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Creep behaviour of polylactic acid reinforced by woven hemp fabric

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ABSTRACT

Woven hemp fabric reinforced polylactic acid composites with different fibre volume fraction (20, 30 and 40%) were manufactured by compression moulding process. To better understand the industrial application limits of the investigated bio-composite, flexural and impact properties were determined and compared to those of the unreinforced bio-polymer and the creep behaviour at different values of temperature was widely investigated adopting the Arrhenius theory. In addition, to predict the long-term mechanical performance of the investigated bio-composite, the possibility to use the Time-Temperature Superposition model was investigated. For this purpose, Dynamic-Mechanical tests were conducted to evaluate the activation energy and then to apply the Time-Temperature Superposition model to the compliance curves, obtained by short-time creep tests under different load conditions. Therefore, to examine the validity of the theoretical model, experimental long-time tests were also carried out. The results show interesting mechanical properties and a good fit between the theoretical and the experimental creep curves, particularly when the fibre volume fraction was equal to 20 and 30%.

1. Introduction

In recent years, the use of renewable resources to produce composite materials has attached a growing attention because of the increasing demand of environmental friendly materials. In this regard, biodegradable materials deriving from renewable agriculture resources can compete with products based on petroleum feedstock in terms of both economic advantages and specific mechanical properties. Indeed, life cycle assessment of bio-based composites has shown favourable results in terms of environmental impact and energy use, compared to petroleum based products [1,2]. Furthermore, for some applications, bio-composites based on biodegradable plastics and natural fibres can be considered as an excellent alternative to the traditional polymer composites, for example for interiors parts in automotive field [3].

Indeed, a great deal of works based on the study of their mechanical [4–6] and fire properties [7,8], on their creep behaviour [9] and on the interaction between natural fibres and polymeric matrices [10–12] has been published.

Polylactic acid (PLA) is a thermoplastic bio-polymer with good mechanical properties and already used for biodegradable products, such as plastic bags and planting cups, but it can also be used as a matrix material in composites [13–16]; it is now beginning to be produced on a large scale from fermentation of corn to lactic acid and subsequent chemical polymerization [17].

Flax and hemp are the strongest and stiffest available natural fibres and have the potential to reinforce polymers. In particular, hemp, consisting of mainly crystalline cellulose (55–72 wt%) as well as hemicellulose (8–19 wt%), lignin (2–5 wt%) and waxy substances, has low density and high specific strength when compared to glass or aramid; in addition, the hemp plant is available as renewable resource and can easily be grown around the world with low cost [18–20].

The combination of hemp fibre and PLA could provide some potential applications for industries. Consequently, different studies on the fabrication and mechanical properties of these bio-composites were carried out and many of these aimed on the development of strategies to enhance the mechanical performances by improving the interfacial adhesion between fibres and PLA [18,21–24]. In fact, natural fibres are highly hydrophilic because they are covered with pectin and waxy materials, that hinder the hydroxyl groups from reacting with polymer matrices.

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This can lead to the formation of ineffective interfaces between fibres and matrices, with problems such as debonding between the two phases [17,25,26]. Consequently, chemical treatments can provide an important and effective method to remove non-cellulosic components on cellulose fibres to enable better bonding in polymer composites. In this regard, for example, the influence of hemp fibre surface treatments (e.g. acetic anhydride, maleic anhydride, silane and alkali solutions) on the interfacial bonding of the fibres with PLA was widely investigated. These studies highlighted that PLA could be reinforced with a maximum fibre weight fraction of about 30 wt% by using conventional injection moulding process, but it could not be processed at higher fibre contents, due to poor melt flow of the compounded materials [25]. Moreover, elastic modulus and impact strength of both short and long hemp fibre reinforced PLA composites increase with the fibre content and flexural strength reaches an optimal value for the 25–35 wt%, reflecting a typical behaviour of the composite materials [27,28]. In addition, composites with treated fibres show better performance than composites produced with untreated fibres.

Furthermore, previous studies show that the creep behaviour of natural fibres reinforced polymer composites depends on filler type and its content, on coupling treatment and on plastics matrix types [29,30]; consequently, to evaluate the limits in application of bio-composites, it is necessary to investigate about the changes of mechanical properties with time and temperature. Since it is often impracticable to conduct long-time creep tests, due to the lifetime of some materials that abundantly exceeds their execution time, several models that determine long-time behaviour starting from the results of short-time tests of viscoelastic materials can be found in literature [31–33]. Among these, the Time-Temperature Superposition (TTS) model is one of the short-time methodologies based on empirical approaches [34–36] that exhibits good suitability to composite materials [37,38] and was applied to generate master curves starting from short-term creep tests.

In this work, bio-composites of PLA reinforced by woven hemp fabric with different fibre volume fraction were manufactured by compression moulding technique and then mechanically characterized in terms of flexural, impact and creep properties. Therefore, Dynamic-Mechanical Analyses (DMA) and creep tests were conducted under different load conditions, in order to study the creep behaviour of these materials. The TTS model was considered to predict the long-term mechanical performance of the material.

Finally, long-time experimental tests were executed and a comparison between the theoretical and the experimental curves was done.

2. Experimental part

This section describes the used materials, the manufacturing of the bio-composite laminates and their thermo-mechanical characterization.

2.1. Materials and laminates manufacturing

Grade 4042D PLA films supplied by NatureWorks LLC, thick 0.2 mm, were used as thermoplastic matrix and woven hemp fabric supplied by Maeko SRL, with areal density 160 g/m^2, as reinforcement. This type of fabric guarantees the manufacturing of laminates with a good finish surface; this can be very useful for their possible applications as interiors parts in the transport field. The fibres were soaked in 2 wt% sodium hydroxide solution at room temperature for 1 h; then, they were washed with water to remove any traces of alkali on their surface and dried in an oven at 80 °C for 48 h.

Bio-composite laminates were manufactured by compression moulding technique, placing alternately PLA films and fabric layers.

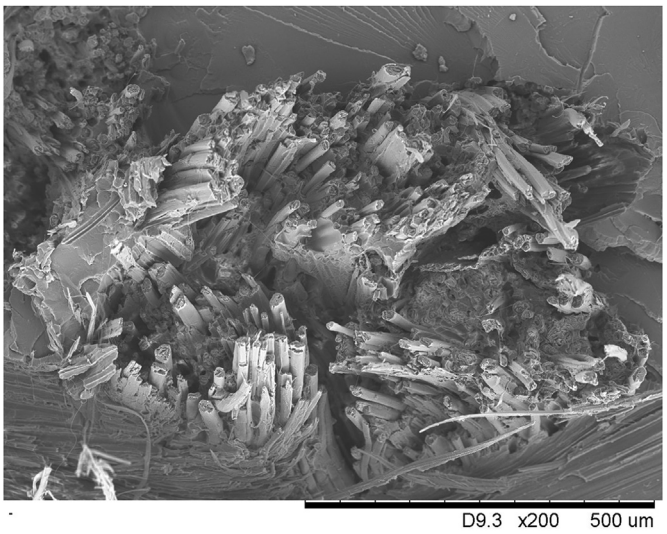

Fig. 1. SEM image of a single hemp yarn fully impregnated by the PLA matrix.

Fibre stacking was chosen to generate laminates with three different fibre volume fractions: 20, 30 and 40% (A, B and C sample types in the rest of the text); the different types of samples were obtained keeping constant the distance between the plates of the hot press machine and varying the number of the fabric layers. The assembly of PLA films and fabric layers was pre-pressed at 175 °C for 5 min at a pressure of 0.2 MPa and, after compacted, at 1 MPa for 3 min. The laminates so manufactured presented a thickness of approximately 2 mm.

SEM observations were performed by using a microscope (Hitachi TM300) on specimens obtained from the laminates through a cryogenic fracture under liquid nitrogen. Prior to the analyses, the specimens were coated with a thin layer of gold to get a good conductivity. From the observations, the laminates exhibited well bonded hemp fibres in the PLA matrix, as shown in Fig. 1.

Table 1
Flexural and impact strength.

Type	A	B	C	PLA
σ_f [MPa]	118.6 (8.0)	116.6 (6.9)	77.9 (8.5)	56.2 (7.3)
a_{cU} [kJ/m^2]	20.5 (0.9)	24.9 (1.2)	29.3 (1.4)	8.9 (0.7)

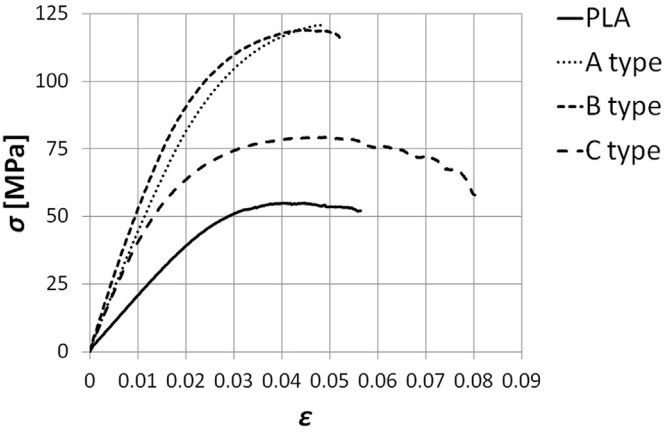

Fig. 2. Typical flexural stress - strain curves for each sample type.