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In-plane permeability characterization of a unidirectional flax/paper reinforcement for liquid composite molding processes

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Principal in-plane permeabilities of a unidirectional flax/paper reinforcement are characterized in terms of reinforcement material and manufacturing parameters at a constant fiber volume fraction (V_f). ANOVA result shows that surface density of the unidirectional flax layer is the most important parameter on the mean and variance of the K_1 permeability. On the other hand all four studied parameters are concluded to affect the K_2 permeability. The K_1 permeability is found close to that of a twill weave flax fiber fabric reported in the literature and only one order of magnitude lower than a plain weave glass fiber fabric. Impregnation of the reinforcement with epoxy resin shows that a large area of the molded plaques was dominated by capillary forces during resin injection. This means capillary number and subsequently the resin injection velocity should be optimized for reducing void content in the final composite.

1. Introduction

Liquid composite molding (LCM) processes are attractive methods to manufacturers as they allow for producing high quality composite parts at affordable tooling costs for low to medium production scales. A usual practice in the industry is to simulate the mold filling process, prior to performing a LCM, through numerical flow simulation software to predict filling time and filling patterns and subsequently optimize the process (e.g. location of resin inlets and outlets) for a good quality impregnation. A prerequisite for such a simulation is the experimentally determined or computationally estimated permeability of the fiber preform to be molded. In fact permeability, which is defined as the resistance to liquid flow inside a porous media, is a determining parameter in the governing equations (via Darcy's law) of resin flow inside a reinforcement preform. Accordingly, many researchers have extensively studied different methods of permeability measurement and characterized several preforms' permeability, as is explained next.

In 1988 Adams et al. [1] proposed a methodology to solve the governing equations of two-dimensional radial flow in an anisotropic porous media based on experimental data of elliptical flow front radii versus time. The original method was further developed by Chan and Hwang [2] and Griffin et al. [3] in 1991 and 1995, respectively. Hoes et al. [4] proposed a new permeability measurement set up for radial injection experiment which uses two steel plates as top and bottom mold haves with embedded electrical sensors in the top mold half to detect the flow front. They tested permeability of several woven glass fabrics and acquired their statistical distributions. Endruweit et al. used radial flow injection method to experimentally study the effect of shear angle on the principal permeabilities of various glass fiber fabrics [5]. Effects of stochastic variation of fiber angles and spacing between fibers on permeability uncertainty are also simulated in other works of Endruweit et al. using 2D radial flow injection method [6,7]. Apart from radial injection technique, linear flow method is also used for permeability measurement [8]. Pan et al. [9] used one-dimensional permeability measurement technique to examine influence of process parameters on permeability variance of knitted and woven glass fabric preforms. It is reported that edge protection, fabric areal weight and complexity of mold shape, have significant influence on the permeability behavior.

In the composites industry, natural fibers are gaining popularity as a replacement to E-glass fibers. This is not only because of their competitive specific tensile modulus (particularly bast fibers e.g. flax, hemp and jute) [10], but also because of their environmental benefits and sustainable character. Natural fibers are harvested from renewable resources in agricultural farms. Their production requires less energy and they are produced at a lower cost compared to synthetic glass fibers. Moreover they are biodegradable, present a recycling potential and can be disposed with lower impact on the environment [11]. As a result permeability of natural

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fiber reinforcements has also been studied in recent years. Umer et al. characterized permeability and compaction response of wood fiber and flax fiber mats in terms of fiber volume fraction (V_f), fiber length and diameter [12,13]. It is reported that apart from fiber volume fraction, permeability is mainly influenced by the characteristics of the open channels, surface structure of the yarn as well as fiber swelling due to the type of test fluid. The authors also reported that a hydrophobic fluid (e.g. mineral oil) is required to avoid fibers swelling during the test. Mekic et al. [14] evaluated in-plane and through-thickness permeabilities of short flax fiber preforms. Based on the acquired values, it is claimed that traditional LCM techniques for glass fiber composites can be used for the fabrication of natural fiber composites. In 2010, Francucci et al. [15] characterized the saturated and unsaturated permeabilities of woven jute fabrics and reported that fluid absorption and swelling are two mechanisms reducing the permeability of natural fiber reinforcements. The permeability–porosity relationship was also investigated for jute and sisal mats [16] based on the empirical Carman–Kozeny model and their permeabilities are reported higher than glass fiber fabrics at the same porosity. More recently, effect of test fluid on saturated permeability of twill weave flax fabrics was examined by Nguyen et al. [17]. Saturated permeability is reported dependent on the test fluid because of different swelling behavior of flax fibers for different test fluids. A higher permeability is reported for engine oil compared to distilled water. The modified Kozeny–Carman model with two constants is also claimed to efficiently simulate the saturated permeability. In another work by Nguyen et al. [18], a model is proposed for resin flow inside flax fiber preforms which takes into account the resin sink and source effects of flax fibers as well as change of permeability with time due to fiber swelling.

In Fig. 1 a novel reinforcement design is shown. It consists of a unidirectional (UD) flax yarns layer deposited on a porous paper layer. The paper layer acts as a binder which functions are to enable better manipulability of the loose UD yarns (when transporting them and placing them in the mold) and to maintain their alignment (under pressure or viscous forces during LCM). Because improving permeability is of fundamental importance for industrial acceptance, ever since this new reinforcement design has been published [19], our research group has been very active in trying to optimize it. For instance, if the paper layer porosity is too low, it can negatively affect the permeability of reinforcement as a whole [19].

In this paper, the unsaturated in-plane principal permeabilities (K_1 and K_2) of the new reinforcement are studied by evaluating the effects of two material and two reinforcement fabrication parameters, while the fiber volume fraction is kept constant at 35%. The material parameters are the paper binder and flax layer surface densities and the fabrication parameters are the forming pressure and drying temperature. It is well-known that permeability is mainly influenced by the fiber volume fraction [20] and the reinforcement of this study is not an exception. However, the main objective of this work is to study the reinforcement's parameters to better control its fabrication process and improve its permeability, thus paving the way for fine-tuning of its mass scale fabrication process [21], and industrial acceptance. A permeability measurement set-up for radial flow injection method at constant inlet pressure was developed and a method for flow front detection was designed.

2. Experimental methods

2.1. Materials

Softwood Kraft pulp provided by Innofibre was used to fabricate the paper layers of the reinforcement. According to Innofibre's datasheet, the consistency of the supplied pulp (defined as the mass ratio of oven dried fibers to pulp stock) stands at 10%. Average fiber length of paper is 1.08 mm and the percentage of fibers having less than 0.2 mm length (fines) is 32.77%. For the flax layer, Tex 200 flax yarns (200 g/km of linear density) provided by Safilin (France) were used. Based on the datasheet, yarn's fibers have a density of 1.45 g/cm^3.

It is reported that engine oil, a non-polar liquid, can better mimic thermoset resins used in LCM processes in contrast to water-based test liquids (e.g. glucose syrup) which make the natural fibers swell [12,14,17]. SAE 20W-50 synthetic motor oil is thus used as the test fluid in the permeability measurement experiments to mimic hydrophobic thermoset resins. Its average dynamic viscosity was measured 0.458 Pa s (458 cP) at room temperature (21 °C), using a DV-E Brookfield viscometer and permeability tests were also conducted at the same temperature.

2.2. Reinforcement fabrication

The paper layer and the layer of UD flax yarns are manufactured separately before they are assembled. Details of the fabrication process can be found in [21]. Generally, it consists of four main steps: winding the UD flax yarns, fabricating the Kraft paper layer with a dynamic sheet former machine, adding the flax layer over the wet paper sheet and pressing them with a sheet press, and finally drying the assembled layers with a sheet dryer.

UD flax layers were aligned using the winding machine shown in Fig. 2. Yarns are winded side by side around a flat plate, taking care of the distance between the yarns to ensure a uniform yarn distribution and consequently uniform surface density. Distance between yarns is controlled by the number of yarns laid down per inch. The two types of UD flax plies evaluated in this study include 16 and 24 yarns/in. plies, resulting in surface densities of 116 ± 4 g/m^2 and 171 ± 7 g/m^2 respectively. Fig. 3 shows the UD flax layers obtained. Likewise, two surface densities studied for the paper layer include 29 ± 1 g/m^2 and 38 ± 1 g/m^2. Throughout this document, the margin of error (figure after '±' sign) is

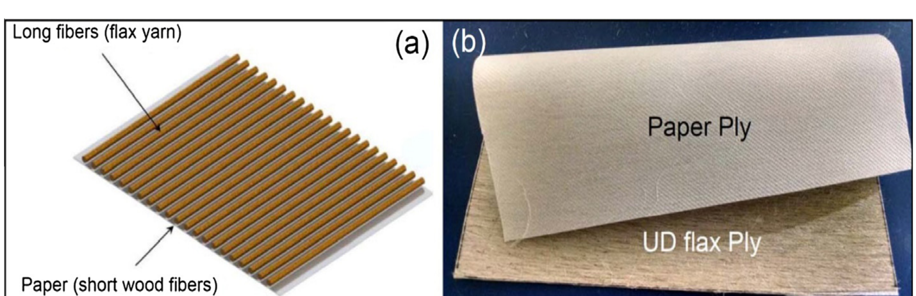

Fig. 1. Unidirectional flax/paper reinforcement, (a) schematic representation, (b) laboratory-made sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)