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# ANALYSIS OF THE TENSILE MODULUS OF POLYPROPYLENE COMPOSITES REINFORCED WITH STONE GROUNDWOOD FIBERS

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One of the most relevant properties of composite materials to be considered is stiffness. Fiberglass has been used traditionally as a fibrous reinforcing element when stiff materials are required. However, natural fibers are been exploited as replacements for synthetic fibers to satisfy environmental concerns. Among the different natural fibers, wood fibers show the combination of relatively high aspect ratio, good specific stiffness and strength, low density, low cost, and less variability than other natural fibers of such those from annual crops. In this work, composites from polypropylene and stone groundwood fibers from softwood were prepared and mechanically characterized under tensile loads. The Young's moduli of the ensuing composites were analyzed and their micromechanics aspects evaluated. The reinforcing effect of stone groundwood fibers was compared to that of conventional reinforcement such fiberglass. The Halpin-Tsai model with the modification proposed by Tsai-Pagano accounted fairly for the behavior of PP composites reinforced with stone groundwood fibers. It was also demonstrated that the aspect ratio of the reinforcement plays a role in the Young's modulus of injection molded specimens.

*Keywords: Stone groundwood; Softwood; Polypropylene; Composites; Stiffness, Modeling*

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## INTRODUCTION

The main engineering properties of composites to consider are stiffness, hygroscopic behavior, dimensional stability, strength, and fracture toughness. During conception, design, and engineering of new products, the stiffness is of great importance, since it determines the fiber concentration needed for a specific application. For structural applications, therefore, the most relevant properties are probably stiffness and dimensional stability. To effectively predict the elastic properties of a composite for a specific application, it is essential to know the elastic properties of the reinforcing fibers.

Thermoplastic materials currently dominate as matrices for biofibers; the most commonly used thermoplastics for this purpose are polypropylene, polyethylene, and poly-(vinyl chloride), while phenolic, epoxy, and polyester resins are the most used as thermosetting matrices.

Fiberglass is the most widely used plastic reinforcing element due to its low cost (compared to other mineral fibers) and fairly good mechanical properties. However, fiberglass products show serious drawbacks because they come from non-renewable sources, are non-biodegradable, and non-recyclable, or at least without leaving residues that are harmful for environment. In contrast to natural fibers, fiberglass is not a $CO_2$-neutral resource. In general, studies comparing the production phase of fiber crops versus synthetic products, such as fiberglass, indicate that fiber crops provide environmental benefits in terms of reduced $CO_2$ and greenhouse gas emission levels and reduced consumption of fossil energy (van Dam 2008).

Over the past two decades, great attention has been dedicated to the exploitation of natural fibers as reinforcement for plastics, replacing synthetic fibers (Habibi et al. 2008; Rahman et al. 2009). These natural fibers are used as a suitable reinforcing material to satisfy environmental aspects and they are now rapidly emerging as a potential alternative for synthetic fibers in engineering composites.

The use of wood fibers as a load-bearing constituent in composite materials has also been gaining increased attention in the field of composites. A combination of properties such as relatively high aspect ratio, good specific stiffness and strength, low density, and low cost, together contribute to a growing interest among the manufacturers of inexpensive low-weight composites. The use of wood fiber reinforcement also means lower variability than many other cellulose-based fibers, such as those from annual crops, although the latter may have somewhat better mechanical properties (Neagu et al. 2006). Wood fibers are commonly used for the production of pulp for paper and board products. Hardwood fibers are in general shorter than softwood fibers. Among the different wood pulps, mechanical, thermomechanical pulp and chemothermomechanical pulps are produced by mechanical defibering.

Generally, the effect of short fiber reinforcement on the Young's modulus a thermoplastic matrix is governed by the following parameters: fiber dispersion, fiber concentration (volume fraction), fiber orientation, fiber aspect ratio, and the fiber intrinsic rigidity. Studies for understanding the influence of these factors on natural-based composites have been carried out and reported in the literature by many researchers (Puglia et al. 2008).

In terms of mechanical performance, though natural fibers' mechanical properties are much lower than those of fiberglass (Wambua et al. 2003), it is generally accepted that their specific properties, especially stiffness, are comparable to the stated values of fiberglass. However, this statement is of great controversy, since the usage of natural-based composites has been restricted to non-structural applications.

Short fiber reinforced polymers can be easily fabricated by the rapid and low-cost injection molding process (Fu and Lauke 1997). In the final products there exist continuous distributions of fiber length and orientation, which are critically determining their mechanical properties. When the elastic modulus of short fiber reinforced composites is evaluated in a given strain (or load) direction, only the orientation angle between the fiber axis direction and the given direction needs to be considered. The elastic modulus of unidirectional short fiber composites has been studied by various methods. Unidirectional and random short fiber composites are the two limiting cases of partially aligned short fiber composites. The elastic modulus of unidirectional short fiber composites has been studied (Fu and Lauke 1997), e.g. by the original shear-lag analysis developed by Cox (Cox 1952) or by the analytical approach proposed by Halpin and Tsai (1969).

In this work, composites from polypropylene and stone groundwood fibers were prepared and mechanically characterized under tensile loads. The Young's moduli of the ensuing composites were analyzed and their micromechanics aspects were evaluated. The reinforcing effect of stone groundwood fibers was compared to that of conventional fiberglass.

## EXPERIMENTAL

### Materials

The composites were prepared using polypropylene (PP) (Isplen PP090 G2M) that was generously provided by Repsol-YPF (Tarragona, Spain) as the polymer matrix. Polypropylene functionalized with maleic anhydride (MAH-PP) (Epolene G3015) with an acid number of 15 mg KOH/g and Mn of 24800 was acquired from Eastman Chemical Products (San Roque, Spain) and used as coupling agent.

Stone groundwood (SGW) derived from softwood (*Pinus radiata*) was supplied by Zubialde, S.A. (Aizarnazabal, Spain) and used as lignocellulosic reinforcement. E fiberglass (FG) was produced by Vetrotex (Chambery Cedex, France) and provided by Maben S.L. (Banyoles, Spain). Morphological characterizations of fiber reinforcement were detailed in previous work (López et al. 2011)

Decahydronaphthalene (decaline) (190ºC boiling point, 97% purity) supplied by Fisher Scientific was used to dissolve PP matrix in the fiber extraction from composites. Reagent grade acetone (95% purity) from Sigma Aldrich was used without further purification.

### Methods

*Composite compounding*

PP composite materials comprising 20, 30, 40, and 50wt% of stone groundwood, or 20, 30 and 40wt% of fiberglass were prepared. The components of the composite material (PP, SGW or FG, and MAH-PP) were compounded by means of Brabender® internal mixing. The mixing process was performed at 80 rpm rotor speed (20 rpm for fiberglass reinforced composites) and at a temperature of 180ºC during 10 min. In the formulations containing MAH-PP, this was added into the plastograph together with the PP pellets. The obtained blends were ground by means of a knives mill, dried, and stored at 80ºC for at least 24 h before processing.

*Composite processing*

The composite blends were injection-molded in a Meteor-40 injection machine (Mateu & Solé, clamping pressure: 40 tons). The machine is equipped with three heating areas working at 175, 175, and 190º C, the highest corresponding to the nozzle. First and second pressures were 120 and 37.5 kgf•cm$^{-2}$, respectively. This equipment and process allowed acquisition of specimens for mechanical characterization under tensile stresses (ASTM D638).

*Mechanical characterization*

Processed materials were placed in a conditioning chamber (Dycometal) at 23º C and 50% relative humidity during 48 hours, in accordance with ASTM D618, prior to testing. Afterwards, composites were assayed by using a Universal testing machine (Instron™ 1122), fitted with a 5 kN load cell, working at 2mm/min. Young's modulus was analyzed using extensometer in dog-bone specimens (of approx. 160x13.3x3.2 mm), according to the ASTM D790 standard. Results were obtained from the average of at least 5 samples.

*Fiber extraction from composites*

Reinforcing fibers were extracted from composites by matrix solubilization using a Soxhlet apparatus and decaline as solvent. Small pieces of composites were cut and placed inside a specific cellulose filter and set into the Soxhlet equipment. A small cotton tab was used to prevent the fibers from getting out of the filtering tube. The fiber extraction was completed after 24 hours. Once the fibers were extracted, they were rinsed with acetone and then with distilled water in order to remove the solvent residue. Finally the fibers were dried in an oven at 105 ºC for 24 hours.

*Determination of the fiber length and fiber diameter*

Fiber length distribution and fiber diameter of the extracted stone groundwood fibers were characterized by means of a Kajaani analyzer (FS-300). A diluted aqueous suspension (1wt% consistency) of fibers was analyzed during 2 to 5 minutes, and the length of the fibers was evaluated considering an amount of individual fibers in the range of 2500 to 3000 units. A minimum of 2 samples were analyzed. The Kajaani analyzer offers complete fiber, fines, and shive morphology characterization, but only the fiber length and fiber diameter distribution were used for the present work.

## RESULTS AND DISCUSSION

The main factors affecting the Young's modulus of injection molded specimens are the fiber content, fiber stiffness, orientation, and the matrix stiffness (Thomason 2000). The aspect ratio of the reinforcement plays also a role, somehow, as will be later demonstrated. This is the expected behavior, presuming a proper dispersion of the reinforcement within the polymer matrix.

### General Aspects on Young's Modulus of SGW-PP Composites

The Young's modulus of short fiber composites follows the known rule of mixtures (Eq. 1), and the Cox-Krenchel model was used as basis of composite stiffness estimation (Eqs. 2-3).

$$E_t^c = \eta_o \eta_l E_t^F V^F + E_t^m V^m \tag{1}$$

In Eq. 1 $E_t$ is the Young's modulus of the material (where c, F, and m refer to composite, fiber and matrix respectively), and $V^F$ denotes the volume fraction of the fiber into the composite. The terms $\eta_l$ and $\eta_o$ represent the efficiency factors of fiber length and orientation. The factor $\eta_l$ is given by:

$$\eta_l = 1 - \frac{\tanh \frac{\zeta \cdot L^F}{2}}{\frac{\zeta \cdot L^F}{2}} \tag{2}$$

$$\zeta = \frac{1}{r} \frac{E^m}{E^F (1-\nu) Ln\left(\frac{\pi}{4V^F}\right)}^{1/2} \tag{3}$$

Here, $L^F$ is the fiber length, $r$ the radius of the fiber, and $\nu$ the Poisson's ratio of the matrix.

The transformation of the fiber load in weight ( $w^F$ ) into volume fraction ( $V^F$ ) is given by,

$$V^F = \frac{w^F / \rho^F}{w^F / \rho^F + w^m / \rho^m} \tag{4}$$

where $\rho^C$ and $\rho^m$ denote the specific weight of the final composite and the matrix, respectively, which were determined by pycnometry. The density of the fiber ($\rho^F$) inside the composite was, afterwards, determined according to Eq. 5:

$$\rho^F = \frac{w^F \rho^m}{\rho^m / \rho^c \left(w^m + w^F\right) - w^m} \tag{5}$$

The Young's modulus of PP-composite materials reinforced with stone groundwood fibers are presented for both uncoupled and MAPP-coupled composites are presented in Table 1. According to Table 1, the Young's modulus increases linearly with the fiber content. This is the expected behavior, always considering well-dispersed reinforcement, for both fiberglass (Thomason 2000) and natural-based reinforcements (Vilaseca et al. 2010; Méndez et al. 2007).

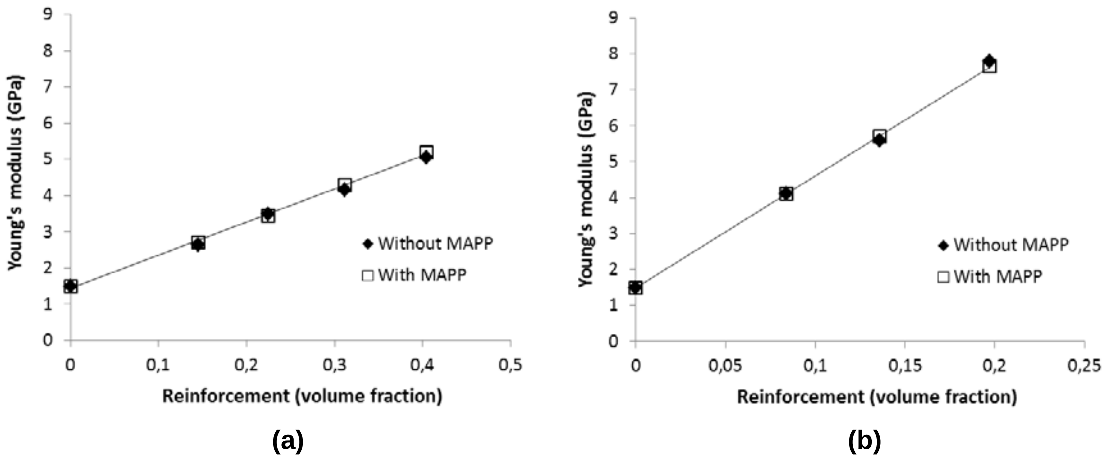
**Table 1.** Young's Modulus of SGW-PP Composites at Different Fiber Content, for Uncoupled and MAPP-coupled Composites *

| *Stone groundwood fibers* | | | |
|---|---|---|---|
| Fiber Content (wt%) | $V^F$ | $E_t^c$ (GPa) uncoupled composites | $E_t^c$ (GPa) MAPP-coupled composites |
| 0 | 0 | 1.50 (0.15) | 1.50 (0.15) |
| 20 | 0.145 | 2.65 (0.1) | 2.70 (0.1) |
| 30 | 0.225 | 3.50 (0.1) | 3.45 (0.05) |
| 40 | 0.312 | 4.15 (0.1) | 4.30 (0.1) |
| 50 | 0.404 | 5.05 (0.1) | 5.20 (0.1) |

* Standard deviation in parenthesis

The Young's modulus was not affected to a significant extent by the quality of bonding at the fiber-matrix interface, as seen in Fig. 1a. The addition of MAPP coupling agent in composites did not produce significant increments, leading to values very close to the uncoupled composites. This fact corroborates the theory that the improvement of the quality of the interfacial adhesion between the components of a composite does not substantially affect the stiffness of the final material (Méndez et al. 2007; Doan et al. 2006; Coutinho and Costa 1999; Karmaker and Youngquist 1996). In the present case, the addition of 50% by weight of stone ground-wood fibers in polypropylene increased the Young's modulus of the plain matrix by a factor of 3.5.

If fiberglass was considered as reinforcement, the Young's moduli of the resulting PP-composites are those shown in Table 2. Due to their brittleness, fiberglass-based composites were prepared at low speed (20 rpm). The current range of short-fiber compounds on the market is limited in their glass content, which is usually 33wt/wt% (volume fraction of 0.153) (Thomason 2000), with a maximum of about 45 wt/wt%. In this case, PP composites containing up to 40wt/wt% were produced. The stiffness of PP composites reinforced with fiberglass also increased linearly with the fiber load, and the modulus was not related to the quality at fiber-matrix interface, as can be seen in Fig. 1b.



(a) (b)

**Fig. 1.** Young's modulus of composites at different fiber load, without and with MAPP coupling agent, in (a) SGW PP-composites and (b) Fiberglass PP-composites

**Table 2.** Young's Modulus of Fiberglass-PP Composites at Different Fiber Content, for Uncoupled and MAPP-Coupled Composites

| *Fiberglass* | | | |
|---|---|---|---|
| Fiber Content (wt%) | $V^F$ | $E_t^c$ (GPa) uncoupled composites | $E_t^c$ (GPa) MAPP-coupled composites |
| 0 | 0 | 1.50 (0.15) | 1.50 (0.15) |
| 20 | 0.084 | 4.10 (0.1) | 4.10 (0.1) |
| 30 | 0.136 | 5.60 (0.1) | 5.70 (0.1) |
| 40 | 0.197 | 7.80 (0.1) | 7.65 (0.1) |

By using fiberglass as reinforcing element, the rigidity of the plain matrix was increased by 5 times, in composites including 40wt% of fiber content. Compared to SGW, the Young's modulus of composites reinforced with fiberglass was 1.55 times the Young's modulus of composites reinforced with SGW, at the same fiber load in weight. This was the case for composites containing 20, 30, or 40 wt% of each reinforcement. However, for similar volume fraction of reinforcement, for instance when the volume fraction was about $V^F$=0.14 (PP-composite at 20wt% of SGW and 30wt% of fiberglass) the Young's modulus of fiberglass composite was 2.1 times the modulus of the stone groundwood composite. Finally, if the same absolute value for this property was intended, for instance 5 GPa, SGW-PP composite comprising 50 wt% of reinforcement (0.4 of volume fraction) was needed, while only 25wt% (0.11 volume fraction) for fiberglass-PP composite would be enough to achieve the same Young's modulus value.

One of the aims of using natural fibers as reinforcement of polymers is in view of the substitution of mineral reinforcing elements such as fiberglass. The advantages of using natural fibers are really known and have been intensively studied by the scientific community (Wambua et al. 2003). In this sense, it has been affirmed that although natural-based composites hold lower mechanical performance than fiberglass, their specific properties are better or equivalent to those of fiberglass composites (Aranberri-Askargorta et al. 2003; Islam et al. 2010), at same fiber load by weight. However, this statement is not accomplished by the present results, as illustrated in Table 3. The specific Young's modulus of the obtained composites, shown in Table 3, were determined considering 2.45 g/cm$^{-3}$ the specific weight for fiberglass and 1.335 the specific weight for stone groundwood fibers.

**Table 3.** Specific Young's Modulus for SGW and Fiberglass – PP Composites at Different Fiber Content

| *SGW – PP composites* | | | | *Fiberglass – PP composites* | | | |
|---|---|---|---|---|---|---|---|
| Fiber Content (wt%) | $V^F$ | $\rho^c$ (g/cm$^{-3}$) | $E_t^c / \rho^c$ (GPa/g·cm$^{-3}$) | Fiber Content (wt%) | $V^F$ | $\rho^c$ (g/cm$^{-3}$) | $E_t^c / \rho^c$ (GPa/g·cm$^{-3}$) |
| 20 | 0.145 | 0.97 | 2.76 | 20 | 0.084 | 1.037 | 3.95 |
| 30 | 0.225 | 1.00 | 3.50 | 30 | 0.136 | 1.118 | 5.05 |
| 40 | 0.312 | 1.04 | 4.05 | 40 | 0.197 | 1.21 | 6.4 |
| 50 | 0.404 | 1.08 | 4.75 | - | - | - | - |

It is observed that in all cases the specific Young's modulus of SGW composites was below the specific property of fiberglass composites, at same fiber load by weight. Concretely, the specific Young's modulus for stone groundwood composite was 58% lower than that of fiberglass in composites comprising 30wt% of reinforcement.

One way to determine the contribution of the reinforcement to the Young's modulus of the composite is by considering the Fiber Tensile Modulus Factor (FTMF) obtained from the rule of mixtures (Eq. 6) (Thomason 2000),

$$E_t^c = \eta E_t^F V^F + (1-V^F)E_t^m \tag{6}$$

where $E_t$ is the Young's modulus, $\eta$ the efficiency factor, $V$ the volume fraction, and c, F, and m refers to composite, fiber and matrix respectively. The fiber tensile modulus factor is, therefore, defined according to Eq. 7:

$$FTMF = \frac{E_t^c - (1-V^F)E_t^m}{V^F} = \eta E_t^F \tag{7}$$

The value $\eta E_t^F$ means the effect of the reinforcement on the Young's modulus of the composite, which is determined by the slope of linear tendency of graphs in Fig. 2. In this case the fiber tensile modulus factor for stone groundwood composites was 10.33 and 32.68 for fiberglass composites, 3.16 times higher. If the intrinsic property of the reinforcement is considered, 71.6 GPa for fiberglass and 18.2 GPa for SGW fibers (López et al. 2011), their relation (3.93) is slightly superior, probably due to the differences in the efficiency factor in each case. The efficiency factor, $\eta$, can be decomposed as the multiplying of orientation factor $\eta_o$ and the length factor $\eta_l$ related to the aspect ratio of the reinforcement ($\eta = \eta_o \cdot \eta_l$).

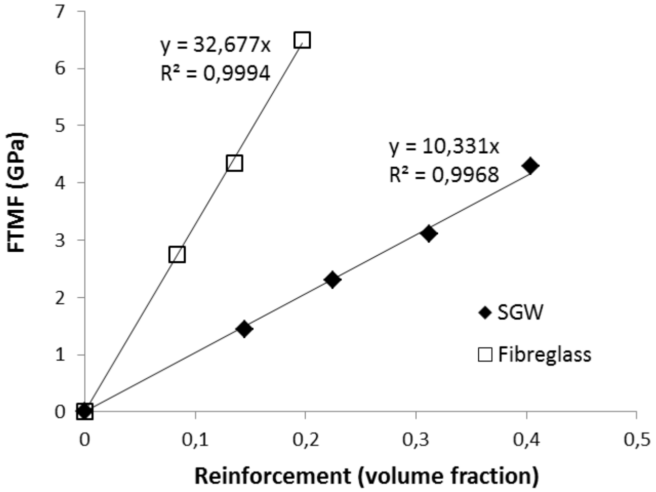


**Fig. 2.** Fiber tensile modulus factor for stone groundwood PP-composites and fiberglass PP-composites at different volume fraction

The orientation factor can be used as a constant for a determined injection molding processing, while the length factor is a function to the shearing forces during the extrusion and molding processes, as well being affected by the nature of the reinforcement.

## Micromechanical Aspects of Young's Modulus of SGW PP-Composites

In previous work the intrinsic Young's modulus of stone groundwood fibers was determined to be 18.2 GPa (López et al. 2011). The micromechanical aspects of the Young's modulus of SGW PP-composites can be analyzed by considering the rule of mixtures (Eq. 1). For the present case, values or efficiency factor of SGW composites are presented in Table 4.

**Table 4.** Efficiency Factor ($\eta$), Mean Fiber Length ($l_w^F$), Fiber Diameter ($d^F$), Length Factor ($\eta_l$) and Orientation Factor ($\eta_o$) for Coupled SGW – PP Composites at Different Fiber Content

| Fiber Content (wt%) | $V^F$ | $E_t^c$ (GPa) | $\eta$ | $l_w^F$ (μm) | $d^F$ (μm) | $\eta_l$ | $\eta_o$ |
|---|---|---|---|---|---|---|---|
| 20 | 0.145 | 2.70 | 0.54 | 778.0 | 33.5 | 0.89 | 0.61 |
| 30 | 0.225 | 3.45 | 0.56 | 698.2 | 31.9 | 0.90 | 0.62 |
| 40 | 0.312 | 4.30 | 0.57 | 670.2 | 30.1 | 0.91 | 0.63 |
| 50 | 0.404 | 5.20 | 0.58 | 549.9 | 29.9 | 0.91 | 0.64 |

From the data in Table 4 it can be observed that the value of efficiency factor for Young's modulus ($\eta$) was different than the compatibility factor described of the rule of mixtures of tensile strength ($f_C$) (Sanadi and Caulfield 2000; Vilaseca et al. 2010). While the compatibility factor ($f_C$) is of about 0.2, the efficiency factor was found to be within the range of 0.5 to 0.6.

Generally, a distribution of fiber lengths and fiber orientations exists in short fiber reinforced polymers. Therefore, in order to elucidate the implication of rule of mixtures, the orientation factor ($\eta_o$) as well as the length factor ($\eta_l$) must be determined. The length factor can be measured from the Cox-Krenchel model described in the Experimental section, by using the mean fiber length and diameter of the reinforcement inside the composite material (see also in Table 4). The Poisson's ratio for homopolymer polypropylene ($v_m$) was 0.36 according to the literature (Crawford 1998; Mittal et al. 1987). The length factor showed little variations with respect to the aspect ratio of the reinforcement.

Knowing the efficiency factors, as well as the length efficiency factors, the orientation efficiency factors shown in Table 4 were obtained. Similarly to what happens with the efficiency factor, the orientation factor for modulus is completely different from the fiber orientation factor described for tensile strength (López et al. 2011).

Fukuda and Kawada (1974) studied the elasticity modulus of short fiber reinforced thermoplastics with orientation distribution, and they obtained the same result as given by Eq. 9 (Sanomura and Kawamura 2003). Therefore, assuming the rectangular distribution (square packing) of orientation distribution function to be,

$$\eta_o = \begin{cases} 1/\alpha_o & (0 \le \alpha \le \alpha_o) \\ 0 & (\alpha_o < \alpha) \end{cases} \tag{8}$$

the orientation efficiency factor can be solved as in Eq. 9,

$$\eta_o = \frac{\sin\alpha_o}{\alpha_o}\left(\frac{3-\nu_m}{4}\frac{\sin\alpha_o}{\alpha_o} + \frac{1+\nu_m}{4}\frac{\sin 3\alpha_o}{3\alpha_o}\right) \tag{9}$$

where $\alpha_o$ denotes the fiber orientation limit angle.

The mean fiber orientation efficiency factor ($\eta_o$) for the ensuing composites was 0.625, which resulted in mean fiber orientation angle of $\alpha_o$=44°, by using the square packing equation approximation (Eq. 9). The value of the orientation angle of the reinforcement into the composite obtained by another route (tensile strength) is similar. Hence, the mean fiber orientation factor deduced from tensile strength was found to be $\chi_1$=0.285 (López, et al. 2011), which would provide a mean orientation angle of the fibers inside the composite of $\alpha_o$=43°, taking into consideration the relation found in the literature of $\chi_1=\cos^4\alpha_o$ (Mittal et al. 1987).

Therefore, one can say that although the value of the orientation efficiency factor described in the rule of mixtures applied to Young's modulus ($\eta_o$) is distinct from the orientation factor from the rule of mixtures applied to tensile strength ($\chi_1$), the values of the ensuing orientation angle of the reinforcement into the composite obtained in every case were very similar.

## Modeling of Young's Modulus of SGW PP-Composites

A number of theoretical models for prediction of the elastic properties of short fiber reinforced composites have been elaborated (Tucker and Liang 1999). The relatively simple Cox-Krenchel model described earlier was found to yield good agreement with experimental modulus values for a range of fiberglass lengths and volume fractions (Thomason 2000) and also to perform acceptably well for random short fiber natural-based composites. In general, the elastic moduli of a unidirectional short fiber composite were estimated using the Halpin-Tsai equations (Halpin and Tsai 1969) with a modification proposed by Halpin (1969) that accounts for the fiber aspect ratio l/d). Equation 10 illustrates the Tsai-Pagano model (Tsai and Pagano 1968; Halpin and Pagano 1969), which makes a combination of the expected longitudinal to the transversal term in the ratio of 3/8 and 5/8 respectively,

$$E^c = \frac{3}{8}E^{11} + \frac{5}{8}E^{22} \tag{10}$$

where $E^{11}$ and $E^{22}$ are the longitudinal and transversal elastic moduli calculated by the Halpin-Tsai model. The stiffness in the fiber direction is then given by,

$$\frac{E^{11}}{E^{m}} = \frac{1+\xi\eta V^{F}}{1-\eta V^{F}} \tag{11}$$

where,

$$\eta = \frac{\frac{E^{F}}{E^{m}} - 1}{\frac{E^{F}}{E^{m}} + \xi} \tag{12}$$

$$\xi = 2\left(L^{F}/d\right) \tag{13}$$

In Eqs. 11 and 12, $\xi$ is a shape fitting parameter to fit the Halpin-Tsai equation to experimental data. The significance of the parameter $\xi$ is that it takes into consideration the packing arrangement and the geometry of the reinforcing fibers. Halpin (1969) concluded that the in-plane shear modulus was not significantly sensitive to the fiber aspect ratio. The same argument is also made for the transverse modulus ($E^{22}$), so that the transverse modulus is approximated to the same Eqs. 11 to 13 while considering $\xi = 2$. In Table 5 the theoretical elastic modulus derived from the application of Tsai-Pagano equations to the obtained results are given.

**Table 5.** Longitudinal Modulus ($E^{11}$), Transverse Modulus ($E^{22}$), Halpin-Pagano Modeled Elastic Modulus ($E^{C}$), and Experimental Young's Modulus ($E_t^{C}$) for SGW – PP Composites at Different Fiber Content

| Fiber content (%) | $V^F$ | $E^{11}$ (GPa) | $E^{22}$ (GPa) | $E^{c}$ (GPa) | $E_t^{c}$ (GPa) |
|---|---|---|---|---|---|
| 20 | 0.145 | 3.52 | 2.08 | 2.62 | 2.70 |
| 30 | 0.225 | 4.65 | 2.47 | 3.29 | 3.45 |
| 40 | 0.312 | 5.96 | 2.97 | 4.09 | 4.30 |
| 50 | 0.404 | 7.24 | 3.60 | 4.96 | 5.20 |

The Tsai-Pagano model is fairly good for adjusting the Young's modulus of SGW PP composites, when they are measured by using an extensometer. This is opposite to what happens when the Young's modulus is determined without an extensometer, as found in the literature (Puglia et al. 2008), where experimental results did not fit with the Tsai-Pagano model.

A comparison of the Tsai-Pagano modeled elastic modulus with the experimental Young's modulus is presented in Fig. 3.

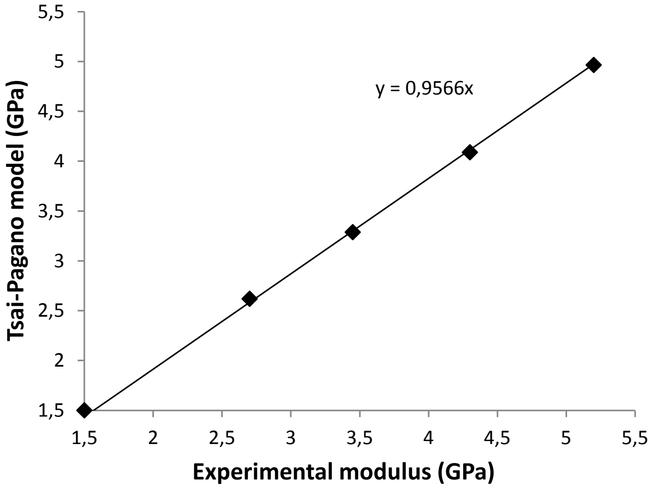


**Fig. 3.** Tsai-Pagano elastic modulus versus experimental Young's modulus versus for stone groundwood PP-composites and fiberglass PP-composites at each volume fraction

The graph shows a good correlation of Tsai-Pagano model with the experimental results. It is worth noting that the intrinsic modulus of stone groundwood fibers was determined to be 18.2 GPa in the previous work (López et al. 2011), by using the Hirsch model (Kalaprasad et al. 1997) for β=0.4. However, the use of the same 3/8 ratio in the Hirsch model (β=0.375) had resulted in intrinsic Young's modulus for SGW of 19.7 GPa.

In any case, it is important to bear in mind that the Hirsch model does not consider the aspect ratio of the reinforcement, while Tsai-Pagano model takes into account the fiber aspect ratio for the longitudinal elastic modulus, which corresponds to the stiffness in the fiber direction ($E^{11}$).

Accordingly, the use of Tsai-Pagano model for the determination of the intrinsic modulus of the reinforcement would bring values of 20.3 GPa. It can be stated, therefore, that the gap in values of the intrinsic modulus of SWG determined by Hirsch or Tsai-Pagano models reveals the influence of the aspect ratio of the reinforcement. Consequently, it can be admitted that the fiber aspect ratio of the reinforcement is also playing a role in the Young's modulus of the composite.

## CONCLUSIONS

1. Stone groundwood-polypropylene (SGW-PP) composites can serve as an alternative to fiberglass-PP composites for those applications with requirements demanding lower stiffness. This is accomplished by doubling the amount of fiber load (in weight) in the final composite. This fact can be considered to be an ecofriendly advantage thanks to the reduced consumption of synthetic polymer and to the well-known intrinsic sustainable characteristics of natural fibers.
2. In the current composites, the specific properties of natural-based composites did not attain the specific properties of fiberglass-based composites.

3. Micromechanical properties of stone groundwood-PP composites showed that although the value of the orientation efficiency factor for elastic modulus is not the same as that described for tensile strength, they both represent the same fiber orientation limit angle, considering a rectangular distribution of the reinforcement (square packing).
4. The Halpin-Tsai model with the modification proposed by Tsai-Pagano is fairly good for adjusting the behavior of PP composites reinforced with stone groundwood fibers. In addition, it has been demonstrated that the aspect ratio of the reinforcement plays a role in the Young's modulus of injection-molded specimens.

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