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Hybrid bio-composites reinforced with sisal-glass fibres and Portland cement particles: A statistical approach

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ABSTRACT

The hybrid configuration of bio-reinforced composites has established a new extended boundary for the development of pro-ecological technologies due to light weight, moderate specific strength, low cost, environmental benefits, and potential applications of natural components. This work investigates the physical and mechanical properties of hybrid composites made of sisal/glass fibres and Portland cement inclusions. A full factorial design was generated to identify the effects of the stacking sequence and cement particles on the flexural strength, flexural stiffness, apparent density, apparent porosity and water absorption of the composites. The significant contributions of these main factors and their interactions were determined via Design of Experiments (DoE) and Analysis of Variance (ANOVA). The fracture features and damage mechanisms of hybrid composite were also reported. The inclusion of cement microparticles led to an increased apparent porosity, as well as enhanced water absorption, flexural stiffness and flexural strength of the hybrid composites. The mechanical properties were strongly dependent on the fibre stacking sequence, which accounts for approximately 98% of the effects observed. Moreover, the stacking sequence affected the damage mechanism of the biocomposites. Finally, the replacement of glass fibres by unidirectional sisal reinforcements may potentially improve the specific properties in structural applications with an environmental sustainable footprint.

1. Introduction

During recent years, new techniques of cultivation, extraction and processing of natural fibres have allowed the development of new classes of sustainable composites derived from renewable sources [1,2]. In particular, hybrid bio-reinforced composites based on the use of natural and glass fibres have gained some traction in structural design for a range of different applications [3,4].

Hybrid composites are multifunctional materials that consist of two or more distinct reinforcement phases and combined in the same matrix. The reinforcements can include two types of individual fibres, or a combination of fibres and multiscale particles.

Hybrid synthetic fibre composites have shown an enhanced mechanical behaviour when ceramic particles are incorporated [5–8]. Santos et al. [9] have studied the incorporation of 1 wt%, 2 wt% and 3.5 wt% of silica particles in glass fibre reinforced composites and observed that ceramic particle reinforcements tend generally to increase the tensile modulus (at 1 wt%), the flexural modulus (at 3.5 wt%) and reduce the tensile and flexural strength of these composites. Detomi et al. [10] have shown that the inclusion of silica and silicon carbide microparticles increases the stiffness of glass fibre reinforced composites. The improvement of the mechanical properties has been attributed not only to the interlocking effect at the interlaminar region favoured by the particles, but also to the increase of the stiffness of the matrix phase [11]. Enhancements in thermal stability [12], tribological performance (wear and friction) [13], mechanical shear strength and impact of composites [14] can also be obtained by the inclusions of particles in polymeric composites.

In general, natural fibres are considered as a potential replacement to synthetic ones, mainly of glass type [15]. The use of natural fibres as reinforcements has been remarkably promising economically as well as in terms of improved environmental impact [16]. Natural fibres can be considered as natural aggregates of cellulose, hemicellulose and lignin, with smaller amounts of free sugars, proteins, extractives and inorganic

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products. The sisal plant (*Agave sisalana*) can produce between 200 and 250 leaves before flowering. Each leaf can reach from 60 up to 100 mm in width, and from 1500 to 2000 mm in length. Each leaf contains approximately 700–1400 bundles of fibres, whose length can vary from 0.5 to 1.0 m [1,2]. In general, the sisal leaf is composed by approximately 4% of fibres, 1% of superficial film (cuticle), 8% of dry matter and 87% of water [17]. These constituents, except for the fibres, are considered as residues originated from the processing, used as organic fertilizers, animal feed and in the pharmaceutical industry [18]. Angrizani et al. [19] have stated that sisal fibres could have their added-value multiplied if used as reinforcements in polymeric composites. Sisal fibres are lightweight, non-toxic, present high tensile specific modulus and strength, and excellent thermal and acoustic insulation properties. Moreover, sisal causes less abrasion damage to moulding equipment and costs about ten times less than glass fibres. In addition, sisal fibres can be easily surface modified, which enhances fibre-matrix adhesion [20].

The mechanical efficiency of natural fibre reinforced composites can be improved even further via hybridization, i.e., by combining synthetic and natural fibres in the same composite [3]. Hybrid composite designs can provide flexibility, high life cycle properties, low cost and sustainable characteristics [3,4,21]. Recent publications have been addressed to hybrid composites of sisal and glass fibres. Padanattil et al. [22] investigated hybrid composites reinforced with sisal and glass fibres as a potential choice for the retrofitting of reinforced concreted structures. KC et al. [23] analysed the influence of injection moulding processing parameters of two sisal-glass fibre composites with different contents using the Taguchi Method. Aslan et al. [24] evaluated the tribological and mechanical responses of sisal/carbon and sisal/glass hybrid fibre reinforced polypropylene (PP) composites.

The incorporation of Portland cement into sisal short fibre reinforced composites was investigated by Santos et al. [25], who reported an increase in water absorption, damping ratio and flexural modulus. Higher stiffness was obtained when 10 wt% of cement microparticles were added. The mechanical behaviour of hybrid glass fibre reinforced composites with cement inclusion was also investigated by Melo et al. [26] and Torres et al. [27]. Melo et al. [26] reported improved flexural properties when cement microparticles were added on the upper beam side (under compression) of the glass fibre laminate. Torres et al. [27] also observed increased flexural stiffness when silica or cement inclusions were incorporated into the upper beam side of unidirectional glass fibre composites. Moreover, the flexural strength and impact resistance were increased when 5 wt% of cement or silica particles were inserted.

This work focuses on the development of novel hybrid composites reinforced with sisal-glass fibres and Portland cement particles as an alternative substitute for glass fibre composites generally used in aircraft, automotive and building applications. This is, to the best of these authors' knowledge, the first attempt to identify the effects of Portland cement on the physical and mechanical properties of hybrid composites containing unidirectional sisal and glass fibres. The cement inclusions and the stacking sequence factors were investigated using a statistical methodology based on the Design of Experiments (DoE) approach.

2. Materials and methods

2.1. Hybrid laminates

The hybrid bio-composites are made of epoxy polymer (RenLam M − 1 and Hardener HY 951) supplied by Huntsman (Brazil), unidirectional sisal fibres sourced by Sisal Sul (Brazil), glass fibre fabric (cross ply, 200 g/m^2) and Portland cement particles (Holcim-Brazil).

The sisal fibres are washed with distilled water at 80 °C for 1 h and oven-dried at 50 °C until they reach a constant mass. Sisal fibres with no visible damage and a fibre length of 1 m have then been selected. The fibres are then pre-tensioned along the longitudinal direction (0°) using

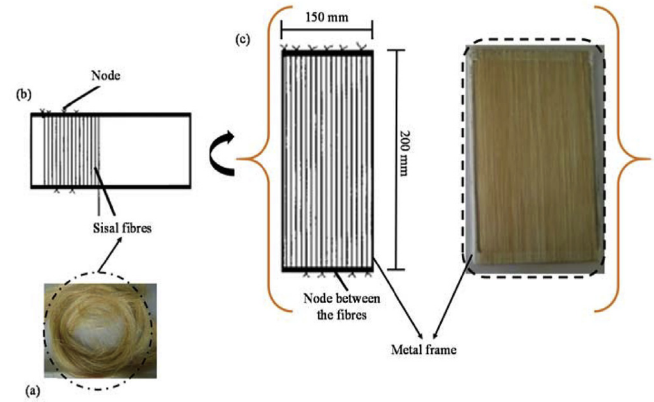

Fig. 1. Sisal fibres weaving: (a) natural sisal fibres, (b) manual aligning procedure of the fibres and (c) aligned unidirectional (0°) fibres.

a metallic mould. The manual weaving of the sisal fibre starts with a knot at the edge of the metallic structure, followed by the joining of the fibres by another knot (Fig. 1). The knot is made at the ends of the metallic mould, ensuring that the working area remains without defects caused by the manufacturing process.

Preliminary tests have been performed to determine the optimized fibre-matrix mass fraction and ensure an adequate superficial finishing of the composites. Based on these tests, a fibre-matrix mass fraction of 30/70 was used to manufacture the laminated composites by hand lay-up. The sisal fibre interspacing was selected so as to approximately obtain the same grammage of the glass fibre fabric (200 g/m^2). A fibre-matrix *mass* fraction is chosen instead of a more classic *volume* fraction, due to the large variability of the density of sisal fibres.

Hybrid laminates have a five-layer architecture considering the stacking sequence of sisal/glass and glass/sisal. This configuration was considered to evaluate mainly the effect of the glass fibre layer position on the flexural stiffness of hybrid composites. Two reference conditions consisting of 5 layers of [0/90°] cross-ply glass fibres and 5 layers of unidirectional sisal fibres were also fabricated to complete the stacking sequence levels. The sisal fibres are unidirectionally disposed at 0° along the direction of the sample length. Sisal fibres are generally thicker than glass fibres. Therefore, the sisal fibre layer was thicker than the glass fibre one, even though 3 unidirectional sisal laminae and 4 cross-ply glass fibre laminae have been used. Specific details of the sisal/glass and glass/sisal fibre stacking sequences are shown in Fig. 2. The laminate composites are compacted by applying a force of 5 N for 10 h, and then cured at room temperature (20 °C) for 7 days. The resulting hybrid composites have a mean thickness of 1 mm.

ASTM-III type Portland cement at 10 wt% is used as the disperse phase in the first two top layers of the laminates. The cement particles are classified by following a sieving process at 200–325 US-Tyler. A previous investigation has been conducted by adding 2.5 wt%, 5 wt% and 10 wt% of cement particles into the epoxy matrix phase; this study has shown that the best mechanical properties can be reached by using 10 wt% of particles, hence the weight fraction used in this work [28].

2.2. Experimental design

The Full Factorial Design is a methodology that makes use of different statistical techniques to provide a structured method for planning, executing and analysing experiments [29]. DoE is also essential to identify which factors and parameters are most significant to the global mechanical and physical properties of the composites [5,9,10,12,20,25].

ANOVA (analysis of variance) is used here to verify if the effect of the main factors and interaction of factors are statistically significant. In this work, ANOVA could detect how the physical and flexural

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