Measurement of the Average Permeability of Natural Fibre Mats in Resin Transfer Moulding Application

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SUMMARY

The permeability of hemp fibre mats used in a resin transfer moulding process were computed from the measured mould filling time, using a simplified mathematical approach. This approach could be applied because of the simple geometry of the mould and because a certain number of assumptions were made The permeability values obtained were found to decrease with increasing fibre content. In addition the hemp fibre permeability was found to be an order of magnitude lower than the value for glass fibre at a fibre content of 19 vol%. This preliminary work shows the importance of studying the permeability of natural fibre systems in order to provide the data necessary for the proper design of industrial moulds.

INTRODUCTION

In recent years injection moulding has attracted more and more attention from the industry as an alternative to traditional moulding techniques such as hand lay-up and spray-up. Resin Transfer Moulding (RTM) is a very attractive process for producing complex shapes for a high-volume production. In addition this technique has low volatile emissions, low tooling costs and good surface finish.

In order to obtain high quality parts it is essential to control and measure a certain number of key variables such as injection pressure, outlet pressure, temperature, resin curing time and mould filling time. This last parameter especially is extremely important from an industrial point of view. The injection time has to be as short as possible while resulting in a completely filled mould. The positioning and number of inlet and outlet ports is therefore crucial to the success of this technique.

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The design of moulds is nowadays achieved by flow simulation techniques, which are more efficient and less costly than the old trial-and-error process[1-4]. To be able to predict the mould filling characteristics properly the models need accurate parameters, especially concerning the reinforcement porosity and permeability. This last value is usually the most difficult to obtain, and therefore is crucial to the success of the prediction.

Many methods such as one-dimensional flow and radial flow have been proposed and investigated to measure the permeability over the past years. Generally fibre reinforcements are anisotropic and have different permeability values in the three spatial directions. Two methods, one dimensional and radial flow, have been shown to give acceptable results for all the components of the permeability tensor In the 1D or linear flow experiments to determine the permeability of a preform, the fluid is injected at constant pressure or constant flow rate in a narrow strip of material from one edge, and the flow front position is recorded as a function of time. The permeability is then computed from these data. The in-plane components of the permeability tensor could be calculated using the same technique, however the radial flow method is usually preferred because it reduces the edge flow influence. In that case the fluid is injected in a circular preform through

its centre at constant pressure and constant flow rate. Once again the progression of the elliptical flow is recorded as a function of time, and the in-plane permeabilities can be computed. These techniques have been extensively described in the literature[5-10].

Usually these measurements are performed with moulds or set-ups especially designed for this purpose. For this reason the results obtained do not take into account the shape of the real mould as well as other variables influenced by the type of mould-making materials (aluminium, stainless steel…). Plexy-Glass® is normally the material of choice for the apparatus to allow visual tracking of the flow pattern. Many other parameters such as the clamping pressure, compaction and capillary pressure were found to have an influence on the permeability measurements[5,11,12]. For instance, low clamping pressure can deform the mould when the resin is injected into it, which changes the volume fraction of the fibres. This means that the measured permeability will not reflect the correct volume fraction of the fibre used. Also, the relation between the pressure and flow rate becomes non-linear when the inlet pressure exceeds the clamping pressure, which is a deviation from Darcy's law. The nesting effect of the fibre layers, i.e. compaction, influence the permeability because it is difficult to arrange the fabric layers in the same manner from one experiment to another. Hence the permeability will vary from experiment to experiment. Capillary effects are negligible if the flow of the resin is higher than 1 mm/s; on the other hand if the resin flow is slower, capillary effects should also be taken into account when computing permeability. Most of these techniques are used to measure the unsaturated permeability where the fluid flows through the dry fibre mat. This is usually the value of interest for mould filling simulations. However, in this case the flow can be separated into two parts, i.e. the flow inside each layer of material and the flow between these layers[10]. It is therefore obvious that different experiments will result in different permeability values.

The methods just mentioned are widely used to evaluate the permeability of fibre preforms. However, as just discussed, they present many drawbacks, which explains why there is still a lot of research to do in this area. Hoes *et al.*[10] presented a new set-up based on a 2D radial flow experiment. Electrical sensors were used to detect the flow front automatically The set-up was validated and the results showed a statistical distribution of the permeability, proving that a single value cannot characterize the whole material. More recently Ding *et al.*[13] also proposed a new approach that uses gas flow to compute the permeability of a preform before injection. This is based on the fact that resin and air permeability are highly correlated. The validity of the technique was established, and even though some measurement errors were observed, the method was considered to be very promising. The advantage is that there is no need for another set-up to compute the permeability data; they can be directly obtained *in-situ*.

Finally, Weitzenböck *et al.*[11] investigated the use of a 3D radial flow test to determine the permeability tensor of a preform. They observed that capillary flow was the dominant flow pattern. The only way to overcome it was to increase the inlet pressure, which resulted in a flow-induced compaction. In conclusion, this technique confirmed the difficulty of getting the full permeability tensor by any easy and fast method.

Recently hemp fibre/unsaturated polyester composites were manufactured using a RTM process[14]. In this work the injection time was longer than expected. The reason was attributed to a low permeability compared to traditional synthetic fibre mats. However, no calculations of the permeability were provided in that paper. It seems of first importance to give some information about the permeability of natural fibre mat. There are no data currently available for these materials, even though they are increasingly popular in the composite industry.

As described earlier, the measurement of permeability usually requires a particular set-up. Since this type of apparatus was not available for this study it was decided to evaluate the permeability by a mathematical approach using the data obtained from the experiments. The method was based on a simplification of the real problem. The objective of the work was therefore not to provide very accurate permeability data but to compare the values obtained for the hemp mats with a reference value for a glass fibre mat computed with the same method.

EXPERIMENTAL

Materials

In this study the commercial unsaturated polyester resin Stypol 040-8086 from Cook Composites and

Polymers was chosen. This resin is manufactured for use in closed mould processes such as RTM. It is a low viscosity resin (100cP at 25 °C), which starts reacting on addition of an initiator. In this case the chosen initiator was methyl ethyl ketone hydroperoxide (MEKP) DDM-9 from Atofina. Following a kinetic study it was decided that a MEKP concentration of 1.5% should give the best results. Like most commercial products, this resin contains small amounts of inhibitor and promoters.

The fibres used in this study were manufactured by Flaxcraft, Inc. A 100% hemp fibre mat, with a thickness of 8mm and a density of 600 g/m^2, was used. For certain samples[14] the Bastmat 100, a 4 mm mat made of 67% hemp fibres and 33% kenaf fibres, was used as well. The average fibre length for the natural fibre mats was not measured. The glass fibres came as a commercial random mat of approximately 200 g/m^2 with an average fibre length of 1 in.

METHODS

Resin Transfer Moulding

The resin transfer moulding equipment used in this work consisted of a square mould, an injection pot and a temperature controlled water bath. A schematic of the experimental set-up is shown in Figure 1. The mould, made entirely of aluminum, was opened and closed manually with 16 screws distributed around the cavity. The dimensions of the cavity were 380 mm by 380 mm by 6.7 mm. The two inlet ports were situated under the mould, close to the corners of the cavity. Their exact position can be found in Figure 2. A vent port was located at the centre of the upper face of the cavity. It should be noted that the thickness of the composite was defined by a frame placed between the upper and lower sections of the mould; it could therefore be modified in further experiments.

Prior to a typical experiment the surfaces of the mould were cleaned with the Frekote® PM mould cleaner and then coated with the Frekote® B-15 Sealer and the Frekote® 700-NC mould release agent. Once these coatings were cured, layers of natural fibres' mats having the mould's size were placed in the cavity. The mould was tightly closed and a vacuum of 725 mm of mercury was created in the cavity through the vent port connected to a venturi aspirator placed on a tap. At this point the fibres were dried for 2 hours by circulating water at 55 °C and this was done to remove the moisture present in the fibre. The mould was then cooled down with cold water. In the meantime the resin was mixed with the initiator and placed in the injection pot. From there the resin was injected into the mould with compressed air at a constant gauge pressure of 172 kPa. This pressure was kept constant in the pressure pot by continuously adjusting the compressed air valve manually. The lines from the injection pot to the mould and from the mould to the venturi aspirator were equipped with low-density polyethylene tubing with an internal diameter of 4.32 mm. All the ports on the mould had this same diameter.

Figure 1. Diagram of resin transfer molding equipment

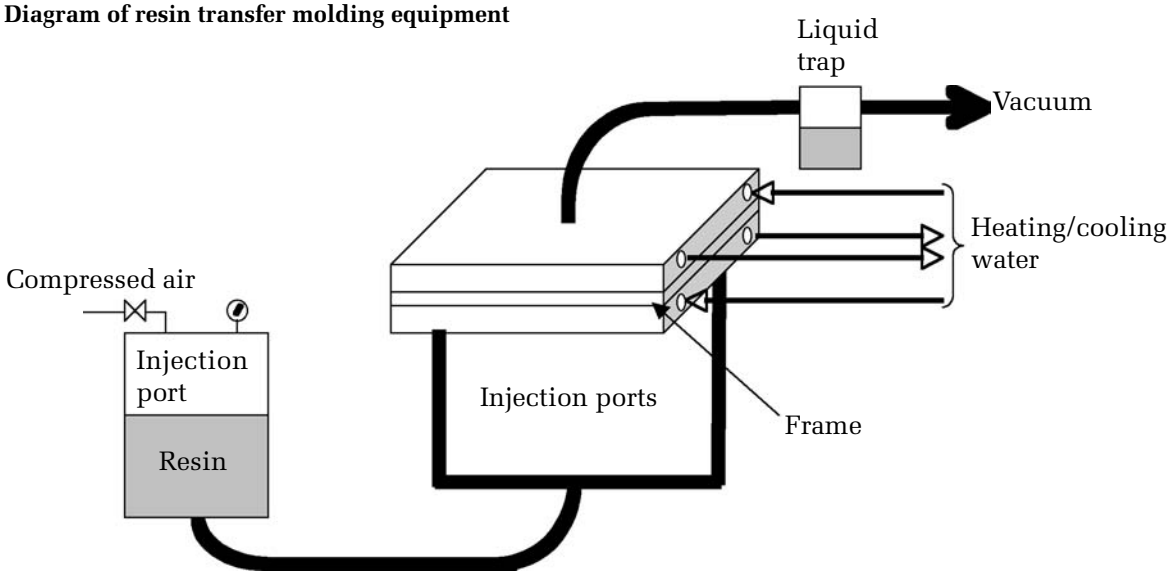
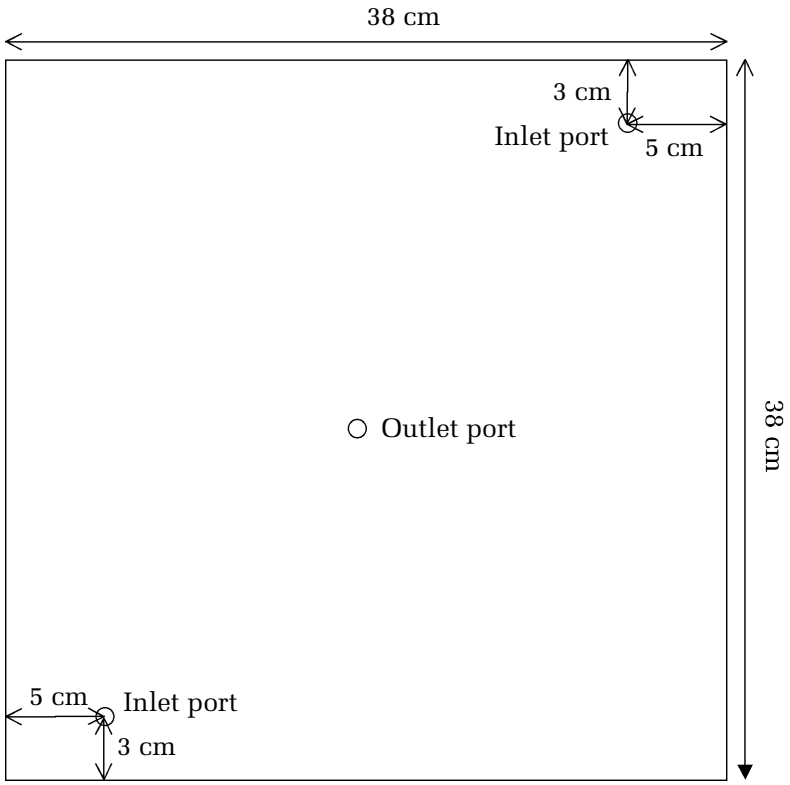


Figure 2. Actual position of the injection port



The injection time, which is of interest here, was defined as the time from the start of the injection to the instant when the resin could be observed exiting the mould through the vent port. A small flask was placed between the vent port and the tap for safety, to prevent any resin from flowing to the tap water. The resin was left flowing at the inlet for 5 more minutes to make sure that the mould was filled completely. Hence, the so-called injection time defined here is not the actual mould filling time. This choice will be explained in the Model section. The injection time was measured for various hemp fibre contents and for 19vol% glass fibre content.

THEORY AND MODEL

Darcy's Law

The basic law relating the fluid velocity to the applied pressure gradient was stated by Darcy in the 19th century[15]. It is commonly used to describe resin flow through preforms in RTM processes. The law relates the fluid velocity to the applied pressure gradient as follows:

$$\bar{u} = -\frac{[k]}{\mu}\Delta P \qquad (1)$$

where $\bar{u}$ is the superficial velocity, [k] the permeability, ΔP the pressure gradient and μ the viscosity of the fluid.

Model

First, two reasonable assumptions were made to define the problem. The thickness of the mould's cavity being a lot smaller than its length and width, the flow in the transverse direction through the mats was neglected. This is a valid approximation since the biggest resistance to the flow to fill the mould comes from the in-plane permeability. This leads to the second assumption: since only random mats were used in the experimental work, the permeabilities in both in-plane directions can be considered as equal. The aim of this work was therefore to describe the flow of resin in the mould mathematically, in order to calculate the value of the in-plane permeability with the data available.

In order to simplify the calculations the inlet port was assumed to be at an equal distance from the two sides of the cavity, as shown in Figure 3 (a). This was only a slight approximation, since the port was fairly close to that position in reality. This allows an analysis only on one side of the mould, since the cavity in that case was symmetric along its diagonal. Moreover, in that configuration the flow of resin could be defined in two different ways, depending on whether the resin did or did not reach the wall of the cavity. In any case, the flow front was assumed to be circular even though, once it was in contact with the walls, friction would have deformed it slightly.

Let us define t_f as the time when the resin reaches the mould's centre. For any time t before t_f the volumetric flow of resin can be written as follows:

$$\dot{V} = u_r(\theta+\theta')rh = -\frac{k}{\mu}(\theta+\theta')rh\frac{\partial P}{\partial r} \qquad (2)$$

where $\dot{V}$ is the resin volumetric flow rate, u_r the superficial velocity of the resin defined by equation 1, r the spatial variable centred on the inlet port, h the thickness of the cavity and (θ+θ') the angle describing the shape of the front (see Figure 3 (b)). Before the front reaches the walls of the cavity this angle is equal to 2π. It should be noted that the angle is a function of the radial position of the front r_f. Equation 2 can then be integrated, knowing that $\dot{V}$ is a constant for any radial position r at time t:

$$\dot{V}\int_{r_0}^{r_f}\frac{dr}{r} = \frac{(\theta+\theta')kh}{\mu}\int_{P_m}^{P_p} dP \qquad (3)$$

where r_f stands for the position of the front, r_0 for the inlet port radius, P_m for the pressure in the mould, and P_p the pressure at the inlet port. The integration of equation 3 gives, after being rearranged:

$$\dot{V} = \frac{(\theta+\theta')kh}{\mu}\frac{(P_p - P_m)}{\ln(r_f/r_0)} \qquad (4)$$

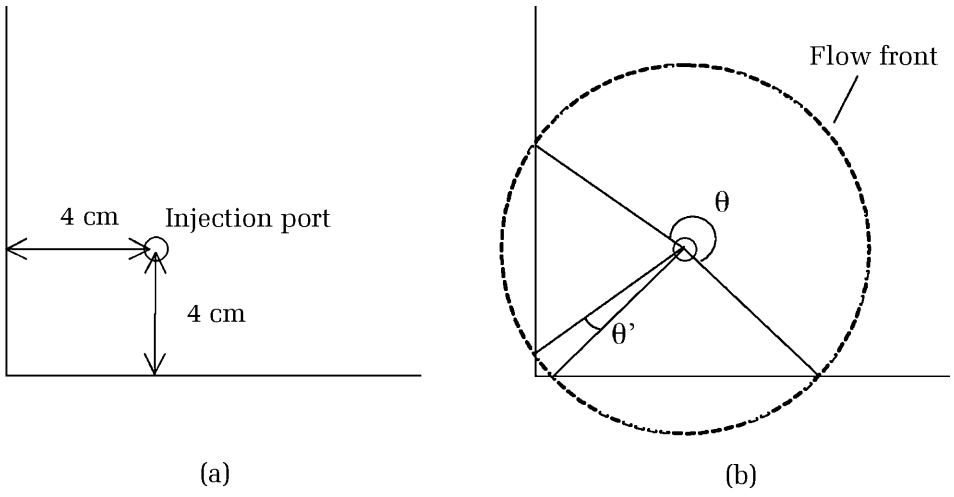
The volumetric flow rate can also be defined as the flow through the circular tube from the injection pot to the inlet port. This result, also known as the Hagen-Poiseuille equation[16], gives:

$$\dot{V} = \frac{\pi r_t^4}{8\mu l}(P_i - P_p - \rho g z) \qquad (5)$$

with r_t the radius of the tubing, l the length of the tubing from the injection pot to the inlet port, P_i the pressure in the injection pot, P_p the pressure at the inlet port, ρ the density of the fluid and z the height difference between the inlet port and the level of fluid in the injection pot. The last two equations can be combined together to eliminate P_p, which is a function of r_f. The result is:

$$\dot{V} = \left(\frac{(P_i - P_m - \rho g z)}{\frac{8\mu l}{\pi r_t^4} + \frac{\mu \ln(r_f/r_0)}{(\theta+\theta')hk}}\right) \qquad (6)$$

Figure 3. (a) Assumed position of the injection port and (b) assumed shape of the flow front



The next step is to express the velocity of the resin front:

$$u_{r_f} = \frac{dr_f}{dt} = \frac{\dot{V}}{(\theta+\theta')\, r_f\, h\varepsilon_0} \tag{7}$$

where ε_0 is the porosity of the preform. This equation, combined with equation 6, can be rewritten as follows:

$$\frac{\partial r_f}{\partial t} = \frac{1}{(\theta+\theta')\, r_f\, h\varepsilon_0} \left(\frac{(P_i - P_m - \rho g z)}{\frac{8\mu l}{\pi r_t^4} + \frac{\mu \ln(r_f / r_0)}{(\theta+\theta')\, hk}} \right) \tag{8}$$

which can be integrated as follows:

$$\frac{1}{\varepsilon_0 h}(P_i - P_m - \rho g z) \int_0^{t_f} dt = \int_{r_0}^{R} r_f\, (\theta+\theta') \left(\frac{8\mu l}{\pi r_t^4} + \frac{\mu \ln(r_f / r_0)}{(\theta+\theta')\, hk} \right) dr_f \tag{9}$$

where R is the distance from the centre of the inlet port to the cavity's centre. For any fixed value of the permeability k this equation can be evaluated numerically, since all the other parameters are known experimental variables. In this case the integral would have to be solved for three separate cases. For r varying from r_0 to R, the angle (θ+θ') is changing as follows (see Figure 3 (b)):

- For $r \le r_1$ (shortest distance from the inlet to the cavity's walls): $(\theta+\theta')=2\pi$
- For $r_1 \le r \le r_1\sqrt{2}$: $(\theta+\theta') = 2\pi - 4\arccos\left(r_1 / r_f\right)$
- For $r_1\sqrt{2} \le r$: $(\theta+\theta') = 3\pi/2 - 2\arccos\left(r_1 / r_f\right)$

The resistance of the pipe from the injection pot to the mould can be neglected since the tubing is fairly short and the flow rates quite low. In addition the mould and injection pot were always kept at the same level, making the term ρgz negligible as well. This simplifies further equation 9:

$$\frac{k}{\mu\varepsilon_0}(P_i - P_m) \int_0^{t_f} dt = \int_{r_0}^{R} r_f \ln(r_f / r_0)\, dr_f \tag{10}$$

This equation can be solved analytically as follows:

$$\tau = \frac{R^2}{2r_0^2}\ln\left(\frac{R}{r_0}\right) - \frac{R^2}{4r_0^2} + \frac{1}{4} \tag{11}$$

where:

$$\tau = \frac{k t_f (P_i - P_m)}{\mu \varepsilon_0 r_0^2} \tag{12}$$

τ is a dimensionless number, which is a function of the geometry of the mould only. This means that for a given mould, τ is a constant. Therefore for two experiments performed with the same mould and the same resin, equation 12 leads to:

$$\frac{k_1 t_{f_1} (P_i - P_m)_1}{\varepsilon_{0_1}} = \frac{k_2 t_{f_2} (P_i - P_m)_2}{\varepsilon_{0_2}} \tag{13}$$

As mentioned earlier, a number of assumptions have been made to solve this problem. The way the equations were solved supposes that once the flow front has reached the cavity's wall, there is no more flow in that direction. The flow towards the dry zones of the mould is the only flow considered. In addition, only a two-dimensional flow was considered in this study, neglecting the transverse flow of resin. This also neglects the resistance of the mat above the inlet port, which is expected to be important since the port's diameter is very small. In order to take into account these approximations and obtain more reliable permeability data, the experiment performed with glass fibre mats was used as a calibration for our system in equation 13. The permeability of glass fibre mats used in this computation were obtained from the literature. Once one term of equation 13 is known it can be used to infer the permeability of other mats from the mould filling time, the injection pressure and the porosity.

Kozeny-Carman Equation

In the case of a packed porous bed with random, tortuous paths available for fluid flow, the Kozeny-Carman equation gives the permeability as a function of the bed's porosity and of a shape factor[17]. This assumption is representative of the assembly present in a non-woven fabric with random fibre orientations throughout the fabric structure. The equation is as follows:

$$k = \frac{1}{K_0 S_v^2} \frac{\varepsilon_0^3}{(1-\varepsilon_0)^2} \tag{14}$$

where K_0 is the Kozeny constant (equal to 4.17), ε_0 the porosity and S_v the shape factor, defined as the ratio of the surface area of the solid phase over its volume. This simple formula should give a good approximation of the permeabilities of randomly oriented mats in RTM moulds.

RESULTS AND DISCUSSION

The main assumption made in this approach is that the flow front was sharp and symmetric about the mould's diagonal. Since there was no way to observe the resin flow in the current set-up, a few experiments were stopped before the mould was completely filled. The mould was then heated up quickly in order to solidify the resin. Pictures of these unfinished parts can be seen in Figures 4 and 5. Figure 4 shows a very early stage of the mould filling process, before the resin hit the cavity's walls. The flow front and the injection gate have been highlighted in white. It is clear from this image that the flow front is sharp and perfectly circular in its early stage. Figure 5 presents the flow front in a later stage of the mould filling process. Once again the injection ports have been highlighted in white as well as the diagonal of the cavity chosen as axis of symmetry. As mentioned earlier in the model section, the inlet ports were assumed to be at equal distances from the walls. It can be noticed that this is not exactly the case. However, the discrepancy between the assumed and the real position is only about one centimetre, which makes this approximation acceptable.

The flow front again was mostly circular and symmetric. The only discrepancy observed was close to the wall, where some edge flow occurred and disturbed the circular profile. This was to be expected since the contact between the fibre mats and the cavity's walls was not perfectly tight. However the edge flow was quite small and did not have a marked influence on the circular front progressing toward the centre of the mould. These observations confirm the validity of the assumptions made earlier.

As described in the model section, the first step to obtain the permeabilities of the fibre mats was to calculate the value of τ (equation 12) from an experiment performed with glass fibre mats and using results from the literature. The experiment was run with 20% glass fibres or a porosity of 0.80. The test was performed at an injection pressure of 308 kPa and the values of the other parameters are summarized in Table 1. The injection time

Figure 4. Incomplete mold filling flow front in the early stage of the filling

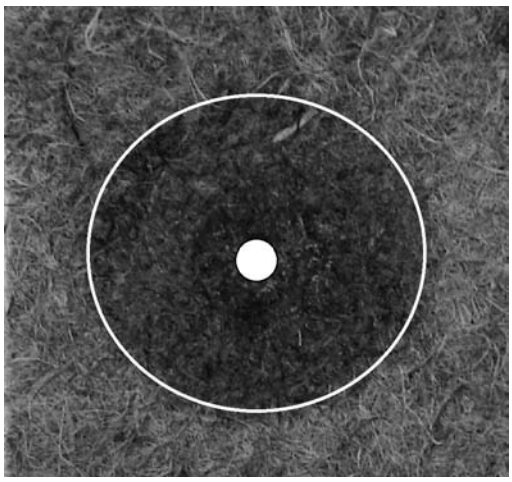
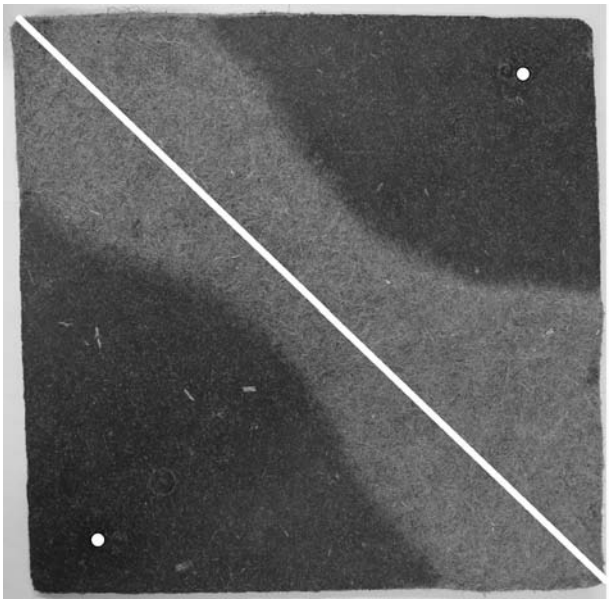


Figure 5. Flow front in a late stage of the mold filling



was 105 s. From the literature[9,10] the permeability of glass fibre mats at 20% fibre content is around 10^{-9} m^2. This leads to:

$$\frac{kt_f(P_i - P_m)}{\varepsilon_0} = 3.982x10^{-2}\ \frac{kg \cdot m}{s}$$

Now that equation 13 has been calibrated to take into account the approximations made in the simplified model, the permeabilities of the natural fibre mats

can be computed. Once again the parameters needed for these calculations are summarized in Table 1. It can be noticed that two values of P_i were reported. The first batch of experiments with the mould was achieved with an injection pressure in the pot of 274 kPa. The injection times obtained with this set-up were given in an earlier publication[14].

The mould filling times measured experimentally with the natural fibre mats are reported in Table 2,

Table 1. Constant parameters

Parameter	Value	Parameter	Value
P_i	308 or 274 kPa	r_0	$2.16x10^{-3}$ m
P_m	4.813 kPa	μ	0.1 kg/(m*s)
R	0.2m		

Table 2. Injection time in function of the injection pressure and the fibre content

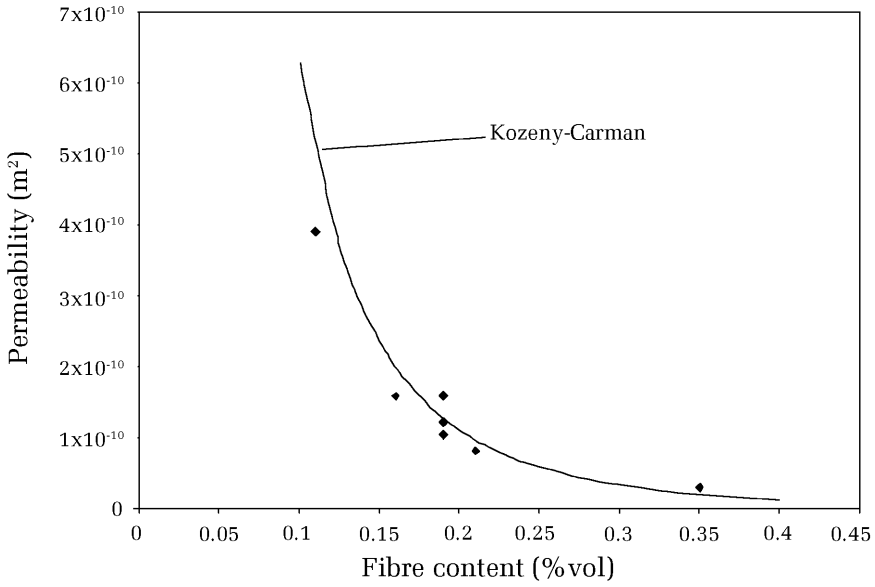
Pressure	Fibre Content	Injection time
274 kPa	11%	300 s
	16%	660 s
	21%	1140 s
308kPa	19%	655 s
	35%	1860 s

as well as the injection pressure used and the fibre content by volume. In the case of the 19% fibre content, four measurements were taken and the value presented is the average of these four values. For the other fibre contents only one test was achieved.

The permeabilities obtained from the resolution of equation 13 were plotted as a function of the fibre content and are shown in Figure 6. As expected, the permeability decreased with increasing fibre content and roughly followed an exponential decay. All the values obtained for 19% fibre content are shown as well. Some of the permeabilities at 19% fibre content were higher than expected. This discrepancy could be explained by the difficulty of keeping the injection pressure constant manually for some of these experiments. A slight difference in injection pressure can make a substantial difference in the mould filling time.

In this particular study the point of interest was the comparison between the glass fibres and the hemp fibres. The permeability for a 20% glass fibre preform was chosen to be 10^{-9} m^2. By looking at Figure 6 the permeability of hemp fibres under the same conditions and for a similar volume content was around 10^{-10} m^2. There was a difference of a factor of 10 between these two materials. This is a very important observation for the application of natural fibres in closed mould processes. With such values existing moulds would have to be modified

Figure 6. Permeability as a function of hemp fiber content



in order to be used with natural fibres and avoid long mould filling steps.

There are various ways to overcome a lower permeability, such as by increasing the inlet pressure, adding more inlet ports or widening the existing inlet ports. It is clear here that the same injection procedure could not be used commercially for a composite containing 20% glass fibres and one containing 20% hemp fibres. In one case the injection time is 105 s while in the other case it is around 15 minutes for a pressure of 308 kPa.

The Kozeny-Carman equation presented earlier (equation 14) was fitted to the experimental data. The fitting parameter was S_v and the best fit was obtained for S_v=166835 m^{-1}. It can be seen in Figure 6 that the curve fitted the results very well, putting more confidence in the approach presented in this work. From the value of S_v the average diameters of the fibres could be evaluated. On the assumption that the fibres all have the same length (a very rough approximation for natural fibres) S_v is:

$$S_v = \frac{4}{\overline{D}} \qquad (15)$$

This gives an average diameter $\overline{D}$ of the fibres of approximately 24 μm. This value is smaller than the average diameter calculated from the size distribution presented in the literature by Prasad and Sain[18]. This average diameter was obtained as follows, assuming that all the fibres had the same length:

$$\overline{D} = \frac{\sum n_i d_i^2}{\sum n_i d_i} \qquad (16)$$

where n_i is the number of fibres of diameter d_i. Equation 16 gave an average diameter of 120 μm.

However, it is expected that the smaller fibres have more influence on the permeability value since they offer the most resistance. Knowing that there was a non negligible number of fibres of this dimension (or even smaller) in the mat, this estimation was within the expected range. Since some of the experimental points used to fit the Kozemy-Carman equation were obtained from single experiments, additional measurements would be needed to have more accurate results. The primary purpose of comparing the experimental results with this equation was to show that the data obtained are in the expected range, and followed an expected trend.

CONCLUSIONS

In this work the permeability of hemp fibres used in a resin transfer moulding process was evaluated using a mathematical approach. This approach was based on certain number of assumptions in order to simplify the problem. The main assumption, which stated that the flow front of the resin was sharp and symmetric, was verified by observing some unfinished parts. Further simplification of the solution resulted in a non-dimensional number that was used for the computation of the permeabilities. In order to take into account the approximations made in the model, the solution was calibrated using data from the literature and experimental results for a 20% glass fibre preform. From this number the permeability obtained from the experimental measurement of the injection time was found to decrease with increasing fibre content. The values obtained for the hemp fibres were shown to be a lot lower than for glass fibres. This first estimation of the permeability of natural fibre mats is of first importance for the future applications of these materials in the industry. Fabrication processes have to be optimized in order to produce a maximum number of parts in a minimum time. In this optic the mould filling time is critical. The proper design of a mould will therefore have to take into account the permeability of the material used in order to minimize this parameter. This preliminary analysis could be applied only to the experimental set-up used in this study. The values reported here are not presented as the actual permeability values even though some good confidence is put in this approach. More specific work will be needed to describe completely the permeability of natural fibres.

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SYMBOLS

k: permeability in m^2

$\overline{D}$: average diameter of the fibres

d_i: diameter of the fibres

h: thickness of the cavity in m

l: length of the tubing in m

K_0: Kozeny constant

N_i: number of fibres of diameter d_i

∇P: pressure gradient

P: pressure in Pa

P_i: absolute pressure in the injection pot in Pa

P_m: absolute pressure in the mould in Pa

P_p: absolute pressure at the inlet port

$\overline{u}$: superficial velocity vector

u_r: superficial velocity of the resin in m/s

u_{r_f}: resin front velocity

R: radial position of the mould's centre from the inlet port in m

r: spatial variable, radial position from the centre of the inlet port in m

r_0: inlet port radius in m

r_f: flow front radial position in m

r_t: radius of the tubing in m

S_v: shape factor

$\dot{V}$: volumetric flowrate m^3/s

z: height difference between inlet port and the level of liquid in the injection pot in m

ε_0: porosity

ρ: density of the resin in kg/m^3

μ: viscosity of the resin in kg/(m*s)

θ and θ': angles defining the flow front