Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 47 (2020) 435–439

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

23rd International Conference on Material Forming (ESAFORM 2020)

Permeability Analysis of Natural and Artificial Fiber Textiles for Liquid Composite Molding Process

Vitantonio Esperto[a, *], Luca Boccarusso[a], Massimo Durante[a], Luigi Carrino[a], Pierpaolo Carlone[b]

[a]*Department of Chemical, Materials and Industrial Production Engineering, University of Naples "Federico II", Piazzale Tecchio, 80, Napoli (NA), Italy*

[b]*Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, Fisciano(SA), Italy*

* Corresponding author. *E-mail address:* v.esperto@studenti.unibg.it

Abstract

In liquid composite molding (LCM) processes a catalyzed resin is forced to flow through a dry fibrous preform, opportunely arranged within a mold. The pressure gradient, positive or negative depending on the particular process, drives the uncured liquid flow at a flow rate which relies on fluid viscosity and preform porosity and permeability. Nowadays, sustainability reasons are pushing the market to the wider usage of natural fibers, such as hemp, jute, flex among others, as an interesting alternative to traditional glass and carbon artificial textiles. This manuscript describes an experimental/numerical approach to analyze the preform permeability and the impregnation flow in the LCM process using different textiles, based on glass, carbon and natural fibers. Unidirectional flow tests were performed using a laboratory scale LCM setup, constituted by a sensed mold in order to dielectrically monitor impregnation and saturation flows. The position of the unsaturated flow front was detected also by means of a camera monitoring the resin flow though milled eyelet sealed using transparent material. The permeability was also numerically inferred using the FlowTex software for all the investigated cases. Numerical and experimental outcomes were finally compared and discussed.

Keywords: Permeability, liquid composite molding, natural fibres, hemp fibres, carbon fibres, glass fibres;

1. Introduction

The need of lightweight materials in aerospace, automotive, sporting good sectors, among other, is driving the attention of industrial and scientific communities toward polymer composite materials. Significant advances have been achieved so far in composites manufacturing technologies [1], but relevant questions are still unsolved. Among the available techniques for manufacturing of composite products, Out of Autoclave (OoA) processes are currently gaining a great deal of attention. Liquid Composite Molding (LCM) processes belong to this class. In LCM processes the impregnation of a dry preform (placed in a mold) is promoted applying a pressure gradient. Flow monitoring and control is a key issue in order to achieve a satisfactory impregnation and saturation of the preform. In recent years, several studies have been carried out using different sensors, characterized by different level of accuracy and invasiveness [2-6]. Nowadays the theme of sustainability encourages scientists to investigate bio materials, like natural fibers namely hemp fibers [7,8].

In literature several works are focused on the numerical and experimental analysis of resin flow and textile permeability [4]. The aim of the present work is to evaluate the in-plane permeability of textiles based on natural as well as artificial fibres, namely hemp, glass and carbon fibers by means of two approaches. The former is based on experimental unidirectional flow tests and the latter on the numerical simulation of the fluid flow through a virtual model of the used textiles.

2351-9789 © 2020 The Authors. Published by Elsevier Ltd.

10.1016/j.promfg.2020.04.328

2. Materials and methods

2.1. Natural and artificial fibers and resin

The permeability analysis has been carried out on three different kind of fibers, twill 2/2 E-glass fibers, plain weave carbon and hemp fibers, with 390 g/m^2, 200 g/m^2 and 160 g/m^2 respectively. The resin used is a Bisphenol modified epoxy resin (SX10EVO), mixed with a medium hardener, whose mainly characteristics are shown in Table 1.

Table 1. Resin properties.

	Density [gcm^{-3}]	Viscosity at 25 °C [mPas]
SX10EVO	1,1-1,15	1200-250
Medium Hardener	0,95	30
Mixture	-	550-800

2.2. Experimental equipment

The measure of permeability is carried out using a lab scale LCM line [5,6], composed by a vessel which contains the resin, an epoxy resin SX10EVO, a trap connected to a vacuum pump, a rigid mold made by two metal parts with an internal pocket 242x379x3 mm^3, in which is contained the dry preform. Vacuum pressure is established in the die cavity to impregnate the fibers. Downstream a resin trap is placed to prevent the arrival of the resin flow to the vacuum pump. A simplified scheme of the system is depicted in Fig. 1.

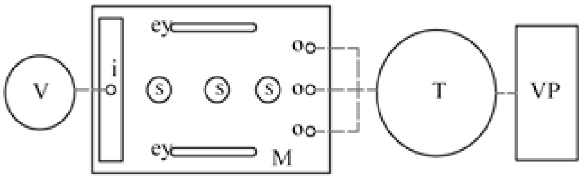

Fig. 1. Lab scale LCM line scheme.

Fig. 2. Lab scale LCM line.

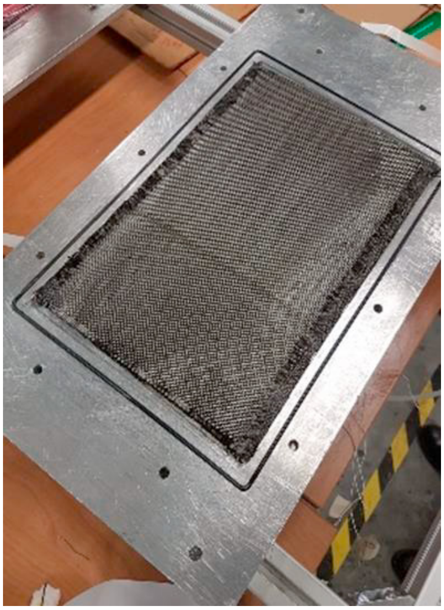

Fig. 3. Dry preform in mold.

The resin contained in the vessel ‘V’ flows from left side toward right side through the inlet ‘i’ enters into the mold ‘M’ and arrive to the three outlets ‘o’. Driving negative pressure is generated by the vacuum pump ‘VP’ connected to the mold by the trap ‘T’. The mold is equipped with three dielectric sensors ‘s’ and with two eyelets to detect the flow front.

In the Figures 2-3 the lab scale LCM line used to perform the flow tests is depicted, including a detail of the stack of carbon fabric positioned in upper half mold.

2.3. Numerical modeling

In order to evaluate the permeability a numerical model of the three fabrics is made using the WiseTex and FlowTex Softwares. The geometry of the preforms has been modeled materials and fabric properties reported in Table 2.

Table 2. Materials and fabrics properties.

Materials	Hemp		E-Glass		Carbon	
Fiber diam. [μm]	15	-	13	-	9	-
Yarn tex [g/km]	-	41	-	320	-	200
Twist [1/m]	30S	-	-	0	-	0
Long, diam. [mm]	-	0.20	-	0.18	-	0.20
Tran. Diam. [mm]	-	0.20	-	1.30	-	1.60
Yarn sp. [mm]	-	1	-	1.60	-	1.90
Ref.	[9, 10, 11]	Meas.	[12, 13]	Meas.	[14, 15]	Meas.

3. Results and discussion

In Figures 4-9 are shown the micrograph and the geometrical model respectively of glass, carbon, and hemp fabrics.

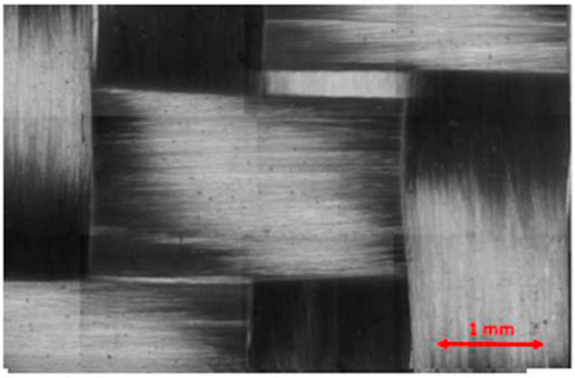

Fig. 4. Glass fabric micrograph.

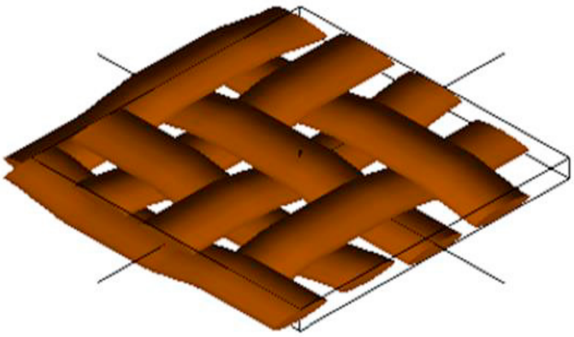

Fig. 5. Glass fabric 3D model.

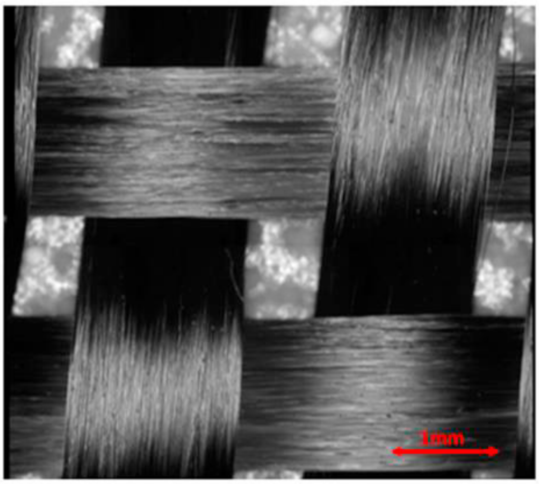

Fig. 6. Carbon fabric micrograph.

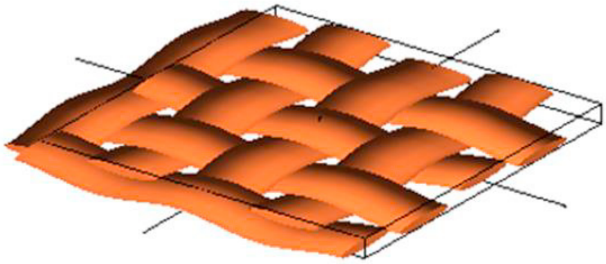

Fig. 7. Carbon fabric 3D model

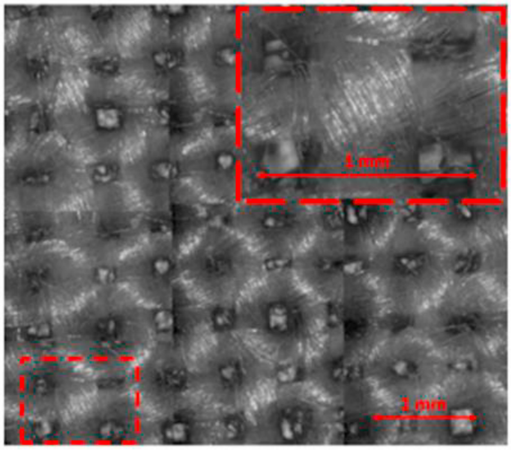

Fig. 8. Hemp fabric micrograph.

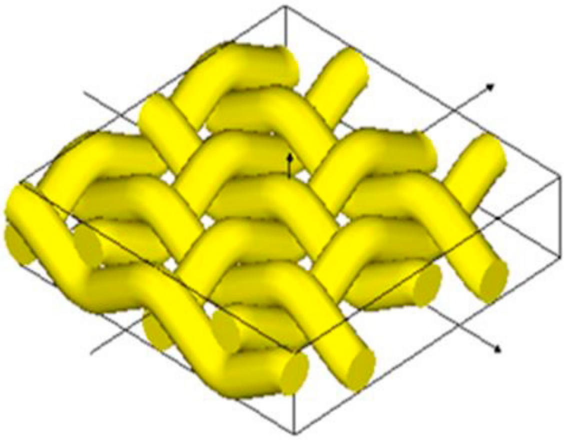

Fig. 9. Hemp fabric 3D model.

The resin position acquired during the experimental tests both from dielectrical sensors and a camera is reported in the below graphs Figures 10-12.

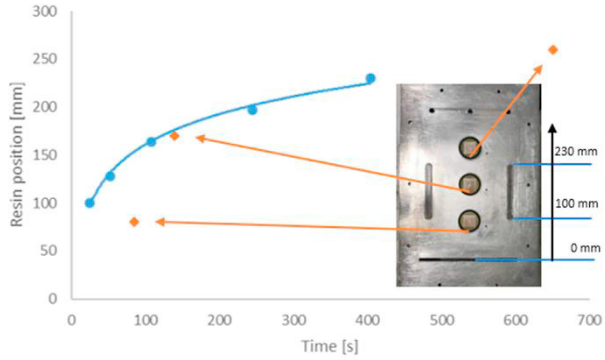

Fig. 10. Resin position in glass fabric.

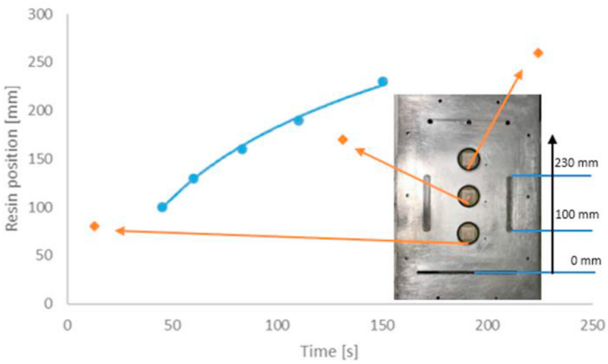

Fig. 11. Resin position in carbon fabric.

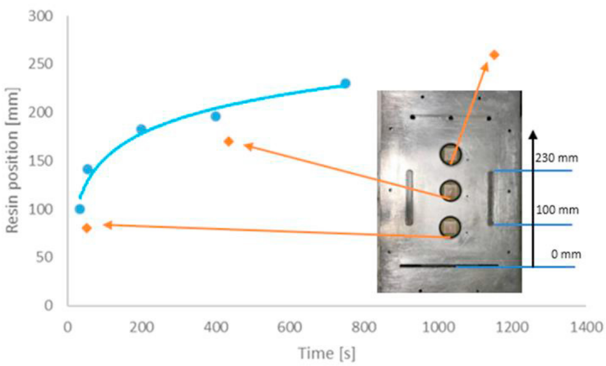

Fig. 12. Resin position in hemp fabric

As well known, liquid flow through porous media can be described using the Darcy's law:

$$v = \frac{K}{\mu} \nabla P \qquad (1)$$

According to this model, the flow front velocity v is related to the pressure gradient by a ratio between a property of the preform, namely the permeability K, and a property of the resin, namely the viscosity μ. Eq. (1) can be solved under specific assumptions, as presented by Amico et al., leading to the closed form solution written in eq. 2 [16]:

$$x^2 = \frac{2K}{\mu\varphi} P\, t \qquad (2)$$

Where x is the resin position related to the time t, from the inlet, as shown in the left side of Fig.10, P is the applied vacuum pressure, φ is the porosity. The latter parameter is calculated starting from the evaluation of fiber volume fraction V_f, using the eq. (3).

$$\varphi = 1 - V_f = 1 - \frac{N_f \rho_f}{H\rho} \qquad (3)$$

Where N_f is the number of fabric layers, ρ_f is the areal density of the fabric, ρ is the fibers density. In Table 3 are shown the values and the results related to the eq. (3).

Table 3. Fiber volume fraction and porosity values.

Fiber	Nf	ρ_A [g*m^{-2}]	H [mm]	ρ_f [gcm^{-3}]	Vf	φ
Hemp	9	160	3	1,54	0,31	0,69
E-Glass	8	390	3	2,55	0,41	0,59
Carbon	10	200	3	1,76	0,37	0,63

Assuming that the x direction is the one longitudinal, the y direction is the transversal one and z is the out of plane direction; the permeability evaluation in the experimental case is the one along the x direction. On the other hand numerical calculations provided the permeability along each direction.

Using eq. (2), assuming for the resin viscosity a medium value of 670 mPas and a value of vacuum pressure of 98 kPa; determining the position and time from the Figures 10-12, the values of permeability calculated are reported in the Table 4.

The origin of the positions reported on the graph of Figures 10-12 is positioned in the inlet point, the cross dots in each graph (see Figures 10-12) represented the first arrive of the resin at the relative sensor as indicated in the right hand side of each figure.

Table 4. Experimental permeability values Kxx in m^2.

Fiber	Kxx [m^2]	
	On sensor	On eyelet
Hemp	1,31*10^{-10}	1,12*10^{-10}
E-Glass	2,24*10^{-10}	2,99*10^{-10}
Carbon	6,73*10^{-10}	8,24*10^{-10}

Slight differences in fabric permeability values evaluated using data from sensors and visual inspection (see Table 4) could be related to mold edge effects.

To numerically evaluate the permeability, for each fabric two steps are made. The first one is to create the geometry model (see Figures 4-9), using WiseTex software [17,18]. This is an important task cause the permeability is highly affected by the geometry. The second step is to create a voxel file and then with Flowtex software calculate the permeability [19].

In the Table 5 are reported the results related to the numerical modeling. These results are obtained neglecting the intra-yarn flow and with periodic conditions at the boundary of the unit cell.

Table 5. Numerical permeability values

Fiber	Kxx [m^2]	Kyy[m^2]	Kzz[m^2]
Hemp	1,31*10^{-9}	1,17*10^{-9}	4,75*10^{-10}
E-Glass	5,15*10^{-10}	5,13*10^{-10}	7,36*10^{-11}
Carbon	1,21*10^{-9}	1,18*10^{-9}	8,68*10^{-10}

Analyzing the values obtained by experimental and numerical methods, it is clear that the numerically calculated permeabilities have always higher values than those obtained experimentally. This is due to the fact that the experimental value is related to an apparent permeability which takes into account of intra-yarn and inter-yarn flows, instead in the numerical case the intra-yarn flow is neglected.

4. Conclusions

In the present work the in-plane permeability of carbon, glass and hemp fabrics have been evaluated using experimental and numerical methods. The following conclusions can be drawn from the analysis of outcomes:

1. The dielectric sensors and the visual observations are able to detect the resin flow front during the infusion;
2. Slight differences in the resin position evaluated by sensors and visual inspection can be due to edge mold effects (race tracking) and layers misallineaments;
3. 3D models of representative volume element (RVE) cells for the three fabrics have been generated by means of WiseTex Suite using the geometrical and physical features of the fabrics;
4. The permeability of the RVEs has beem computed by FlowTex Software. In the preliminary analysis, the intra-yarn flow has been neglected;
5. The values of permeability evaluated from experimental data are lower than those numerically calculated.The mismatching can be related to the assumption made in the modelling.

References

[1] Aleksendrić D and Carlone P. Soft Computing in the Design and Manufacturing of Composite Materials: Applications to Brake Friction and Thermoset Matrix Composites. Cambridge: Woodhead Publishing; 2015.

[2] Marin E, Robert L, Triollet S, Ouerdane Y. Liquid Resin Infusion process monitoring with superimposed Fibre Bragg. Polym Test 2012; 31:1045–1052.

[3] Tucci F, Rubino F, Carlone P. Strain and Temperature Measurement in Pultrusion Processes by Fiber Bragg Grating Sensors. AIP Conf Proc 2018, https://doi.org/10.1063/1.5034837.

[4] Carlone P, Rubino F, Paradiso V, Tucci F. Multi-scale modeling and online monitoring of resin flow through dual-scale textiles in liquid composite molding processes. Int J Adv Manuf Tech 2018; 96:2215-2230.

[5] Rubino F, Paradiso V, Carlone P. Flow monitoring of microwave pre-heated resin in LCM processes. AIP Conf Proc 2017, https://doi.org/10.1063/1.5008004.

[6] Esperto V, Durante M, Carlone P, Carrino L. Resin Microwave Preheating in Liquid Composite Molding Process. AIP Conf Proc 2019, https://doi.org/10.1063/1.5112650.

[7] Boccarusso L, Durante M, Langella A. Leightweight hemp/bio-epoxy grid structure manufactured by a new continous process. Compos Part B-Eng 2018; 146:165-175.

[8] Boccarusso L, Carrino L, Durante M, Formisano A, Langella A, Memola Capece Minutolo F. Hemp fabric/epoxy composites manufactured by infusion process: Improvement of fire properties promoted by ammonium polyphosphate. Compos Part B-Eng 2016; 89:117-126.

[9] Islam M, Pickering K and Foreman N. Influence on alkali treatment on the interfacial and physic-chemical properties of industrial hemp fiber reinforced polylactic acid composites. Compos Part A: Appl Sci Manuf 2010; 41: 596.

[10] Berzins R, Kakitis A, Berzins U, Cukurs J. Hemp fiber and shive coefficient of friction. Eng Rur Develop 2013; 526-530.

[11]Corbin A-C, Soulat D, Ferreira M, Labanieh A-R, Gabrion X, Malecot P, Placet V. Towards hemp fabrics for high-performance composites: Influence of weave pattern and features. Compos Part B-Eng 2020; https://doi.org/10.1016/j.compositesb.2019.107582.

[12] Sarasini F, Fiore V. A systematic literature review on less common natural fibres and their Biocomposites. J Clean Prod 2018; 195:240-267.

[13]Subramaniam N, Sinha B-R, Blum F-D, Chen Y-R & Dharani L-R. Glass Fiber Based Friction Materials. Int J Polym Mater 1991; 15:93-102. https://doi.org/10.1080/00914039108031526.

[14]Liu Y, Zwingmann B and Schlaich M. Carbon Fiber Reinforced Polymer for Cable Structures-A Rewiew; Polymers 2015; 7:2078-2099. https://doi.org/10.3390/polym7101501.

[15] Schön J. Coefficient of friction and wear of a carbon fiber epoxy matrix composite. Wear 2004; 257:395-407. doi:10.1016/j.wear.20.04.01.008.

[16]Amico S, Lekakou C. An experimental study of the permeability and capillary pressure in resin transfer moulding. Key Eng Mater 2001: 61:1945-1959.

[17]Lomov S-V. Integrated textile pre-processor WiseTex. Version 3.2, Computational models, methods and algorithms, Leuven 2013.

[18]Lomov S-V. Integrated textile pre-processor WiseTex. Version 3.2, user's guide, Leuven 2013.

[19]Roose D, Lomov S-V, Peeters T,Verleye B. Flow through porous media. Flowtex Version 3.0, User's guide, Leuven 2013.