ON THE VALIDITY OF SOME MODELS FOR PERMEABILITY-POROSITY CORRELATION IN PLANAR FLOW THROUGH THREE-DIMENSIONAL TEXTILES

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Three-dimensional textiles have shown excellent damping properties, making them a good candidate for impact protection when imbibed with liquids. Permeability is a key parameter within the current study, being used to describe the fluid flow on which the damping effect is based. The current paper presents an experimental measurement of permeability for two materials in the case of unidirectional in-plane flow, for which a novel in-house made permeameter was used. The device allows the compression of the three-dimensional textiles and a pressure differential up to 6bar. The permeability was calculated assuming the validity of Darcy's law. The measured permeability variation with porosity was fitted using the well-known Kozeny-Carman equation and other relevant equations available in the literature.

Keywords: 3D spacer, porous, permeability, porosity, Darcy

1. Introduction

Lately, the industrial market has shown an increasing interest in applications using three-dimensional textile materials (referred herein as 3D spacers or S3D), which led to the growth and diversification of the production, as well as the decrease of related costs. Impact protection is one among many applications linked to the usage of 3D spacers. This is due to the high compressive strength during buckling and bending of the wires used for manufacturing of such materials [1][2]. The structure of 3D spacers consists of equally-spaced, parallel polyester yarns, interweaved between two parallel knitted faces.

Recently, 3D textiles have been analysed experimentally as a cushioning solution - which can be further improved when imbibing the 3D spacers with a fluid. When the structure is compressed, the fluid is expelled, and resistance to its flow through the porous structure generates a load, in addition to that of non-

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transverse fibers. This mechanism, known as eX-Poro-HydroDynamic (XPHD) lubrication [3], has recently shown promising results both theoretically and experimentally. The theoretical modelling of this process is based on the correlation between the permeability (ϕ) and porosity (ε) of the material, where permeability varies with porosity, and porosity changes depending on the level of compression.

Permeability is an intrinsic property, which depends on the internal structure (morphology) of the material. Therefore, it is difficult to find general forms to describe ϕ=f(ε) the permeability-porosity correlation. The variation of permeability with porosity has been studied extensively, in connection with various applications. Even though the bibliographical study revealed many equations having the form ϕ=f(ε), their validity when applied to a certain material should be validated experimentally .The most famous of all is the Kozeny-Carman (K-C) equation, the first which allows to determine the permeability based on structural parameters: particle diameter (*d*) and porosity of the materials (ε), respectively. The formulation of these correlations is based on the model of flow through capillary tubes, using the hydraulic radius principle.

The squeeze of the liquid imbibed inside sheets of 3D textiles generates an in-plane, axi-symmetric flow inside void space of the internal fibrous structure. Some permeability-porosity correlations were obtained theoretically for structures with parallel, perpendicular, or randomly disposed fibers with respect to the direction of flow. Many of the studies found in the literature regarding the permeability of fiber-based porous structures were focused on resin transfer molding (RTM). Parnas and Salem [4], as well as Gebart [5] initiated the research for resin flow inside dense fibrous woven reinforcements. Woven reinforcements have a principal orientation of fibers, and the flow is usually parallel to the fibers or perpendicular, across the fibers. Both papers validate their specific flow models using unidirectional and radial permeameters, respectively. Another theoretical model for the compression of porous or fiber composites with three-dimensional flow inside the solid structure was developed by Gutovski at al. [6]. The fiber composites have high solid fraction and under compression multiple fiber/fiber contacts are created, with an important impact on permeability.

Ghadar [7] adapted the K-C equation for fibrous materials using the hydraulic radius principle, and this version is widely used in the literature. McGregor [8] explored the absorption of dyes on fibers and proposed a different value for the K-C constant. Lawrence and Shen [9] also proposed a new value for the K-C constant for the flow inside nonwovens with polypropylene fibers for applications in wet-press concrete casting. The cross-plane and in-plane permeabilities were measured experimentally in support of their model. Zhu et al. [10] studied experimentally the compression-dependent Darcy permeability of soft fibrous porous media, evaluated K-C equation and proposed two other semi-empirical with good performance.

For the flow through fibers, three important international benchmarks [11-13] should be mentioned. These papers present in a gathering manner experimental results for the in-plane flow through engineering textiles – which are, in general, reinforced composites.

One of the most extensive analyses of the experimentally obtained permeability-porosity correlation of fibrous materials was carried out by Jackson and James [14], based on 16 bibliographic sources. Using these results, they proposed a model taking into consideration a supplementary direction of flow through three-dimensional arrays.

Based on the literature survey, we can state that the methods of measurement are not yet standardized. Moreover, the scattered values of the measured permeability led to differences of more than one order of magnitude [11]. It can also be concluded that, in general, results obtained for 3D fabrics, even though extensive, are limited by the specific application envisaged within a study (which usually leads to a narrow interval for permeability) [15-16], as well as by the fluids and the porous materials of interest. No experiments have been reported for the axisymmetric permeability of 3D fabrics taking into consideration a variation with the level of compression. the current work aims to determine experimentally the permeability of two selected S3D fabrics and to develop new permeability-porosity correlations, in order to widen their range of applicability. A review of empirical and analytical models for flow through fibers is presented and some revisions of representative models are proposed to increase accuracy.

2. Materials and experimental procedure

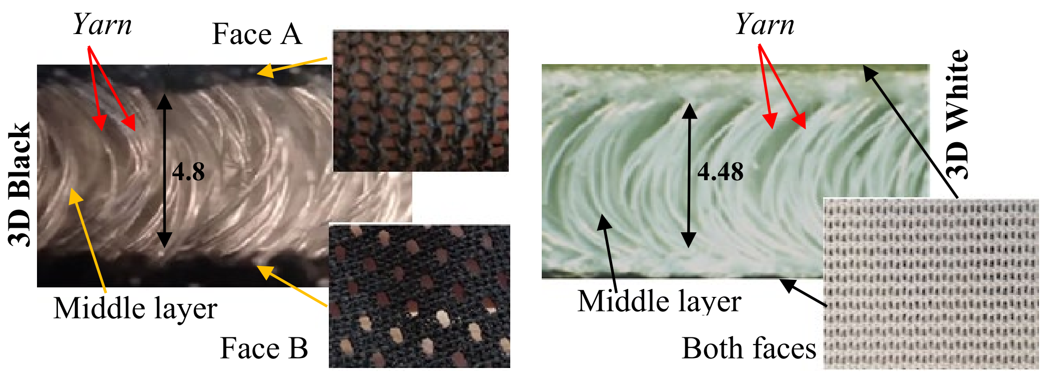

Fig. 1. Internal structure and faces for 3D Black (*left*) and 3D With (*right*)

An accurate description of the internal structure is a prerequisite to understand the fluid flow inside 3D fabrics. For the experimental study presented herein, two 3D fabrics from different manufacturers were selected, having close geometric configurations and dimensions, but structural particularities that allowed differentiation. The two materials are hereafter referred to by their colour: 3D Black (manufacturer Heatcoats, UK) and 3D White (manufacturer VOMATEX GmbH, Germany).

While the so-called "3D Black" material (Fig. 1) was studied previously by the authors (the characterization of its internal structure is presented in [17]), the 3D White material only came recently to our attention. 3D White is relatively different, compared to 3D Black, because its two faces have identical patterns (Fig. 1). The curvature of the yarn and the density of the middle layer are also different, when comparing the two materials. The typical properties (density, thickness, yarn and wire thickness, yarn density) for both materials are summarized in Table 1.

Table 1

Structural characteristics of the materials evaluated experimentally.

	3D Black	3D White
Material	100% Polyester	100% Polyester
Mass per unit area [g/m^2]	770 ± 30	570 ±60
Thickness [mm] h_0	6.3 ± 0.4	5.5 ± 0.4
Faces thickness S1/S2 [mm]	0.85/0.645	0.51
3D Spacer yarn thickness (SEM *measurements*) [µm] d_f	157	153

The porosity of the materials was measured using different methods (Table 2): gravimetric determination, volumetric determination (using simple immersion in liquid and measuring the displaced volume). For both materials, the faces were carefully detached, allowing the measurement of porosity separately.

Table 2

Porosity measurements.

Method	Layer	Porosity ε	
		3D Black	3D White
Gravimetric Determination	Face S1/S2	0.760/0.803	0.904
	Spacer yarn	0.961	0.931
Volumetric Determination (using immersion in liquid)	S1/ S2	0.762/0.812	0.942
	Spacer yarn	0.953	0.936

In-plane measurements for the selected materials were made using an in-house built permeameter [18] on specimens of 100mm outer diameter and 15mm the inner diameter. The fluid flows through the material and it is collected on the outer circumference of a disc sample. The pressures on different radial positions

(Fig. 2) (including the pressures at the inlet *(p_1)* and outer limit *(p_4)* of the material sample) were measured, in order to find the pressure, drop along the direction of flow (pressure sensors $p_1...p_4$ were placed at radius $r_1...r_4$). Two supplementary pressure sensors (p_5 and p_6) were used on the same radii as pressure sensors p_2 and p_3, in order to verify if the pressure perpendicularly to the direction of the flow is constant.

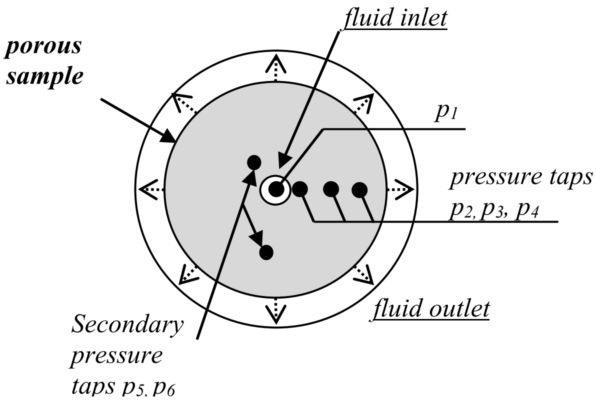

Fig. 2. The geometry of the experimental device – *radial permeameter*

Each specimen of 3D fabric was compressed with successive compaction levels and the rate of flow was measured for several distinct values of the input pressure. The measurements were repeated more than three times and as a rule the average of the measured values were used for visual representation. To correlate the rate of compression with the porosity, it was assumed that the solid matrix of the porous layer does not change its in-plane area during compression (the conservation of solid fraction); as a consequence, the product between the solid phase and the thickness (h) of the porous layer is constant:

$$(1-\varepsilon_0)h_0 = (1-\varepsilon)h \qquad (1)$$

The volumetric flow rate (Q) measurement is straightforward, being based on weighting the amount of fluid flowing through the permeameter over a given accumulation time. Further, the mean velocity of the fluid $u(r)=Q/A$ (also called *Darcian velocity*) was obtained by dividing the rate of flow (Q)to the cross-section area ($A=2\pi r\cdot h$). For this measurement, the flow through the faces was considered negligible and was disregarded, thus the rate of flow was calculated only for middle section, consisting of the yarns. This approximation was made based on the noticeably high difference in porosity between faces and middle yarn layer.

Attempts were made to measure experimentally the permeability of faces on manually produced samples. The results showed that for zero compression, the parasitic wall flow was too high to be neglected, affecting significantly the results.

For the study of permeability under compression, the permeameter could not generate enough force to significantly compress the faces, which were very thin and had a considerable stiffness.

3. Experimental results

For each thickness and supply pressure values, there were at least three series of tests performed successively. The scatter of the results has shown relative differences of ± 5% and thus, they were averaged. The permeabilities of both materials were calculated with the Darcy model - eq. (2) –by using the pressure gradient and rate of flow. For an easier comparison of the results obtained the *relative permeability* is used by dividing the permeability to the square of fiber diameter d_f.

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{\eta}{\phi} u(r) = -\frac{\eta}{\phi} \cdot \frac{Q}{2\pi r \cdot h} \tag{2}$$

The graphs from Fig. 3 presents the correlation between the pressure gradient (between the inlet and outer limit of the permeameter) and flow velocity.

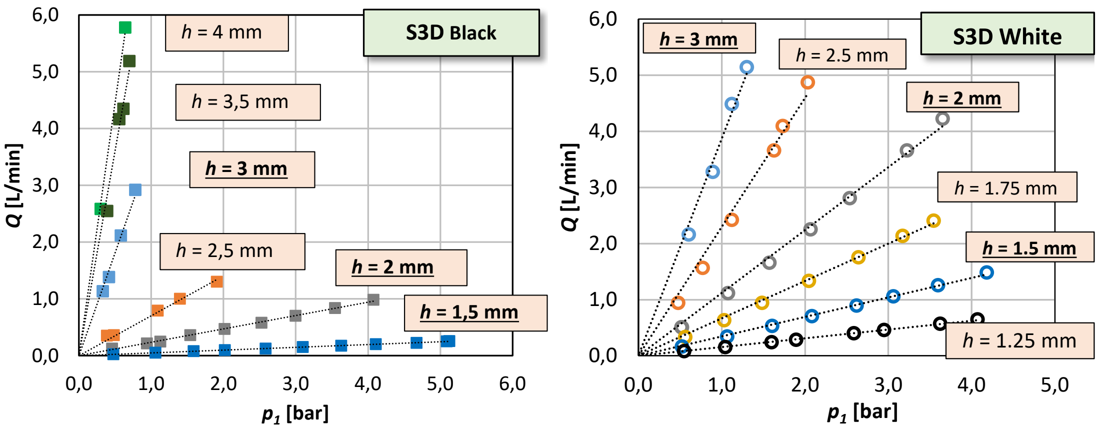

Fig. 3. Correlation between pressure gradient and mean flow velocity for 3D Black (*left*) and 3D White (*right*)

Fig. 4 depicts the relative permeability measured for different compression levels of the materials as a function of the supply pressure. One can see that the permeability is not influenced by the supply pressure when the material is highly compressed. However, when the material is lightly compressed, the soft and deformable structure is affected by high pressures and the relative permeability increases with pressure.

The use of Darcy's model is limited by a series of assumptions, namely a laminar, isothermal flow of a homogeneous fluid. There are some debates on defining the limits of laminar flow in porous media, but the accepted limit of laminar flow is the unit value of the corrected Reynolds number (*Re*) with the permeability: $Re = \rho u \sqrt{\phi_{\max}}$. For both materials, the values of *Re* are below 0.6.

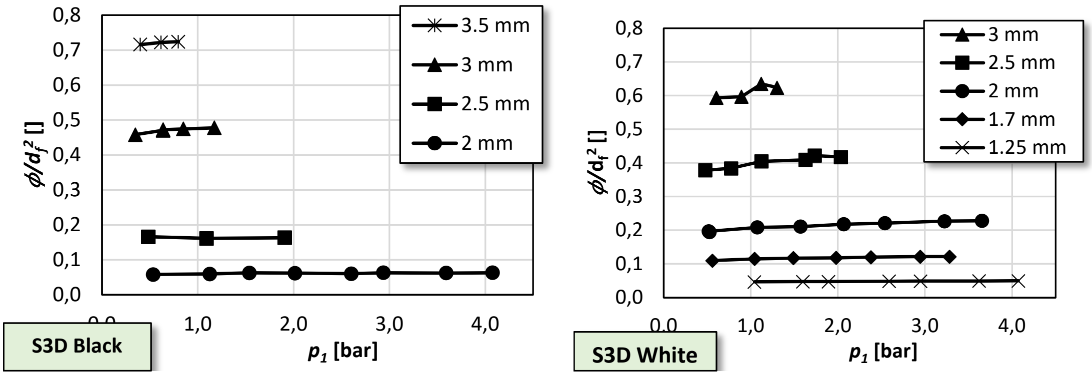

Fig. 4. Permeability variation with supply pressure for 3D Black (left) and 3D White (right)

Based on the solid fraction conservation, for each measurement, the permeability can be correlated with the porosity of the compressed material. In Fig. 5 the permeability is presented as a function of porosity. These graphs have also integrated the stress-strain response of the material during compression. The stress-strain response was measured using a standard compression machine, and the strain was correlated with porosity by using the solid fraction conservation (eq. (1)).

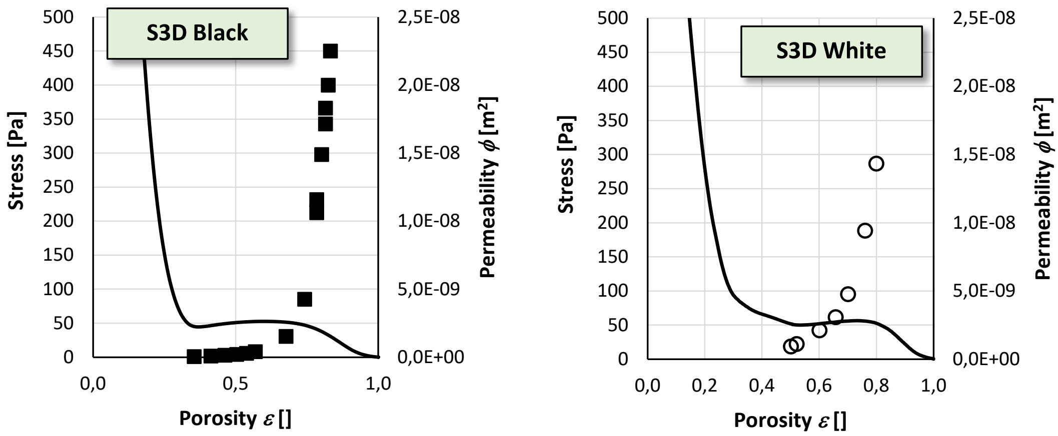

Fig. 5. Stress-porosity diagram during compression, correlated with the permeability variation for 3D Black (left) and 3D White (right)

From the graph in Fig. 6 one can remark the relative permeabilities for both materials are almost overlapped. The error bars represented in Fig. 6 show relative grade differences for the permeability measured at the same thickness because they include values obtained for the entire range off supply pressure as shown in Fig. 4.

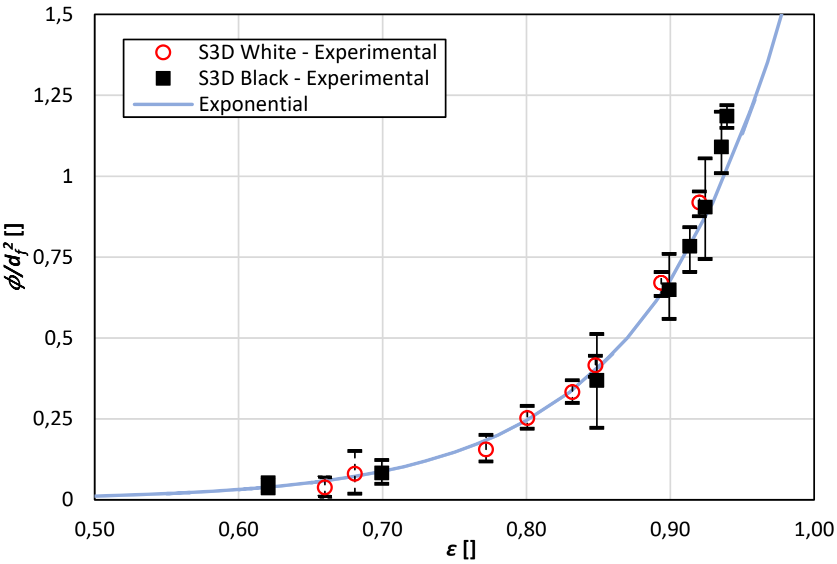

Fig. 6. Permeability-porosity variation measured experimentally and fitted with an exponential equation

Correlation models between permeability and porosity are obtained both theoretically and experimentally. The theoretical models are based on two similar approaches: the effective hydraulic radius model, and the friction coefficient model ("*drag coefficient*"), which are applied when the fluid flows through interstices with tubes aligned with, perpendicular to, or inclined relative to the direction of flow. The study emphasizes that no correlation model has general applicability, being only valid for particular cases, for materials and fluids limited to the area of interest of the respective study. Table 3 presents synthetically the models found in the widely circulated literature for fibrous materials. A first theoretical validation of the experimental data collected for both materials relied on the Kozeny-Carman relation. The data regarding the permeability variation where approximated with the K-C equation using the least-square method:

$$S = \sum_{i=1}^{N} (y_i - y_{i,\exp})^2 \tag{3}$$

where y_i and $y_{i,\exp}$ are the predicted and experimentally measured values, and n is the total number of data.

Table 3

Relevant permeability eq. selected from the literature for fibrous materials

Model	Equations	Coefficients*
Effective hydraulic radius	$\frac{\phi}{d_f^2}=\frac{1}{16k}\frac{\varepsilon^3}{(1-\varepsilon)^2}$ - Ghaddar [7] modified form of Kozeny-Carman	*k*=9.47
	$\frac{\phi}{d_f^2}=\frac{1}{16k}\frac{\varepsilon^n}{(1-\varepsilon)^m}$ - Generalized Kozeny-Carman	*k*=6.33 *n*=0.84 *m*=5.28
	$\frac{\phi}{d_f^2}=\frac{1}{16k}\left(\sqrt{\frac{1-\varepsilon_{\lim}}{1-\varepsilon}}-1\right)^3/\left(\frac{1-\varepsilon_{\lim}}{1-\varepsilon}+1\right)$ - Gutowski et al.[6]	*k*=0.15 ε_{lim}
	$\frac{\phi}{d_f^2}=\frac{k}{4}\left(\sqrt{\frac{1-\varepsilon_c}{1-\varepsilon}}-1\right)^{5/2}$ - Gebart [5]	*k*=0.52 ε_c=0.25

**Specific coefficient determined for presented experimental results*

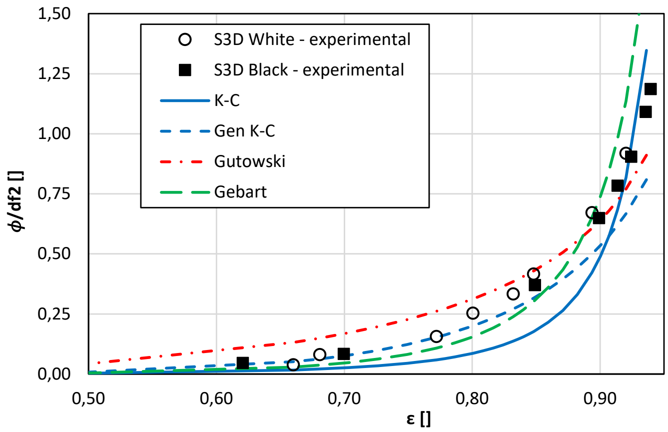

Fig. 7. Permeability-porosity variation and approximations using generalized equations based on the literature for combined experimental results

Fig. 7 shows a good correlation for a value of the K-C constant *k*=9.47, which shows that the determined values are very similar when compared to *k*=5..10, indicated by Ghadar [5] for other fibrous materials. Specific coefficients were also found for all the equations presented in Table 3, using the least-square method. When compared with experimental results, (Fig. 7) a good correlation was found for K-C and a generalized variant. A good performance was revealed for the models of Gebart [5] and Gutowski et al. [6]; the specific coefficients found after fitting the results were also presented in Table 3.

4. Conclusions

Permeability was evaluated experimentally for two selected three-dimensional textiles using an axi-symmetric permeameter. Relative high input pressure (reaching maximum 5bar) and various compression rates were used to measure the permeability and to determine its variation with porosity. The validity of Darcy's law was verified, and the results showed a proportional dependence between the rate of flow and pressure. Our efforts were directed towards finding a single equation capable to predict permeability for both studied materials, since they were similar from a yarn structure point of view. The combined results for permeability were fitted with the Kozeny-Carman equation and two other formulations selected from the literature, namely Gutowski et al. and Gebart. The specific coefficient of the Kozeny-Carman equation was obtained, being in accordance with widely accepted values (k= 5…10). A simple exponential equation was also used to fit the results with a good approximation next to a generalized form of the Kozeny-Carman equation with 3 variable parameters. For all selected equations, relating permeability and porosity on a large interval of porosity values is impossible. Good performance can be found only on a limited interval of porosity.

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