CAPILLARY EFFECTS IN LCM WITH HIGH-VISCOSITY MATRICES AND HIGHLY ANISOTROPIC NON-CRIMP FABRICS

D. Salvatori, V. Michaud

Laboratoire de Technologie des Composites et Polymères (LTC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne CH-1015, Switzerland.
Corresponding authors' emails: damiano.salvatori@epfl.ch, veronique.michaud@epfl.ch

Keywords: *capillary effects; non-crimp fabric; in-plane flow; unsaturated permeability*

Introduction

Capillary phenomena play an important role in Liquid Composite Molding (LCM). For instance, capillary pressure drop (ΔP_γ) at flow front can either enhance or hinder the flow, acting as a wetting or non-wetting force, respectively. Capillary effects are generally evaluated based on the hypothesis that the saturation zone is very narrow (slug-flow assumption). ΔP_γ at flow-front is then extrapolated by a series of experiments performed at constant applied negative pressure difference (ΔP_{app}) [1-3].

Unsaturated (K_{unsat}) and saturated (K_{sat}) permeabilities, which can be determined in a single flow experiment, can be used to understand the extent of capillary phenomena [4]. The saturated permeability is assumed to be independent of the fluid, whereas the unsaturated permeability value depends on the fluid-fabric system and on the flow dynamics. If the flow is enhanced/slowed during impregnation, due to wetting/non-wetting behavior, the unsaturated permeability should be higher/lower than the saturated, thus the ratio $R_s = \frac{K_{unsat}}{K_{sat}} = 1 + \frac{\Delta P_\gamma}{\Delta P_{app}}$ should be higher/lower than 1.

In this study, R_s is used to investigate the role of capillary phenomena and explore the limits of slug-flow assumptions, in long-range infiltration of high-permeability glass non-crimp fabric, through a series of experiments at varying pressure, by means of intermediate-viscosity fluids, which are relevant from an industrial point of view for the development of a thermoplastic melt-RTM process.

Materials and Methods

The glass-fiber preform is a stack of highly anisotropic non-crimp fabric (G-PLY™, *Chomarat*) (*720 g/m²*), consisting of dense longitudinal tows stitched on a highly-permeable transverse layer, which create large channels of *3-4 mm* width in the flow direction. *5* plies of size *5x25 cm* are placed with the same orientation and compacted in a metallic frame of *3 mm* thickness to a final volume fraction of *46%*. The sizing is a formulation compatible with thermoplastic resins, notably polyamides.

An aqueous solution of poly(ethylene glycol) (PEG 35kDa, *Sigma Aldrich*) at *30%wt* and silicon oils (Bluesil™, *Bluestar Silicones*) with varying viscosity (η) and surface tension (γ) are used as test fluids. The viscosity is measured in flow mode in a concentric-cylinders and plate-plate rheometer (*TA-Instruments AR2000*) and the surface tension in air is measured through the pendant drop method.

Saturated and unsaturated permeability values are calculated from experimental data [5-6]. In typical measurements, unidirectional, in-plane fabric impregnation is performed in a transparent mold at constant fluid pressure and ambient temperature. The fluid is contained in a pressure chamber, and the pressure regulated with compressed air and measured in the resin with a sensor (*Keller S35X*) just before the inlet. The fluid flow is recorded with a digital camera (*Canon EOS700D, 1920x1080* pixels resolution at a frame-rate of *29.97 fps*) for post-experiment analysis of the flow velocity (v) and calculation of the unsaturated permeability. Squared flow front method is used for the unsaturated permeability calculation, using the final range of flow (typically between *14* and *25 cm* length), when the pressure is stabilized. The flow-rate of the outcoming fluid is measured by means of a scale for the calculation of the saturated permeability. An average capillary number, which is defined as

$$Ca = \frac{v\eta}{\gamma} \quad (1)$$

is calculated for each experiment in the same range as the unsaturated permeability.

Results

Viscosity (η), surface tension in air (γ) and density (ρ) of the three fluids at ambient temperature are reported in Table 1. A typical flow front progression result is given in Figure 1a, together with the range of Ca number considered for permeability measurement. Average saturated permeability values are also given in Table 1, showing fairly good agreement. The ratios R_s for all the experiments at various pressures are displayed in Figure 1b. For all fluids, R_s is always close to 1, indicating that capillary forces are not significant for the selected fabric architecture, fluid systems and range of pressure. Flow observation suggests that, due to the very large scale of the inter-tow channels, the flow always proceeds preferentially inside the wide channels, rather than within the longitudinal tows or the transverse layer. In some cases, during the whole measurement, the flow never reaches a saturated state. Interestingly, in the case of the PEG solution, a transition from apparently non-wetting to apparently wetting is observed when applied pressure increases. A correlation might be found between R_s and the average capillary number (Figure 1c). At low capillary numbers, capillary forces might play a role, even though minimal. The fluid partly flows within the intratow spaces, where it faces a higher resistance to flow, causing an overall slowing. Conversely, at higher capillary numbers, the fluid flows mostly within the wide channels, where it can proceed faster, leaving behind a large unsaturated region. In future experiments, the same methodology will be applied to different fabric architectures where pore size distribution is more uniform.

Table 1: *Properties of the test-fluids used for the permeability measurements, and saturated permeability values*

	η *(Pa.s)*	γ *(mN/m)*	ρ *(g/cm^3)*	K_{sat} *(10^{-9} m^2)*
Bluesil™ 47V1000	1.0	21.1	0.97	0.90±0.04
Bluesil™ 47V12500	12.8	21.1	0.97	1.07±0.04
PEG 30%wt	0.9	56.6	1.05	1.16±0.08

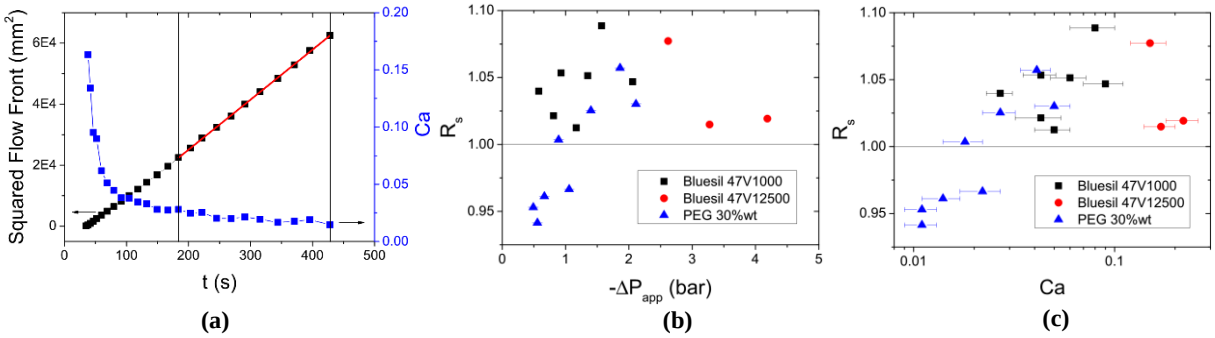

Figure 1: *(a) Squared flow front and capillary number against time for the experiment with Bluesil™ 47V1000 at 0.46 bar. (b) Ratio R_s for all the experiments as a function of the applied pressure difference. (c) Ratio R_s as a function of the average capillary number for all the experiments.*

Acknowledgements

The authors would like to acknowledge the Swiss Competence Center for Energy Research-Mobility, and *Solvay* (*Centre de Recherche et Innovation de Lyon*) for financial support and *Chomarat* for kindly providing the glass-fabrics.

References

[1] K.J. Ahn, J.C. Seferis, and J.C. Berg, Simultaneous measurements of permeability and capillary pressure of thermosetting matrices in woven fabric reinforcements, *Polymer Composites*, 12:146–152, 1991

[2] S. Amico and C. Lekakou, An experimental study of the permeability and capillary pressure in resin-transfer moulding, *Composites Science and Technology*, 61:1945–1959, 2001

[3] J. Verrey, V. Michaud, and J.-A.E. Månson, Dynamic capillary effects in liquid composite moulding with non-crimp fabrics, *Composites Part A: Applied Science and Manufacturing*, 37:92–102, 2006

[4] J. Bréard et al., Analysis of Dynamic Flows Through Porous Media. Part I: Comparison Between Saturated and Unsaturated Flows in Fibrous Reinforcements, *Polymer Composites*, 24:391-408, 2003

[5] R. Arbter et al., Experimental determination of the permeability of textiles: A benchmark exercise, *Composites: Part A*, 42:1157–1168, 2011

[6] N. Vernet et al., Experimental determination of the permeability of engineering textiles: Benchmark II, *Composites: Part A*, 61:172–184, 2014