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Material Behaviour

Influence of water on damage and mechanical behaviour of single hemp yarn composites

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ABSTRACT

This study aims to investigate the influence of water ageing on local deformation around a yarn in a hemp/epoxy composite. Specific single yarn composites were manufactured with the yarn oriented at 90° with respect to the tensile direction and with two types of epoxy resin, one being fully synthetic and the other one partially bio-based. First, a quantification of damage due to the water ageing is realised and photoelasticimetry analysis is used to study the evolution of the state of stress. Then, dumbbell samples with or without water ageing were tested under an optical microscope, and strain fields around the yarn were measured with the Digital Image Correlation (DIC) technique. The experimental results showed an increase in the measured strain after the water ageing. The local constitutive behaviour of the different constituents of the specimens could be approached by local analyses, and the evolution of the apparent stiffness values are discussed.

1. Introduction

With the growth of economic and environmental concerns, synthetic fibres tend to be replaced in composites by plant-based reinforcements, which present good specific properties compared to those of glass fibres [1–3]. However, a crucial issue with plant fibre composites is their durability when they are subjected to the presence of moisture. Indeed, plant fibres are highly hydrophilic. The main component of plant fibres, cellulose, is a semicrystalline polysaccharide which gives the fibre its hydrophilic property by the high percentage of hydroxyl groups (OH) that it contains [4]. Hemicellulose is the principal contributor to the moisture absorption, due to its open structure containing hydroxyl (OH) and acetyl (C_2H_3O) groups. The remaining principal components, lignin and pectin, have only small influence on water absorption. In plant fibre composites, the incompatibility between the fibres and the matrix which have different affinities with water induces a decrease in interfacial characteristics compared to glass/polymer composites [5]. Moreover, sensitivity to moisture of the plant fibres decreases even more the mechanical properties of fibre/matrix interface when the material is exposed to water ageing [6,7]. The evolution of the mechanical properties of eco-composites due to water is more significant than for synthetic fibre composites, in which the absorption of water is lower [8]. Indeed, in synthetic fibre composites, moisture absorption is essentially governed by the matrix, whereas in plant fibre composites it is mainly governed by fibres. This high sensitivity to moist environment constitutes, for the development of these materials, a real barrier which needs to be studied in order to use plant fibres as reliable and long lasting reinforcements in composite materials.

In literature, the water uptake is usually presented as generating local degradation, which can appear during the ageing but also when the material is dried [7,9,10]. It has been reported that water diffuses in plant fibre reinforced polymer composites by three different mechanisms [10]. The first concerns the water molecules getting into the microgaps between polymer chains. The second involves capillarity transport into the gaps and flaws at the fibre/matrix interfaces, which are created by poor wetting and impregnation defects between the two components during the composite manufacturing. The last may involve transport by microcracks in the matrix arising from the swelling of fibres. Indeed, the absorbed water, by causing swelling of the natural fibres, lets stresses at the fibre/matrix interface develop. Moreover, water-soluble substances can leach from the fibres [9] and, when the composite dries, the decrease in fibre section due to the leaching and the matrix distortion caused by molecular relaxation [7] lead to the

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appearance of cracks at the fibre/matrix interface. Nevertheless, no quantification of this damage can be found in literature, while it constitutes useful and necessary information for the full understanding of the behaviour of these materials.

Studies concerning the influence of water ageing on the mechanical properties of natural fibre composites at macroscopic scale can be found in literature, for example with hemp [10–12] or flax [8,13] reinforcements. At the whole composite scale, a decrease in Young's modulus and ultimate tensile strength, and an increase in elongation at break, are generally seen. However, in order to fully understand the mechanisms at the origin of such modifications, local investigation needs to be performed. Only a few papers deal with the influence of water on eco-composites at microscale. Recently, nanoindentation has been used on water aged flax fibres [14], or at the yarn scale on a composite made of a hemp yarn embedded in epoxy resin [15]. Other studies have been carried out on the adhesion between bamboo and vinyl ester matrix [16], flax and epoxy resin [17] or jute and polypropylene [18] by using a pull-out test or its derivative, the microdroplet test. These techniques measure the interfacial shear strength, which is indicative of the quality of the adhesion between the components, but full strain fields also require to be investigated. Thus, this work follows a previous study which has presented strain field measurements by Digital Image Correlation (DIC) on non-aged single hemp yarn composites [19].

In this paper, the influence of water ageing on damage and mechanical behaviour of single hemp yarn/epoxy composites is analysed. At first, damage due to water desorption is quantified at the yarn section and along the yarn. Then, photoelasticimetry enables us to observe modifications in the state of stress for the studied composites. In a last part, tensile tests are performed with the use of DIC under optical microscope in order to analyse the local strain fields at the yarn scale after water ageing.

2. Materials and methods

2.1. Materials

The composite materials studied were made of a single hemp yarn embedded in an epoxy matrix. The hemp yarns were composed of non-treated fibres with an average diameter of 13 ± 5 μm [20], and had a diameter of about 300 μm. They were produced with a twist level of 324 tpm, leading to a twist angle of 11° [21]. Two different epoxy resins were used as matrices. The first was a fully synthetic epoxy resin, Epolam 2020 (Axson Technologies), having a density of 1.16 g/cm^3 after curing [22]. The second one was a partially bio-based resin, Greenpoxy 56 (Sicomin), containing 56% of bio-based carbon atoms, with a density of 1.18 g/cm^3. Composite plates were manufactured at Pprime Institute by contact moulding in a specific mould [23]. In order to reach a maximum degree of crosslinking, the plates were cured with optimised cycles as defined in Ref. [19]. Glass transition temperatures were measured by differential scanning calorimetry and were found to be 89 ± 2 °C for Epolam 2020 resin and 83 ± 2 °C for Greenpoxy 56. Square samples, with dimensions about 10 × 10 mm^2, cut from 2 mm thick plates were used to observe the evolution of damage due to water ageing along the yarn by transparency and at the yarn section at the top surface (Fig. 1a). Dumbbell samples (designated SYE for specimens with Epolam resin and SYG with Greenpoxy resin) 53 mm long were cut in such a way that the yarn was oriented at 90° with respect to the tensile direction (Fig. 1b). The specimens were polished down to a final polishing suspension particle size of 1 μm. Then, they were immersed in water at ambient temperature and desorption observations were made in ambient atmosphere.

2.2. Damage analysis

An optical microscope ZEISS Axio Imager.Z2 Vario, with which specimens can be lit with reflected or transmitted light, was used for the observation of damage caused by water desorption. The square specimens were observed at different times after the end of the water ageing to follow the evolution of the created damage. Using reflected light, the area of selected cracks on the top edge of the samples (Fig. 1a) was measured with the image analysis program Fiji [24]. On the front face, the progression of damage along the yarn could be evaluated by transmitted light, with which damage at the fibre/matrix interface appeared dark.

2.3. Photoelasticimetry technique

Photoelasticity is a well-known full field stress analysis technique based on the optical properties of transparent birefringent materials [25]. The experimental set-up used is made of two plane polarisers, placed on each side of the sample (called polariser and analyser). The polariser was aligned with the (1, 1, 0) direction (with respect to the reference system in Fig. 1), and the position of the analyser with an angle of π/2 leads to perform the observations in dark field. Samples were lit on one side with white light, and pictures were taken with a reflex camera in the three possible specimen orientations, i.e. in planes (x,y), (x,z) and (y,z).

2.4. DIC measurements

Plane strain fields were measured on the edge of each dumbbell specimen by digital image correlation. This technique has many advantages, including low sensitivity to vibrations, white light illumination and relative simplicity of the material surface preparation with sufficient accuracy [26,27]. The principle of this technique is based on a unique random pattern, recorded twice, once

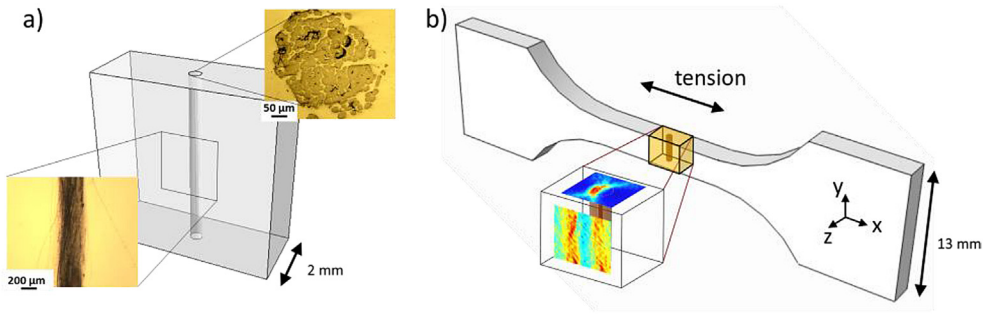

Fig. 1. a) Studied areas for observation of desorption effect, b) single hemp yarn/epoxy sample for tensile tests and areas of strain field measurements.