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Constitutive model to predict the viscoplastic behaviour of natural fibres based composites

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ABSTRACT

The mechanical behaviour of traditional composites is usually assumed as linear-elastic up to failure. However, composites based on natural fibres are characterized by non-linear elasticity, viscous effects and plastic strains before failure. This study presents a rheological model to predict the viscoplastic behaviour of natural fibres based composites. The model was calibrated using a stress-strain curve and two relaxation tests for three different composites reinforced with flax, jute and cotton fibres. The model predicted successfully the behaviour of biocomposites loaded at different strain rates.

1. Introduction

Traditional composites consist on the combination of synthetic fibres from mineral origin as glass or carbon fibres with oil-based polymer matrices as epoxy, polyethylene or polypropylene. In the last years, natural fibres (flax, cotton, sisal, jute, etc.) were introduced as potential substitutes of synthetic fibres in order to reduce the environmental impact of composites [1]. Few years ago, also vegetal origin polymers as polyhidroxybutyrate (PHB) or poly-lactic acid (PLA) were studied for their application as matrices to obtain a fully biodegradable composite, recyclable and with competitive mechanical properties [2]. The high specific mechanical strength of some fibres as well as their reduced costs make biocomposites suitable to preplace traditional composites for numerous applications [3].

Natural fibres as reinforcement of non-biodegradable plastics have already been used in automotive industry [4] and numerous publications studying these materials can be found [3–5]. However, the interest on fully biodegradable composites is growing as the authorities require ever more the use of recyclable materials due to environmental social concerns [6].

The disposal of theoretical models to predict the mechanical behaviour of biodegradable composites can help to get a better understanding of their performance and their use in industrial applications can increase. The mechanical behaviour of traditional composites has been widely studied [7–9]. Their behaviour can be usually assumed as linear-elastic up to failure [7], and the main objective in the development of predictive models is the implementation of accurate failure criteria [8] and the prediction of their energy absorption capability [9]. However, the development of constitutive models to predict the mechanical behaviour of biocomposites is an almost unexplored field. The results of experimental studies have shown viscoelastic and viscoplastic effects [10], thus traditional composites models assuming linear-elastic behaviour can be implemented in biocomposites only as a first approach [11].

The preliminary studies that have been initiated to predict the mechanical behaviour of natural fibres based composites can be divided into three different categories. The first category includes models for the prediction of the elastic properties and they are based on the rule of mixtures. The next step is the development of micromechanical models based on the reproducibility of a unit cell with FEM (finite element modelling), these models can be grouped in the second category. Finally, the third category includes constitutive models developed to consider the viscoplastic behaviour of biocomposites in a simplified mathematical formulation.

Numerous publications can be found in the first category, for example, Ihueza et al. [12] simulated the behaviour of polyester and natural fibre composites under multiaxial stress state. Facca et al. [13] developed a model to predict the elastic modulus of natural fibres reinforced thermoplastics. Virk et al. modelled the tensile properties of jute fibres [14] and predicted the elastic modulus and strength of natural fibre composites [15]. These models are based in the prediction of the elastic properties, but

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they cannot include the strain rate dependency or the presence of permanent strains.

Regarding the micromechanical models, Andersons and Modniks [16] reproduced the tensile stress/strain behaviour of short fibre flax/epoxy composites. Sliseris et al. [17] also developed a micromechanical model based on the generation of fibres, bundles and fibre defects randomly with FEM to consider the fibre orientation, reproducing the stress/strain behaviour of short fibre and woven fabrics of flax reinforcing an epoxy matrix. Muttrand et al. [18] created a numerical model to reproduce randomly the cross-section geometry of flax fibres inside a flax/epoxy composite. Beakou and Charlet [19] simulated a flax bundle through a numerical model. These models are based on the definition of the fibre configuration, what means an overly high computational cost when implementing this in a macro mechanical FEM model.

Very few works can be found in the third category. Andersons et al. [20] developed a semiempirical tensor-linear model in order to predict the non-linear stress/strain behaviour of unidirectional flax/epoxy composites. Only the model proposed by Poilane et al. [10] can be considered a constitutive model considering the viscoelastic behaviour present in natural fibre composites. They developed a non-linear phenomenological model for flax/epoxy composites, based on rheological elements with eight parameters. The repetitive loading and unloading tensile tests on flax/epoxy composites with different yarn configurations were successfully predicted. However, this model was applied only to flax/epoxy composites, thus none model has been able to predict the viscoplastic behaviour of fully-biodegradable composites

In this work, a rheological model is introduced to define the viscoplastic behaviour of biocomposites. The model predicted accurately the viscoplastic behaviour of PLA based composites reinforced with three different woven fibres (flax, jute and cotton). One of the main goals of the present model is that it can be calibrated using only quasi-static tests; the influence of strain rate can be obtained from relaxation tests. Once the model is calibrated, it predicts the stress-strain curves obtained at different strain rates.

2. Experimental procedure

2.1. Materials

Three different woven fibres (flax, jute and cotton) with no chemical pre-treatments were acquired to verify the capability of the model to predict the mechanical behaviour of different biocomposites. Cotton and flax have 2 × 1 basket weave configuration while jute fabric configuration is plain. PLA matrix can be obtained from roots, sugarcane or corn starch polymerization [3]. For this study, PLA 10361D was acquired from Natureworks LLC, and it is defined as a biodegradable thermoplastic resin specifically aimed as a natural fibre binder. Fibres and matrix properties were studied in a previous work [21].

2.2. Manufacturing process

Biocomposites were produced by compression moulding process. First, three PLA layers and two woven fibres plies were alternatively stacked, then the laminate was place between two thermoheated plates, and pressure was applied by a universal testing machine. An optimization of the manufacturing process was performed as reported in [21], revealing that the optimum manufacturing parameters are 185 °C plates initial temperature, applying 8–16 MPa of pressure during 3 min after 2 min of preheating time. The fibre weight ratio was stated in 65% as studied by Ochi et al. [22]. The size of manufactured plates was 150 × 150 mm, while thicknesses were different for each raw material: 1.50 ± 0.05 mm for cotton, 1.15 ± 0.03 mm for jute and 1.27 ± 0.02 mm for flax composites.

Fabric and PLA plies were maintained in an oven under 95 °C during 30 min before the compression moulding processing to remove water content. All the materials were stored in stable constant conditions of 46% RH and 20 °C before and after the manufacturing process to control the environmental conditions influence.

2.3. Mechanical testing

An Instron 8516 universal testing machine was used to perform both tensile and relaxation tests. Manufactured plates were cut into 120 × 15 mm rectangular specimens. Cotton and flax 2 × 1 basket weave samples were oriented longitudinally.

Three different crosshead velocities were used for the tensile tests to obtain the stress-strain curves: 0.5 mm/min, 5 mm/min and 20 mm/min. The free length between clamping areas was established in 40 mm for all the tests, thus strain rates were $2.08{\cdot}10^{-4}\,s^{-1}$, $2.08{\cdot}10^{-3}\,s^{-1}$ and $8.33{\cdot}10^{-3}\,s^{-1}$.

Relaxation tests were performed imposing an initial displacement of the head with a 10 mm/s crosshead speed, leading to a strain rate equal to $2.5{\cdot}10^{-1}\,s^{-1}$. This initial displacement was maintained until the recorded force was relaxed to a constant value.

3. Model description

Rheological models are based on the use of elastic, plastic and viscous elements [23] to determine the mechanical behaviour of a material and its temporal dependence under different loading conditions.

The model used in this work is defined with three branches in parallel, as shown in Fig. 1. In the first branch (a), the non-linear elastic behaviour of the material is defined through a Yeoh model [24], a phenomenological model based in rubber behaviour that defines the non-linear elastic behaviour using the strain energy density function. In the second branch (b), the viscous behaviour of the material is defined through a Maxwell model. Finally, in the third branch (c), the plasticity is introduced by a frictional analogy to the Maxwell model. Fig. 1 represents the scheme of the whole model, defined by only five elements.

3.1. Constitutive equations

Yeoh non-linear elastic model is based on incompressible materials, thus, the energy density function depends on the first invariant of the left Cauchy-Green deformation tensor in a cubic form, as Eq. (1) shows.

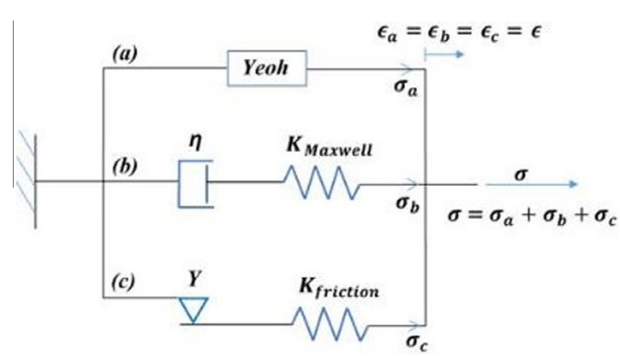

Fig. 1. Rheological model scheme. Branch (a) describes non-linear elasticity, branch (b) considers viscous effects and branch (c) includes plasticity.