EXPERIMENTAL DETERMINATION OF TEXTILE PERMEABILITY: A BENCHMARK EXERCISE

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ABSTRACT: The design of an optimal liquid composite mould is a difficult and time-consuming process. To optimise the mould without too much trial and error, the production process is simulated for different mould models. An important input parameter for these simulations is the permeability of the preform permeability. The permeability can be obtained experimentally, or by CFD simulations. In this paper we concentrate on the experimental process, and we compare different set-ups and their results. The paper examines the existing methods of measurement of permeability of textile preforms. It compares values of permeability of the same non-crimp and woven fabrics, measured in the benchmarking exercise in eleven laborato ries employing different methods, e.g. saturated and non-saturated permeability, radial and unidirectional flow. It is demonstrated that many methods yield a dispersion of different orders of magnitude of permeability values for the same textile. These results highlight the need for normalisation of permeability measurements.

KEYWORDS: Darcy, Permeability, Fibrous reinforcement, Textile, Benchmark, Experimental.

INTRODUCTION

Liquid Composite Moulding (LCM) is one of the most used production techniques for composite materials. The name groups subclasses like Resin Transfer Moulding and Injection/Compression Moulding. All LCM techniques involve the flow of a resin through the textile that is draped inside the mould. The mould design and the way the textile layers are deformed to fit inside the mould, have an important influence on the production time and the resulting part quality. The placement of the inlets and outlets e.g. is to be chosen very carefully. To help the mould designer, different LCM simulation packages exist. One of the most important input parameters these tools require, is the permeability of the textile.
The permeability K is the ratio of an externally applied force on a porous medium, and the averaged velocity u of the fluid that flows through the medium. Written as the law of Darcy, this results in:

$$\mathbf{u} = \frac{\mathrm{Re}}{L^2}\mathbf{K}\left(\frac{\mathbf{f}}{\mathrm{Fr}} - \nabla p\right) \tag{1}$$

The applied force can be the pressure gradient ∇ p, or a body force f . The 13 equation is written in dimensionless form,

$$\mathrm{Re} \equiv \frac{\rho_\infty u_\infty L}{\mu} \tag{2}$$

and

$$Fr \equiv \frac{u_\infty^2}{L\|\mathbf{f}\|} \tag{3}$$

are the Reynolds and Froude number of the flow. Here, μ is the dynamic viscosity. For an incompressible fluid, ρ_∞ is the constant density. The constant u_∞ is normally the mean fluid velocity, and L is a characteristic length of the concerning structure, e.g. the moulds length. The validity of this law has been addressed analytically byWhitaker [1] with the volume averaging technique, and by Mikelic [2] with mathematical homogenisation. The authors do not mention a strict law for validity, however, both authors come to the conclusion that the pore size must be much smaller than the size of the total porous medium. From literature we know that the permeability ranges from 10^{-7}m2 for porous gravel to 10^{-18}m2 for granite [3]. These data do not determine a condition for the average pore size, however they show that Darcy's law is used for a large range of materials and pore sizes. Note that the permeability of the unsaturated and the saturated medium will be different. The permeability K is a 3D tensor and contains nine elements that have to be determined. However, the tensor is symmetric [1, 2], so there is a system in which the tensor is a diagonal matrix. In this system, called the principal system, only three elements have to be determined. The saturated permeability can be estimated analytically, as function of the volume fraction and packing arrangement and also as function of deformations like shear. These analytical formulae, however, have parameters that are not known beforehand, and for the determination of which computational modeling or experimental measurement of at least some permeability values is necessary. Numerical simulation of the permeability, based on computer models of the textile is possible. To determine the permeability experimentally, a broad range of different experimental setups have been developed. These setups range from uni-directional saturated experiments, to 2-directional flow front tracking with electronic sensors. Results of experiments have been published [7], but not yet have the results of these setups been compared thoroughly with the objective of going into a normalization procedure. The goal of this paper is to compare different setups, in order to identify the scatter range between the different experimental setups and techniques, aiming at establishing calibration parameters and ultimately at standardisation of the permeability measurement. The following institutes have agreed to be part of a benchmark exercise: Clausthal (CSL), Centre of Structure Technologies (CST), Ecole des Mines de Douai (EDM), Ecole Polytechnique Fédérale de Lausanne (EPFL), Ecole Polytechnique de Montréal (EPM), Deutsches Zentrum für Luft und Raumfahrt (DLR), K.U.Leuven (KUL), Université du Havre (LH), Ecole des Mines de St. Etienne (MSE), ONERA, University of Nottingham (UN), Vrije Universiteit Brussel (VUB). The fabrics were kindly provided by Hexcel (France). None of the methods and setups used in this paper are exactly the same. Previous results demonstrated that the permeability values determined by different institutes/methods can differ by more than an order of magnitude. This comes on top of the scatter that is found on the permeability values resulting from different tests on one setup only.

The benchmark is organised by ONERA and K.U. Leuven. Most of the international actors have been contacted but due to limited amount of reinforcements, the list of participants has been limited to the first responders.

EXPERIMENTAL SET-UPS

Measurement of the resin velocity or flux

There are different characteristics to describe an experimental permeability identifying setup. Some of the experimental setups used have certain characteristics in common, but none of them are exactly the same for all properties. This makes it difficult to compare the influence of e.g. the experience of the person that conducts the experiments, the influence of the pre-treatment of the textiles and the post-processing of the results. We concentrate on characteristics like dimensionality and the flow velocity measuring technique. A first distinction can be made between 1D and 2D setups. The former can only determine one component of K per experiment. The 2D setups track the elliptical flow front in the two in-plain directions and can determine two components Kx and Ky in one experiment. In either case, the trough-the-thickness permeability Kz cannot be determined together with the in-plan permeability values, but is obtained with a different experiment.

The permeability of porous medium has been defined by Darcy in the case of saturated porous medium. Following Darcy's hypothesis, the permeability is an INTRINSIC parameter of the material, i.e. it does not vary as function of pressure, nature of fluid, … What we all *abusively* call dry or unsaturated or transient permeability of the porous medium is NOT an INTRINSIC parameter of the material. Nevertheless, we will use the word permeability for both saturated and dry experiments in this paper. The textile permeability can be determined for saturated or dry textiles. In the first case, the textile is first impregnated with the resin, and only then the resin flux and pressure drop are measured. In the latter case the velocity is measured while impregnating the dry textile. In the 1D case, one also distinguishes between flow front tracking setups, and setups that measure the flux as function of the time. Flow front tracking devices use electrical sensors or have a translucent upper mould have, so that the flow front can be traced with an optical device. The electrical sensors of the VUB sense the change of electrical conductivity when the fluid reaches the sensor, while the sensors of UoN are pressure sensors. A completely different approach is used by EDM2. Instead of measuring the fluid flux and pressure, here the textile compression response is measured, and from that the permeability of the textile is computed.

In the case of "dry permeability" setups, the flow front arrival times must be post-processed in order to determine the permeability. Different methods exist and yield different results, even if the same arrival times are used as input. This important aspect will not be discussed in this short paper.

INFLUENTIAL PARAMETERS

Two of the most important parameters are the flow arrival times or flux and the pressure gradient. How these are determined was discussed in previous section. However, more parameters are important when it comes to comparing different permeability values.

Fluid characteristics

To determine the permeability, once the fluid pressure and velocity are known, the law of Darcy is used, which also holds the viscosity of the fluid. Moreover, the law of Darcy (1), is only valid for Newtonian fluids, although there is no perfect Newtonian fluid. Thus, it is important to use fluids as Newtonian as possible. The most used fluid in the test is corn syrup. To use the law of Darcy (Eqn. 1) to compute the permeability once the average velocity and/or pressure drop are determined, also the fluid density and viscosity must be known. Therefore it is important to accurately determine the experiment conditions like temperature, and keep them constant during the experiment. Two institutions have tested if the fluid was Newtonian, EPM and KUL. EPM found that for shear rates higher than $\approx$ 0.1 /s the fluid shows Newtonian behaviour. KUL found that the fluid does not have a pure Newtonian behaviour. It exhibits shear-thinning behaviour following a power law.

Volume fraction

Another source of possible errors and diverging permeability values, is the determination of the volume fraction Vf of the textile inside the mould. This is an important parameter, as the permeability is always expressed as function of Vf, and, what is more, the permeability is substantially sensitive to changes in Vf. The volume fraction is normally computed according to the formula $Vf = (n*\rho_s)/(h*\rho_v)$. With n the number of plies inside the mould, h the cavity thickness, ρ_s the superficial density of the fabric and ρ_v the volumetric density. The number of plies n is the only parameter in this equation that is unarguably fixed. The densities are provided by the manufacturer of the textile, however, measurement of the institutions not uncommonly yield deviant values. Depending on the type of setup, the height of the mould cavity can (or can not) easily be measured, and is normally not a source of large errors. Indeed, transparent mould haves are often not stiff enough, and bend due to the high imposed pressure. This changes the shape, and thus the height, of the mould cavity.

BENCHMARK FABRICS

Three different fabrics were used for this study, all three provided by Hexcel. The fabric named G1113, is a woven twill glass fabric (areal mass of about 390 g/m²), the second fabric, G986, is a woven twill carbon fabric (areal mass of about 285 g/m²), and finally NC2 is bi-axial a non-crimp fabric (areal mass of about 420 g/m²).

RESULTS AND DISCUSSION

The Table 1 present the types of setup used by the different partners. The in-plane permeability values for the G1113 fabric are presented in Fig. 1. Fig. 2 presents the anisotropy, τ = Kxx/Kyy, for the same textile. For the G986 fabric permeability and anisotropy are plotted respectively on Fig. 3 and Fig. 4. Immediately from these results it can be seen that there is a large scatter between the values from the different institutes. The values for the Kxx of G1113 range from $2.0e^{-11}$m² for Vf = 0.51 to $4.4e^{-10}$m² for Vf = 0.50, which is more than one order of magnitude difference. The same is true for the G986 fabric. Moreover, results from the same institution on the same textile show deviation of up to 40-50%. This agrees what was found in previous permeability measurement studies. On the figures, a distinction is made between 1D and 2D permeability values, and between dry and saturated values respectively. For the X-values, different least squares fits are shown. One fit is the fit of all permeability values in the X-direction, and the other fits make a distinction between dry and saturated permeability values, and 1D and 2D values respectively. From these figures, we can conclude that the difference in permeability values obtained with 1D or 2D set-ups is not significant. The saturated and dry permeability values on the contrary, differ significantly. From Figures 2 and 4, one can only conclude that the set-up has no direct influence on τ.

Table 1 Overview of the properties of the different setups

Institution	1D/2D	Saturated/Dry	Constant pressure
Technical University of Clausthal	1D	D	Y
ETHZ	2D	S	Y
DLR-AIRBUS 1	2D	D	N
DLR-AIRBUS 2	2D	S	N
Ecole des Mines de Douai 1	1D	S	Y
Ecole des Mines de Douai 2	2D	D	n/a
EPFL	1D	S	Y
Ecole Polytechnique de Montréal 1	1D	D	Y
Ecole Polytechnique de Montréal 2	1D	S	Y
K. U. Leuven	2D	D	Y
Université du Havre 1	1D	D	Y
Université du Havre 2	1D	S	Y
Mines de Saint Etiennes	1D	S	N.A.
ONERA/DMSC	1D	S	Y
University of Nottingham	2D	D	Y
Vrij Universiteit van Brussels	2D	D	Y

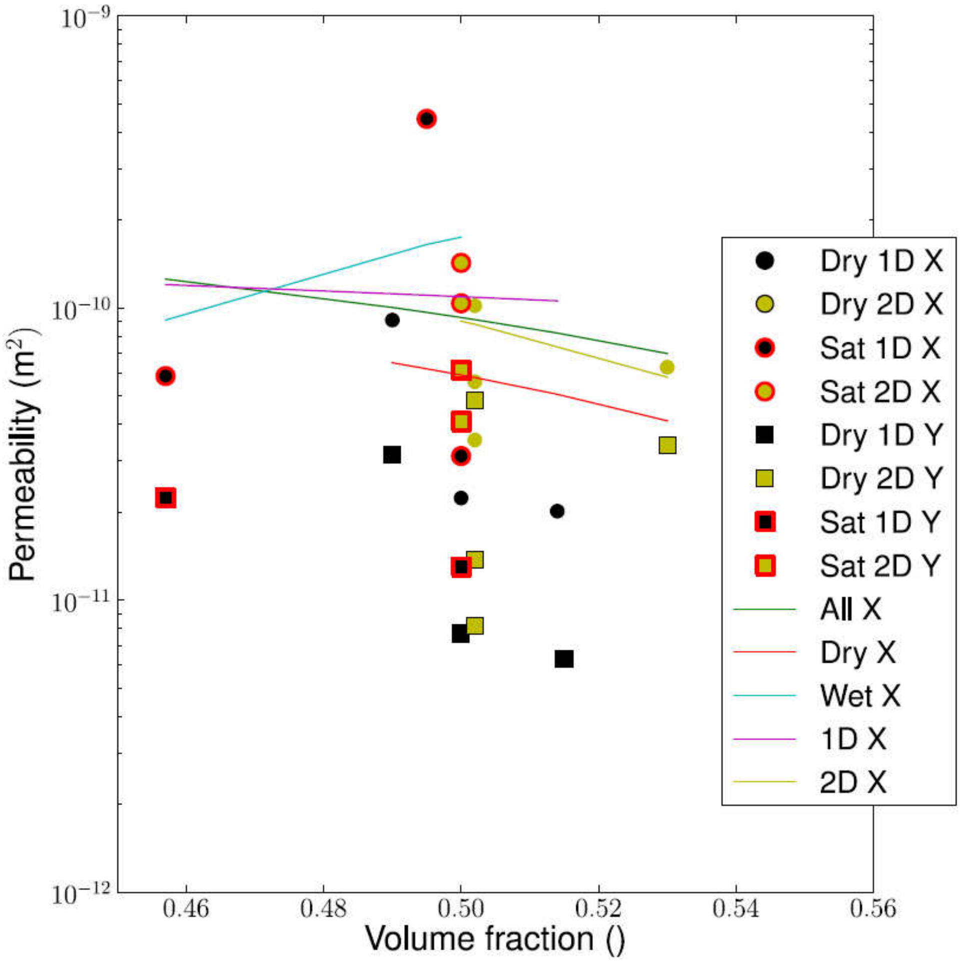

Fig. 1 Experimental in-plane permeability values of the G1113

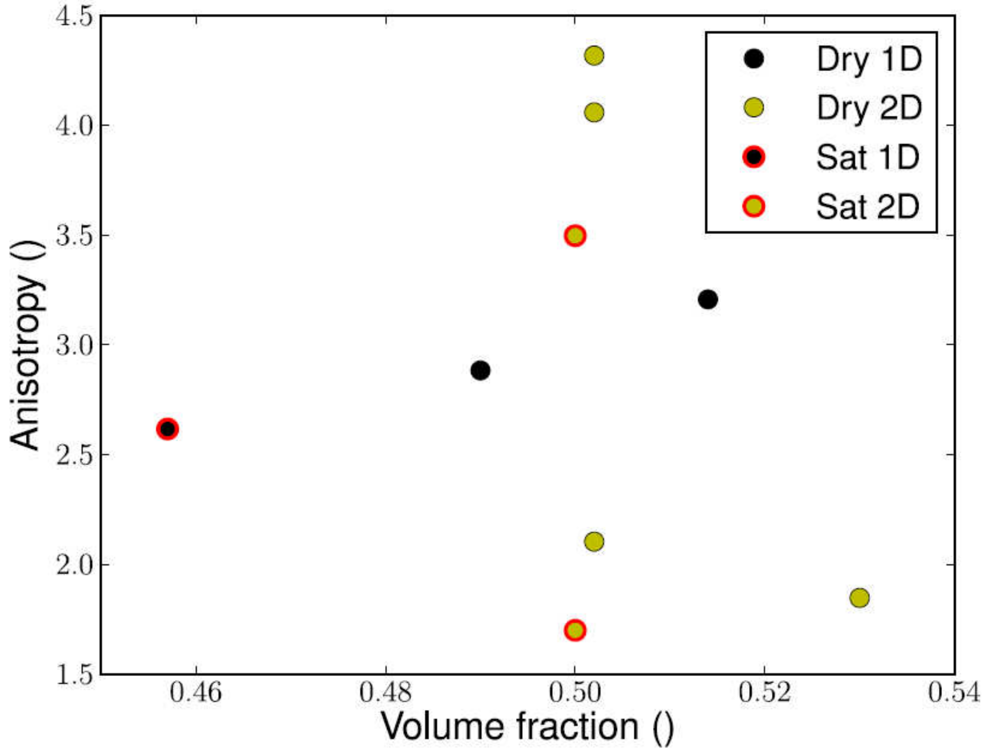

Fig. 2 Experimental in-plane anisotropy values of the G1113

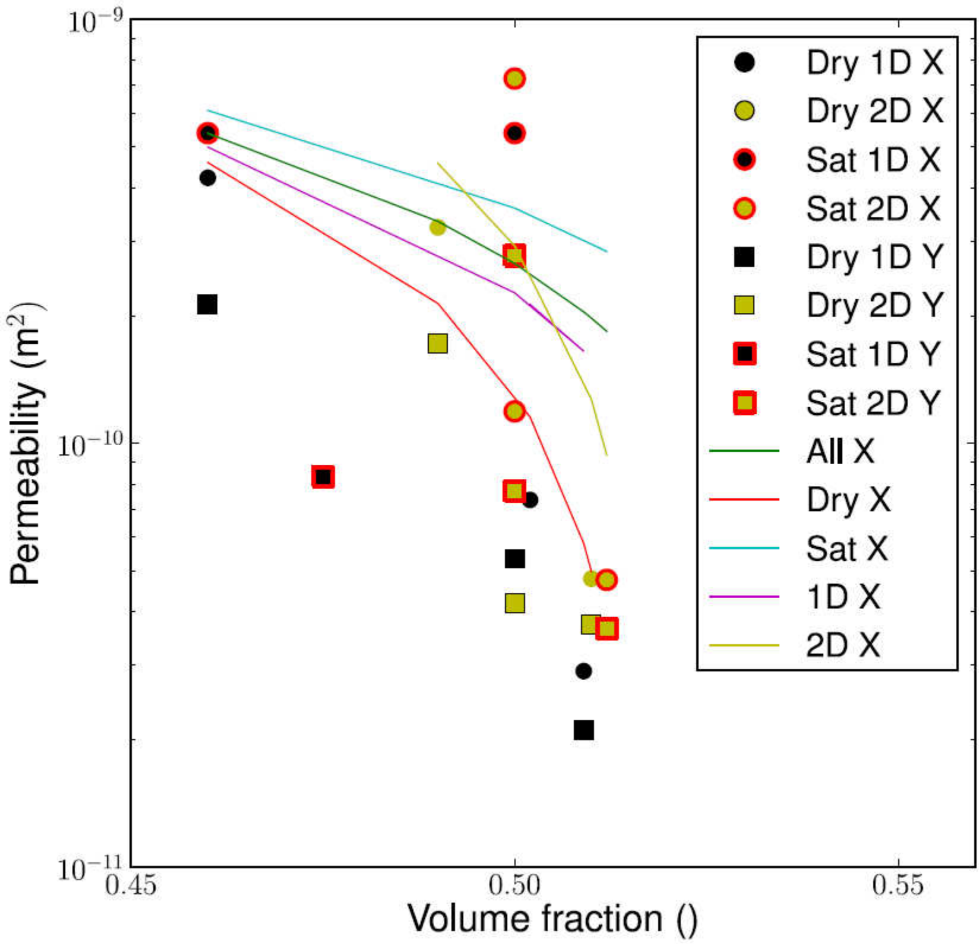

Fig. 3 Experimental in-plane permeability values of the G986

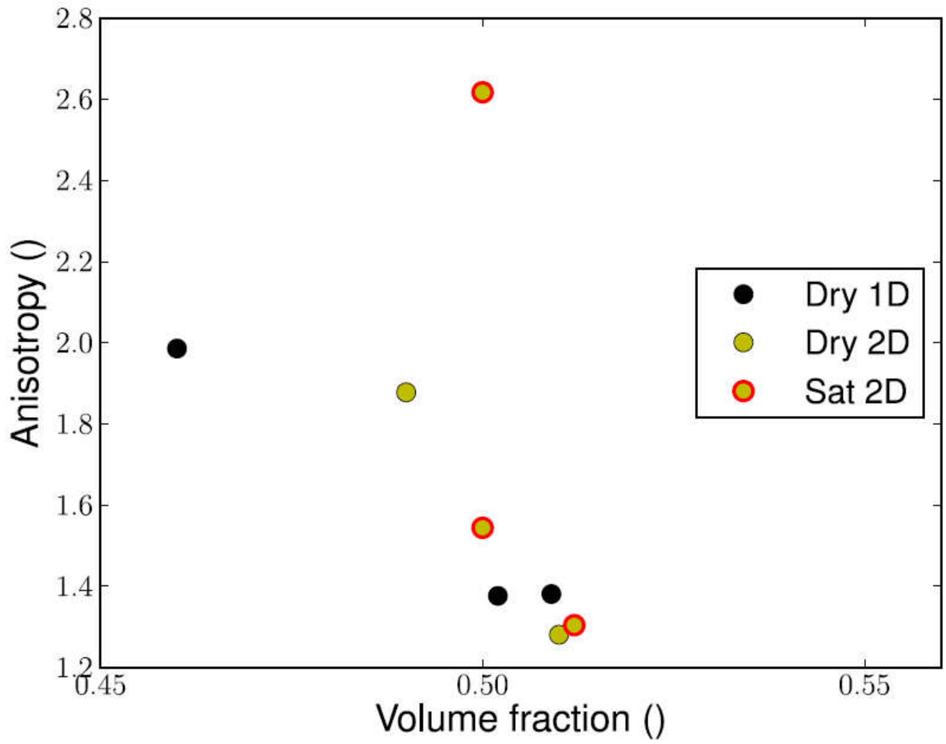

Fig. 4 Experimental in-plane anisotropy values of the G986

CONCLUSION

Permeability measurement methods and set-ups of eleven institutes have been benchmarked. For this exercise, three different textiles were used: a glass and a carbon twill woven fabric, and a non-crimp fabric. Firstly, the exercise confirms what was previously found, i.e. the values from the same set-up and institute can differ by up to 40-50%. Secondly, it shows that even larger scatter, up to three orders of magnitude, exists between results form different institutes. The aim of the exercise is to establish a calibration factor between unidirection and bi-directional set-ups on the one hand, and, dry and wet permeability values on the other hand. Therefore, it was taken care of to exclude the influence of other parameters like the fluid viscosity and fibre volume fraction. Dispate the large scatter, one can come to two conclusions with caution:

- The permeability of a saturated preform is higher than the permeability of a dry preform;
- There is no significant distinction between 1D and 2D set-ups.

This paper is the result of a first step towards a calibration. Further research will involve the participation of more groups and experiments on more textiles or other specimens. Also, a comparison with numerically computed values will help to come to an established calibration.

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