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Capillary wicking in flax fabrics – Effects of swelling in water

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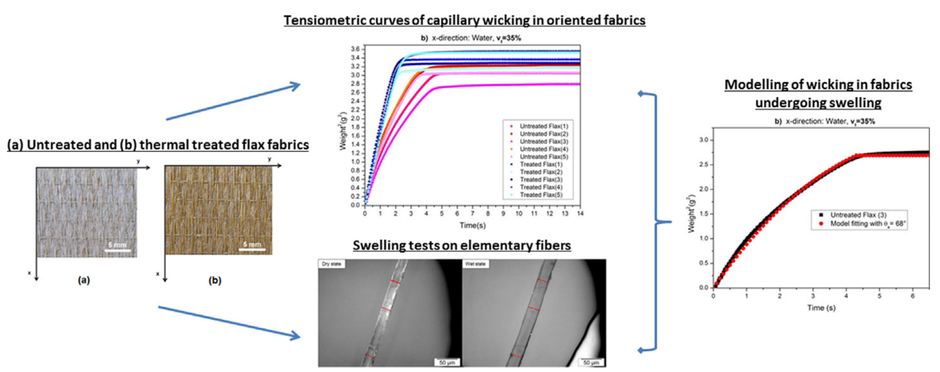
HIGHLIGHTS

- Treatment of flax fibers and modification of their swelling.
- Capillary wicking in untreated and treated flax fabrics for composite manufacturing.
- Modeling of wicking during swelling.
- Identification of wetting parameters by fitting experimental curves with the model.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, wicking in flax fabrics was investigated through an experimental method coupled with Washburn theory. This method was previously shown effective for carbon fabrics (Pucci et al. [21]) to determine morphological characteristics and apparent advancing contact angles. For natural fibers, Washburn equation is not sufficient to describe wicking because of moisture sorption that causes fiber swelling during liquid imbibition. Some flax fabrics were submitted to a thermal treatment known to modify fibers chemistry. Wicking tests with water were performed on both fabrics at different fiber volume ratios. It was observed that wicking trend is very different for these two types of reinforcements: treated fabrics show typical linear trends described by Washburn equation, while untreated flax fabrics lose linearity during wicking. Sorption tests performed on elementary fibers proved that swelling is less significant for treated flax fibers. A model was proposed and was shown to describe properly wicking in natural fabrics undergoing swelling.

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1. Introduction

Natural fibers are more and more considered as reinforcements in composite materials, but their chemical composition and morphology induce more complexities compared with synthetic fibers for manufacturing and durability of composite preforms [1–4]. It is well-known that many natural fibers have a hydrophilic character [5], making them difficult to wet with hydrophobic resins commonly used for Liquid Composite Moulding (LCM) processes. Moreover this hydrophilic character implies moisture sorption, decreasing mechanical performance. In literature, several studies focus on the kinetics of water sorption in different types of natural fibers, and propose some chemical treatments allowing to reduce those effects, but which can affect drastically the fiber mechanical properties [6–10]. Other few studies focus also on some capillary rise methods in order to evaluate the water uptake, but they only consider wicking in fiber plant straw fractions [11,12] or single technical fibers and bundles [13–15]. Those effects have to be

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considered to allow manufacturing of bio-based composites with no porosity and an adequate fiber volume fraction by LCM processes.

Generally wicking flow in a porous medium, and also in fiber arrangements, can be described by the Washburn theory [16], but it was proved that the conventional equation cannot describe wicking for natural fibers absorbing water [17–19]. Wicking depends on both the morphology of the porous medium (porosity ϵ, tortuosity τ...) and the interactions between the medium and the liquid (liquid surface tension γ_L and an apparent advancing contact angle θ_a) [20]. As natural fibers are sensitive to moisture sorption, they swell during wicking in water, causing changes in medium porosity, while the Washburn equation is verified when the morphology remains constant during wicking. Porosity is here referred to as spaces between fibers and tows, to be consistent with experimental methods based on the Washburn theory applied to synthetic fabrics [21], in order to determine some morphological parameters of fabrics porous media and wetting interactions. More precisely, a geometric product $(c\bar{r})$ taking into account the tortuosity and a mean porous radius and an apparent advancing contact angle (θ_a) can be estimated. This method, which keeps the sample volume constant thanks to a sample holder with fixed dimensions [21], turns out to be relevant for the estimation of capillary parameters (such as capillary pressure P_{cap}) influencing resin flow during LCM processes for orthotropic fabrics. Those capillary parameters will be used in numerical models in order to predict accurately voids formation [22–24]. It is one aim for studying the spontaneous impregnation of fabrics [25–27]. In this field, works concerning natural reinforcements coupled with the phenomenon of fibers swelling are rare and focus on change in the permeability K of porous media due to liquid sorption [28–30].

The main contribution of the present work is the prediction of capillary wicking in natural fiber fabrics undergoing swelling. A thermal treatment [31] that modifies surface chemistry making flax fibers more hydrophobic was applied here to fabrics. The effects on wicking were evaluated at the macro-scale of reinforcements. Wicking tests were then carried out in the warp direction of quasi-unidirectional untreated and treated fabrics at different fiber volume ratios thanks to a tensiometer, allowing to record the liquid mass as a function of wicking time. Results of experimental tests show a good accordance with the Washburn analytical model for treated fabrics, allowing to estimate both morphological characteristics of porous media and values of the apparent advancing contact angle θ_a. For untreated flax fabrics, the typical Washburn trend was not found. Tests of swelling in water were then also performed for untreated and treated elementary fibers in order to evaluate swelling, and a model of wicking in a porous medium undergoing swelling was developed.

2. Theory

In this section the conventional Washburn equation formulated for fabrics is presented. During wicking with water for flax reinforcements, it is also necessary to include the effect of swelling. A semi-empirical model taking into account this phenomenon is then proposed. The change of fabric microstructure, particularly the diminution of both mean pore radius and porosity during wicking, were considered.

2.1. Washburn equation for fabrics

The Washburn equation describes capillary rise of a liquid in a tube, and by extension into a porous medium [16]. Eq. (1) defines the flow front position of a liquid over time $h(t)$ into a porous material packed in a column assuming a mean capillary radius referred to as $\bar{r}$, and a factor c inversely related to the tortuous path of liquid in the equivalent capillary tube arrangement [21].

$$h^2(t) = \left[\frac{(c\bar{r})}{2}\right] \frac{\gamma_L \cos\theta_a}{\eta} t \tag{1}$$

θ_a is the apparent advancing contact angle, γ_L and η are respectively the liquid surface tension and viscosity.

This equation can be rearranged as a function of the squared mass gain in a cylindrical sample holder filled with a porous medium:

$$\begin{aligned} m^2(t) &= \underbrace{\left[\frac{(c\bar{r})\epsilon^2(\pi R^2)^2}{2}\right]} \frac{\rho^2 \gamma_L \cos\theta_a}{\eta} t \\ &= \qquad C \qquad \frac{\rho^2 \gamma_L \cos\theta_a}{\eta} t \end{aligned} \tag{2}$$

where ϵ is the relative porosity, R the inner radius of the sample holder and C a constant known as "geometric porous medium factor". It was proved that this equation fits experimental curves for synthetic fabrics [21].

2.2. Swelling model

During wicking in water, flax fibers swell under the effect of moisture sorption and then swelling has to be included in the Washburn equation describing capillary wicking. Swelling of fibers implies that the geometric product $c\bar{r}$ and the porosity ϵ in Eq. (2) are not constant and their variation has then to be expressed. Pores in the present study exclude lumens and only consider the spaces between fibers and tows. Indeed in first approach, lumens volume is considered as negligible compared to the volume between fibers and tows at the scale of fabrics. Swelling in water should cause a decrease over time of both porosity $\epsilon(t)$ and mean capillary radius $\bar{r}(t)$ since the sample volume is set by the sample holder [21]. The mean pore radius modification is mainly due to individual fibers swelling since the present study considers wicking in the warp direction of quasi-unidirectional fabrics. In this section we propose a semi-empirical model in which we express the variation of porosity against the geometric product, neglecting the modification of tortuosity.

2.2.1. Empirical relationship of porosity modification

Modification of porosity $\epsilon(t)$ is related to the variation of the geometric product $c\bar{r}(t)$. In order to take into account this correlation in a model, it is here proposed to link both parameters through a linear relationship (Eq. (3)):

$$\epsilon(t) = \epsilon_{ini} + b\Delta(c\bar{r}) = \epsilon_{ini} + b\left[(c\bar{r})(t) - (c\bar{r})_{ini}\right] \tag{3}$$

where ϵ_{ini} and $(c\bar{r})_{ini}$ are respectively the porosity and the geometric product of the porous medium before wicking. Parameter b is a coefficient describing how porosity changes along with the geometric product $c\bar{r}$. This relationship was verified experimentally, and coefficient b was identified in Section 4.4. However with this preliminary assumption, the change of geometric product over time $c\bar{r}(t)$ has to be defined during wicking.

2.2.2. Pore radius diminution

During wicking of water, the pore radius of natural fabric decreases because of swelling [28]. In literature, a linear change of this parameter over time was assumed [17–19]. Neglecting the effect of tortuosity, it is here considered that the geometric product varies also linearly over time from the initial value $(c\bar{r})_{ini}$ (determined experimentally through the Washburn equation) to a final lower value $(c\bar{r})_{fin}$. With a classical calculation of the pore radius

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