Mechanical properties characterization of the Ichu fibers composites

S Charca and S Candiotti
Department of Mechanical Engineering, Universidad de Ingeniería y Tecnología – UTEC, Medrano Silva 165, Barranco, Perú
Corresponding author: samuel.charca@upr.edu

Abstract. In the recent years, natural fibers are gaining an outstanding position as a reinforcement material, due to diverse advantages like high specific properties, low cost and low environmental impact. On the other hand, according to the market studies, in the next years the offer of the natural fibers will be in deficit; therefore, exploration of new natural fibers from new resources can be an alternative to fill this gap. Along the Andean region there are diverse natural resources from which cellulosic fibers can be extracted, like the *Stipa obtusa* grass, also commonly known as Ichu. The main purpose of this research was to determine the mechanical properties of unidirectional composite laminates made from Ichu fibers mixed with polyester resin; tensile, compressive and shear properties were evaluated. Results show that the stiffness in the principal direction ($E_1 \sim 16$ GPa) and the transverse direction ($E_2 \sim 4.7$ GPa) are over the average values compared to the composites made from the commercial fibers; similar behavior was observed in its shear and compression characteristics. Strength shows values around $\sigma_1 \sim 118$ MPa, $\sigma_2 \sim 13$ MPa, $\tau_{12} \sim 46$ MPa and $\tau_{23} \sim 18$ MPa, which is similar to the values reported in the literature for the commercial natural fiber composites. Based on these results, the Ichu fiber has a great potential as a reinforcement in composites materials.

1. Introduction

During the last decades, environmentally friendly processes and materials are gaining great momentum and demand [1], due to the diverse benefits they offer compared to current man-made materials [2]; particularly in the area of composite materials, natural fibers have been successful used as a reinforcement due to their low density, excellent specific mechanical properties and low cost; likewise, the processing of this kind of fibers is less hazardous for the environment and processing equipment during their manufacturing [3]. For these reasons, natural fibers are being used in nonstructural parts in automobile and marine industry [4-6]. On the other hand, natural fibers are a combination of cellulose, hemicellulose, lignin, and other extractive components; from these, cellulose is the main component which give the natural fibers their strength and stiffness characteristics [7]. However, raw fibers have low cellulose content and generally, poor bonding characteristics with a polymeric resin matrix, if the purpose is to manufacture composites; as a consequence, in order to increase the cellulose content and improve the bonding characteristics, natural fibers would need to be treated. One of the simplest and most commonly treatment used in the industry is the mercerization; this treatment is a thermochemical process, where an alkaline solution is the commonly chemical used [8-9]. With this treatment, dimensional and thermal stability can be reached; furthermore, an increase in their density and mechanical properties is observed as well, mainly due to the increment in their relative cellulose content [8-11]. Raw natural fibers are naturally hydrophilic with high surface energy, this give to the raw fibers...
a poor bonding characteristic with synthetic resins (nonpolar matrix); however, after the alkali treatment, substantial improvement in the compatibility to the resin can be observed [12-13].

In recent years, different sources of natural fibers are being studied, with one of those being the fibers extracted from Ichu plant. Ichu is a grass type plant, which can grow above 3000 m a.s.l. This plant was commonly used as a rope and roofing material; however, with the development of new materials their uses have been reduced. Some recent studies presented an optimal extraction method of the Ichu fibers and their mechanical properties, showing potential to be use as a reinforcement in composites materials [11, 14-15]. Furthermore, this fiber has a particular characteristic: In their natural state, raw fibers are hydrophobic (low surface energy), due to the presence of waxes and other extractives on the fiber surface; after the alkali treatment these components are removed and, while the surface energy increases, the fiber maintained their hydrophobicity [11, 14]. The main purpose of this research is to evaluate the tensile, compressive, shear and bending mechanical properties of unsaturated polyester composites reinforced with extracted Ichu fibers; considering the fiber longitudinal and transverse direction.

2. Materials and methodology

Raw Ichu fibers were harvested from Cusco (Peru) at 3600 m a.s.l. The fiber extraction process was performed by thermochemical treatment, using a solution of 1.5 M NaOH diluted in distilled water at 70 °C, for a treatment of 45 minutes; with these parameters being established by Mori et al and Tenazoa et al as the optimal, to bring the best physical properties and chemical characteristics of the fibers [14-16], although, based on their last studies, treatment with lower NaOH solution can reach equivalent results, however it requires a prolonged time of treatment [11, 17]. After treatment, the fibers were cleaned and dried, making sure to keep the axis of the fibers in one direction to form a unidirectional matt; and afterwards, were maintained in a desiccator to avoid the moisture intake. To manufacture composites, vacuum assisted resin transfer molding (VARTM) technique was used, and to make economically feasible the use of this fiber as a reinforcement, an unsaturated polyester resin was used (Tekno 285, $\sigma_m \sim 102 \pm 20.11 \text{ MPa}, E_m \sim 3.13 \pm 0.17 \text{ GPa}, \epsilon_m \sim 3.3 \pm 0.89 \%$ tested in three point bending according to ASTM D790 [18]). In order to get a 45 minutes delay before the resin begins to cure, an appropriate mixing proportion of resin, catalyst (Methyl Ethyl Ketone Peroxide, MEKP) and accelerator (Cobalt Octoate) were set. After composites were made, laminates were post cured in an oven for 12 hours at 60 °C; afterwards, the testing specimens were cut using a water jet cutting system, in dimensions according to ASTM D3039 [19], D3410 [20], D5379 [21] and D7264 [22] standards.

In order to measure the deformation of the samples, a digital image correlation (DIC) technique was used. The deformation process was recorded using a Manta G505 2/3” Monochrome CCD Camera (Allied Vision) with AF Micro-Nikkor 60 mm f/2.8D lenses. In order to validate results, strain gauges were glued to one face of the samples, and the other face was painted with white color (basecoat) followed by fine black speckles. Data acquisition was synchronized appropriately in order to get a reliable result. Images obtained were processed using the open source 2D DIC MATLAB Software Ncorr v1.2. Samples were tested using a MTS Landmark system with a 100 kN load cell. According to the standards, tensile, compressive and bending tests were performed at a 0.01 strain/min rate, and for the shear test a crosshead displacement rate of 2 mm/min was used. Finally, in order to determine the fiber volume fraction of the composites, optical microscopy was used on a polished cross-sectional surface of specimens obtained from the laminates.
3. Results and analysis

3.1. Testing results

From the measurement, fiber volume fraction on the composites was determined to be $v_f = 0.36 \pm 0.020$. On the other hand, Figure 1 to Figure 4 shows the typical stress-strain curves observed during the tensile, compressive, shear and bending tests. For tensile test (Figure 1), curves show linear behavior, with brittle failure in the end, for the longitudinal (axial) and transverse direction of the fibers. Contrary to the tensile test, compressive behavior is non-linear (Figure 2), for the longitudinal and transverse direction of the fibers, mainly due to the mechanics of failure, where debonding and micro buckling happens; and afterwards, the overall bucking and development of these processes is progressive. Shear stress-strain curve present a non-linear behavior along the 12 direction (Figure 3(a)), as when the load is transversely applied to the axial direction of fibers, the principal failure mode is the debonding of the fiber/matrix interface near the notch, followed by the transversely deformation of the fibers. On the other hand, if the load is applied along the 21 direction, aligned to the fiber longitudinal axis, is the interface who fails upon reaching their maximum capacity with a sudden failure (Figure 3(b)). Bending stress-strain curve shows a slight non-linearity for the longitudinal fiber direction (Figure 4(a)), with sudden failure at the end, while the transverse stress-strain curve is perfectly linear with sudden failure at the end as well.

![Figure 1. Typical tensile stress-strain curve for the Ichu laminate composites, a) longitudinal direction, b) transverse direction.](image1)

![Figure 2. Typical compressive stress-strain curve for the Ichu laminate composites, a) longitudinal direction, b) transverse direction.](image2)
Figure 3. Typical shear stress-strain curve for the Ichu laminate composites, a) load applied transverse to the fibers direction, b) load applied in fibers direction.

Figure 4. Typical bending stress-strain curve for the Ichu laminate composites, a) longitudinal direction, b) transverse direction.

3.2. Comparative results analysis
Comparative charts (Figure 5 to Figure 8) show the results obtained in this study compared to results found in the literature [23-34]; unfortunately, in the case of transverse testing results there is no data available in the reviewed literature. Furthermore, it is well known that epoxy resin is excellent material to work with natural fibers; however, the main disadvantage is their cost, which is considerable high compared to the unsaturated polyester (UP); so, in order to have a general comparison, composites made with epoxy resin are include as well. Volume fraction ($v_f$) of the fibers into the composites is reported besides the fiber/matrix used, since it can be variable from literature to literature, due to the natural fibers characteristics and the method used to manufacture composites.

Composites made with Ichu and UP ($v_f = 0.36 \pm 0.020$) present tensile strength over 100 MPa (Figure 5), which can be equivalent to the composites made with jute/epoxy ($v_f = 0.5$), flax/vinyl ($v_f = 0.25$), jowar/UP ($v_f = 0.4$), bamboo/UP ($v_f = 0.4$) and jute/UP ($v_f = 0.4$); furthermore, their strength is higher than sisal/UP ($v_f = 0.4$) and kenaf/PLA ($v_f = 0.4$) composites. For the stiffness, it is evident that modulus is considerable higher than jute/epoxy ($v_f = 0.5$), flax/vinyl ($v_f = 0.25$), jowar/UP ($v_f = 0.4$), bamboo/UP ($v_f = 0.4$), jute/UP ($v_f = 0.4$), and kenaf/PLA ($v_f = 0.4$) composites; and equivalent to the harakeke/epoxy ($v_f = 0.5$), sisal/epoxy ($v_f = 0.48$) and hemp/epoxy ($v_f = 0.65$) composites.
Figure 5. Comparative strength and stiffness for different natural fibers composites under tensile test, a) longitudinal strength and b) longitudinal modulus.

Longitudinal compressive strength and modulus comparisons are shown in the Figure 6. The compressive strength (Figure 6(a)) is quite variable; however, their values are close to the results for Flax/Vinyl ($v_f = 0.25$), flax/epoxy ($v_f = 0.4$) and coir/epoxy ($v_f = 0.4$); nevertheless, lower than the bamboo/epoxy ($v_f = 0.4$) composites. Modulus in the other hand (Figure 6(b)), is considerable low compared to the flax/vinyl ($v_f = 0.25$), flax/epoxy ($v_f = 0.4$) and bamboo/epoxy ($v_f = 0.4$); however, similar to the values obtained for coir/epoxy ($v_f = 0.4$). At the bottom of the Figures 6 (a) and (b), Ichu/UP (T) correspond to the transverse direction properties.

Figure 6. Comparative strength and stiffness for different natural fibers composites under compression test, a) longitudinal strength and b) longitudinal modulus.

Shear strength and shear modulus comparative chart is shown in Figure 7. Unfortunately, the information of shear properties available in the literature for the unidirectional composites reinforced with natural fibers is quite limited; although there are results for strand mat and for woven fibers composites [33]; which are included in the chart as well. From the results, $\tau_{12}$ is over 45 MPa; however, $\tau_{21}$ are considerable low around 17 MPa. At the bottom of the Figures 7 (a) and (b), Ichu/UP (T) correspond to the transverse direction properties.
Figure 7. Comparative strength and stiffness for different natural fibers composites under isosipescu shear test, a) shear strength and b) shear modulus.

Bending strength and stiffness comparison chart is shown in the Figure 8. The bending strength of Ichu/UP composites is higher than Jowar/UP, Sisal/UP, Bambu/UP and Kenaf/PLA; however, lower than Flax/Epoxy, Hemp/Epoxy, Jute/Epoxy, Flax/Vinyl, Harakeke/Epoxy and Flax/PP composites, although, in these cases, the fiber $\nu_f$ is higher than the Ichu/UP composites. On the other hand, bending stiffness of the Ichu composites shows values around 10 GPa, which is higher to the values observed for composites made using unsaturated polyester; however, lower for most of the composites made with epoxy as a matrix. At the bottom of the Figures 8 (a) and (b), Ichu/UP (T) correspond to the transverse direction properties.

Figure 8. Comparative strength and stiffness for different natural fibers composites under flexural test, a) longitudinal strength and b) longitudinal modulus.

4. Conclusion
Ichu fiber composites were manufactured using the VARTM technique, reaching fiber volume fraction around 0.36; furthermore, the strain stress curves from mechanical testing were built, including: tensile, compressive, shear and flexural tests. The composites show a linear and brittle behavior for tensile and flexural test, like most of the results reported in the literature. On the other hand, comparative analysis of the mechanical properties to the literature, shows that Ichu fiber composites have properties above the average when compared to the composites made with unsaturated polyester resin; and furthermore, their properties can be equivalent and superior to some composites made using epoxy resins.
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6. References

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