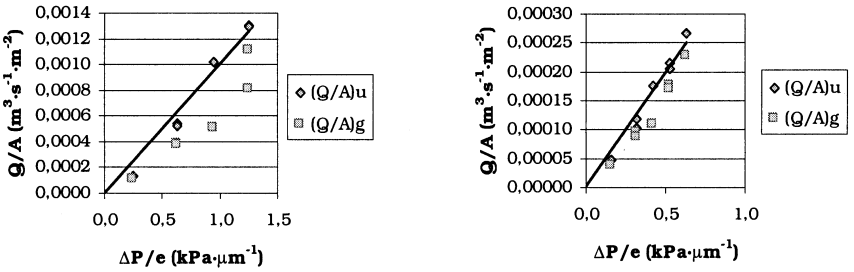

Figure 3. Examples of linearity (velocity, Q/A vs. pressure gradient across the sample, $\Delta P/e$) and repeatability for two different sheets (Q: flow rate; A: area; ΔP: pressure drop; e: thickness).

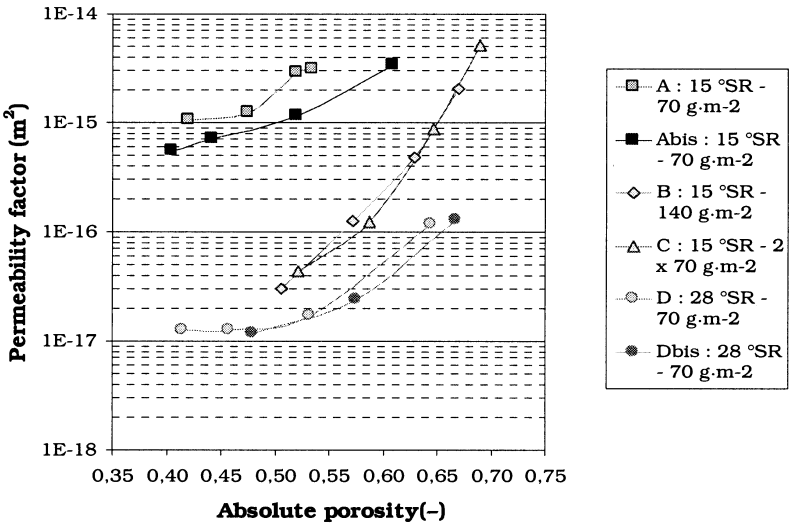

Figure 4. Results obtained for different handsheets with the PTP (beaten and unbeaten softwood webs).

For unbeaten pulp ($^{\circ}\mathrm{SR} = 15$) reproducibility is not very good due to non-homogeneity of the pulp (samples A and Abis). This result indicates the necessity to test samples with a minimum thickness. Indeed, the local changes in paper structure at low surface weight causes an uneven water flow through the permeable material. Thus, the measured permeability is affected and the validity of Darcy's law is strongly questionable.

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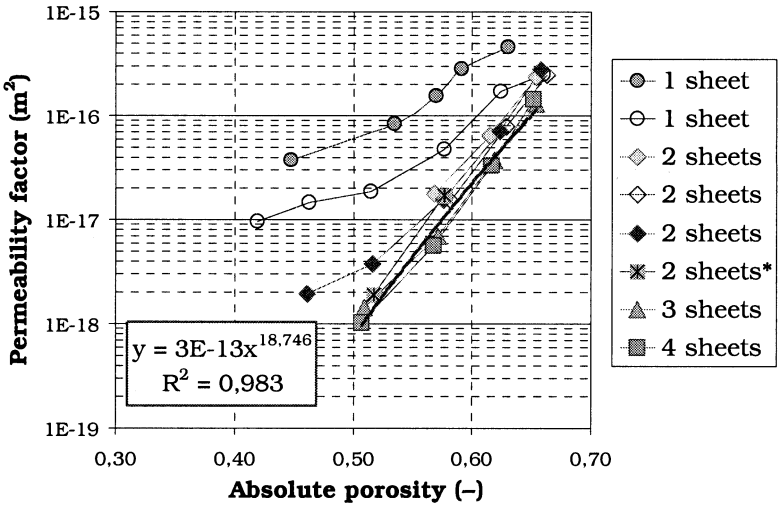

Figure 5. Results obtained for different stacked samples (softwood pulp; $80\,g{\cdot}m^{-2}$) (for the trial "2 sheets", the sample was changed for each level of porosity).

The necessity to stack samples in order to calculate an intrinsic parameter is demonstrated in Figure 5. Indeed, the intrinsic parameter **K** may be calculated provided a minimum basis weight as shown before. Otherwise, the permeability factor is over-estimated and results are not reproducible.

The results presented in Figure 6 are for paper sheets made on a pilot paper machine for different conditions of pressing: the load is applied onto two nips and the linear loads range from 200 to $1000\,kN \cdot m^{-1}$ leading to an increased dryness. The resulting permeability measured in the PTP is increased. In other words, the higher the dryness of the sample tested, the higher the permeability factor is.

These results are in agreement with those found by Lindsay (1993-b) concerning the effect of pressing and drying on the transverse permeability (see Figure 8). Indeed, he stated that, even if compression of the sheet lowered permeability by reducing the pore volume, at a certain level of compression (or sheet porosity) a sheet made from never-dried fibers that had experienced previous water removal by pressing or blotting and air drying could exhibit higher permeability than a similar sheet at the same degree of compression that had been nearly saturated since formation.

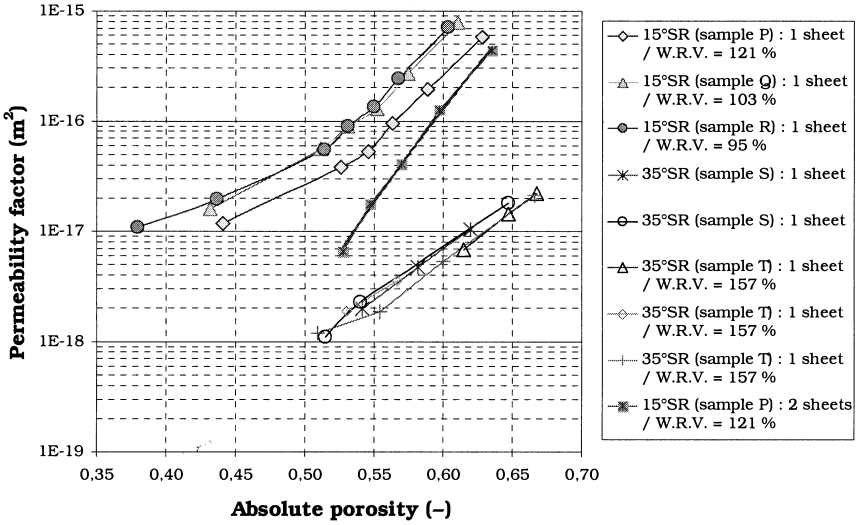

Figure 6. Results obtained with the PTP for samples made on a pilot paper machine for different conditions of pressing (initial dryness for samples *P*, *Q* and *R* are respectively 43, 48 and 50 % and basis weight for all the samples is $100\,g \cdot m^{-2}$).

Table 1. Sample Characteristics (N.B.: Water Retention Value is Measured on the Sample After Pressing and Before a Permeability Test)

Sample	°SR	Basis weight ($g \cdot m^{-2}$)	Level of pressing ($kN \cdot m^{-1}$)	Dryness (%)	Water retention value
P	15	100	200–200	43	121%
Q	15	100	200–1000	48	103%
R	15	100	1000–1000	50	95%
S	35	100	1000–1000	41	–
T	35	100	200–200	35	157%

We checked the effect of pressing by measuring the water retention value of the samples before a permeability test; indeed, for the highly pressed samples, the water retention value was lowered and the permeability factor increased.

In Figure 7, correlations [a.exp(b.n)] are plotted and it can be noticed that they fit rather well with the experimental points.

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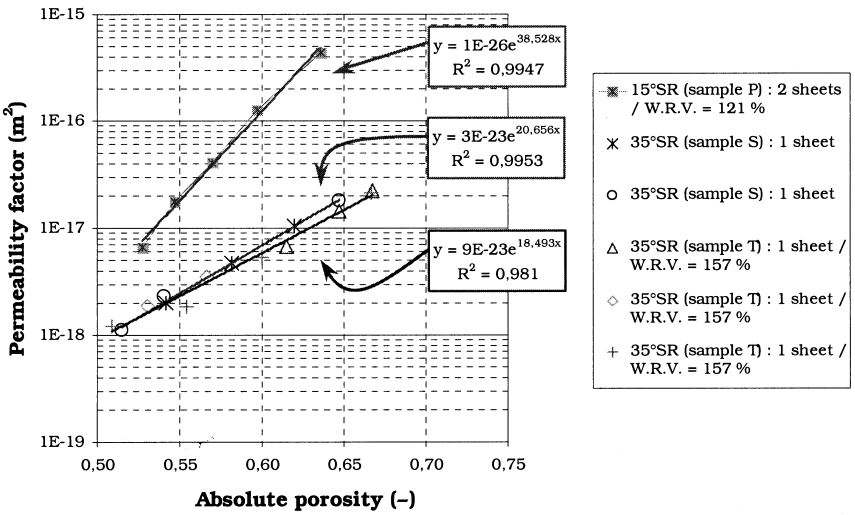

Figure 7. Correlations [a.exp(b.n)] obtained for different samples of softwood pulp (basis weight for all the sheets is $100\,g \cdot m^{-2}$).

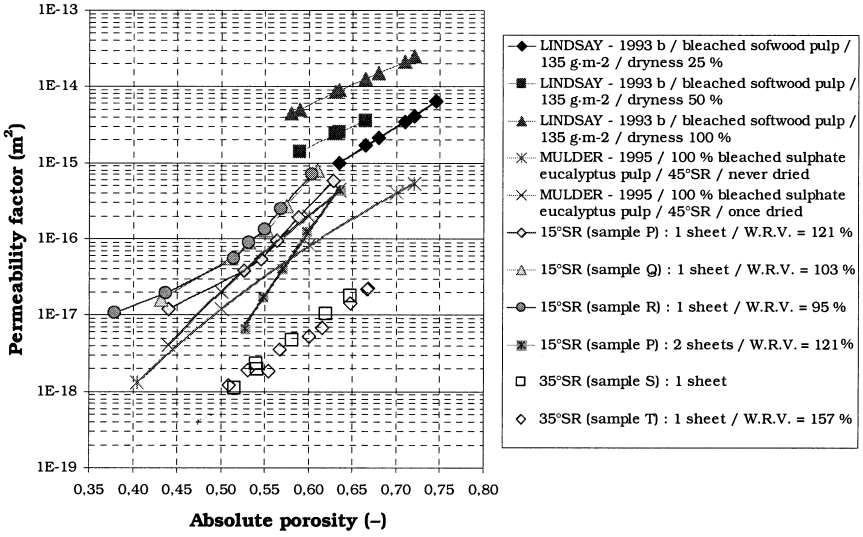

Figure 8. Comparison of the present study results with those found in the literature.

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Table 2. Different Sources of Uncertainties During a Permeability Test

Parameter	Adjustment–Measurement	Accuracy
Thickness	1 micrometer	10 micrometers
Pressure drop	air pressure: 0,01 bar (1 kPa)	± 1,05 kPa
Water temperature	thermometer	± 0,5°C
Water viscosity	evaluated with table	± 0,02 mPa.s
Water weight	balance	0,001 g
Sample area	cut with a scissor (17671 mm^2)	± 234 mm^2
Sample weight (oven dry)	balance	0,001 g

Experimental Uncertainty Levels

The permeability factor K is calculated by plotting the superficial velocity (Q/A) versus the pressure gradient $(\Delta P/e)$ across the sample: the slope of the curve represents the term (K/μ). By this mean, (K/μ) is calculated from the measurement of four to five couples $[(\Delta P/e); (Q/A)]$ by the least square method; the regression is forced to be at zero value at the origin. The slope is calculated by the formula:

$$\frac{K}{\mu} = \frac{N \cdot \left[\sum (\Delta P/e) \cdot (Q/A)\right] - \left[\sum (\Delta P/e)\right] \cdot \left[\sum (Q/A)\right]}{N \cdot \left[\sum (\Delta P/e)^2\right] - \left[\sum (\Delta P/e)\right]^2} \tag{5}$$

with N, the number of points for the determination of the slope.

The Table 2 summarizes the different sources of uncertainties concerning the measured parameters. The design choices were made in order to minimize the uncertainties made on each measure.

CONCLUSIONS

The designed compressibility–permeability device (PTP) is adapted for static studies of water permeability of thin materials (from about one hundred micrometers up to 3 mm), such as wet fiber pad, subjected to a mechanical stress. The presented results show that the apparatus gives repeatable and reproducible results.

It was demonstrated that it was necessary to stack samples in order to calculate an intrinsic parameter, especially for low basis weights (below a basis weight of 100 $g \cdot m^{-2}$ if the pulp is unbeaten). In this case, we can wonder if the permeability factor is the appropriate term to consider to classify the sheets in terms of flow.

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Comparison of the present results with those found in literature (Lindsay– 1993-a-b, Mulder– 1995) shows a good agreement concerning the tendencies of variation of the permeability factor. Nevertheless, the range of porosities investigated is different (especially with Lindsay's experiments) because the stresses he used were lower than 800 kPa so he could not reach low level of porosity.

The two orders of magnitude drop of the permeability factor when the beating level increases (from 15 to 35°SR) must be emphasized because it has a huge importance both for the equipment design and for the papermaking process. This modification may also explain the behavior modifications of wet pad during pressing depending on the pulp and the applied technology. The adapted optimization of the press nip may therefore be deduced: increasing either the press length nip or the load imposed on the rolls depending on both, the rheology and the filtration properties.

NOMENCLATURE

A	Sample area (m^2)
ΔP	Pressure drop across the sample (Pa)
e	Sheet thickness at a given level of deformation (m)
Gr	Basic weight ($g \cdot m^{-2}$)
$\mathbf{K}$	Permeability factor (m^2)
μ	Water viscosity (Pa.s)
m_{oven}	Oven-dry mass of the sheet (kg)
n	Absolute porosity (–)
N	Number of points for the determination of the slope (–)
Q	Volumetric flow rate passing through the sample ($m^3 \cdot s^{-1}$)
ρ_c	Density of cellulose ($kg \cdot m^{-3}$)
T	Liquid temperature (°C)
V_{app}	Apparent or total volume (m^3)
V_{cell}	Volume of cellulose (m^3)
V_v	Void volume or pore volume (m^3)

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