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Optimal tensile properties of a Manicaria-based biocomposite by the Taguchi method

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ABSTRACT

Environmental awareness of the global waste problem has driven the development of new green composites made from either renewable or biodegradable materials. Among the variety of available green composites, natural composites based on poly-lactic acid (PLA) have shown noteworthy performance due to their short degradation time after disposal, good strength, and ease of processing by conventional methods. In particular, green composites manufactured with PLA matrix reinforced with Manicaria Saccifera fabric (MF) display mechanical properties that have shown to be very competitive compared with similar materials. In this study, the tensile properties of a green composite of PLA reinforced with MF are optimized by using a Taguchi method approach. The processing parameters, fabric chemical treatment parameters, compression molding parameters, and fiber content are analyzed simultaneously to yield the optimum biocomposite properties. The predicted optimum parameters are experimentally verified. Tensile tests and scanning electron microscope (SEM) analysis are used. Significant improvements on both the tensile strength (114.2%), and the elastic modulus (120.6%) of the biocomposite are achieved.

1. Introduction

Green composites are one of the most promising alternatives to replace synthetic plastic goods and glass-fiber reinforced composites [1]. Their eco-friendly character and competitive mechanical properties make green composites very suitable for use in some industrial applications, such as the automotive industry, where synthetic plastics and composites are being partially substituted [2]. This movement to replace traditional polymer composites is mainly driven by environmental awareness of the global waste problem and the mitigation of petroleum-based materials. Therefore, the development of new biodegradable products made from renewable raw materials such as green composites currently is an active research topic.

Among the green composites currently used for industrial applications, natural composites based on poly-lactic acid (PLA) have shown noteworthy performance [3]. PLAs properties, such as short degradation time after disposal, good strength, and ease of processing by conventional methods, have resulted in its use in several natural, biodegradable composites in various industrial and engineering fields [4]. In fact, PLA has been widely studied in biocomposites reinforced with natural fibers such as jute [5], flax [6], kenaf [7], hemp [8], bamboo [9], abaca [10], lyocell [11], wood [12], ramie [13], oil palm [14], artichoke [15] and arenga pinnata [16]. Most of these studies have focused on the use of short or unidirectional fibers. However, green composites with more stiffness and strength can be developed using natural fabrics as reinforcement by exploiting their load-carrying capacity [17,18].

In particular, one of the most interesting available green composites developed with a PLA matrix is reinforced with Manicaria Saccifera fiber (MF) [19]. This natural fabric, consisting of a brown cellulosic material with a particular nonwoven design, is obtained from the inflorescence of the palm and shows appropriate properties to reinforce PLA. Due to its displayed mechanical properties and biodegradability, the PLA/MF green composite has proven to be a very competitive material that can be used in many applications.

In addition, improving the performance of green composites is important to broadening its applications [20]. Identifying and adjusting the processing parameters of green composites has attracted great attention in the manufacturing industry and scientific fields [21]. For example, natural fiber type and content are parameters influencing the performance of the composite. Usually, increasing fiber content of the composite significantly increases its stiffness [22,23]. In addition, the mechanical properties depend

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significantly on the degree of adhesion between the natural fiber and the matrix. Fiber surface modification treatments are widely used to optimize fiber/matrix bonding. Parameters such as treatment time and solution concentration are elements key to achieving the optimum mechanical behavior of composites [24,25]. Similarly, manufacturing technique affects the performance of the composite. In compression molding techniques, the selection of process parameters such as pressure, temperature, and holding time have been shown to greatly influence the properties and interfacial characteristics of the biocomposites [26,27].

However, owing to the high cost of experimenting, the parameters that govern the manufacturing process are typically studied independently, disregarding the possible interactions among them. However, new trends in the manufacturing industry are prompting integrated studies of processing parameters to maximize the performance of the composite materials. The Taguchi method has shown reliable results in robust design and has the capability to integrate processing parameters to optimize material performance [28]. This method allows the optimization of the materials performance by adjusting the materials parameters through a robust experimental design that has the capability to analyze many parameters with fewer experiments than in traditional experimental designs. In fact, this technique, widely used for improving the quality of manufactured goods, has recently been implemented in the development of green composites. For example, it has been used to study and improve the wear behavior of natural fiber composites [29–31] and to optimize the mechanical properties [32–34].

This study optimized the tensile properties of a green composite of PLA reinforced with MF by using the Taguchi method approach. Fabric chemical treatment parameters (time and concentration), compression molding parameters (temperature, pressure, and time), and fiber content (fiber-weight ratio) were analyzed simultaneously to yield the optimum biocomposite properties. The predicted optimum parameters were experimentally verified and compared with neat PLA properties and with those of an untreated fabric composite. Tensile tests and scanning electron microscope (SEM) analysis were used.

2. Materials and methods

2.1. Materials

PLA produced by Nature Works LLC was used as the polymeric matrix, and a novel natural fabric extracted from the bract of the *Manicaria Saccifera* palm was used as reinforcement. Manicaria bracts of from 0.8 to 1.2 m in length were provided by a native community in the Choco region in Colombia. They were made of brown fibrous material constituted of numerous cross-linked fibers with a particular woven design resembling a fabric, which in this study, is called Manicaria Fabric (MF) [35].

2.2. Preparation of composites

PLA granulate was converted into a sheet using a Brabender Plasticorder 331 single-screw extruder. The extruder temperatures were set according to the technical datasheet temperature processing profile (180–210 °C). In addition, the MF was subjected to a chemical treatment to improve the interfacial bonding properties between it and the PLA matrix. Two concentration levels and three soaking-time levels of chemical treatment were evaluated; therefore, six types of treated fabrics were prepared. Composite laminas were produced by compression molding process using the film-stacking method. The PLA and treated MF were layered alternately and heat compressed using a conventional molding press (Dake Press, model 44–251). The temperature, pressure, and molding time were set according to the experimental design values, as well as the fiber content.

2.3. Tensile tests

Tensile tests were carried out in accordance with the ASTM D3039 standard on a universal testing machine (Instron 3367). Rectangular geometry specimens were tested at a crosshead speed of 2 mm/min and a gauge length of 50 mm. An extensometer device was used to measure the elongation during the test. Ten specimens were tested from each experimental run.

2.4. Microscopic analysis (SEM)

The fabric surface and the tensile-fractured samples were examined using a JEOL scanning electron microscope (SEM), model JSM-6490LV. Prior to the analysis, samples were coated with a layer of gold using a Dentom Vacuum Desk IV device to improve conductivity. In addition, the Energy Dispersive X-ray Spectroscopy (EDS) method was used to identify elements in the samples.

2.5. Experimental design

The mechanical properties of biocomposites are highly influenced by a number of parameters, including fiber content, fiber modification by chemical treatments, and the processing method. The Taguchi method is a powerful analysis tool for conducting experimental designs involving the study of multiple parameters. The method uses orthogonal arrays to determine the minimum number of experiments needed to provide enough information to determine factor effects and optimal values, offering advantages in terms of experimental cost and time.

This study considered six factors: chemical treatment concentration (A), chemical treatment time (B), compression molding temperature (C), compression molding pressure (D), compression molding time (E), and fiber-weight ratio (F). Table 1 shows the selected levels for each factor. In addition, an L_{18} $(2^1 * 3^7)$ orthogonal array was used to set up the processing conditions under which biocomposite laminas were fabricated, as shown in Table 2.

An L_{18} orthogonal array can handle eight factors assigned to each column. As shown in Table 2, six columns were used to set up the control factors (AF), and the remaining two columns were used as empty columns to estimate experimental error in the matrix. In addition, this array described the level settings for each of the 6 factors that were used for the 18 experimental runs. Each run presented the processing conditions of the laminas. For the first run, all factors were set at Level 1. For the second run, factors C, D, E, and F were changed to Level 2; A and B remained at Level 1. The remaining runs were set up as coded in the matrix until all 18 runs were completed. Two laminas were manufactured for each experimental run, and five specimens were tensile tested for each lamina. The ultimate strength and the Youngs modulus were used as analysis criteria (output). To determine the optimal parameter

Table 1
The selected factors and levels for the experimental design.

Factors	Level 1	Level 2	Level 3
A: Chemical treatment concentration (w/v%)	Low	High	–
B: Chemical treatment time (min)	Low	Medium	High
C: Compression molding temperature (C)	Low	Medium	High
D: Compression molding pressure (MPa)	Low	Medium	High
E: Compression molding time (min)	Low	Medium	High
F: Fiber weight ratio (wt.%)	Low	Medium	High