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PRELIMINARY EXPERIMENTAL ASSESSMENT OF RADIAL FLOW PERMEABILITY VARIATION WITH THE COMPRESSION LEVEL OF 3D FABRICS

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Abstract: *During the last two decades, continuous efforts have been made in our research group to evaluate the damping capacity of soft, porous layers imbibed with liquids and subjected to normal impact. The effect is strongly related to the liquid permeability of structures and its variation with the level of compression. Recently, a new candidate material has been successfully tested for impact damping, namely a three-dimensional fabric. This paper presents preliminary experimental results obtained on a radial permeameter for a commercially available 3D fabric. Data analyses have shown a quasi-linear pressure variation with liquid velocity and excellent repeatability. Based on Darcy's law for axi-symmetric in-plane flows, the variation of permeability with the thickness of the layer was obtained. The experimental results have been confronted with the predictions of the well-known Kozeny-Carman equation.*

Keywords: *porous material, permeability, three-dimensional fabric, Darcy*

1. INTRODUCTION

During the last two decades, continuous efforts have been made in our research group to evaluate the damping capacity of soft, porous layers imbibed with liquids and subjected to normal impact. This mechanism is based on the resistance to in-plane flow of the fluid expelled out through the complex porous structure, during its compression. The effect is strongly related to the permeability of structures and its variation with the degree of compression. The activities conducted by the research group led by prof. M.D. Pascovici on this subject revealed multiple applications in viscous pumps [1], bearings or squeeze dampers [2]. A large variety of porous materials have been tested (foams woven textiles, felt, etc.) and in all these cases the evaluation of their liquid permeability with the degree of compression was necessary and unavailable in literature; henceforward experiments were necessary ([3], [4], [5]). Both radial and axial flow permeameters have been used but the tests were limited at very low pressure drop across the tested material.

Recently 3D fabrics (tridimensional textiles) came to attention of researchers interested in identifying new solutions for impact damping. The 3D textile material is a fiber-based porous material composed of three different parts, the two faces which are similar but not identical, with different porosities, and the polyester wires which are knitted between the two faces. 3D fabrics have an intrinsically capacity to attenuate impact due to the resistance to buckling and bending of these polyester wires when subjected to compression, [7]-[8]. Due to attenuation properties, spacer fabrics could be a good replacement of the polymeric foams for cushioning and damping, making it a perfect material for protecting clothing and equipment.

The intrinsic capacity of 3D fabrics to damp shocks can be augmented by the resistance to flow of a fluid imbibed inside the structure. This capacity was already studied experimentally, and promising results have been obtained [6][8]. Their in-plane permeability is of main interest for further modeling of the XPHD mechanism.

Many experiments reporting permeability measurements are available in literature for fiber-based porous materials, but the results are limited by the application envisaged and by the fluids and the porous materials of interest. Few experiments have been done for in-plane flow and the available data are valid for narrow intervals of permeabilities [9]-[10].

Numerous permeability measurements for in-plane flow have been made for fluids used in resin transfer molding (RTM) [10]. Parnas and Salem [11] were among the first who reported in-plane permeability measurements using a radial flow and determination of flow front velocity. Their experiments were done for very high viscosity fluids and a constant thickness of the porous material. there are reported Three important international benchmarks [12][13][14] are reported for the same application; they revealed that the methods of measurement cannot be yet standardized, and the results have limited application. It was also found scatter of the measured permeability values of more than one order of magnitude [12].

The literature survey shows a great number of models for permeability-porosity relationship, starting with the well-known Kozeny-Carman (K-C) formula [15] derived for permeability of packs of spherical particles. The K-C formula as well as some many related models predict the permeability vanishing at complete compaction (when porosity vanishes), which has been proven unrealistic. At high rates of compression, the material compaction becomes so high as all the pores are closed and permeability vanishes; this happens when solid fraction takes values under 0.7 and some porosity is retained near full densification depending on the type and morphology of the porous structure [16].

The K-C formula was later extended for fiber-based homogenous porous materials assuming ordered identical fibers parallel or perpendicular flow direction. A comprehensive review of these models can be found in [17]. More recent, with the development of the computational resources, 3D flows models have been proposed [18], [19]. Most of these models can be used for structurally homogenous materials which is not the case of 3D fabrics. Few of these theoretical models take into consideration the limits of permeability function of the compaction of the material. Gebart [20] and Gutovski at al. [21] models are among the most cited models which include the limit of compaction.

The work reported herein presents the measurements of permeability for an axisymmetric, in-plane flow at various degrees of compression, of a three-dimensional fabric. Glycerin has been used as test fluid supplied at moderate pressures (up to 6 bars) and the porous material was subjected to a large range of compressions. To our best knowledge, no experiments have been reported for the axisymmetric permeability of 3D soft materials with a high initial porosity, subjected to various compression degrees. The experimental data are fitted with the equations proposed by Gebart and Gutowski et al. and a modified empirical equation is also proposed.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The material of interest is a 3D fabric of thickness h_0=6.25mm with a structure consisting of two faces (layers) knitted with bundles of polyester fibers (figure 1) and joined together by transverse monofilament polyester fibers of diameter d_f=0.16mm a. The two faces of different thickness, have a relatively different structure; their cumulated thickness is 1.5mm.

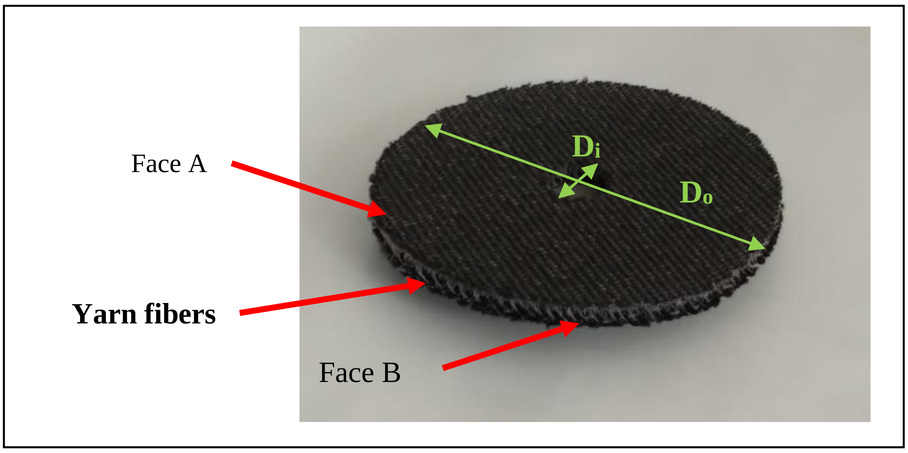


Figure 1. Structure of the material Spacer 3D

The overall *solid fraction* σ, for the uncompressed material was found experimentally by two methods:

(a) by a simple volumetric method, measuring the volume of the solid structure when submersed in water (σ_0=0.093).

(b) by weighting and using catalogue values for polyester density (σ_0=0.103).

This difference, even if it is small may conduct to quite important differences when solid fraction is calculated with the assumption of constant cross-section area of the deformed layer. For the present work, the initial solid fraction was considered σ_0=0.1.

The fluid used for the permeability measurement is glycerin (water 0.02% and glycerol 99.8%), which is a Newtonian fluid of density 1.262g/cm^3 and dynamic viscosity 0.335 Pa·s at 22°C. The choice for this fluid which is non-toxic was imposed by the envisioned applications like supplementary human body protection. The fluid temperature was measured inside the inlet pipe and was observed to be constant during an experiment.

The experimental setup used is an in-house designed and manufactured radial permeameter which allows to accurate measurement of the pressure variation across the analyzed porous material. The permeameter is designed to measure the pressure drop for an in-plane, axisymmetric radial flow. The system is composed of a gear pump, a pressure controller, and a pressure regulator, used to adjust the supply pressure to the testing cell

(permeameter) where the porous material is placed. The porous specimen is placed between two rigid plates and the distance (gap) between their mating surfaces can be set with an accuracy of 0.01mm, using micrometric screws. The lower plate with a central zone, where the specimen is set, has the diameter D_o=100mm and allows the fluid flow through three large slits cut circumferentially allow the fluid to drain out unrestrictedly into a collecting container; therefore, there the outboard pressure is assumed the atmospheric pressure. A schematic of the testing cell is shown in figure 2.
The fluid is supplied on the top of the upper plate inside a central pocket of diameter Ø15mm from where the fluid starts flowing radially through the material up to the slits. The mass of liquid collected in the container from the slits is measured and mass flow rate can be determined. Pressure taps placed along a radius of the rigid plate and 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=18mm and r_2=35.5mm). Two supplementary pressure taps placed at the same intermediary radial positions (circumferentially shifted with 120°) are used to check the axisymmetry of the pressure distribution.

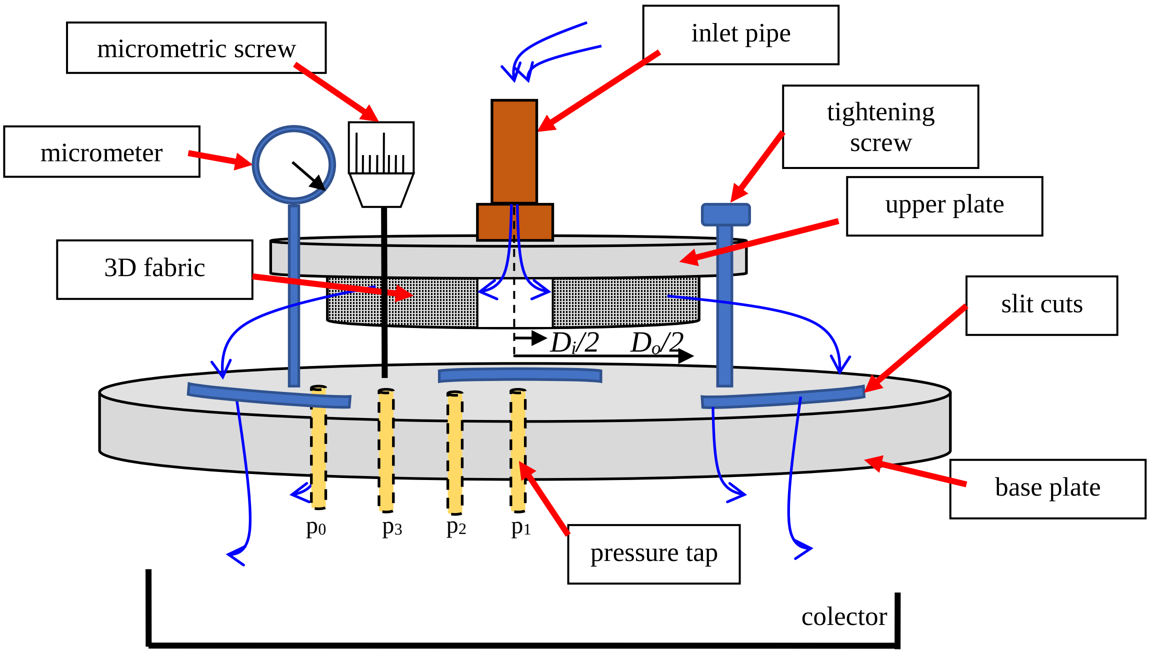


Figure 2. 3D model of the permeameter

3. RESULTS AND DISCUTION

Annular samples with the inner diameter of D_i = 15mm and outer diameter of D_o = 100mm (figure 1) were cut with a laser machine from sheets of material with the initial thickness h_0 =6.25mm. Each sample was progressively compressed from the initial thickness h_i=4mm down to a minimum thickness h_f=1mm with steps of 0.5mm. Most of the tests were performed at pressures up to 6 bars, except the cases of 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. For each compression level, the pressure was varied in steps of 0.5 bars and each time, three test measurements were performed and the average permeability was further considered for analysis. Each test included readings of pressure and time duration for a pre-set mass of liquid to be accumulated in the container. The dispersion of the results can be considered good, taking into consideration similar experiments where great dispersions have been reported [12].
The unprocessed experimental data expressed in terms of volumetric rate of flow function of the supply pressure are shown in figure 3. One can remark the linear variation of rate of flow with pressure differential for different compression degrees expressed in terms of material h.
A first analysis of the experimental data was focused on the applicability of the classical Darcy flow model [22], which assumes the pressure differential proportional with the pore-averaged fluid velocity.
Representative results are shown in figure 4, for two samples of 3D fabric of different thicknesses; the fluid velocity was calculated at the corresponding mid-radius and the pressure differential was calculated assuming a simplified linear variation between two consecutive pressures taps. The three curves corresponding to each

pressure interval, along with an averaged curve, are depicted in figure 4. The linearity of the corresponding trend lines suggests that Darcy's equation fits excellent with the experimental data.

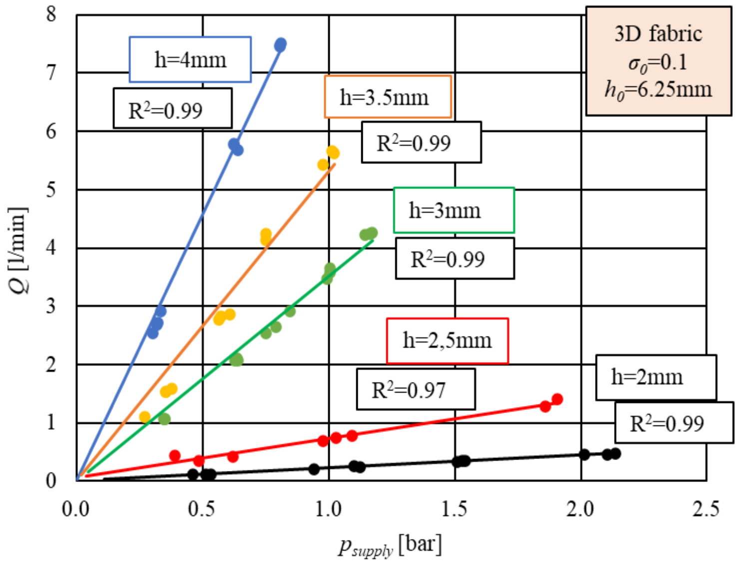
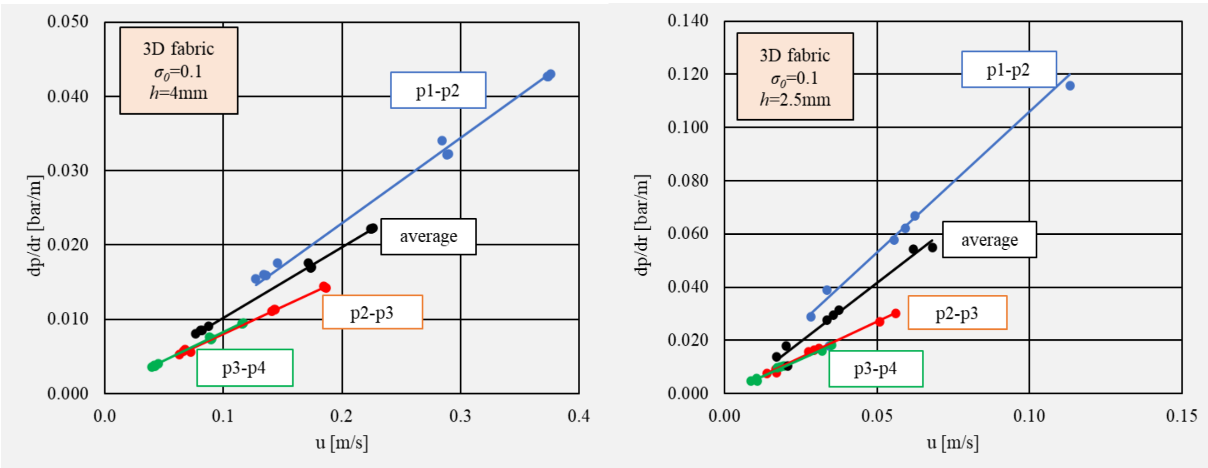


Figure 3 Flow rate for different inlet pressure at various compression height



(a) (b)

Figure 4 Pressure differential dp/dr function of the averaged flow velocity u at different thickness for a) h=2.5mm and b) h=4mm

The character of the flow can be defined by the values of the fiber-based Reynolds number: $Re_\phi=\rho u d/\eta$: a laminar flow is characterized by Re_ϕ <1 [23]. For the experiments reported herein, the maximum value of the pore-based Reynolds number is 0.2, when h= 4mm.

Finally, the experimental data have been fitted with two well known models developed for flow perpendicular to the arranged packs of fibers:

– Gebart [20] model for quadratic fiber arrangement with an supplementary correction coefficient, :

$$\phi=\frac{4d_f^{\,2}}{9\pi\sqrt{2}k_1}\left(\sqrt{\frac{\sigma_c}{\sigma}}-1\right)^{5/2} \tag{2}$$

Gebart model is theoretically valid up to a maximum solid fraction σ_c=0.9.

– Gutovski et al. [21] proposed a similar expression for transverse permeability for a fiber bundle:

$$\phi=\frac{d_f^{\,2}}{16k_2}\left(\sqrt{\frac{\sigma_c}{\sigma}}-1\right)^{3}/\left(\frac{\sigma_c}{\sigma}+1\right) \tag{3}$$

where σ_c is also a limit value. There is no direct indication of this limit, but from the compression experiments presented in [21] values between 0.8-0.9 should be considered.

The limit of permeability, σ_c, included in both formulas raises some uncertainty; a few studies dealing with this limit can be found in literature. However, a parametric study shows that different values of σ_c produce a slight rotation of the curve. These values correspond also with the compression curve characteristic of the 3D fabrics, where one can remark the densification inception around σ_c=0.66 [6]. Other theoretical or experimental studies show that compressibility of pore-based materials is limited at volume fractions values around σ_c=0.6…0.9 [24]. For the present analysis, a value σ_c=0.7 was assumed.

The averaged permeability data are presented in figure 5 in terms of dimensionless permeability ϕ/d_f^2 function of solid fraction, σ. Using a least square regression Gebart formula was fitted to our data with the correction factor k_1=0.85; this value is close to 1, which corresponds to the ideal model of Gebart. Gutowski's equation best fits with the experimental data for the correction factor k_2=0.12, a value close to 0.2 which was found experimentally [21]. One can remark a relatively good prediction of these two models for medium and high compression grades. However, the differences are quite important for low compression (low solid fraction). One possible reason for these differences can be attributed to the experimental results: at low compression and high-pressure gradients, it is possible to have side flow (flow between the upper solid plate and the compressed material).

In order to minimize the differences between the experimental data and the models a new relationship for permeability variation is proposed:

$$\phi = 85 \cdot 10^{-5} \frac{(1-\sigma)}{\sigma^4} \tag{3}$$

The curve represented in figure 5 shows an excellent approximation. At the same time this formulation can be easily used in theoretical models for XPHD lubrication due to its simple form.

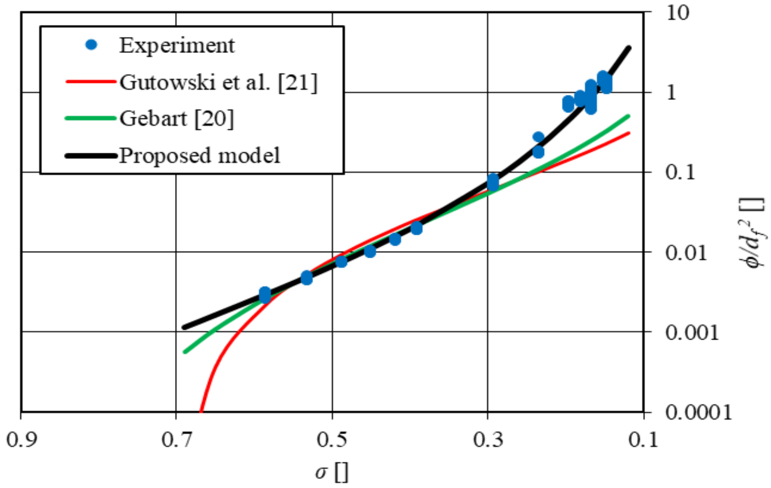


Figure 5. *Permeability variation with solid fraction*

4. CONCLUSIONS

The paper presents original experimental data for the permeability variation with the thickness of 3D fabrics. It was found that for pressures up to 6bars and compression levels down to 1mm the laminar regime is preponderant and Darcy law can be accurately used for permeability assessment. The experimental results show a reasonable dispersion, especially at low thickness compression.

The experimental results are well correlated with the predictions of two well-known theoretical formulations for permeability-solid fraction relationship in the case of medium and high compression levels. However, these models underestimate the experimental data.

A new empirical formulation was proposed which can be very useful in theoretical analyses of squeeze flow in impacted porous materials.

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