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Mechanical characterization and optimization of a new unidirectional flax/paper/epoxy composite

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Flax fibers are superior to E-glass fibers in terms of specific Young modulus. Many researchers have recently tried to exploit this feature and use flax fibers in polymeric composites to compete with glass fiber composites. In this work, a new type of unidirectional flax/paper reinforcement obtained after resin transfer molding with epoxy is investigated. Reinforcement's parameters (paper ply and flax ply surface densities) and manufacturing parameters (forming pressure and drying temperature) are optimized to obtain the best possible composite strength and modulus. Internal bond strength between flax and paper layers is also investigated. Results show that at equivalent V_f the new flax/paper/epoxy composite is superior, in both specific strength and modulus, to another flax/epoxy composite (without the paper layer). It also surpasses the specific stiffness of a unidirectional E-glass/epoxy composite and the specific strength of a commercially available similar reinforcement.

1. Introduction

In recent times, there is increasing research on environmentally friendly, sustainable natural fiber reinforced polymer composites [1]. Not only production and disposal of natural fibers make much less pollution emissions when compared to synthetic fibers [2], but also the specific stiffness of some types of natural fibers (particularly bast fibers e.g. flax, hemp and jute) is favorably comparable with those of E-glass fiber [3,4]. Natural fibers are also not suspected to cause health issues for those involved in their production and handling.

Over the past years many researchers have tried to exploit the high specific stiffness of flax fibers in reinforced polymer composites, particularly for load-bearing applications, through developing continuous (fabrics or unidirectional) flax fiber reinforcements. Among the first works in this regard, one can refer to Goutianos et al. [5] in 2006, who developed uniaxial and biaxial wrap knitted fabrics as well as biaxial plain weaves out of flax yarns and evaluated flexural and tensile performance of their thermosetting composites. Specific flexural and tensile stiffness of the unidirectional flax composites are reported superior to their unidirectional glass fiber counterparts. Miao and Shan [6] fabricated highly aligned nonwoven mats of flax fibers as an alternative to unidirectional woven fabrics and used them in polypropylene thermoplastic composites. Tensile and flexural stiffness are reported to stand at 7.34 and 8.34 GPa respectively, at 29% of fiber volume fraction (V_f). Plain weave and weft rib-knitted fabrics made with flax yarns were manufactured by Muralidhar [7] and several composite plates with different stacking sequences and lay-up angles were hand laid-up using epoxy resin. Maximum specific tensile modulus of 3.0 GPa/g cm^{-3} is reported for $V_f = 27\%$ and [90°/0°] lay-up angle. Xue and Hu [8] introduced a biaxial weft-knitted flax fabric made with a modified flat knitting machine. The reinforcement is characterized in terms of tensile behavior of the flax yarn and fabric as well as of the resulting composite. Experimental results showed that sodium hydroxide (NaOH) treatment improves mechanical properties of the composites. Tensile strength and stiffness of 176.6 MPa and 8.9 GPa are respectively reported at $V_f = 31.6\%$. Recently, Khalfallah et al. [9] developed new unidirectional flax tapes out of long technical flax fibers and used the Acrodur™ thermoset resin to impregnate them. Optimum specific tensile modulus and strength of 19.4 GPa/g cm^{-3} and 103 MPa/g cm^{-3} are respectively acquired at $V_f = 35\%$. Based on these values this reinforcement performance is considered adequate for integration into automotive applications.

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According to Lucintel [10], the automobile industry is the largest industrial sector using bast fiber based composites. Using such fibers in this industry results in fuel consumption economy and other environmental benefits [11]. Application of NFCs in this industry has been evaluated in the literature [12–14] and numerous examples of non-structural parts (for example interior door panels) can now be found [15–18]. Ford motor employed wheat straw reinforced polypropylene for storage bin and inner lid of 2010 their Flex crossover model [19]. They have also used 30 wt % sisal fiber reinforced polypropylene for interior trims for Ford model "Ka" [11]. Natural fiber prepregs using an acrylic polymer is employed in door panels of the BMW 7 series sedan model [19].

For the automobile industry the lower mechanical properties and poor humidity resistance of NFCs must be substantially enhanced for their use in other, more structural parts. Some of the challenges to be addressed in this regard and their solutions are discussed in Ref. [20]. Generally speaking NFCs can be principally used in stiffness-driven applications and not strength-driven ones. One of the solutions to cope with low strength of NFCs is hybridization of natural fibers with synthetic ones, which has also been studied in the literature [21,22].

NFCs have also been used in other areas of application, for instance mobile phone casings (NEC Eco Mobile, 2006), and tennis racquets (Artengo, 2009). Phillips and Lessard [23] developed a flax/epoxy sandwich composite and manufactured six prototype ukuleles out of it. Material is characterized in terms of static and dynamic behaviors and a manufacturing process was developed to hand lay-up the monocoque ukuleles. Another potential applications for NFCs is wind turbine blades [24]. Shah et al. [25] fabricated a full-scale 3.5 m flax/polyester rotor blade using a light RTM process and compared it with its glass/polyester counterpart. It is reported that flax fiber blade satisfies the structural integrity requirements and thus is a suitable replacement to glass fiber blades in small wind turbine blade applications. However, the flexural rigidity of flax fiber blade was reported around half that of a glass fiber blade.

Most load bearing application use continuous natural fiber reinforcements, where the fiber yarns are mechanically bonded together either through weaving, crimping, stitching, or knitting. In this study a nonwoven, unidirectional flax/paper reinforcement made of unidirectional (UD) flax yarns layer attached on a porous paper layer is examined (Fig. 1) [26]. UD flax yarns are held together through chemical and mechanical bonds with the paper layer. It is believed that the paper ply could play a role in the dry reinforcement's geometrical conformability, for example by reducing reinforcement wrinkles while placing it in curved molds, or maintaining fiber orientation under resin flow pressure. The new reinforcement also allows using low-twist yarns (which are normally too loose to be handled without a binder). No twist nor crimp is used. This should provide the best mechanical properties of the resulting composite when compared to woven, crimp and knitted configurations [5,9,27,28]. The aims of this paper are threefold: to develop quality composites plaques out of this new reinforcement; to optimize the reinforcement's material and manufacturing parameters in order to obtain the best possible tensile performances of the final composite; to compare these performances with those of other UD flax or UD E-glass composites at equivalent V_f.

2. Experimental methods

2.1. Materials

The paper layer is made of softwood Kraft pulp provided by Innofibre. Pulp consistency (defined as the ratio of oven dried fiber mass to the mass of pulp stock) is 10%. Average fiber length and percentage of fines (short fibers up to 0.2 mm length) are 1.08 mm and 32.77%, respectively. The flax yarns supplied by Safilin (France) have a linear density (tex) of 200 g/km and a fiber density of 1.45 g/cm^3. For composite molding an Adtech Marine 820 epoxy laminating system mixed with 18% by weight of hardener Marine 824 is used. Molded composites are post-cured at 80 °C for 4 h. Based on the manufacturer datasheet the mixed epoxy system has a cured density of $\rho_m = 1.09$ g/cm^3.

2.2. Flax/paper reinforcement fabrication

The paper layer and the flax yarns layer are manufactured separately before they are assembled. Details of the fabrication process can be found in Ref. [29]. 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.

Two types of UD flax layers are evaluated in this study: 16 and 24 yarns per inch which result in 116 ± 4 and 171 ± 7 g/m^2 surface densities, respectively. Likewise, surface density of the paper layer depends on the mass of the 10% consistency Kraft pulp used. In this study two surface density values are studied for the paper layers: 70 g and 100 g of pulp, yielding theoretical surface densities of 29 ± 1 and 38 ± 1 g/m^2, respectively. The effective paper surface density values were measured after fabrication of the paper layers. The final surface density of the assembled flax/paper layers is discussed in section 2.7.

2.3. Internal bond strength (IBS) measurement

To evaluate the shear strength between the flax and paper layers, the shear cohesion test originally developed for paper products [30] is adapted for our particular application. The original method measures fiber-to-fiber bonding strength via delaminating two paper coupons. The modified technique in this work is depicted in Fig. 2. Flax/paper reinforcement samples of dimension 25 mm × 150 mm (1 in. × 6 in.) are prepared and from each end a portion of either paper or flax layer is peeled off such that an overlap area (jointed area in Fig. 2) of 25 mm × 25 mm (1 in. × 1 in.) remains in the middle of the specimen. Then the samples are

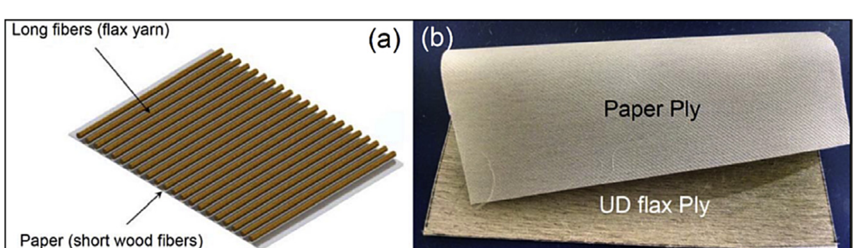

Fig. 1. Unidirectional flax/paper reinforcement, (a) schematic, (b) laboratory-made sample.