CAPILLARY EFFECTS IN VACUUM ASSISTED RESIN TRANSFER MOLDING WITH NATURAL FIBERS

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ABSTRACT: Automotive industry has shown in the last years a growing interest in the use of green composites. Fibrous reinforcements made from natural resources have the advantage of being renewable, abundant, and cheaper than synthetic fibers and pose comparable mechanical properties. Liquid Composite Molding (LCM) techniques have proved to be suitable for processing natural fibers. Nevertheless, few issues still to be resolved, such as fiber impregnation and bonding to the polymeric matrix. Capillary effects have shown to be key in the impregnation of the fibers, mainly when the resin is infused or injected at low pressure. In the case of natural fibers, important capillary effects take place during impregnation due to the hollow structure of the fibers, small diameter and molecular polarity. In this work, the capillary pressure of a woven jute fabric was measured for different fiber volume fractions and its effect on permeability was studied. Permeability tests were conducted with different fluids in order to evaluate the impact of the chemical nature of the fluids in the infiltration process. This research gives an insight on capillary effects occurred during LCM with natural fibers.

KEYWORDS: natural fibers, capillary pressure, permeability, constant flow, VARTM

INTRODUCTION

Capillary pressure is defined as the energy per unit volume of a porous medium needed for replacing a gas (or vacuum) by a liquid. Capillary effects have shown to be determinant in the mechanisms of void formation during infiltration of fabrics [1-4]. There is an optimal infiltration velocity that produces composites with minimal void content. Below that velocity, capillary forces domain the infiltration process leading to void formation in the inter-tow region. But above the optimal value, viscous flow dominates and the voids are mainly created within the fibers tows [5]. In general, when

modeling flow trough dual scale porous media (woven or stitched fabrics), is necessary to analyze the flow in fiber tows, which have low permeability. Therefore, flow velocities are low and capillary effects cannot be ignored.
Several studies have been conducted in order to determine the magnitude of the capillary pressure developed in synthetic fabrics infiltration. Batch et.al.[3] investigated the capillary impregnation of aligned fibrous beds and found an optimal fluid speed for which micro and macro flow have the same rate and the void formation is minimized. Capillary pressures obtained for DOP fluid (dioctyl phthalate) and glass fiber (40-60 vol%) were in the order of 10 kPa. Patel et.al analyzed the resin-fiber wettability by conducting wicking test and capillary pressure measurements with different test fluids. They found, as a general trend, an increase in the capillary pressure with the decrease in matrix-fiber surface tension. Following the same experimental approach, Amico and Lekakou [6,7] conducted capillary rise experiments in glass fiber bundles with epoxy resin and silicon oil. They found good correlation between experimental and theoretical values of equilibrium capillary pressure for epoxy resin (9.6 KPa). Nevertheless, they did not explore dynamic effects in capillary pressure. Verrey et al [8] conducted infiltration experiments in non-crimp fabrics with different test fluids. They found negative values of capillary pressure for polyethylene glycol and lauryllactam 12 and positive values for epoxy resin. But in the last case, they found that for low capillary numbers (low fluid velocity), the resin changes its behavior from non-wetting to wetting, giving to flow enhanced by capillary forces
In the case of natural fibers (like jute) the capillary effects can be increased due to the hollow structure, low diameter and a polar character of the fibers. Nevertheless, scanty work has been conducted in order to study capillary effects in natural fiber preforms. In this work, the capillary pressure of a bidirectional jute fabric was measured for different porosities and type of fluids. The effect on the permeability determination was also analyzed.

EXPERIMENTAL

Materials

The fabric used in the experiments was a biaxial woven jute preform (Castanhal Textil, Brasil; surface density = 0.0300 g/cm^2). Fabrics were washed with a 2% V/V distilled water and detergent solution, to remove contaminants and normalize the fabrics conditions for all the tests. The fluids used for conducting the infusion tests were a 22 % V/V water/glycerin solution (viscosity values near 0.150 Pa.s), and a vinyl ester resin (Derakane 411-350 from Ashland, viscosity values near 0.5 Pa.s). A red colorant was used to improve the flow front visibility.

Methods

Two kind of infusion strategies were used in this work: constant pressure and constant flow rate experiments. All the experiments were performed in a rectangular metallic mold (500mm x 100mm) with a 2 cm thick acrylic lid. Permeability test were conducted in constant pressure mode.
In order to obtain the capillary pressure developed during the infiltrations, both constant pressure and constant flow rate experiments were conducted, following the procedure proposed by Verrey et.al. [8]. Under constant pressure, the total pressure difference (ΔP) that acts in the fluid is defined by

$$\Delta P = \Delta P_c - \Delta P_{app} \quad (1)$$

were ΔP_c is the capillary pressure and ΔP_{app} the applied pressure difference. If we integrate Darcy's law for unidirectional flow we obtain

$$x^2 = \theta^2 t \quad (2)$$

$$\theta^2 = \frac{2K}{\mu(1-V_f)} \left(\Delta P_c - \Delta P_{app}\right) \quad (3)$$

were x is the flow front position at a time t and θ^2 is a kinetics parameter (depending on the permeability K, the viscosity μ and the fiber volume fraction V_f) and it can be plotted as a function of the applied pressure difference. When extrapolating the line to $\theta^2 = 0$, ΔP_c can be calculated. For constant flow rate (Q), the expression for calculating ΔP_c is [8]

$$\Delta P_{app} = \frac{Q^2 \mu}{A^2(K(1-V_f)} t + \Delta P_c \quad (4)$$

were A is the cross sectional area of the mold. By plotting applied pressure difference vs time, ΔP_c can be estimated in a single experiment.

RESULTS AND DICUSSION

Fig. 1 shows the permeability of the jute fabric for different porosities measured with the two different test fluids. As observed by other authors [6,9] the dependence of the permeability on the type of fluid is an evidence of the importance of the wetting behavior and capillary forces acting in the infiltration process. Due to its chemical composition glycerin solution has higher polar character than the vinylester resin. The surface tension of the first fluid is 63 mN/m and for the resin is 37 mN/m. Unlike synthetic fibers, natural fibers have hydroxyl groups in the surface, which make them more compatible with polar fluids. In that case, a negative value of the capillary pressure is expected, i.e. it would enhance the flow. That would lead to an increase on the measured fabric permeability. In order to quantify the capillary forces, constant pressure experiments were conducted at different applied pressure and Eqn. 3 was potted (Fig. 2)

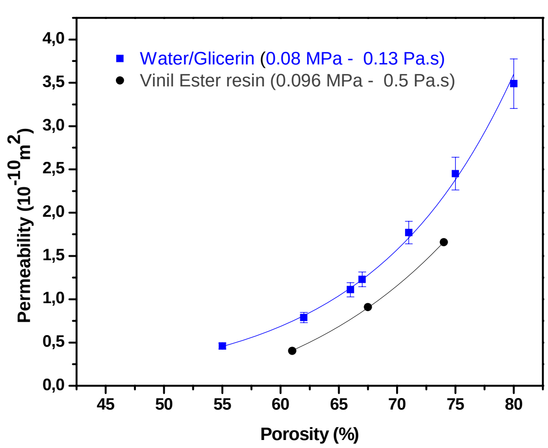

Fig. 1 Permeability – porosity relationship measured with different test fluids

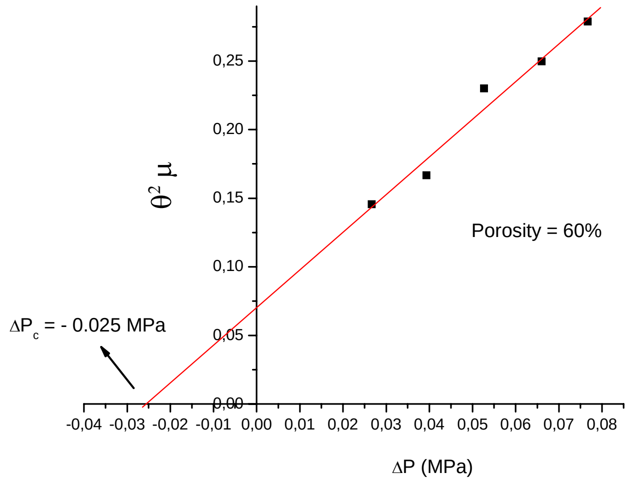

Fig. 2 Calculus of the capillary pressure (constant pressure infusions)

The results show that the capillary pressure is high but in the order of magnitude of the values found by other authors [batch amico]. As expected, negative values were found (spontaneous infiltration can occur). It is interesting to note that the capillary pressure can represent more than 20% of the external apply pressure, and therefore, it is important not to ignore this effect to avoid miscalculation of the fabric permeability. Although, the method used for the calculation can only give the order of importance of the capillary forces but do not give a value that could simply be added to the applied external pressure. During an infiltration process at constant pressure, the fluid velocity changes and so does the capillary number. As a consequence, the capillary pressure drop changes during the infiltration and with all the factors that can change the fluid velocity (external pressure, fiber volume fraction, fluid viscosity)

A more accurate way to measured capillary pressure is using constant flow rate infiltrations (0.075 ml/s – resin viscosity 0.5 Pa.s). Since only one experiment is enough to get a value, it is easier to determine the effect of fabric porosity. Fig. 2 shows the capillary pressure vs. fiber volume fraction for jute using vinyl ester resin as injection fluid (results from the literature for carbon fibers were added to the plot for comparison purposes).

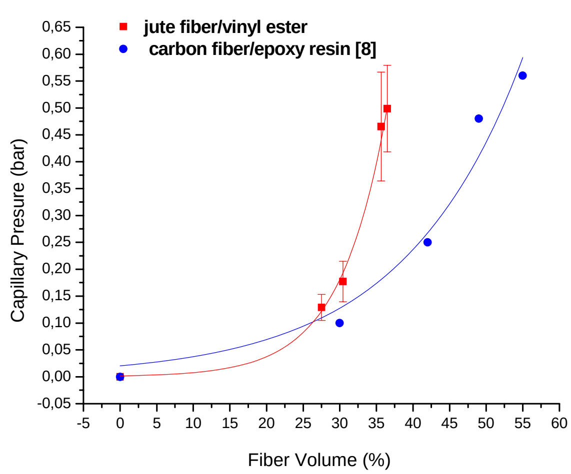

Fig. 4 Capillary pressure as a function of the fiber volume.

The results are in accordance with the difference observed in the permeability values obtained with the two fluids. The capillary forces are strong, probably due to the hollow and imperfect structure of the fibers that generates micropores on its surface.
When the fiber volume fraction increases, the capillary forces grow, but unlike the experiments conducted with the glycerin solution, the values are positive. That means that no spontaneous infiltration takes place with the vinyl ester resin. When comparing with the results obtained in the literature y can be seen that capillary effects grow more sharply in the natural fiber fabrics.
Studies at different flow rates and fluids are being developed in order to have a better understanding of how the capillary effects affect the infiltration process of natural reinforcements in Liquid Composite Molding techniques.

CONCLUSIONS

Infiltration experiments were conducted in order to determine the effect of the type of fluid on the permeability and capillary pressure of jute fabrics. The following conclusion can be state:
- Even when vinyl esters are consider compatible with natural fibers due to the presence of hydroxyl groups on its structure, the capillary pressure measured in this work show positive values measured in dynamic conditions.
- The differences observed in permeability and capillary pressure values observed for glycerin and vinyl ester resins is an indication that the permeability data obtained with a certain test fluid (in general non-reactive fluids) cannot be used for simulating actual infusion processes without taking into account the chemical similarity (polarity) with the resin.

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