# Stiffness of Rapeseed Sawdust Polypropylene Composite and Its Suitability as a Building Material

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Increasing environmental concern in developed countries has supported the search for greener building materials. In this regard, using materials from renewable resources is of great interest, including the case of wood-plastic composites in replacement of fiberglass-reinforced composites. Since in the Mediterranean regions annual plants are more abundant than wood forests, in the present work, agroforestry wastes were used as reinforcing elements in composites. Specifically, rapeseed wastes were used to produce polypropylene copolymer based composites. The mechanical behavior of the resulting composites was studied, as well as the influence of a coupling agent in the formulation. From the results, rapeseed sawdust exhibited reinforcing capacity and was considered a plausible substitute for wood-plastic composites in certain uses. The stiffness of the composites was affected by the coupling agent, as the Young's Moduli progressed from 3.2 to 4 GPa for the formulation containing 50wt% of rapeseed sawdust. Micromechanical analysis was used to identify the contribution of each phase by means of a modified rule of mixtures and Halpin-Tsai equations. The micromechanical study confirmed the competitive stiffening capability of rapeseed sawdust in composite materials.

*Keywords: Rapeseed sawdust; Polypropylene; Wood-plastic composites; Stiffness; Micromechanics; Building materials*

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## INTRODUCTION

Environmental concern has continued to increase. Thus, the usage of green technology in the production of consumer goods is an emerging goal of developed countries (Schwarzkopf and Burnard 2016). Industries, including the automotive, aeronautics, product design, and building industries, are increasing their efforts to identify and substitute pollutant or non-environmentally friendly materials (Scott 2000; Schöggl *et al.* 2017). However, the substitution of a material by another one with different properties may necessitate changes in the product's design or in the manufacturing processes. Usually, industry is resistant to such changes and only a clear message from society or regulations can convince companies to innovate in the field of materials. The most favorable case would involve minor or no changes in the product design or in manufacturing processes to adopt a new material. In this sense, eligible materials will show the same or comparable mechanical properties, be environmentally friendly, accept the same manufacturing processes, and show, at best, the same costs (Serrano *et al.* 2014).

Injection molding is one of the most used manufacturing processes for the aforementioned industries. The most common polymers are polyolefin-like polypropylene (PP) and polyethylene (PE), mainly due to their good balance between mechanical properties and cost. Despite the initial mechanical properties of these matrices, they are insufficient for some purposes and require the use of reinforcements (Granda *et al.* 2016a; Sambale *et al.* 2017). Glass fiber (GF) reinforced PP is one of the most frequently used composites, showing a good ratio between reinforcement and price. Nonetheless, these composites have some drawbacks. The GF is a fragile reinforcement that tends to decrease in length during the mixing and mold-injection processes, hindering the recycling capabilities of such composites (Serra *et al.* 2017; Oliver-Ortega *et al.* 2018b). Thus, research groups have made efforts to substitute GF with more environmentally friendly fibers such as wood fibers or fibers from annual plants (Dunne *et al.* 2016; Pickering *et al.* 2016; Yan *et al.* 2016). Such reinforcements come from renewable sources, are less abrasive and with lower density, and their composites have shown favorable mechanical properties (Friedrich and Luible 2016b; Schwarzkopf and Burnard 2016). Wood-plastic composites are presently a success and can be found in car parts, product design, and building materials (Julián *et al.* 2012; Campos *et al.* 2016; Friedrich and Luible 2016b). Examples of commercially available of wood-plastic composite profiles are presented in Fig. 1.

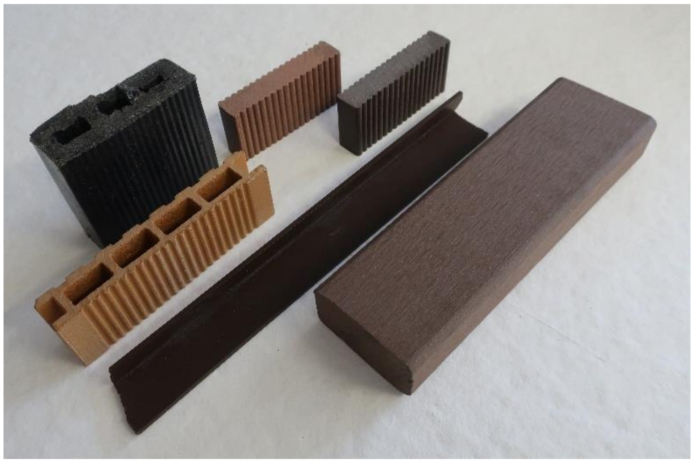

**Fig. 1.** Example of commercially available wood-plastic composite extruded profiles

In the building industry, the most used green composites are wood-plastic composites. Nonetheless, some areas like the Mediterranean are richer in annual plants than in trees. The case of rapeseed is a clear example. Producers are interested in the rapeseed seed and consider the stems and leaves as a zero-value byproduct (Oliver-Ortega *et al.* 2018a). These wastes, in the shape of rapeseed straws, can be used as livestock bedding or be incinerated with the consequent $CO_2$ emissions. Thus, if such wastes were used as a source of reinforcing fibers, the chain of value of rapeseed would be extended.

In general, building materials are chosen by analyzing criteria such as availability, the ease with which they can be gathered and transported, service life, environmental factors, and costs, among others (González and Mesa 2004). The ideal material must be inexhaustible and always available for replacement, cheap to produce, strong, rigid and dimensionally stable under different temperatures, lightweight, resistant to corrosion and wear, environmentally friendly, biodegradable, and have numerous applications (Jacobs *et al.* 1997; Vatalis *et al.* 2013). Fundamentally, selection methods of building materials are based on a series of parameters between physical, mechanical, thermal, electrical, and manufacturing that determine the technical utility of the material (González and Mesa 2004). In addition to all these parameters, the requirements and restrictions established by regulations in the construction sector must be considered.

Most researchers have focused their attention on the mechanical properties of building materials. Among all of them, one of the most outstanding is modulus of elasticity or Young's modulus (MOE). This modulus defines the relation between stress and strain in the material. Values of MOE are obtained in the linear elastic range of the material, and they are directly related to the stiffness of the material. There are two ways to measure the Young’s modulus: statically and dynamically. The static Young’s modulus is obtained from several types of tests, including a static bending test (at three or four points), compression test, or tensile test– all destructive tests– while the dynamic Young’s modulus can be obtained by non-destructive tests like modal testing. The analysis of the Young's modulus in the building materials (wood, steel, concrete, mortar, composites, *etc*.) is fundamental because the materials within the elastic range, where they recover their initial form when the applied load is removed.

In this work, composites based on rapeseed sawdust (RS), as reinforcement, and impact-modified polypropylene (PPc), as matrix, were formulated and tested under tensile conditions to obtain the Young’s modulus. The behavior of the Young’s modulus against the volume fraction of the reinforcements was analyzed, and the differences between the coupled and uncoupled composites were identified and evaluated. The contribution of each phase was investigated by following a micromechanics analysis. Two different models were considered: a modified rule of mixtures, and Halpin and Tsai equations. The first model uses experimental values and the second adds the morphological properties of the reinforcements. The composite materials showed promising stiffness that allowed a comparison against commercial wood-plastic composites. In geographical zones such as the Mediterranean, with high availability of agroforestry byproducts but less availability of wood, the use of wastes from annual plant harvesting are a promising source of environmentally-friendly reinforcements.

## EXPERIMENTAL

### Materials

A PP-PE based copolymer Capilene SW 75 AV by Carmel Olefins Ltd. (Haifa, Israel) was used as a matrix for all of the composites. This copolymer is mainly composed of polypropylene, and low percentages of polyethylene are added to improve the impact strength of the PP. The density of the polymer is 0.905 g/cm$^3$ and its melt flow index (MFI), at 230 ºC and under 2.16 kg load, is 65 g/10 min.

A coupling agent was added to some of the composite materials; polypropylene functionalized with maleic anhydride (MAPP) (Epolene G3015) was produced and commercialized by Eastman Chemical Products (San Roque, Spain). This MAPP has an acid number of 15 mg KOH/g and Mn of 24800 Da.

Cal Gall (Sant Gregori, Girona, Spain) kindly provided the rapeseed sawdust, an agricultural residue from their rapeseed harvesting.

Decahydronaphtalene provided by Scharlau S. L. (Sentmenat, Spain) was used to dissolve the matrix and recover the reinforcement fibers from the composite.

## Methods

### *Fiber preparation*

The fibers were received from the producer as a mixture of crushed stems and leaves of different dimensions. Thus, to homogenize the lengths of the reinforcements and avoid the presence of long fibers, the raw material was cut in a knives mill by Agrimsa (Sant Adrià de Besós, Spain). The result was a mix of particles with lengths in the range from 1 mm to 2 mm. Then, this mixture was ground 3 times during 1 min in a Sammic SK-5 food processor (Barcelona, Spain). Afterwards, the fibers were stored in an oven for 24 h at 80 ºC to dry them and facilitate the mixing processes. Lastly, the fibers were screened through a 1-mm hole sieve, and used afterwards, to ensure the regular dimensions of the reinforcements.

### *Composites mixing*

All of the composites were prepared in a Gelimat® kinetic mixer by Draiswerke (Mahaw, NJ, USA). The mixer was started at a rate of 300 rpm. This speed was maintained during the matrix and reinforcement loading phase. The 4% of MAPP, against the reinforcement content, was also added during this stage to produce the coupled composites. When all of the components were inside the mixer, its speed was increased up to 2500 rpm. This speed was maintained for approximately 2 min while the temperature of the mix increased. Once a temperature of 200 ºC was obtained, the composite was discharged by gravity.

The obtained composites were pelletized by using a cutting mill from Retsch (Haan, Germany) with a sieve size of 10 mm and stored in an oven, at 80 ºC, during the 24 h before its mold-injection.

### *Specimen mold-injection*

The normalized samples for the tensile test were obtained *via* mold-injection. The shape and size of the specimens was in accord with ASTM D638 (2010). A total of at least 10 valid specimens for every composite formulation were obtained in an injection molding machine Meteor manufactured by Mateu & Solé S.A. (Barcelona, Spain). The first and second pressures were 121 kgf/cm$^2$ and 38 kgf/cm$^2$, respectively. The temperature profile was 175 ºC, 175 ºC, and 190 ºC, corresponding with the last temperature to the injection nozzle.

### *Young's modulus measurement*

Prior to measuring the Young's moduli of the composites, the specimens were stored in a conditioning chamber made by Dycometal (Barcelona, Spain). The conditioning of the specimens was performed in agreement with ASTM D638 (2010), during the 48 h prior to the tensile test. The conditioning chamber parameters were 23 ºC and 50% relative humidity as per the requirements of ASTM D638 (2010).

The specimens were assayed in a universal testing machine (Instron 1122, Cerdanyola, Spain) with a 5 kN load cell. The test was carried out at 2 mm/min in agreement with ASTM D638 (2010) and ASTM D790 (2017). An extensometer was added to increase the accuracy on the measurement of the specimen deformations (ASTM D638 2010; ASTM D790 2017). At least 5 samples of every composite were tested.

*Extraction of the fibers and morphological analysis*

The rapeseed fiber reinforcements were recovered from the composite by dissolving the matrix with decahydronaphthalene. Small pieces of composite were cut-out from a specimen and placed in Soxhlet apparatus for 24 h. Afterwards, the recovered fibers were rinsed with distilled water to remove any solvent residue.

The recovered fibers were morphologically analyzed in a MorFi analyser by Techpap SAS (Grenoble, France) in agreement with the ISO 16065-2 (2014) standard. The measurement was repeated 3 times for the different batches of fibers.

## MICROMECHANIC MODELS

### Modified Rule of Mixtures

The modified rule of mixtures (mRoM) for the Young's modulus of a semi-aligned short fiber reinforced composite has been extensively used to model the micromechanics of such composite materials (Neagu *et al.* 2006; Lopez *et al.* 2012; Oliver-Ortega *et al.* 2016; Delgado-Aguilar *et al.* 2017). This mRoM (Eq. 1) obtains the Young's modulus of the composite from the contributions of the reinforcement and the matrix,

$$E_{\mathrm{t}}^{\mathrm{C}} = \eta_{\mathrm{e}} \cdot E_{\mathrm{t}}^{\mathrm{F}} \cdot V^{\mathrm{F}} + (1 - V^{\mathrm{F}}) \cdot E_{\mathrm{t}}^{\mathrm{M}} \tag{1}$$

where $E_{\mathrm{t}}^{\mathrm{C}}$, $E_{\mathrm{t}}^{\mathrm{F}}$, and $E_{\mathrm{t}}^{\mathrm{M}}$ are the Young's modulus (GPa) of the composite, the reinforcement, and the matrix, respectively. The efficiency factor $\eta_{\mathrm{e}}$ is a variable that equalizes the impact of the morphology and the mean orientation of the reinforcements in the contribution of the reinforcement to the Young's modulus of the composite. The coupling factor can be obtained by multiplying a length efficiency factor ($\eta_{\mathrm{l}}$) and an orientation efficiency factor ($\eta_{\mathrm{o}}$). Finally $V^{\mathrm{F}}$ is the volume fraction of the reinforcement.

There are more elaborate formulations for a mRoM, but Eq. 1 has been extensively used before (Virk *et al.* 2012).

### Fiber Tensile Modulus Factor (FTMF)

The Young's moduli of the composite and the matrix can be easily experimentally measured. However, the intrinsic Young's modulus of the reinforcements is more difficult to measure. Thus, the mRoM presented two unknowns, the coupling factor and the intrinsic Young's modulus of the matrix. Some authors have proposed the use of a fiber tensile strength factor (FTSF) to compute the neat contribution of the reinforcements to the Young's modulus of the composite. These authors rearrange the mRoM, thereby obtaining Eq. 2:

$$\eta_{\mathrm{e}} \cdot E_{\mathrm{t}}^{\mathrm{F}} = \frac{E_{\mathrm{t}}^{\mathrm{C}} - (1 - V^{\mathrm{F}}) \cdot E_{\mathrm{t}}^{\mathrm{M}}}{V^{\mathrm{F}}} \tag{2}$$

The left hand of Eq. 2 is the neat contribution of the reinforcement. Such contribution changes with the amount of reinforcement. The obtained values can be plotted against the volume fractions, and a regression line can be obtained. Then, the slope of such regression line is the FTMF (Lopez *et al.* 2012; Granda *et al.* 2016a; Jiménez *et al.* 2017).

### Hirsch's Model

Hirsch's equation is also widely used to model the micromechanics of semi-aligned short fiber-reinforced composites (Hirsch 1962), as shown in Eq. 3:

$$E_{\mathrm{t}}^{\mathrm{C}} = \beta\left(E_{\mathrm{t}}^{\mathrm{F}} \cdot V^{\mathrm{F}} + E_{\mathrm{t}}^{\mathrm{M}}(1 - V^{\mathrm{F}})\right) + (1 - \beta)\frac{E_{\mathrm{t}}^{\mathrm{F}} \cdot E_{\mathrm{t}}^{\mathrm{M}}}{E_{\mathrm{t}}^{\mathrm{M}} \cdot V^{\mathrm{F}} + E_{\mathrm{t}}^{\mathrm{F}}(1 - V^{\mathrm{F}})} \tag{3}$$

The equation combines the Voigt and Reuss models to equalize the impact of the mean orientation of the fibers. The parameter $\beta$ is used for such purposes. Literature shows a value of $\beta = 0.4$ returned sensible results for the semi-aligned short fiber-reinforced composite.

In this work, Eq. 3 was used to compute the value of the intrinsic Young's modulus of the reinforcement from the experimental data. Once such a value is known, the efficiency factor is the only unknown quantity, and its value can be easily computed.

### Tsai and Pagano Model and Tsai and Pagano Equations

Hirsch's model is not the only one that can be used to model the micromechanics of semi-aligned short fiber reinforced composites. While Eq. 3 is quite simple and needs few experimental values to model the micromechanics of a composite material, there are some factors, such as the morphology of the fibers, which are not explicitly used as an input. Thus, the Tsai and Pagano model was proposed as a means to obtain a second value for the intrinsic Young's modulus of the reinforcement (Halpin and Tsai 1969), as shown in Eq. 4,

$$E_{\mathrm{t}}^{\mathrm{C}} = \frac{3}{8}E^{11} + \frac{5}{8}E^{22} \tag{4}$$

where $E^{11}$ and $E^{22}$ are the longitudinal and transversal Young's modulus of the composite (GPa). These values were computed using the Tsai and Pagano equations,

$$E^{11} = \frac{1 + 2(l^{\mathrm{F}}/d^{\mathrm{F}}) \cdot \lambda_{\mathrm{l}} \cdot V^{\mathrm{F}}}{1 - \lambda_{\mathrm{l}} \cdot V^{\mathrm{F}}} E_{\mathrm{t}}^{\mathrm{M}} \tag{5}$$

$$E^{22} = \frac{1 + 2 \cdot \lambda_{\mathrm{t}} \cdot V^{\mathrm{F}}}{1 - \lambda_{\mathrm{t}} \cdot V^{\mathrm{F}}} E_{\mathrm{t}}^{\mathrm{M}} \tag{6}$$

where $l^{\mathrm{F}}$ and $d^{\mathrm{F}}$ are the mean length and diameter of the reinforcements (µm) and the $\lambda_{\mathrm{l}}$ and $\lambda_{\mathrm{t}}$ terms are defined by:

$$\lambda_{\mathrm{l}} = \frac{(E_{\mathrm{t}}^{\mathrm{F}}/E_{\mathrm{t}}^{\mathrm{M}}) - 1}{(E_{\mathrm{t}}^{\mathrm{F}}/E_{\mathrm{t}}^{\mathrm{M}}) + 2(l^{\mathrm{F}}/d^{\mathrm{F}})} \tag{7}$$

$$\lambda_{\mathrm{t}} = \frac{(E_{\mathrm{t}}^{\mathrm{F}}/E_{\mathrm{t}}^{\mathrm{M}}) - 1}{(E_{\mathrm{t}}^{\mathrm{F}}/E_{\mathrm{t}}^{\mathrm{M}}) + 2} \tag{8}$$

The Tsai and Pagano model implicitly inputs the aspect ratio of the reinforcements ($l^{\mathrm{F}}/d^{\mathrm{F}}$). A goal of the present work was to compare the values obtained from Hirsch's and the Tsai and Pagano models.

## RESULTS AND DISCUSSION

### Young's Modulus

The current work is devoted to the analysis of the stiffness of rapeseed sawdust-based materials. In general, the stiffness of a product is related to the material property and to the geometry of an object, while the Young's modulus refers specifically to the material property. By knowing the Young's modulus of composites, the stiffness of an object or an element can be analyzed. Table 1 shows the Young's modulus of the uncoupled and coupled composite materials. The amount of coupling agent was established in previous works with the objective of achieving the highest tensile strengths (Oliver-Ortega *et al.* 2018a).

**Table 1.** Young's Moduli and Strains at Break of the Rapeseed Sawdust (RS) the Coupled and Uncoupled Composites.

| Composite | $V^F$ (%) | Young's Modulus (GPa) | Strain at break (%) |
|---|---|---|---|
| PPc | 0.0 | 1.1 ± 0.1 | 6.3 ± 0.3 |
| PPc + 30% RS | 22.3 | 2.1 ± 0.1 | 2.2 ± 0.1 |
| PPc + 40% RS | 30.9 | 3.0 ± 0.1 | 1.6 ± 0.1 |
| PPc + 50% RS | 40.1 | 3.2 ± 0.2 | 1.0 ± 0.1 |
| PPc + 30% RS + 4% MAPP | 22.3 | 2.6 ± 0.1 | 2.8 ± 0.2 |
| PPc + 40% RS + 4% MAPP | 30.9 | 3.3 ± 0.2 | 2.6 ± 0.1 |
| PPc + 50% RS + 4% MAPP | 40.1 | 4.0 ± 0.2 | 2.4 ± 0.1 |

The Young's moduli of the coupled and uncoupled composites showed similar behaviors, which increased with increased amount of reinforcement. These increases were generally linear, with coefficients of determination ($R^2$) for the uncoupled and coupled composites of 0.96 and 0.99, respectively. This is consistent with the fact that the rapeseed sawdust has higher modulus than the matrix, and with relatively uniform dispersion of the reinforcement, as related with previous literature (Thomason 1999; Granda *et al.* 2016b). However, one unexpected result was the differences observed in the Young's modulus of the coupled composites compared to the uncoupled ones, for every formulation, which were statistically different. In general, the interfacial interactions influence the ultimate tensile properties of composites (Pukanszky 1990), but they do not affect the modulus of composites, as the Young's modulus is measured at very low deformations. The property (stiffness) is measured within the elastic zone and for very little deformations; therefore, the consequence is that usually the Young's modulus is dependent to the amount of reinforcement but independent to the interface. It is accepted, therefore, that the quality of the interface has little impact on the Young's modulus of a composite (Karmaker and Youngquist 1996; Oliver-Ortega *et al.* 2016; Jiménez *et al.* 2017). However, in the present work, the coupled composites showed higher Young's moduli than the uncoupled ones. Thus, for the composites at 30 wt%, 40 wt%, and 50 wt% of reinforcement, the property improved 1.9 times, 2.8 times, and 2.9 times for the uncoupled composites, while it was enhanced 2.4 times, 3 times, and 3.6 times for the coupled composites, respectively, at the same reinforcing level. The presence of coupling agents clearly influenced the stiffness of the composites. This can be attributed to the nature of the polymer matrix used in the present work. The current PP-PE copolymer is a modified polypropylene with improved impact properties, where the ethylene content permits higher extensions as compared to the homopolymer composites (Feng *et al.* 2001). Under such situations, a strong interface might contribute to a higher stiffness of the compound.

Compared to a wood-plastic composite, such as PP reinforced with stone groundwood (SGW), the RS-based composites delivered much improvement in the Young's modulus for the same reinforcement content (Espinach *et al.* 2013); the formulation with 50% SGW enhanced the Young's modulus of the matrix 3.3 times (not

3.6 times as in the present case). However, for GF composites, this level of improvement was achieved at 30 wt% of reinforcement. Clearly, glass fibers possessed higher stiffening capabilities than either natural reinforcement.

It was worth noticing that while the Young's modulus is a material property, the final stiffness also depends on the product geometry. Thus, proper product design can allow the use of RS-based composites. Moreover, composites with 50 wt% RS content showed similar Young's moduli to the composites with 40 wt% SGW content or with 20 wt% GF content. Furthermore, while SGW and GF had aspect ratios above 10, the RS reinforcement showed aspect ratios of approximately 6.4 (mean diameters of 50 µm and mean lengths of approximately 320 µm); therefore, lower strengthening and stiffening capabilities were expected. Past literature illustrates that particles with aspect ratios below 10 tend to perform more as a filler than as reinforcement (Li *et al.* 2009; Vallejos *et al.* 2012). However, RS sawdust used in this work showed reinforcing capabilities; indeed, the presence of a coupling agent evidently increased such capabilities.

Regarding the strain at break, the presence of a coupling agent noticeably increased the capacity of the composites to deform. It was affirmed that the coupled RS-composites are a convenient solution for the use of RS as a wood-plastic composite because they showed higher tensile strength, Young's modulus, and strains at break.

## Fiber Tensile Modulus Factor

One way to analyze the stiffening capabilities of the reinforcement is to define the FTMF. The FTMF expresses the neat contribution of the fibers to the Young's modulus of the composite. For the present case, the computed FTMF values plotted against the reinforcement volume fraction are depicted in Fig. 2.

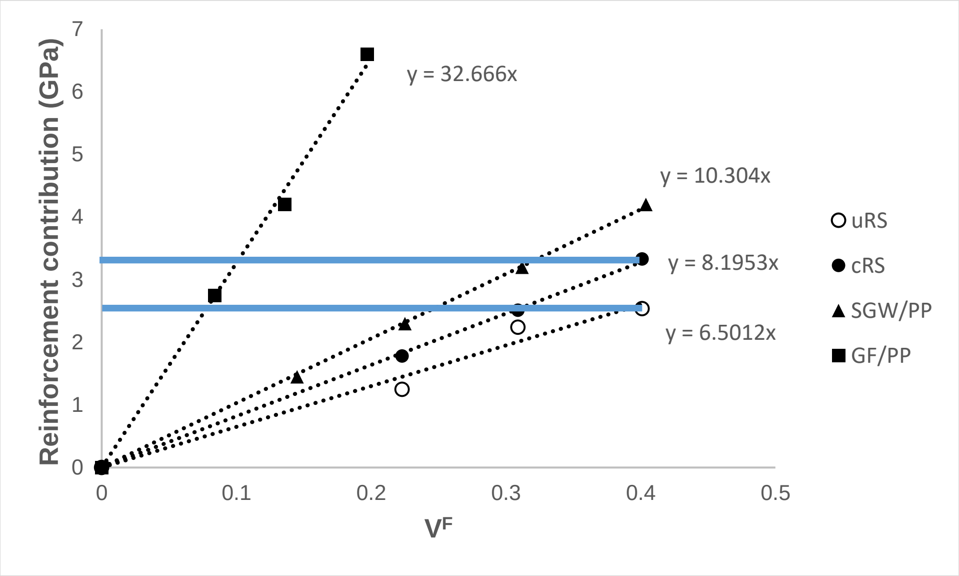

**Fig. 2.** Fiber tensile modulus factor of RS-, SGW-, and GF-based composites

The analysis of the reinforcements' contributions to the Young's modulus gave similar results to the analysis of the modulus. The GF gave the highest stiffening impact per volume fraction unit, being at least 3 times higher than the others. Wood fibers (SGW) showed a 10.34 value, noticeably 20% higher that a coupled RS fiber (cRS). The fibers with the lowest stiffening impact were the uncoupled RS fibers (uRS). The results indicated that 50% cRS had the same contribution as 40% SGW or approximately 15% GF. In contrast, 50% uRS was equivalent to 40% cRS, 32% SGW, and 9% GF, in terms of the contribution to the Young's modulus of the composite per volume fraction unit of reinforcement.

To know the effect of the intrinsic properties of the reinforcement, the intrinsic Young's modulus of RS was computed using Hirsch's model and the Tsai and Pagano equation.

## Micromechanics of the Young's Modulus

Table 2 presents the computed values of the intrinsic Young's modulus of the RS fibers, calculated using two different models, Hirsch's model and Tsai and Pagano's model.

**Table 2.** Intrinsic Young's Modulus of the Rapeseed Sawdust as Reinforcement of PPc

| Composite | $E_t^{F*}$ (GPa) | $E_t^{F**}$ (GPa) |
|---|---|---|
| PPc + 30% RS | 10.2 | 9.0 |
| PPc + 40% RS | 14.4 | 13.6 |
| PPc + 50% RS | 12.1 | 10.4 |
| Mean | 12.2 ± 2.1 | 11.0 ± 2.3 |
| PPc + 30% RS + 4% MAPP | 16.3 | 16.7 |
| PPc + 40% RS + 4% MAPP | 16.5 | 16.3 |
| PPc + 50% RS + 4% MAPP | 16.6 | 15.7 |
| Mean | 16.5 ± 0.2 | 16.2 ± 0.5 |

*: Computed using Hirsch's model
**: Computed using Tsai and Pagano's model

It was found that the intrinsic Young's modulus of the RS was a function of the presence of a coupling agent. For the fibers extracted from the uncoupled composites, the intrinsic Young's modulus ranged from 10.2 GPa to 14 GPa when computed by Hirsch's model, and from 9 GPa to 13.6 GPa when computed with the Tsai and Pagano model. However, the mean values were similar, considering the deviation. It is worth mentioning that both micromechanics models worked optimally for the composites that incorporate reinforcements. In the case of the uncoupled composites, the RS acted more like filler, under the stiffening point of view. In contrast, the intrinsic Young's moduli of RS from the coupled composites were very similar when measured by either model. Both models returned comparable values with low standard deviations. Hence, the values were considered statistically equivalent, with a 95% confidence.

Stone-ground wood fibers had intrinsic Young's moduli around 18.2 GPa, just 2 GPa above the one for rapeseed sawdust. Thus, better results can be expected when rapeseed fibers are used instead of sawdust. A more accurate treatment of the RS fibers can provide individualized reinforcements with higher aspect ratios. Thus, wood-plastic composites can be substituted by coupled RS-reinforced materials with little or no changes in the geometry of the products. In contrast, coupled RS-reinforced composites can be used to substitute GF-reinforced composites for applications at low GF contents.

When wood fiber composites are applied for decking and cladding solutions, coupled RS-reinforced composites are eligible for the same or similar uses. The design of new solutions must account for the properties of the materials and propose inertia moments in certain sections to ensure that regulations are followed. In the case of architecture, these regulations usually refer to the admissible deformations of the designs and rarely refer to the ultimate service strength. Thus, architectural designs show considerable security factors. In contrast, the use of standard sections (Fig. 1) for different uses also ensures a high security factor when considering deformations. The substitution of one material for another while keeping similar properties seems, therefore, feasible.

## CONCLUSIONS

1. Rapeseed sawdust-reinforced impact-modified polypropylene (PPc) composites showed a similar Young’s modulus to commercial wood-plastic composites, being a suitable alternative to such materials. The main advantage of rapeseed sawdust is its high availability in geographical zones richer in annual plants than in woods, such as the Mediterranean.
2. The addition of a coupling agent resulted in much stiffer composites. Rapeseed sawdust in uncoupled composites behaved as filler materials, with increases in their rigidity due to the inclusion of a more rigid phase. In contrast, for coupled composites, rapeseed sawdust behaved like reinforcement materials, exhibiting higher mechanical properties of the composite. Unlike other composite materials, the quality of the interface had a noticeable impact to the Young’s modulus of the composites.
3. The intrinsic Young’s modulus of the rapeseed reinforcement was clearly affected by the presence of a coupling agent. The intrinsic properties of the uncoupled composites were lower and showed higher variability than those of the coupled composites.
4. The implicit inclusion of the morphologic properties of the reinforcements did not affect the intrinsic Young’s modulus values. Hirsch’s model and Tsai and Pagano’s model returned statistically equivalent values.
5. The stiffness of a design depended on its geometry and on the mechanical properties of the materials used for its manufacture. The Young’s modulus influenced the rate of deformation of a section with a determined moment of inertia. Thus, the proposed materials, with a Young’s modulus similar to wood-plastic composites, can substitute for building materials in applications where the stiffness is more important than the strength.

## ACKNOWLEDGMENTS

The authors are grateful for the support of the University of Girona and its researcher progress program.

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Article submitted: July 12, 2018; Peer review completed: August 31, 2018; Revised version received and accepted: September 4, 2018; Published: September 12, 2018.
DOI: 10.15376/biores.13.4.8155-8167