Manufacture and evaluation of the tensile properties of a biodegradable composite material reinforced with Colombian coconut fibers

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Abstract. The mechanical properties of a biodegradable composite material made with Colombian coconut fibers were studied. The study was carried out considering a random distribution of fibers within the composite material for three fiber/matrix compositions (10, 20 and 30) in weight-to-weight percentage. Each of these was subjected to tensile tests to evaluate the effect of the fibers in each composition, taking into account the mechanical properties of ultimate tensile strength and elastic modulus that allow selecting the composition of greater rigidity and subsequently evaluating its properties under the effects of compression forces. The results obtained show that the more rigid composite material corresponds to the fiber/matrix 20 percent composition, which presented a tensile strength of 13.83 MPa and an elastic modulus of 924.46 MPa comparable with those reported in the literature. This composition is the most fragile with a percentage of elongation is 2.27% and with low tenacity to withstand impact efforts. Finally, the behavior of the more rigid material was compared with the mechanics of Ramberg-Osgood and Hollomon, the latter being the most adjusted allowing to predict the properties of this type of materials. The results obtained expand the uses of Colombian coconut fibers as a biodegradable composite.

1. Introduction
Coconut fiber is a durable, renewable, biodegradable material with a good combination of strength, length, moisture recovery, high resistance to sunlight, salt water and microbes [1]. It is also a product that has been evaluated as a thermal and acoustic insulator [2] and has been widely used as a reinforcement in biodegradable composites for its high strength [3], low cost and availability [4], as well as evaluating the possibility of replacing asbestos in some industrial products [5].

Different studies that have been conducted in the manufacture of composite materials reinforced with coconut fibers emphasize the importance of understanding the effects of fiber treatment on fiber / matrix interfacial adhesion [6]. This process is carried out with the objective of improving the mechanical properties as demonstrated by the work of Diao et al. who studied the wheat gluten compound hardened and reinforced with treated coconut fibers obtaining values of flexural rigidity up to 1.4 GPa [7]. In addition to these studies, it has also been investigated the different variations that can affect the properties of a material reinforced with coconut fibers to obtain compounds with high yields and
different applicability [8]; as in the work of Duraibabu et al., in which epoxy compounds were reinforced with treated coconut fibers achieving an increase in mechanical properties and thermal stability [9].

Similarly, and taking into account the potential of Colombian coconut fibers within the area of composite research, the use of short fibers distributed randomly within a biodegradable polymer matrix that establishes fiber/matrix compositions is proposed 0/100 (FM0), 10/90 (FM1), 20/80 (FM2) and 30/70 (FM3) in weight to weight percentage, which by means of tensile tests allowed to select the composition of the material with greater rigidity. Fiber distributions are random in order to facilitate material engineering applications. Also, the compositions were selected by the orderly partition of a matrix without reinforcement FM0 and the maximum load supported FM3 in the test piece.

2. Materials and methods
The material of the test pieces was made with coconut fibers (CF) with an average of 2.5 cm in length and mixed with an elaborated matrix of polyvinyl acetate (PVA) and corn starch (CS). The coconut fiber is alkaline treated with sodium hydroxide (NaOH) to remove oily substances and impurities and improve the interfacial adhesion between the fiber and the matrix. The geometry of the specimens and the parameters of the tensile test are carried out according to the specifications of ASTM D3039 [10] and in the compression, test the parameters established by the ASTM D695 standard [11] are taken into account.

The tensile tests were performed with a speed of 5 mm/min and the compression tests were performed with a speed of 1.3 mm/min. For both tests, the MTS Bionix universal testing machine was used and the tests were carried out at room temperature (25 °C). Finally, a micrograph with a scanning electronic microscope (SEM) Phenom ProX-2015 in the range of 200 - 1200 μm is taken over the cross-sectional area of the fracture of one of the specimens submitted to the tensile tests.

2.1. Alkaline treatment of fibers
In a typical treatment, 400 g of coconut fiber are immersed for 6 hours in an amount of 10 L of NaOH solution with a concentration of 50 g/L diluted in deionized water, following the suggestions made by Ridzuan et al [6]. Subsequently, the fibers are removed from the solution, rinsed to remove the excess NaOH and finally dried at room temperature for 72 hours.

2.2. Preparation of the matrix
The matrix of the composite material was made using PVA and CS in a 2:1 ratio of the percentage by weight of the two materials; subsequently, the mixing process is carried out until the mixture of these two components is homogenized.

2.3. Preparation of the composite material
The composite material is made by mixing the coconut fiber with the matrix in the specified proportions (see Table 1), until obtaining a uniform impregnation of the fibers with the matrix. Finally, the mixture is poured into molds to obtain the test pieces of each of the compositions of the composite material (see Figure 1) and they are subjected to a time of 72 hours of curing to the environment.

| Composition | FM0 | FM1 | FM2 | FM3 |
|-------------|-----|-----|-----|-----|
| Fiber/Matrix | 0/100 | 10/90 | 20/80 | 30/70 |
3. Results and discussion

After making three replicas of the tensile test for each of the compositions of the composite material, the ultimate tensile strength, elastic modulus and elongation percentage of each were determined, obtaining the results presented in Figure 2 and Table 2.

Evaluating the results presented in Table 2, it can be deduced that the material with greater rigidity is the composite FM2 because it has the highest value of the elastic modulus with respect to the other percentage compositions. Table 3 shows the mechanical properties of the FM2 compound subjected to tensile stresses.

Table 2. Comparison of the mechanical properties of the specimens.

| Composition (fiber/matrix) | FM0  | FM1  | FM2  | FM3  |
|---------------------------|------|------|------|------|
| Ultimate tensile strength (MPa) | 3.62 | 7.67 | 13.83| 3.67 |
| Elastic Modulus (MPa)      | 83.88| 189.73| 924.46| 363.51|
| Elongation percentage (%)  | 16.03| 13.86| 2.27 | 3.75 |

From the results presented in Table 3, it can be deduced that the FM2 composite has a low tenacity value, reducing its capacity to withstand impact forces, it is a fragile material with an elongation of only 2.27%, but it has a high value of ultimate tensile strength.
Table 3. Mechanical properties of the FM2 compound (tensile test).

| Mechanical property           | Quantity       |
|------------------------------|----------------|
| Tenacity                     | 9.1x10^{-5} J/m^3 |
| Elastic modulus              | 924.46 MPa     |
| Ultimate tensile strength    | 13.83 MPa      |
| Creep resistance             | 7.55 MPa       |
| Elongation percentage        | 2.27 %         |

Figure 3 shows the experimental stress-strain curve of the FM2 material along with the curves of the Hollomon and Ramberg-Osgood models. Next, we define the nomenclature of the equations presented in Table 4 of each of the models represented:

Figure 3. Comparison of the experimental data of the stress-strain curve of the FM2 compound with the models of Hollomon [12] and Ramberg-Osgood [13].

According to the curves shown in Figure 3, we can affirm that the Hollomon model’s tendency adjusts to the tensile-deformational behavior of the experimental curve of the FM2 material; contrary to what happens with the trend of the curve of the Ramberg-Osgood model, which adjusts well to the data of the experimental curve in the range of the elastic zone and when exceeding the yield point loses representativeness in the range of the permanent deformations. Table 4 shows the equations of the models represented in Figure 3.

Table 4. Equations of the Hollomon and Ramberg-Osgood models.

| Hollomon model                       | Ramberg-Osgood model                   |
|-------------------------------------|----------------------------------------|
| \( \sigma = k \varepsilon^m \)     | \( \varepsilon = \frac{\sigma}{E} + 0.002 \left( \frac{\sigma}{S_y} \right)^{n_0} \) |
| \( \sigma = 165.2 \varepsilon^{0.652} \) | \( \varepsilon = \frac{\sigma}{924.46} + 0.002 \left( \frac{\sigma}{7.55} \right)^{13.94} \) |

\( k \) = Hardening coefficient; \( n \) = Hardening exponent; \( E \) = Elastic modulus; \( S_y \) = Creep effort; \( n_0 \) = Non - linearity constant; \( \sigma \) = Engineering effort; \( \varepsilon \) = Engineering deformation.

Continuing with the mechanical characterization, three replications of the compression test were made to the FM2 composition, obtaining the results presented in Table 5.
Table 5. Mechanical properties of the FM2 compound (compression test).

| Mechanical property                  | Quantity |
|--------------------------------------|----------|
| Tenacity                             | 2.08x10^{-3} J/mm³ |
| Elastic modulus                      | 70.01 MPa |
| Ultimate compression strength        | 9.03 MPa |
| Creep resistance                     | 2.85 MPa |
| Shortening percentage                | 20.02 %  |

The material subjected to compression reaches a final resistance value of 9.03 MPa lower than that obtained by tensile tests, with a percentage of shortening of 20.02%, evidencing that the fibers inside the material do not offer a high resistance to compression forces. Figure 3 shows an SEM image of the cross-sectional area where the FM2 material failed. Figure 4 (a) shows the fiber rupture after the stress test. In the enlargement of the image (Figure 4 (b)) it is possible to show the rupture of the fibers and their diameters, it is then suggested that the variability in the fiber diameters could allow the concentration of stresses and thereby contribute to the failure of the material.

![Figure 4](image)

**Figure 4.** SEM micrograph of the transversal area where the failure of the FM2 composite material occurs.

4. Conclusions
We have demonstrated that the Colombian coconut fiber offers positive effects for each of the compositions studied, highlighting that a high ultimate tensile strength (13.83 MPa) with composition FM2 was achieved, this being the composition of the material with greater fragility (elastic modulus of 924.46 MPa and percentage of elongation of 2.27%), the results obtained in the tensile test that the tensodeformational behavior of the compound have a behavior similar to the materials modeled by the model of Hollomon. It is recommended that in order to improve the mechanical properties, uniform compaction and distribution of the fiber should be guaranteed together with the matrix, evited the efforts are concentrated causing the fracture. We believe that the material composites with coconut fibers are particularly attractive for the design of novel materials useful for a wide range of potential applications, and its detailed studies on this approach are underway.

Acknowledgements
The authors gratefully acknowledge the “Universidad Industrial de Santander”, the “laboratorios de Mechanica” of the “Escuela de Ingeniería Mecánica” and the “laboratorio de Microscopía” of the “Parque Tecnológico Guatiguára” who allowed the development of this work.
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