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Thermochemical and statistical mechanical properties of natural sisal fibres

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ABSTRACT

The paper describes from a statistical perspective the diameter-dependence tensile strength and Young's modulus in 40 sisal fibres samples. The fibres tensile properties depend significantly upon their diameter, which has been determined using optical and SEM microscope techniques. Further characterisation of the sisal fibres has been carried out using FT-IR and DSC techniques. The fibres' ultimate tensile strength and Young's modulus have been evaluated using four different estimation methods from two and three-parameter Weibull distribution statistics. We show the significant sensitivity of the Weibull predictions versus the number of fibres samples used in the distributions, with the Weibull modulus m_σ obtained from our results being 10% smaller compared to what is reported in open literature. The scatter of the mechanical properties of the sisal fibres shown in this work is also compared to analogous distributions present in other works.

1. Introduction

The use of natural fibres as reinforcements in composite materials represents a suitable alternative to some classes of synthetic fibres. Although the mechanical properties of the natural fibres are in general significantly lower than those of synthetic origin (like. glass [1]), composites made by natural reinforcements show some significant potential for use as building materials. Several research teams have investigated the use of natural fibres such as okra [2], banana [3], artichoke [4], agave americana [5], jute [6], hemp [7], cactus [8], and sisal as reinforcements in polymer matrices [9]. The application of natural fibres is motivated by a combination of environmental sustainability, cost-effectiveness, recycling and biodegradation properties [10,11]. Natural fibres are also much less abrasive to tooling and moulds compared to glass fibres. In addition, single sisal fibres feature acceptable levels of tensile stiffness and strength, with high specific values for these mechanical parameters due to the low density of the fibre [9]. As a drawback, natural fibres tend to exhibit low transverse and compressive strength, and a significant sensitivity to environmental factors such as temperature and moisture.

The use of natural fibres as reinforcement in structural applications is rapidly taking place primarily within the automotive industry. European renewable fibres such as flax and hemp are now used to manufacture door panels and the roofs of cars [12], and also recently used to produce truss cores with complex architectures [13]. However, accelerating the substitution of synthetic fibres by natural reinforcements requires a greater availability of the latter. On the opposite, the production levels of flax and hemp do not meet the current demand. New plants must be found that enable easy and cost-effective extraction methods which are not detrimental to the physical properties of the fibres. These new natural reinforcements must be investigated to determine their physical, chemical and mechanical properties [14].

Sisal fibres (*Agave sisalana*) are extracted from sisal plant leaves in the form of long fibres. A sisal plant produces between 200 and 250 leaves before flowering [15], each plant containing approximately between 700 and 1400 fibres with a length of about 0.5–1.0 m [16]. The sisal leaf consists of a sandwich structure composed of approximately 4% fibre, 1% cuticle, 8% dry matter, and 87% water [15]. Silva et al. [17] studied the monotonic tensile behaviour of sisal natural fibres at four different gauge lengths (10 mm, 20 mm, 30 mm and 40 mm). Weibull statistics were used to quantify the degree of variability in fibre strength at the different gauge

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lengths. The Weibull modulus (m_σ) showed a decrease from 4.6 to 3.0 as the gauge length increased from 10 mm to 40 mm respectively. De Rosa et al. [18] performed tensile tests on natural fibres at three different gauge lengths (20 mm, 30 mm and 40 mm) to assess the effect provided by the gauge length on the tensile strength and Young's modulus. The results were processed using a two-parameter Weibull distribution.

The present work builds on a previous investigation carried out by Belaadi et al. [19]. It is widely reported in open literature that there is large scatter in results from tests carried out to characterise the mechanical properties of natural fibres. Between the factors affecting the dispersion of the mechanical properties, the most significant ones are the environmental conditions sustained by the plants during the growing process, the maturity (age) of the plant, fibre dimensions and the plant extraction process. Because of the dispersion generated by the different environmental and manufacturing parameters affecting the production of natural fibres, a statistical analysis of the mechanical properties is necessary. The use of natural sisal fibres in biocomposites requires also an appreciation of the mechanical performance of the fibres themselves. In this work the focus is about the characterisation of fibres with a gauge length of 20 mm. A spectroscopy characterisation of the fibres has been also carried out through Fourier Transform Infrared (FT-IR) techniques, as well as Differential Scanning Calorimetry (DSC) in both air and N_2 environments. The fibre strength and Young's modulus are analysed using Weibull statistics (2 and 3-parameters) for different estimators used in the open literature. A sensitivity study of the influence provided by the number of the samples population over the Weibull modulus and characteristic strength is also performed. As demonstrated in the case of biomedical materials (sintered zirconia), the size of the samples population used to extract the parameters in Weibull distributions significantly affects the choice of the cumulative distribution function, and therefore the estimates related to the modulus and the strength [20]. As it will be demonstrated in the rest of the paper, the same type of phenomena can be observed in the case of sisal fibres. A novelty of this work is also represented by the extended DSC analysis of the sisal fibres, with a comparison between the results obtained in air and nitrogen present in open literature. It must be pointed out that the low thermal stability of sisal fibres constitutes one of the limiting factors for the use of these ligno-cellulosic fibres as reinforcement in biocomposite structures [2]. Moreover, to the best of the authors' knowledge, this is the first time that an extensive use of two and three Weibull probability distributions with sensitivity analysis on sisal fibres is made, over the largest sample population for this particular type of fibre shown so far in open literature.

2. Material and testing techniques

The sisal fibres (*A. sisalana*) used in the present study are the same type of natural reinforcement evaluated in a previous work by Belaadi et al. [19]. The fibres were supplied by the Blida Packaging and Ropes Factory, Algeria. The surface of the fibre was identified using ZEISS optical microscope equipped with a Moticam 2500 camera digitally controlled by MoticImages Plus V2.0 image processing program. The fibres can have a variation in diameter along their length, as well as exhibiting some slight deformation of their apparent circular shape. The effective cross-sectional area of the fibres was determined using their mean diameter, whilst assuming their shape to be perfectly cylindrical [20]. Average diameters of the fibres were measured at three different locations (middle section and the two ends). The average values were obtained from three measurements at each location, this being considered sufficient since only fibres with minor diameter variability were carefully selected for testing. The average diameters detected for the fibres were within the range 140–372 μm.

The surface of the sisal fibre and its cross-section were also examined using a JSM-5600 scanning electron microscope (SEM). The fibres were coated with a fine layer of gold to make them conductive. SEM images were obtained with various magnifications under an accelerating voltage of 10–30 kV (Fig. 1). The overall microstructure of the sisal fibre used in this work appears to have a homogeneous cellular topology, compared to the hierarchical and

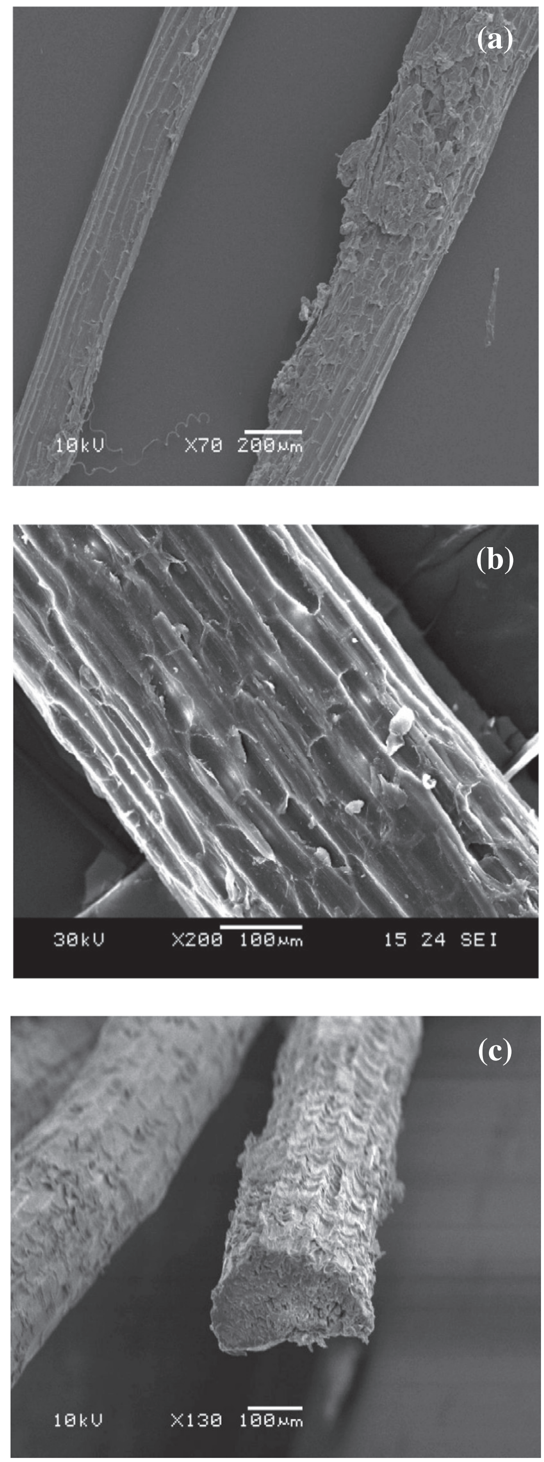

Fig. 1. SEM micrographs of longitudinal view (a), zoom of the surface (b), and cross section of the sisal fibre (c).