Sugarcane Bagasse Reinforced Composites: Studies on the Young's Modulus and Macro and Micro-Mechanics

Ana M. Jiménez,[a,b] Marc Delgado-Aguilar,[a] Quim Tarrés,[a] Germán Quintana,[b,]* Pere Fullana-i-Palmer,[a, c] Pere Mutjè,[a] and Francesc X. Espinach [d]

The stiffness of a material greatly influences its possible use as an engineering material. Thus, despite the theoretical environmental advantages of natural fiber reinforced composites, or fully biodegradable composites, if certain mechanical properties are not achieved, a material can have fewer engineering uses. In this work, sugarcane bagasse fibers, a by-product of the sugarcane-juice extraction process, were used to obtain reinforcing fibers. Two polyolefins, a polypropylene and a high-density polyethylene, and a starch-based polymer were used as matrices. The composite materials were prepared and tested to obtain their tensile properties such as the Young's moduli. Some micromechanical models were used to obtain the intrinsic Young's moduli of the fibers and the efficiency factors. The dependence of such parameters on the matrix and fibers characteristics was studied. The fiber orientation efficiency factor was used to compute the orientation angle of the fibers inside the composite under three different distributions. Finally, the Tsai and Pagano models, and the Halpin and Tsai equations were used to compute the theoretical values of the Young's moduli of the composites.

Keywords: Biocomposites; Young's modulus; Micromechanics

Contact information: a: LEPAMAP Group, Department of Chemical Engineering, University of Girona, c/M. Aurèlia Capmany, nº 61, Girona 17071, Spain; b: Pulp and Paper Research Group, Department of Chemical Engineering, University Pontificia Bolivariana, Medellín, Colombia; c: UNESCO Chair in Life Cycle and Climate Change, School of International Studies (ESCI-UPF), Pg. Pujades, nº 1, Barcelona 08003, Spain; d: Design, Development and Product Innovation, Dept. of Organization, Business, University of Girona, c/ M. Aurèlia Cap many , nº 61, Girona 17071, Spain;
** Corresponding author: german.quintana@upb.edu.co*

INTRODUCTION

In engineering terms, the development of materials with higher tensile and flexural strengths is very important. Such materials enable lighter designs that make it possible to fulfill all the structural requirements using less material. The composites are a clear example of such strategy. The use of a stiff matrix in conjunction with a rigid fibrous reinforcement generates a combination of materials with enhanced mechanical properties. Usually the resultant materials will show higher tensile and flexural strengths, Young's moduli, and show less ability to sustain deformations (compared to the matrix) without crack formations. As a rule, the engineering artifacts are not designed to handle the ultimate strength of the materials with which they are manufactured, it is more usual to define limit deformation states that ensure a correct deployment of a function. This is especially true for materials like steel or polymers, with high strains before the breaking point. In the case of stiffer materials, such as some fiber-reinforced polymers, their low strains at break point emphasize the importance of the ways such materials will deform and respond under loads. Usually, the Young's modulus is seen as an indicator of the stiffness of a material (Serrano *et al.* 2014).

The most common thermoplastic fiber-reinforced materials are the glass fiber-reinforced polyolefins. The use of glass fibers (GF) ensures a material with highly enhanced tensile strengths and Young's modulus. In fact, composite materials with low amounts of GF could double or triple the tensile strength or the Young's moduli of their matrices (Lopez *et al.* 2011, 2012b). Nonetheless, the GF has some drawbacks, mainly related to the amount of energy required to manufacture them. Further, such composites difficult to recycle, and their abrasiveness results in early wearing out of manufacturing machinery, as well as an unhealthy working environment for its operators (Wang *et al.* 1993; Granda *et al.* 2016). A lot of effort has been devoted to searching for more environmentally friendly and healthier alternatives to GF as composite reinforcement, and many authors have pointed to natural fibers as a possible replacement (Martinez-Urreaga *et al.* 2015; Scarponi and Messano 2015; da Luz *et al.* 2016; Granda *et al.* 2016). In contrast to GF, the natural fibers are cheap, easily available, and a renewable source of reinforcement material. In addition, these materials are less abrasive or non-abrasive in nature, and are healthier to handle (Dicker *et al.* 2014; Fazita *et al.* 2016). However, the natural fibers also possess some disadvantages, mainly related to the high standard deviations of their intrinsic properties, and their lower relative strengthening and stiffening abilities. Nevertheless, there are some studies that have shown that it is possible to obtain comparable tensile strengths or Young's modulus by using natural fibers in place of GF (HDPE) (Hill and Hughes 2010; Lopez *et al.* 2012a; Majeed *et al.* 2013; Reixach *et al.* 2013b).

There is a growing environmental concern towards the substitution of oil-based materials. Thereby, the use of polyolefin is also a matter of concern. Some researchers have pointed out that bio-based polymers can be used as possible substitutes, being the most discussed: polylactic acids, caprolactones, some polyamides, and starch-based polymers. While some of the abovementioned polymers show higher mechanical properties than the polyolefins, others, such as the starch-based polymers have very low tensile strengths and Young's moduli. There are studies showing the mechanical capabilities of natural fiber-reinforced bio-based polymers (Oksman *et al.* 2003; Hu and Lim 2007). Such works show a promising road towards more environmentally friendly composite materials that could be a real alternative to GF- reinforced polyolefin.

In this work two polyolefins, polypropylene and high-density polyethylene, as well as a starch based polymer, were used as matrices. The used reinforcing fibers were sugarcane bagasse (SB). SB is a fibrous byproduct of the sugarcane crushing process after its juice extraction. SB is commonly used as biofuel, as pulp for papermaking, or as a component for building materials. These materials contain fibers originated from the sugarcane and it constitutes core (40 to 50%), pith (30 to 35%), vessels, and skin. Such fibers show different morphologies and intrinsic properties, and some researchers have used only the core or the core and pith fibers to obtain higher mechanical properties. In this work, the SB was used as received, without any separation. The SB was then submitted to different treatments to obtain SB sawdust, and mechanical, thermomechanical, and chemo-thermomechanical pulps. Different composite materials were obtained by mixing a 30 wt% of the SB fibers with the proposed matrices. Those materials were tensile tested to obtain their Young's moduli and their strain at break. Hirsch equation and the modified rule of mixtures were used to obtain the intrinsic

Young's moduli of the different SB reinforcements, as well as other micromechanical properties such the efficiency, length, and orientation factors. The limit and mean orientation angles of the fibers were also computed, attending to different possible fiber configurations. The mean angles were compared with the mean orientation angle predicted by the tensile strength micromechanics to choose the most probable fiber distribution (Jiménez *et al.* 2016a,b). Finally, the Tsai and Pagano model, and the Halpin and Tsai equations were used. The intrinsic Young's moduli obtained with the Hirsch equation was then employed to calculate the theoretical Young's moduli of the composites and compared it with the experimental results.

EXPERIMENTAL

Materials

Sugarcane bagasse (SB) from *Saccharum officinarum* was provided by the University of Pontificia Bolivariana (Medellín, Colombia).

Three different matrices were used to prepare the composites, two polyolefins and a starch-based polymer. The two polyolefins used were: a polypropylene (PP) homopolymer (Isplen PP099 K2M), kindly provided by Repsol-YPF (Tarragona, Spain), and a high-density polyethylene (HDPE) Rigidex HD5226EA (INEOS Polyolefins, Barcelona, Spain). The starch-based polymer (PTA), was a Mater-bi® YI014U/C, supplied by Novamont (Novara, Italy).

Other reactants used for the fiber treatments were sodium hydroxide (Merck KGaA, Germany) and anthraquinone (BASF AG, Germany). These were used without any further purification.

Methods

Preparation of sugarcane bagasse derivatives

The SB biomass was ground and screened through a cutter-mill, using a 5 mm sieve. The sawdust (SD) was then prepared by further grinding to 0.2 mm through a mill. To obtain mechanical pulp (MP), some SB samples were defibered in a Sprout-Waldron refiner (Muncy, USA), under cold aqueous conditions. This process showed almost 100% yield with respect to the starting material. Another SB sample was submitted to a thermo-mechanical process (vaporization followed by defibering). For this purpose, the SB was heated to 160 ºC for 15 min using a fiber to liquor ratio of 6:1. The resulting pulp was water rinsed and passed through the Sprout-Waldron equipment to obtain the thermo-mechanical pulp (TMP) with around 95% yield. For SB CTMP fibers, the SB was submitted to a sodium hydroxide/antraquinone (AQ) cooking process (5% NaOH w/w, 0.1% AQ w/w) in a liquid to fiber ratio of 6:1, working at 160 ºC for 30 min. Afterwards, the slurry was washed and passed through the Sprout-Waldron equipment, giving around 90% yield.

Compounding and injection molding

The SD, MP, TMP, and CTMP fibers were dried for 24 h at 105 °C. Then the fibers were mixed (30% w/w) with the PP, HDPE, and PTA matrices in a Gelimat kinetic mixer model G5S by Draiswerke (Mahaw, USA). The process parameters used were 2500 rpm for 2 min until discharge temperatures of 210, 180, and 140 °C were attained, for the PP, HDPE, and PTA polymers, respectively. The obtained mixtures were granulated in a knives mill. The composites were labeled as "M30F", where M denotes the matrix (PP, HDPE, or PTA), 30 is the reinforcement content, and F indicates the reinforcement (SD, MP, TMP, and CTMP).

The obtained materials were used for the production of specimens in a Meteor 40 injection-molding machine (Mateu and Solé, Barcelona, Spain). The specimens were conditioned in a climatic chamber at 23 °C and 50 % relative humidity for 48 h before the tensile tests were performed, according to the ASTM D618-13 (2013) and ASTM D638-14 (2014) standards.

Mechanical and morphological characterization

The composites were assayed using a universal testing machine DTC-10 supplied by IDMtest (San Sebastián, Spain), fitted with a loading cell of 5 kN and working at a speed of 2 mm/min. The tensile tests were performed according to standard ASTM D638-14 (2014). Young's modulus was analyzed using an MF, MFA 2 extensometer (Velbert, Germany) with dog-bone type specimens. Results obtained were from the average of at least 5 samples.

The length and diameter distributions of the extracted fibers were characterized by means of a MorFi Compact (Morfological fiber analyser), from Techpap SAS, (France). A minimum of two samples were analyzed in each set. The fibers were extracted from the PP-based composites.

Micromechanics

Fibers intrinsic Young's modulus

The intrinsic tensile modulus (E_t^f) of the sawdust, MP, TMP, and CTMP samples from the SB were determined using the Hirsch model (Eq. 1) (Hirsch 1962; Rodriguez *et al.* 2010; Vilaseca *et al.* 2010; Lopez *et al.* 2011),

$$E_t^C = \beta \cdot \left(E_t^f V^f + E_t^m \left(1 - V^f\right)\right) + \left(1 - \beta\right) \frac{E_t^f \cdot E_t^m}{E_t^m \cdot V^f + E_t^f \left(1 - V^f\right)} \tag{1}$$

where E_t^C, E_t^f, and E_t^m denote the elastic moduli of the composite, the reinforcement, and the matrix respectively; V^f represents the volume fraction of the reinforcement. The model is a lineal combination between the parallel, Reuss, and the serial, Voigt models. It has been reported that, for natural fiber composites, a value of β=0.4 adequately reproduces the results obtained experimentally (Kalaprasad *et al.* 1997; Vilaseca *et al.* 2010).

Modified rule of mixtures for the Young's modulus

The modified rule of mixtures (mROM) (Eq. 2) (Thomason 2000), is a common micromechanical model to predict the Young's modulus of composite materials,

$$E_t^C = \eta_e \cdot E_t^f \cdot V^f + E_t^m \cdot (1 - V^f) \tag{2}$$

where E_t^C, E_t^f, and E_t^m represent the elastic moduli of the composite, the reinforcement, and the matrix, respectively, and η_e is an efficiency factor used to correct the contribution of semi-aligned fibers.

Efficiency, length, and orientation factors

The efficiency factor can be expressed as the product of the orientation factor and the length efficiency factor ($\eta_e = \eta_o \cdot \eta_l$). Usually the η_o is a consequence of the process and the machinery parameters, and η_l is linked to the morphology of the reinforcements (Vallejos *et al.* 2012).

The length factor was computed according to Cox-Krenchel's model (Krenchel 1964),

$$\eta_l = 1 - \frac{\tanh\left(\beta \cdot l^f / 2\right)}{\left(\beta \cdot l^f / 2\right)} \tag{3}$$

with

$$\beta = \frac{1}{r}\sqrt{\frac{E_t^m}{E_t^f \cdot (1-\nu) \cdot Ln\sqrt{\pi / 4 \cdot V^f}}} \tag{4}$$

where β denotes the coefficient of the stress concentration rate at the ends of the fibers, r indicates the fiber mean radius, l^f represents the fiber's weighted length, and ν is the Poisson's ratio of the matrix. The values for the PP, HDPE, and PTA were 0.36, 0.30 and 0.44, respectively (Pena *et al.* 2012; Espinach *et al.* 2013a; Reixach *et al.* 2013a). The efficiency factor η_e can be expressed as $\eta_e = \eta_o \cdot \eta_l$ and the identity was used to calculate η_l.

Tsai and Pagano model and Halpin and Tsai equations

The Tsai and Pagano model (Eq. 9) and the Halpin and Tsai equations (Eq. 10, 11) (Halpin and Pagano 1969; Halpin and Tsai 1969) can be also used to predict the intrinsic Young's modulus of the reinforcements. In this case, the equations were used to back-calculate the Young's modulus of the composite, using the intrinsic Young's modulus of the fibers computed by the Hirsh model. The stiffness in the fiber direction is given by:

$$E_t^C = \frac{3}{8}E^{11} + \frac{5}{8}E^{22} \tag{5}$$

Here, E^{11} and E^{22} are the longitudinal and transversal elastic modulus, calculated by the Halpin –Tsai equations (Espinach *et al.* 2013b):

$$\eta_l = \frac{\left(E_t^f / E_t^m\right) - 1}{\left(E_t^f / E_t^m\right) + 2\left(l^f / d^f\right)} \quad \text{(6a)}, \qquad E^{22} = \frac{1 + 2 \cdot \eta_t \cdot V^f}{1 - \eta_t V^f} E_t^m \quad \text{(6b)}$$

Parameters η_l and η_t are given by,

$$\eta_l = \frac{\left(E_t^f / E_t^m\right) - 1}{\left(E_t^f / E_t^m\right) + 2\left(l^f / d^f\right)} \quad \text{(7a)}, \qquad \eta_t = \frac{\left(E_t^f / E_t^m\right) - 1}{\left(E_t^f / E_t^m\right) + 2} \quad \text{(7b)}$$

where l^f and d^f represent the length and diameter of the SB, respectively.

RESULTS AND DISCUSSION

Experimental Results

The composite specimens were tensile tested to obtain their Young's moduli. Table 1 shows the experimental results. A large increase of the Young's modulus of the composites against the matrices was observed for all tested composites. The highest increase corresponded to the PTA-based composites, resulting in 5.6, 7.7, 6.7, and 7.7 multipliers for the SD, MP, TMP and CTMP samples, respectively. Nonetheless, Young's moduli of the PTA-based composites were much lower than that of the PP or HDPE-based composites, but showed Young's moduli similar to that of the polyolefin. Anyhow, their use as a replacement of polyolefin needs more research to ensure that the PTA-based composites meet all the applicable requirements. On the other hand, the polyolefin-based composites showed mean increases of its Young's moduli against its matrices ranging from 2.2 to 2.5 times. The increases on the Young modulus varied little with the different fiber treatments. However, this was not true for the tensile strength, where the quality of the fibers had a more notable effect on the mechanical properties (Jiménez *et al.* 2016c).

Table 1. Experimental Young's Modulus and strain at break for all composites.

	V^f	E_t^C (GPa)	ε_t^C (%)
PP	-	1.499±0.008	9.21±0.01
PP30SD	0.218	3.612±0.037	2.43±0.11
PP30MP	0.212	3.377±0.063	4.27±0.39
PP30TMP	0.212	3.284±0.038	4.47±0.09
PP30CTMP	0.213	3.413±0.051	3.8±0.47
HDPE	-	1.008±0.024	12.9±0.31
HDPE30MP	0.222	2.536±0.067	3.12±0.34
HDPE30TMP	0.222	2.501±0.043	3.57±0.10
PTA	-	0.172±0.004	274.7±19.63
PTA30SD	0.276	0.963±0.052	4.65±0.30
PTA30MP	0.269	1.323±0.038	4.15±0.17
PTA30TMP	0.268	1.165±0.012	4.63±0.19
PTA30CTMP	0.270	1.332±0.047	3.89±0.18

In the case of the PP-based composites, the Young's modulus compared well with that of a PP stone groundwood (SGW) reinforced composites (Lopez *et al.* 2012b). The Young's modulus obtained with the SGW was slightly higher (3.5 GPa), but the SGW fibers could be also considered to be of higher quality than the SB used. As an industrial product, the SGW can be expected to show less standard deviation in its mechanical properties. In any case, all the composites showed Young's moduli values far from that of a PP glass fiber (GF) reinforced composite. Such composites showed 4.10 and 5.6 GPa values for 20% and 30% w/w GF contents, respectively. Nevertheless, from an engineering point of view, a smart product design (*i.e.*, adding ribs) could solve such differences in properties.

Micromechanical Analysis of the Young's Modulus

The Hirsch model was used to compute the intrinsic Young's moduli of the fibers. Table 3 shows the obtained results. The intrinsic Young's moduli of the fibers showed a high dependence on the matrix. Furthermore, omitting the SD sample, the MP, TMP, and CTMP samples showed very similar Young's moduli for the same matrix. In that sense the reinforcing fibers showed values around 20, 15, and 8 GPa for the PP, HDPE, and PTA polymers, respectively. In principle, as the same fibers were used as reinforcement material, the same intrinsic properties were also expected. Nonetheless, some authors defend the differences between the intrinsic properties of a single fiber and the back-calculated ones, using experimental data (Shah *et al.* 2016). The reason could be found in the non-entirely elastic behavior of the fibers and the composites, in addition to the use of matrices with various strains at break that could highly influence the final result. The Young's moduli of the composites were measured when the strain was around 2% to 3%. The differences between intrinsic properties of the SD and the rest of the fibers could be explained by their aspect ratios, being 9.4 for the SD and higher that 20 for the rest of the fibers.

Table 3. Micromechanical Aspects of the SB Reinforced Composites

	V^f	E_t^F (GPa)	η_e	η_l	η_o
PP30SD	0.218	23.090	0.485	0.735	0.659
PP30MP	0.212	21.045	0.492	0.844	0.583
PP30TMP	0.212	19.962	0.497	0.880	0.564
PP30CTMP	0.213	21.357	0.491	0.894	0.549
HDPE30MP	0.222	15.342	0.493	0.841	0.587
HDPE30TMP	0.222	14.953	0.496	0.875	0.566
PTA30SD	0.276	6.992	0.434	0.639	0.679
PTA30MP	0.269	10.524	0.423	0.725	0.582
PTA30TMP	0.268	9.092	0.426	0.797	0.535
PTA30CTMP	0.270	10.567	0.423	0.813	0.520

With the objective of pondering the combined effect of the intrinsic Young's modulus and the efficiency factor, the value of such factor was computed by using the mROM (Eq. 2). Table 3 shows the obtained results. It was found that the efficiency factor was very stable, with slight differences between the values for the polyolefin and the starch-based polymer. The mean value for the polyolefin was 0.492 with a 0.004 standard deviation. In the case of the PTA-based composites, the mean value was 0.427, with a 0.005 standard deviation. The values grant a 15% advantage to the polyolefin-based composites. Nonetheless, the values were very similar, while the intrinsic tensile Young's moduli were very matrix dependent. Although the literature indicates that the interphase between the fibers and the matrix has little influence on the Young's modus of a composite, this seems to be certain when the matrix was the same, or belongs to the same chemical family (Lopez *et al.* 2012b; Reixach *et al.* 2013a; Granda *et al.* 2016).

The Cox-Krenchel's model (Eqs. 7 and 8) was used to model the fiber length efficiency factor (Table 3). As expected, it was found that such factor increased with increasing fiber length. The values for the polyolefin-based composites were found to be higher than of the PTA-based ones. The values were in agreement with prior natural fiber reinforced composites micromechanical analyses (Lopez *et al.* 2012b; Espinach *et al.* 2013b; Granda *et al.* 2016).

Once the fiber length efficiency factor was known, it was possible to compute the value of the fiber orientation efficiency factor, by the ratio between η_e and η_l. Table 3 shows the results. It was found that such factor was less matrix-dependent and more fiber typology-dependent. The values of the orientation efficiency factor decreased against the intensity of the treatments and the length of the fibers. Anyhow, when the SD-based composites were discarded, the value was very steady. The values of length and orientation efficiency factor, when η_e is stable, could be read as the factor having the greatest influence on the Young's modulus of the composite.

A very interesting study by Fukuda and Kawata (1974) established a connection between the fiber orientation angle and a defined limit angle (α_o). The cited authors propose different fiber distributions inside the matrix and then compute the fiber orientation factor from such limit angle:

Rectangular distribution:

$$\eta_O = \frac{\sin(\alpha_O)}{\alpha_O} \cdot \left(\frac{3-\nu}{4} \cdot \frac{\sin(\alpha_O)}{\alpha_O} + \frac{1-\nu}{4} \cdot \frac{\sin(3\alpha_O)}{3\alpha_O} \right) \tag{8}$$

Triangular distribution:

$$\eta_O = 4 \cdot \frac{1-\cos(\alpha_O)}{\alpha_O^2} \cdot \left(\frac{3-\nu}{4} \cdot \frac{1-\cos(\alpha_O)}{\alpha_O^2} + \frac{1+\nu}{4} \cdot \frac{1-\cos(3\alpha_O)}{9\alpha_O^2} \right) \tag{9}$$

These equations were used to compute the limit angle. Then, an orientation parameter (f_p) suggested by Sanomura and Kawamura (2003) (Eq. 10) was used to compute the mean orientation angle of the fibers inside the composite (α) (Table 4).

$$f_p = \frac{\sin(2\alpha_O)}{2\alpha_O} = 2 \cdot \cos^2(\alpha) - 1 \tag{10}$$

Table 4. Limit Angle and Mean Orientation Angle of the Fibers for the Rectangular and Triangular Distributions

	Rectangular		Triangular	
	α_o	α	α_o	α
PP30SD	42.4	23.9	62.0	33.7
PP30MP	48.6	27.1	71.8	38.1
PP30TMP	50.1	27.9	74.4	39.2
PP30CTMP	51.4	28.5	76.4	40.1
HDPE30MP	49.0	27.3	72.9	38.4
HDPE30TMP	50.7	28.2	75.2	39.6
PTA30SD	40.1	22.6	58.3	32.0
PTA30MP	47.7	26.6	70.5	37.6
PTA30TMP	51.1	28.6	76.8	40.2
PTA30CTMP	52.8	29.2	78.9	41.1

It was found that, independently of the fiber distribution, the SD-based composites showed the lowest orientation angles. The reason could be due to its lower aspect ratio. On the other hand, the MP, TMP, and CTMP fibers showed similar orientation angles, regardless of the fiber distribution. The mean orientation angles were 28.05º ± 0.871 and 39.4º ± 1.191, for the rectangular and triangular distribution, respectively. If the value is compared with orientation angle obtained from the micromechanical analysis of the tensile strength (41.9º), the most similar orientation belongs to the triangular distribution hypothesis (Jimenez *et al.* 2004; Jiménez *et al.* 2016a).

Finally, the Tsai and Pagano model, and the Halpin and Tsai equations were used to compute a theoretical Young's modulus of the composites. The intrinsic Young's moduli of the fibers computed by the Hirsh equation were used (Tables 3 and 5). The Halpin and Tsai equations, contrary to the Hirsch equation, account for some morphological properties of the fibers. Table 5 shows the obtained results.

Table 5. Theoretical Young's Moduli of the Composites Computed by Using the Tsai and Pagano Model, and the Halpin and Tsai Equations

	E_t^F (GPa)	E_t^C (GPa)	E_t^{C*} (GPa)	*Error*	*Error (%)*
PP30SD	23.090	3.61	3.25	0.36	11.08%
PP30MP	21.045	3.38	3.32	0.06	1.81%
PP30TMP	19.962	3.28	3.29	-0.01	0.30%
PP30CTMP	21.357	3.41	3.40	0.01	0.29%
HDPE30MP	15.342	2.54	2.50	0.04	1.60%
HDPE30TMP	14.953	2.50	2.50	0.00	0.00%
PTA30SD	6.992	0.96	0.57	0.39	68.42%
PTA30MP	10.524	1.32	0.78	0.54	69.23%
PTA30TMP	9.092	1.16	0.77	0.39	50.65%
PTA30CTMP	10.567	1.33	0.84	0.49	58.33%

It was found that the Tsai and Pagano model, and the Halpin and Tsai equations predicted very well the Young's moduli of the polyolefin-based composites. In fact, the percentage errors, excluding the SD, were very low, and inside the standard deviations of the experimental Young's moduli. On the other hand, the predicted Young's moduli of the PTA-based composites showed high error percentages. A later analysis of the Halpin and Tsai equations showed that when the Young's modulus of the matrix was lower than 1, the model showed difficulties in converging with the experimental results.

CONCLUSIONS

1. Sugarcane bagasse reinforced polyolefin composites showed Young's moduli similar to that of high quality natural fiber reinforced polyolefin. The main advantages of SB are its low cost, and little need of treatments, for preparing SD and MP samples. The

main disadvantage is its availability. The SB-PP composites could be a replacement to glass fiber-PP composites for certain semi-structural applications.

2. SB reinforced PTA showed similar Young's modulus to PP and HDPE polymers. In some cases, such composites could replace a polyolefin. More research is needed to establish its environmental advantages.
3. The intrinsic Young's moduli of the fibers were found to be highly dependent on the matrix. The efficiency factor of the modulus on the modified rule of mixtures was dependent on the matrix' chemical family. The orientation efficiency factor was dependent on the reinforcement fiber typology.
4. A triangular distribution of the fibers inside the composite showed orientation angles in line with that computed from the micromechanical analysis of the tensile strength.
5. The Tsai and Pagano model, as well as the Halpin and Tsai equations, showed reliability for computing the Young's moduli of the polyolefin-based composites. The results obtained with such model or with the Hirsch equations were similar. On the other hand, the Tsai and Pagano model, and the Halpin and Tsai equations were unable to predict the Young's moduli of the PTA-based composites.

REFERENCES CITED

da Luz, S. M., da Costa, S. M., Goncalves, A. R., Del'Arco Junior, A. P., and da Costa, S. A. (2016). "Polypropylene composites reinforced with biodegraded sugarcane bagasse fibers: Static and dynamic mechanical properties," *Materials Research-Ibero-American Journal of Materials* 19(1), 75-83. DOI: 10.1590/1980-5373-mr-2015-0410

Dicker, M. P. M., Duckworth, P. F., Baker, A. B., Francois, G., Hazzard, M. K., and Weaver, P. M. (2014). "Green composites: A review of material attributes and complementary applications," *Composites Part a-Applied Science and Manufacturing* 56, 280-289. DOI: 10.1016/j.compositesa.2013.10.014

Espinach, F. X., Julián, F., Alcalà, M., Tresserras, J., and Mutjé, P. (2013a). "High stiffness performance alpha-grass pulp fiber reinforced thermoplastic starch-based fully biodegradable composites," *BioResources* 9(1), 738-755. DOI: 10.15376/biores.9.1.738-755

Espinach, F. X., Julian, F., Verdaguer, N., Torres, L., Pelach, M. A., Vilaseca, F., and Mutje, P. (2013b). "Analysis of tensile and flexural modulus in hemp strands/polypropylene composites," *Composites Part B-Engineering* 47, 339-343. DOI: 10.1016/j.compositesb.2012.11.021

Fazita, M. R. N., Jayaraman, K., Bhattacharyya, D., Haafiz, M. K. M., Saurabh, C. K., Hussin, M. H., and Khalil, A. H. P. S. (2016). "Green composites made of bamboo fabric and poly (lactic) acid for packaging applications - A review," *Materials* 9(6). DOI: 10.3390/ma9060435

Granda, L. A., Espinach, F. X., Lopez, F., Garcia, J. C., Delgado-Aguilar, M., and Mutje, P. (2016). "Semichemical fibres of *Leucaena collinsii* reinforced polypropylene: Macromechanical and micromechanical analysis," *Composites Part B-Engineering* 91, 384-391. DOI: 10.1016/j.compositesb.2016.01.035

Halpin, J. C., and Pagano, N. J. (1969). "The laminate approximation for randomly oriented fibrous composites," *Journal of Composite Materials* 3(4), 720-724.

Halpin, J. C., and Tsai, s. W. (1969). "Effects of environmental factors on composite materials," Technical report AFML-TR-67-423.

Hill, C., and Hughes, M. (2010). "Natural fibre reinforced composites. Opportunities and challenges," *Journal of Biobased Materials and Bioenergy* 4(2), 148-158. DOI: 10.1166/jbmb.2010.1079

Hirsch, T. (1962). "Modulus of elasticity of concrete affected by elastic moduli of cement paste matrix and aggregate," *Journal of American Concrete Institute* 59(3), 427-451. DOI: 10.14359/7924

Hu, R., and Lim, J.-K. (2007). "Fabrication and mechanical properties of completely biodegradable hemp fiber reinforced polylactic acid composites," *Journal of Composite Materials* 41(13), 1655-1669. DOI: 10.1177/0021998306069878

Jiménez, A. M., Espinach, F. X., Delgado-Aguilar, M., Reixach, R., Quintana, G., Fullana-i-Palmer, P., and Mutjé, P. (2016a). "Starch-based biopolymer reinforced with high yield fibers from sugarcane bagasse as a technical and environmentally friendly alternative to high density polyethylene," *BioResources* 11(4), 9856-9868. DOI: 10.15376/biores.11.4.9856-9868

Jiménez, A. M., Espinach, F. X., Granda, L., Delgado-Aguilar, M., Quintana, G., Fullana-i-Palmer, P., and Mutje, P. (2016b). "Tensile strength assessment of injection-molded high yield sugarcane bagasse-reinforced polypropyene," *BioResources* 11(3), 6346-6361. DOI: 10.15376/biores.11.3.6346-6361

Jimenez, L., Angulo, V., Garcia, E., and Rodriguez, A. (2004). "Cellulosic pulp from vine shoots," *Afinidad* 61(511), 194-203.

Kalaprasad, G., Joseph, K., Thomas, S., and Pavithran, C. (1997). "Theoretical modelling of tensile properties of short sisal fibre-reinforced low-density polyethylene composites," *Journal of Materials Science* 32(16), 4261-4267. DOI: 10.1023/a:1018651218515

Krenchel, H. (1964). *Fibre Reinforcement*, Akademisk Forlag, Copenhagen.

Lopez, J. P., Mendez, J. A., El Mansouri, N. E., Mutje, P., and Vilaseca, F. (2011). "Mean intrinsic tensile properties of stone groundwood fibers from softwood," *BioResources* 6(4), 5037-5049.

Lopez, J. P., Mendez, J. A., Espinach, F. X., Julian, F., Mutje, P., and Vilaseca, F. (2012a). "Tensile strength characteristics of polypropylene composites reinforced with stone groundwood fibers from softwood," *BioResources* 7(3), 3188-3200.

Lopez, J. P., Mutje, P., Pelach, M. A., El Mansouri, N. E., Boufi, S., and Vilaseca, F. (2012b). "Analysis of the tensile modulus of PP composites reinforced with stone grounwood fibers from softwood," *BioResources* 7(1), 1310-1323.

Majeed, K., Jawaid, M., Hassan, A., Abu Bakar, A., Abdul Khalil, H. P. S., Salema, A. A., and Inuwa, I. (2013). "Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites," *Materials & Design* 46(0), 391-410. DOI: 10.1016/j.matdes.2012.10.044

Martinez-Urreaga, J., Gonzalez-Sanchez, C., Martinez-Aguirre, A., Fonseca-Valero, C., Acosta, J., and de la Orden, M. U. (2015). "Sustainable eco-composites obtained from agricultural and urban waste plastic blends and residual cellulose fibers," *Journal of Cleaner Production* 108, 377-384. DOI: 10.1016/j.jclepro.2015.06.001

Oksman, K., Skrifvars, M., and Selin, J.-F. (2003). "Natural fibres as reinforcement in polylactic acid (PLA) composites," *Composites Science and Technology* 63(9), 1317-1324. DOI: 10.1016/S0266-3538(03)00103-9

Pena, L., Gonzalez, I., Bayer, R. J., El Mansouri, N. E., and Vilaseca, F. (2012). "Mechanical behavior of thermo-mechanical corn stalk fibers in high density polyethylene composites," *Journal of Biobased Materials and Bioenergy* 6(4), 463-469.

Reixach, R., Espinach, F. X., Franco-Marquès, E., Ramirez de Cartagena, F., Pellicer, N., Tresserras, J., and Mutjé, P. (2013a). "Modeling of the tensile moduli of mechanical, thermomechanical, and chemi-thermomechanical pulps from orange tree pruning," *Polymer Composites* 34(11), 1840-1846. DOI: 10.1002/pc.22589

Reixach, R., Franco-Marquès, E., El Mansouri, N.-E., de Cartagena, F. R., Arbat, G., Espinach, F. X., and Mutjé, P. (2013b). "Micromechanics of mechanical, thermomechanical, and chemi-thermomechanical pulp from orange tree pruning as polypropylene reinforcement: A comparative study," *BioResources* 8(3). DOI: 10.15376/biores.8.3.3231-3246

Rodriguez, M., Rodriguez, A., Bayer, R. J., Vilaseca, F., Girones, J., and Mutje, P. (2010). "Determination of corn stalk fibers' strength through modeling of the mechanical properties of its composites," *BioResources* 5(4), 2535-2546.

Scarponi, C., and Messano, M. (2015). "Comparative evaluation between E-Glass and hemp fiber composites application in rotorcraft interiors," *Composites Part B: Engineering* 69, 542-549. DOI: 10.1016/j.compositesb.2014.09.010

Serrano, A., Espinach, F. X., Tresserras, J., Pellicer, N., Alcala, M., and Mutje, P. (2014). "Study on the technical feasibility of replacing glass fibers by old newspaper recycled fibers as polypropylene reinforcement," *Journal of Cleaner Production* 65, 489-496. DOI: 10.1016/j.jclepro.2013.10.003

Shah, D. U., Nag, R. K., and Clifford, M. J. (2016). "Why do we observe significant differences between measured and 'back-calculated' properties of natural fibres?," *Cellulose* 23(3), 1481-1490. DOI: 10.1007/s10570-016-0926-x

Thomason, J. L. (2000). "The influence of fibre properties on the properties of glass-fibre-reinforced polyamide 6,6," *Journal of Composite Materials* 34(2), 158-172. DOI: 10.1106/26vu-xn4p-8qdy-8cjy

Vallejos, M. E., Espinach, F. X., Julian, F., Torres, L., Vilaseca, F., and Mutje, P. (2012). "Micromechanics of hemp strands in polypropylene composites," *Composites Science and Technology* 72(10), 1209-1213. DOI: 10.1016/j.compscitech.2012.04.005

Vilaseca, F., Valadez-Gonzalez, A., Herrera-Franco, P. J., Pelach, M. A., Lopez, J. P., and Mutje, P. (2010). "Biocomposites from abaca strands and polypropylene. Part I: Evaluation of the tensile properties," *Bioresource Technology* 101(1), 387-395. DOI: 10.1016/j.biortech.2009.07.066

Wang, B. J., Lee, J. Y., and Wang, R. C. (1993). "Fiberglass dermatitis: Report of two cases," *Journal of the Formosan Medical Association* 92(8), 755-8.

Article submitted: January 10, 2017; Peer review completed: March 4, 2017; Revised version received and accepted; March 20, 2017; Published: March 29, 2017.
DOI: 10.15376/biores.12.2.3618-3629