Experimental assessment of permeability variation with the compression of soft reticulated foams

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Abstract. The resistance to flow of imbibed fluids in soft porous structures subjected to compression can be a solution for impact attenuation. The mechanism, named ex-poro-hydrodynamic (XPHD) lubrication, is based on permeability variation with porosity, which, at its turn, depends on the compression degree of the porous structure. A literature survey revealed scarce information regarding the permeability of compressed reticulated foams or 3D fiber-based structures, used in XPHD applications. Moreover, the permeability depends on the fluid and its velocity. This paper presents experimental data of the permeability of glycerine for an in-plane, axisymmetric flow through a porous material subjected to various degrees of compression. The experiments were done on an in-house made radial permeameter with pressure differentials up to 6 bars. The experimental data was compared with the predicted results, using the well-known Kozeny-Carman equation and related formulations.

1. Introduction

The mechanism named by Pascovici [1] ex-poro-hydrodynamic (XPHD) lubrication consists of load generation produced by the squeeze effect inside a soft layer of porous material under compression and it is based on the variation of permeability with porosity.

Fluid flow inside a porous structure is characterized by permeability, which depends on the solid fraction structure and strength, on the fluid properties and on the material-fluid compatibility. Permeability can be characterized through experiments, or theoretically, using models based on detailed porous matrix geometries.

Permeability measurements of porous layers can be done for out-of-plane flows (across the thickness of the layer) or for in-plane flows. The in-plane flow is characteristic to thin layers, which is the case of interest for our applications. In-plane permeability can be evaluated for axial (parallel/one-directional) flows or for radial flows. The former is used for anisotropic porous structures, whilst the latter method is appropriate for isotropic materials like the reticulated foams which represent the subject of our interest. Most of the experiments are based on the measurement of the rate of flow for a given pressure differential across the porous structure, and subsequently apply of the well-known law of Darcy, for laminar flows.

There are many experiments reporting permeability measurements, but the results are limited by the type of the porous material and the application envisaged; it is practically impossible to generalize their results. To our best knowledge, no experiments have been reported for the axisymmetric permeability of soft materials with a high initial porosity, subjected to high compression levels.

Parnas and Salem [2] reported the first measurements of in-plane permeability using a radial flow. They measured the permeability of woven composite reinforcements with viscous Newtonian fluids. The variation of porosity was achieved by compressing the materials between two parallel plates of which one was transparent. The permeability was measured using the velocity of the front of the flow. The objective of their experiments was to find the permeability of anisotropic, low porosity ($\epsilon = 0.2...0.5$) materials. The same principle of permeability measurements was later used by Waizenbock [3] for resin transfer molding with focus in the determination of the orientation of permeability tensor axes. Further, Lundstrom et al. [4] employed a similar device and the same method of measurements.
Dawson et al. [5] measured the permeability of compressed reticulated foams with pore size in the range 175...235μm. Their experiments were made at low compression levels (strains less than 0.6) with water at a very low pressure differential (a few mmH₂O). They also propose a model for the permeability-strain correlation, which is different from the Kozeny-Carman model or related models. Extrapolating their experimental results, we can conclude that the permeability did not vanish.

Pascovici et al. [6] reported measurements of in-plane permeability of high porosity (ε > 0.85) textile materials under various compression levels. Two fiber based porous materials were tested with water at very low pressures (free flow from a constant height reservoir) and several levels of compression. The experiments – which measured the inlet pressure and the rate of flow – were performed only for very low pressures (p < 0.2 bar) and on a poorly instrumented test rig.

There are also reported measurements for the permeability variation with the level of compression made on soft materials with in-line (parallel flow) permeameters [4][7][10], but the materials and the fluids are different and generalization is not possible. It is worth mentioning the extended experimental work reported by Arbter et al. [10], done in 16 different laboratories, for measuring the in-plane permeability of a carbon fabric used in liquid composites molding. Their results have shown differences, from simple to double, despite apparently identical experimental conditions.

Among the models relating permeability to porosity, there is one which is often used: the Kozeny-Carman model [9], developed initially for porous structures consisting of ordered spheres and based on a hydraulic radius concept. Its validity was restricted to values of porosity ranging between 0.2 and 0.8, but due to its simplicity, it was frequently used beyond this interval and for a broad range of porous materials with different structures. Its applicability remains questionable and it is one of the objectives of the present work.

The motivation of the work reported herein is to extend the measurement of permeability for an axisymmetric, in-plane flow at various levels of compression of extremely soft open-cell reticulated foams. The particularity of these experiments is the very high initial porosity of the reticulated foams and the large range of porosities covered. The experimental data are fitted with the Kozeny-Carman equations in order to analyze their applicability.

2. Experimental setup
The experimental setup (figure 1), in-house designed and manufactured, consists of a complex hydraulic supply system, which allows to accurately control the pressure. The system is composed of a gear pump, two filters, a hydraulic accumulator, a pressure controller and a pressure regulator, used to adjust the supply pressure to the testing cell (permeameter). The air is purged through a breather placed before the permeameter inlet. The supply pressure ranges from 0.5 bar up to a maximum of 8 bars.

The permeameter is designed to measure the pressure drop for an in-plane, axisymmetric radial flow, a configuration first suggested by Parnas et al. [2]. The porous specimen is placed between two rigid plates, which can be tightened (using six cap screws) to a pre-set distance (gap) between their mating surfaces, measured with three equally spaced comparators. This distance, which represents the thickness of the compressed specimen, can be adjusted with an accuracy of 0.01mm, using three micrometric screws. The upper plate slides inside a tight clearance centering the cylindrical surface, ensuring thus a less than 0.02mm misalignment of the two mating surfaces. An O-ring seal is placed on the outer diameter of the upper plate. The maximum distance between the plates can be 15mm. The lower plate, where the specimen is set, has the diameter D₀=100mm.

The fluid is supplied on the top of the upper plate into a larger (Ø15 mm) pressure compensator pocket that allows the uniform distribution of the fluid. Three large slits cut circumferentially allow the fluid flowing radially through the specimen to drain out unrestrictedly into a collecting container (figure 2). The container is placed on a precision balance (accuracy 0.01g) that allows the measurement the mass
flow rate. Four pressure taps placed along a radius of the rigid plate, connected to four manometers (accuracy class 1.6), are used to measure the pressure at the inlet pocket, at the outside diameter and at two intermediary radial positions ($r_1=18\text{mm}$ and $r_2=35.5\text{mm}$). Two supplementary pressure taps placed at the same intermediary radial positions (circumferentially shifted with $120^\circ$) are used to check the axisymmetry of the pressure distribution. The location of these pressure taps can be seen in figure 3.

**Figure 1.** Experimental setup.

**Figure 2.** Permeameter – 2D sketch.
Figure 3. Permeameter pressure taps and large openings.

3. Experimental procedure

The ensuing procedure was followed for each specimen: the upper plate was first positioned on the lower plate without the material, the comparators were set to zero and the micrometric screws tightened until they touched the lower plate. The micrometric screws were used to lift the upper plate until a certain distance (the envisaged compressed height of the material), measured with three comparators was achieved. Then, the upper plate was removed, the specimen was carefully centered on the lower plate and finally, the upper plate was screwed down with the tightening screws, limited by the micrometric screws. The pump was started, the maximum supply pressure adjusted and the permeameter fed in closed circuit for approximately 2 minutes, in order to obtain a uniform temperature and rate of flow.

Each sample was progressively compressed with steps of 0.5mm down to a thickness of 1mm. Further compression levels were tested down to a minimum value, dependent on the initial porosity and on the maximum torque required for cap screws tightening. For each compression level, the pressure was varied up to 6 bars in steps of 0.5 bars and each time, three test measurements were performed; each test included readings of the six manometers and timing the duration of a pre-set mass of liquid to be accumulated in the container. The mass of fluid collected for rate of flow assessment depended on the level of compression and varied between 20g at high compression levels up to 1kg for high porosity values. For each compression level and supply pressure, three measurements were made, and the average was further considered for analysis.

Most of the tests were performed at pressures up to 6 bars, except the cases for higher thicknesses (low compression), when the rate of flow was found too high for an accurate measurement, due to the quick time necessary to reach the upper limit of the weighting.

4. Experimental results

The experiments reported herein have been done on samples cut from sheets of polyurethane – typically used as filter media. Two similar types of open-pore foams with very low density were tested. The specific characteristics of these two materials, as given by the producer, are listed in table 1. Annular samples with the inner radius of \( r_1 = 7.5\text{mm} \) and outer radius of \( r_e = 50\text{mm} \) (figure 4) were cut from sheets of material with the initial thickness \( h_0 \) (uncompressed). The initial porosity of each material was measured using a volumetric method.

The fluid used was glycerin, a highly viscous bio-compatible fluid with the main properties given in table 2.
Table 1. Porous materials properties (at 25°C).

| Disc No. | Foam symbol | Commercial name | Pore size [mm] | Initial porosity $\varepsilon_0$ | Thickness $h_0$ [mm] |
|----------|-------------|-----------------|---------------|----------------|-------------------|
| 1        | F450        | FILTREN® TM 25450 | 3.4÷5.6       | 0.987           | 10.5              |
| 2        | F280        | FILTREN® TM 25280 | 2.2÷3.4       | 0.982           | 11.5              |

Table 2. Glycerin properties (at 25°C).

| No. | Parameter | Value         |
|-----|-----------|---------------|
| 1   | Density   | 1.262 g/cm³   |
| 2   | Glycerol  | 99.8%         |
| 3   | Water content | 0.020%       |
| 4   | Viscosity | 1 Pa·s        |

Figure 4. Annular shape of the foam specimen.

The experiments have been performed at relatively high levels of compression, starting with a 3mm thickness and decreasing to minimum thickness, when the compression force exceeds the safe tightening force of the screws.

The unprocessed experimental data expressed in terms of volumetric rate of flow function of the supply pressure are shown in figure 5 for F450 material and F280 material, respectively. One can remark the great differences of the measured rate of flow at the same supply pressure and thickness, between the two specimens. This can be explained by the differences in initial thickness and initial porosity. Surprisingly, a difference of 0.5% in the initial porosity leads to a great difference in the permeability, due to the variation of current porosity with material thickness.

Figure 5. Flow rate for different inlet pressure at various compression height.

A first analysis of the experimental data was focused on the applicability of the classical Darcy flow model, which assumes the pressure differential proportional with the averaged fluid velocity. The effects
of boundary friction (included in Brinkman term) in terms or fluid inertia (included in Forchheimer term) must be evaluated.

For an axisymmetric flow, Darcy’s equation takes the form:

\[ \frac{dp}{dr} = -\eta \frac{u(r)}{\phi} \]  \hspace{1cm} (1)

where \( u(r) \) is the so-called Darcian velocity, calculated with the dimensions of the cross-section normal to the flow direction:

\[ u(r) = \frac{q}{2\pi rh} \]  \hspace{1cm} (2)

The applicability of Darcy’s equation for data analysis can be evaluated using the graphical representation of the pressure differential with respect to the averaged speed calculated with equation (2). Taking into consideration the four values of pressure recorded along the radial direction, the pressure differential and the velocity can be calculated separately for each of the three intervals between two consecutive pressure taps.

![Graph showing the pressure differential function of the averaged flow velocity at the same thickness.](image)

**Figure 6.** Pressure differential function of the averaged flow velocity at the same thickness.

The pressure differential was calculated assuming a simplified linear variation between two consecutive pressures, and the fluid velocity was calculated at the corresponding mid-radius. The three curves corresponding to each interval, along with an averaged curve, are depicted in figure 6 for both tested foams at a compression level \( h=1.5\text{mm} \). One can remark the important differences between these three similar curves, in the case of F450 material explained by the linear approximation and by the end effects for the first and last intervals. At the same time, the averaged values of pressure differentials and velocity are very close to those calculated with the pressures measured on the second interval. However, the linearity of the corresponding trend lines suggests that Darcy’s equation fits excellent with the experimental data.

The same behavior, as shown in this sample graph (figure 6), was found for all the experimental data; therefore, further analysis was made using averaged values.
Figure 7. Pressure differential function of the averaged flow velocity at different thicknesses.

Figure 7 presents the variation of the averaged pressure differential with the average fluid velocity for all the compression levels analyzed. For all these cases, there is a linear variation between the two parameters, which leads to the conclusion that Darcy’s prediction is very accurate. As a consequence, both Brinkman and Forchheimer extensions of the Darcy law can be neglected.

The laminar character of the flow can also be defined by the values of the pore-based Reynolds number:

$$Re_f = \frac{\rho ud}{\eta} \tag{3}$$

In our case, these values are less than 0.03 for both materials, which is under the accepted limit for pure a laminar flow ($Re_f < 1$).

The following step regarding data analysis was to fit the best approximation of Darcy’s equation to the experimental data. The combination of equations (1) and (2) and integration with the boundary conditions $p=p_i$ at $r=r_i$ and $p=p_o$ at $r=r_o$ yield to the radial pressure equation:

$$p(r) = p_i e + \frac{p_i - p_o}{\ln(r_i / r_o)} \ln(r / r_o) \tag{4}$$

Figure 8. Radial pressure variation across the specimen for various supply pressures.
Taking into consideration the theoretical pressure equation (4), the experimental data points were approximated with a logarithmic function:

\[ p(r) = a + b \ln(r / r_e) \]  

(5)

Two methods were used to fit the experimental data: first, a simple approximation was obtained by fitting the logarithmic function - equation (5) with the pressure values at the two boundaries of the specimen \( r_i \) and \( r_e \), respectively. A more elaborate approximation was obtained by using the least square fit method. The differences between the two approximation functions were very small (under 3% differences for the two coefficients, \( a \) and \( b \)).

Figure 8 shows the approximation curves for a series of experiments made at the same specimen thickness and increasingly supply pressures. The correlation coefficients listed for each curve demonstrate a fair agreement of the measured data with the approximation logarithmic curves.

Using the approximation functions - equation (5), one can immediately obtain the pressure differential:

\[ \frac{dp}{dr} \bigg|_{r} = \frac{b}{r} \]  

(6)

and corresponding permeability from equations (1) and (2):

\[ \phi = -\frac{h \eta}{2\pi b} \]  

(7)

The results are presented synthetically in figure 9. One of the most remarkable results is that the permeability is quasi-constant with the pressure variation for all the levels of compression. This strengthens the conclusion that the experimental data are highly consistent.

**Figure 9.** Permeability variation with supply pressure for different thicknesses.

Finally, we analysed if the Kozeny-Carman equation:

\[ \phi_{KC} = \frac{De^3}{(1-e)^3} \]  

(8)

is suitable for the prediction of permeability of highly porous reticulated foams.
The coefficient $D$ of the Kozeny-Carman equations was originally defined as:

$$D = \frac{d^2}{16k} \quad (9)$$

where $d$ is a characteristic dimension of the porous structure and $k$, a constant taking values between $5\rightarrow10$.

The equation (9) was originally proposed for beds of spherical particles and $d$ was the mean diameter of these particles. Extensions of equation (9) were proposed for fiber-based materials, but there is no reliable formulation in the case of cellular structures, where the characteristic dimension is the pore size. Consequently, we decided to calculate the value of $D$ which best approximates the experimental values.

The results are presented in extension in figure 10. For the F280 foam, the result shows an excellent consistency: $D$ is quasi-constant for the range of pressures and thicknesses experimentally used. Even in the case of the F450 foam, the differences between the values of $D$ obtained for various levels of compression are within acceptable intervals.

![Figure 10. Variation of the constant $D$ from the Kozeny-Carman equation with pressure and compression.](image)

![Figure 11. Measured versus predicted permeability.](image)

Finally, the averaged values of $D$ were introduced in the Kozeny-Carman equation and the predicted permeability was compared with that measured on the entire interval of thickness variation (figure 11).
When the compression increases, the predictions of this equation highly underestimate the experimental data. In the case of the F280 foam, at low porosity levels, the permeability shrinks asymptotically, a behavior related to the experimental evidences of highly compressed dry foams, which revealed a non-uniform compression [5]. It is supposed that the compression of the solid fraction cannot close completely all the cells of the structure, and some tunnels remain open and allow the fluid flow.

5. Conclusions
An original experimental study is presented in this paper, dedicated to measure the in-plane permeability of soft materials subjected to compression, using an in-house built test rig. The first test campaign revealed good reliability of the testing device and a high accuracy and consistency of the experimental data.

The applicability of Darcy's law for permeability assessment using the experimental data was evaluated and it was concluded that this equation is adequate to describe the fluid flow in highly compressed reticulated foams subject to medium differential pressures.

By fitting Darcy's predictions with the experimental data, the permeability variation with the compression level was estimated. The results can be considered consistent for a large interval of variation of the experimental parameters.

Based on these estimations, the permeability - porosity correlation was found and the validity of the Kozeny-Carman equation was analyzed. The comparison showed that the Kozeny-Carman equation fits well with the experimental data for high and medium porosities. When porosity reduces, Kozeny-Carman predictions underestimate permeability with several orders of magnitude.

An asymptotic limit of minimum permeability was put in evidence experimentally. This can be explained by the compaction of the solid phase which cannot close completely the flow tunnels. Further experiments should be performed for multiple materials, with different pore structures in order to find an analytical formulation for this limit.

LIST OF NOTATIONS

| Latin alphabet | Greek alphabet |
|----------------|----------------|
| d pore size [m] | \( \varepsilon \) porosity [-] |
| \( D \) constant in Kozeny-Carman eq. [m²] | \( \eta \) viscosity [Pa·s] |
| h thickness [m] | \( \phi \) permeability [m²] |
| p pressure [Pa] | \( \rho \) density [kg/m³] |
| q rate of flow [m³/s] | Subscripts |
| r radius [m] | o outer |

6. References

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