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Use of wet-laid techniques to form flax-polypropylene nonwovens as base substrates for eco-friendly composites by using hot-press molding

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Abstract

The wet-laid process with flax (base) and polypropylene (binder) fibres has been used to obtain nonwovens for further processing by hot-press molding. Mechanical characterization of nonwovens has revealed that slight anisotropy is obtained with the wet-laid process as better tensile strength is obtained in the preferential deposition direction. The thermo-bonding process provides good cohesion to nonwovens which is critical for further handling/shaping by hot-press molding. Flax:PP composites have been processed by stacking 8 individual flax:PP nonwoven sheets and applying moderate temperature and pressure. As the amount of binder fiber is relatively low (< 30 weight %) if compared with similar systems processed by extrusion and injection molding, it is possible to obtain eco-friendly composites as the total content on natural fiber (flax) is higher than 70 weight %. Mechanical characterization of hot-pressed flax:PP composites has revealed high dependency of tensile and flexural strength on the total amount of binder fiber as this component is responsible for flax fiber embedment which is a critical parameter to ensure good fiber-matrix interaction. Combination of wet-laid techniques with hot-press molding processes is interesting from both technical

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and environmental points of view as high natural fiber content composites with balanced properties can be obtained.
Keywords: wet-laid; flax fiber; polypropylene; hot-press molding; hybrid nonwovens

1. Introduction.

In the last years a growing interest in the use of high environmental efficiency composite materials has been detected. The use of natural fibers such as jute, flax, kapok, sisal, hemp, etc. [1-3] as reinforcement embedded in a thermoplastic polymeric matrix from petroleum (polypropylene-PP, polyamide-PA, polycarbonate-PC, polyethylene-PE, etc.) [4-7] or from renewable resources such as polylactic acid-PLA, polycaprolactone-PCL, polyhydoxibutyrate-PHB, etc. [8-11] could lead to eco-friendly composites with interesting properties such as balanced mechanical behavior, cost effective materials, easy processing by conventional extrusion and injection molding, thermal and acoustic insulation, etc. [12] For this reason, it is possible to find technical uses of green composites in automotive, building, aeronautics, etc. industries [13-19]. These materials generally appear in the form of interior panels or secondary structures which do not require high mechanical performance.

The use of a thermoplastic polymer matrix allows processing by conventional extrusion or compounding process followed by injection molding so it is possible to obtain complex shapes as typical of an injection molding [20]. Nevertheless these conventional processes offer some restrictions. One important restriction is the fiber length as the mixture with the melted thermoplastic polymer must cross trough a small nozzle so that short fibers (< 5 mm) are preferred to ensure optimum flow avoiding nozzle block. Typical lengths for these processes are shorter than 2 mm [5, 21] and, in many cases in the μm range [22]. On other hand as the composite material is shaped as a mixture of melted polymer and fiber reinforcement, relatively high amounts of thermoplastic material is required to provide good fluency to the mixture, so that, in many cases, the total amount of fiber reinforcement is lower than 50 weight % [23, 24].

It is true that much has been done in the field of reinforced thermoplastics with natural fibers processed by conventional extrusion (compounding) and subsequent injection molding. But it is also true that these processes require relatively high amounts of thermoplastic matrix materials to ensure optimum rheological properties during processing [25]. Higher reinforcement amounts find enormous difficulties for processing by conventional extrusion and injection molding due to the low amount of thermoplastic matrix or binder which is the only component that confers easy fluency when melted.

One interesting technique to obtain composite materials with higher amounts of fiber reinforcement is the hot-press molding or thermo-compression. Textile technologies offer different solutions to obtain base materials for further processing by hot-press molding such as natural fiber-thermoplastic polymer core-spun yarns [26], nonwovens of randomly dispersed natural and thermoplastic fibers [27], etc. The thermoplastic polymer melts when hot-pressed and acts as a binder resin to provide cohesion to the composite material though fiber embedment. These composite materials do not show a continuous matrix but it is possible to obtain complex and large panels for technical applications with balanced mechanical properties. The main problem for this process is formation of a homogeneous mixture with the fiber reinforcement and the thermoplastic polymer. The wet laid is a processing technique highly used in the paper and textile industry for nonwoven formation. In the case of nonwoven textiles, a final bonding stage is required to obtain nonwovens with balanced mechanical properties [28, 29]. So that it is possible to use the wet-laid process to obtain a good mixture with a base fiber (which will act as a reinforcement component) and a binder fiber (which will act as the embedding media to provide cohesion). These nonwovens could be the base materials for composite processing by hot-press molding as the application of both pressure and temperature can melt the binder fiber to partially embed base fibers thus obtaining composite materials for potential use in technical applications such as automotive [29-32]. Although many binding fibers such as polypropylene, polyamides, polyethylene, etc. are petroleum-based materials, the wet-laid technique can be useful to obtain nonwovens characterized by high amounts of natural fibers (even higher than 90% wt. %) with relatively low contents of binder fibers so that, leading to high renewable content materials with regard to conventional natural fiber composites obtained by extrusion or injection molding.

In this work we report the use of the wet-laid technique with flax (base fiber; total content in the 70-90 weight % rage) and polypropylene (binder fiber) to obtain flax:PP nonwoven sheets which will represent the base substrates for further processing by hot-press molding. The efficiency of the wet-laid process in terms of the homogeneity, isotropy and mechanical properties is determined by standardized tests. Flax:PP composites are obtained by stacking eight individual flax:PP nonwoven sheets and applying temperature and pressure in a typical hot-press molding process. The obtained composites are characterized by standard mechanical tests (flexural, tensile, hardness and impact) and microstructure of fractured surfaces is studied to evaluate the influence of the PP binder fiber content on overall mechanical performance of flax:PP composites.

2. Experimental.

2.1. Materials.

Base flax fibers for nonwoven formation were commercial reference F 513/6 supplied by STW Fibers (SchwarzwälderTextil-werke, Schenkenzell, Germany) which consists in a mix between thick technical fibers (50-100 μm in diameter) and elementary fibers (10-20 μm in diameter). General properties of these fibers can be found in Table 1.

The binder fiber to give cohesion to the nonwoven was a polypropylene (PP) commercial grade PP 2.8/6 supplied by STW Fibers (SchwarzwälderTextil-werke, Schenkenzell, Germany) with the main properties summarized in Table 1.

Table 1

2.2. Formation of flax-PP nonwovens by the wet-laid process.

In a first stage, flax and polypropylene fibers were weighed to obtain different weight % flax:PP ratios (90:10, 80:20 and 70:30) and immediately they were poured into a pulper with a maximum capacity of 35 L. This pulper was supplied by PILL Nassvliestechnik (PILL Nassvliestechnik GmbH, Reutlingen, Germany). The fiber concentration in the water dispersion was 10 g L^{-1}. To obtain optimum fiber separation, vigorous agitation at 2300 rpm was maintained for 10 min. After this initial stage, the water dispersion is transferred to a larger polyethylene tank (1200 L maximum capacity) in which, the fiber dispersion is diluted up to 1 g L^{-1} with less aggressive agitation at 170 rpm for a total time of 15 min. After this, the fiber dispersion is ready to be transferred to the hydroformer station by different hydraulic pumps. In this work a hydroformer station supplied by PILL Nassvliestechnik (PILL Nassvliestechnik GmbH, Reutlingen, Germany) was used. The main features of this station are: maximum wide= 510 mm, take-off angle= 20º, formation rate between 1-10 m min^{-1}. Before the fiber dispersion reaches the main hydroformer strip, the water dispersion is diluted once again up to a concentration of 0.33 g L^{-1}; then, the fiber-water dispersion is transferred to the main strip with a continuous speed which acts as a water filter thus allowing the formation of the nonwoven over the strip as water is removed by a vacuum system.

Once the nonwoven is formed, additional thermo-bonding process must be carried out in order to melt PP fibers to embed flax fibers thus increasing nonwoven cohesion. A first drying stage was carried out initially in a drying oven SDT-600 by Tacome (Tacome S.A., Ontinyent, Spain) at a fixed temperature of 195 ºC for 15 min. After this stage, the dried nonwoven is subjected to a calendering process in a CL-600 calendersupplied by Tacome (Tacome S.A., Ontinyent, Spain). The surface temperature of the roller was maintained to 200 ºC and the linear pressure over the nonwoven was fixed to 0.124 MPa m (124 N mm^{-1}). Finally, the continuous nonwoven was rolled in a roller machine EN-600 supplied by Tacome.

2.3. Composite formation by hot-press molding of flax-PP nonwovens.

Formation of engineering composites was done by hot-press molding with a Robima S.A. (Valencia, Spain) 10 Tn press with temperature control Dupra S.A. (Dupra, Castalla, Spain). The composites were manufactured using aluminum plates with a hollow space of 20x20 cm^2.

8 sheets sizing 20x20 cm^2 were cut and were placed between the plates in order to consolidate the composite. Then a constant force of 4 Tn was applied at 160 ºC for 60 min and then proceeded to cool the mold for 20 min at room temperature to appropriately unmold.

2.4. Morphology characterization by SEM.

Scanning electron microscopy (SEM) was used for surface characterization of flax-PP nonwovens and fractured surfaces of hot-pressed composites from impact tests. A scanning electron microscope FEI mod. Phenom (FEI, Oregon, USA) was used. Prior to sample observation, samples were coated with a gold-palladium alloy in a Sputter Coater EMITECH mod. SC7620 (Quorum Technologies Ltd., East Sussex, United Kingdom).

2.5. Determination of thickness and surface mass.

Nonwovens were characterized by determining their thickness and surface mass. The thickness was determined by following the guidelines of the UNE-EN-ISO 9073:1997 – Method A, standard using a SODEMAT thickness apparatus with a test pressure of 0.5 KPa.

With regard to surface mass, a circular preform with fixed surface of 1 dm^2 was cut with a shape former mod. 1.333 RS supplied by Horvecal (Horvecal S.A., Villena, Spain). Five different samples were cut and weighed in a precision balance GR-200-EC by A&D Instruments Ltd. (A&D Instruments Ltd., Oxfordshire, United Kingdom) and average values of surface mass were calculated.

Temperature and relative humidity were maintained at 20 ±2 ºC and 65 ±4 % respectively for both tests.

2.6. Mechanical characterization.

Mechanical characterization was carried out on both nonwovens and hot-pressed composites.

Regarding to nonwovens, tensile strength and elongation at break (longitudinal and transversal direction) were determined following the UNE-EN-ISO 29073-3:1993 standard with an Instron dynamometer Mod. 4501 (Instron, Barcelona, Spain). Samples sizing 50 mm in width were cut on both longitudinal and transversal directions. The length was enough to ensure a clamp distance of 200 mm. The test rate was set to 100 mm min^{-1}. A minimum of 5 different samples were tested and average values were calculated. Temperature and relative humidity were maintained at 20 ±2 ºC and 65 ±4 % respectively.

With regard to mechanical characterization of hot-pressed composites, tensile, flexural, hardness and impact properties were studied. Tensile and flexural tests were carried out on an Ibertest ELIB 30 (S.A.E. Ibertest, Madrid, Spain) following the UNE-EN-ISO 527-1 (tensile) and 178 (flexural) standards with a load cell of 5 kN and a constant crosshead rate of 5 mm min^{-1} (tensile) and 2 mm min^{-1}(flexural). Tensile samples sized 200 mm x 20 mm and flexural samples sized 80 mm x 10 mm. The average thickness of samples for tensile and flexural tests was around 3 mm.

Hardness of hot-pressed flax-PP composites was determined using a shore durometer mod 673D (Instruments J. Bot S.A., Barcelona, Spain) with the D scale following the guidelines of the UNE-EN-ISO 868. Impact test were carried out with a Charpy type pendulum (6 J), supplied by Metrotec (Metrotec S.A., San Sebastian, Spain) following the UNE-EN-ISO 179:1993.

At least five different samples were tested for the different standardized tests and average values of the corresponding property were calculated. Temperature and relative humidity were maintained at 20 ±2 ºC and 65 ±4 % respectively.

3. Results and discussion.

3.1. Characterization of flax:PP nonwovens.

The thermo-bonding process is a critical parameter to take into account in order to obtain easy handling nonwovens. This process is responsible for formation of interlock points between different flax fibers thus contributing to overall substrate cohesion which is critical for good handling and further shaping. Fig. 1 shows SEM images of flax nonwovens with different PP binder fiber content. For low PP binder fiber contents (around 10 wt. %) we do not distinguish presence of interlock points characterized by aggregates of melted polypropylene fibers (Fig. 1a and 1b); so that, mechanical properties of these substrates are expected poor due to lack of adhesion between different flax fibers. As the PP binder fiber amount increases, we observe presence of dispersed polypropylene clusters or aggregates which can play an important role in overall mechanical performance of nonwoven substrates. As seen in Fig. 1c for low magnification (200x) we can detect presence of polypropylene clusters resulting from polymer melting in the thermo-bonding process. This melted polymer can easily move and it can partially embed some flax fibers; in addition to this, the melted polymer can accumulate to form small aggregates which are hot-pressed during calendering after the thermo-bonding process. These clusters or aggregates allow interaction between different embedded flax fibers and surrounding areas thus acting as interlock points with the typical flat shape as a consequence of the press during calendering as observed in Fig. 1d for 20 wt. % PP binder fiber at 400 x. Obviously, as the PP binder fiber amount increases, we observe presence of more interlock points/areas as it is evident from observation of Fig. 1e which corresponds to flax nonwovens with 30 wt. % PP binder fiber (200x). Higher magnification (400x, Fig. 1f) allows to observe that some flax fibers are fully covered-embedded by polypropylene melted fibers and this fact has a positive effect on establishing interactions between randomly dispersed flax fibers thus contributing to nonwoven cohesion. It is expectable that mechanical properties of flax nonwovens increase as the PP binder fiber content increases as more interlock points are formed during the thermo-bonding process.

Figure 1

With regard to the mechanical properties of individual nonwovens as a function of the PP binder fiber amount, Table 2 and Table 3 show a summary of the main mechanical parameters: tensile strength and elongation at break for longitudinal and transversal directions. As the hydroformer station has a preferential deposition direction (longitudinal) it is expectable some anisotropy on nonwovens. This fact could be important for further processing of these nonwoven structures by hot-pressing molding of stacked nonwoven substrates in order to obtain high isotropic composite materials. With regard to longitudinal direction, the tensile strength changes from nearly 270 N for flax nonwovens with 10 wt. % PP binder fiber up to almost double values (520 N) for PP binder fiber amounts in the 20-30 wt. %, and this represents a percentage increase of about 92.6 %. If we compare these values with those obtained in transversal directions (Table 3), we can conclude that the wet-laid process produces intrinsically slight anisotropic nonwovens due to a preferential deposition direction. The transversal tensile strength changes from 174 N (for flax nonwovens with 10 wt. % PP binder fiber content) up to 316 N for 30 wt. % PP content which represents a percentage increase of about 81.6 %. These values indicate that mechanical performance is remarkably increased in a similar way for both longitudinal and transversal directions as the PP binder fiber content increases from 10 wt. % to 30 wt. %. Nevertheless absolute values for longitudinal and transversal tensile strength values are different being the transversal direction less resistant than the longitudinal direction. Similar anisotropic behavior has been observed with flax-PP composites from needle-punched hybrid nonwovens [33].

Regarding the elongation at break, values remain close to 3 % for all the composition range and both longitudinal and transversal directions thus showing that this mechanical property is not highly affected by the PP binder fiber content and the preferential deposition direction.

Table 2

Table 3

Other typical physical properties have been determined in order to characterize the effectiveness and reproducibility of the wet-laid process in the production of nonwoven structures: surface mass and thickness. Table 4 shows summarized average values for surface mass and thickness. With regard to surface mass, it is important to remark that the wet-laid process leads to highly homogeneous nonwovens as the relatively low standard deviation (SD) values indicate. The surface mass variability is close to 4.5 %, 5.7 % and 4.0 % for 10, 20, 30 wt. % PP binder fiber respectively. With the use of the parameters described in the experimental section, it is possible to obtain nonwovens with a surface mass in the 370 – 390 g m^{-2} range for the PP binder range between 10 – 30 wt. %. Regarding the thickness of the obtained nonwovens, it is important to remark that an increasing tendency is detected with the PP binder fiber content as observed in Table 4. The variability of the thickness is slightly higher than the observed for surface mass but even in this case, the maximum variation doesn’t exceed 15% thus indicating that the wet-laid process is an effective technique to obtain quite homogeneous nonwoven structures.

Table 4

3.2. Mechanical properties of hot-pressed composites derived from flax:PP nonwovens.

The previous section has focused on mechanical and physical properties of individual nonwoven substrates. Although these nonwoven structures could find interesting applications in technical uses as acoustic or thermal insulation materials, it is possible to widen the potential use of these nonwoven structures by using these individual nonwoven structures as base materials for composite formation by hot- press molding as these substrates contain both reinforcement (flax fiber) and matrix (melted polypropylene). The previous results have shown that the wet-laid process is a useful technique to obtain nonwoven structures characterized by high homogeneity in terms of surface mass and thickness. On other hand mechanical properties are remarkably increased as the binder content increases so that it is possible to obtain nonwovens with balanced mechanical properties for further processing by hot-press molding. This new processing operation requires no breakage during handling and easy shape adaptation to avoid breaks while being pressed.

In this section, results regarding mechanical characterization of composites obtained by hot-press molding of eight stacked flax:PP nonwoven sheets are shown. Fig. 2 shows a plot representation of the tensile strength and modulus for hot- pressed flax:PP composites with different PP content (in the form of binder fiber in nonwovens). As we can clearly see, both the tensile strength and modulus increases as the PP binder fiber content increases from 10 wt. % up to 30 wt. %. The tensile strength is increased from 9.2 MPa for composites with 10 wt. % PP binder fiber up to values close to 20 MPa for composites containing 30 wt. % PP binder fibers which represents a percentage increase of almost 112 %. It is important to remark that tensile strength is highly sensitive to reinforcement-matrix interactions as good interaction leads to good stress transfer between the fiber and the polymer matrix. On other hand, poor fiber-matrix interactions are responsible for early fracture as a consequence of stress concentration phenomena. Intense fiber-matrix interactions (chemical and mechanical) can occur if fibers are completely embedded by the polymeric matrix; as the reinforcement fiber is usually stiffer than the polymer matrix, this interaction allows stress transfer between matrix and fiber thus obtaining a reinforcing effect on the composite material. This situation is typical for composites with high contents of polymer matrix since it is possible to fully embed fibers; but even in this case, optimum stress transfer can’t be ensured as full embedment is only a premise since additional mechanical and chemical interactions between the polymer matrix and the fiber are needed. In fiber-polymer matrix composites with higher reinforcement contents as the system we are describing in this work (more than 70 wt. % fiber content) the stress transfer is even more difficult since the melted polymer doesn’t form continuous matrix as we have observed in Fig. 1 (melted binder fiber clusters or aggregates). In this case, the polymer matrix acts as a binder to provide shape cohesion but in general terms, mechanical properties are lower than similar systems with more matrix content. So that as the PP binder fiber content increases, we observe a remarkable increase in tensile strength since higher amounts of melted polypropylene enables flax fibers embedment and these areas act as interlock points for stress transfer which has a positive effect on tensile strength.

With regard to the tensile modulus, we also observe an increase from 1.5 GPa for flax:PP composites with 10 wt. % PP binder fiber up to values close to 1.9 GPa for

PP binder fiber contents of 30 wt. %. As we can see, an increasing tendency can be detected but it is important to remark that tensile modulus is not as sensitive to composite interactions as tensile strength. In general terms, the tensile modulus values of the different flax:PP composites are lower than 2.0 GPa which represents a usual value for composites with relatively low fiber-matrix interactions.

Figure 2

Regarding the flexural behavior of these composites we observe similar tendencies as those described for tensile behavior. Fig. 3 shows a plot evolution of flexural strength and modulus. The flexural stength is increased from 2.1 MPa for flax:PP composites with 10 wt. % PP binder fiber up to 3.6 MPa for 30 wt. % PP binder fiber and this represents a percentage increase of about 71% which is in agreement with the tensile results. With regard to flexural modulus no clear tendency can be observed and the flexural modulus is mantained near 3 GPa.

Figure 3

In addition to tensile and flexural mechanical behavior, the Charpy impact energy and the Shore D hardness of flax:PP composites has been determined by standardized tests and average values are summarized in Table 5. The ability of composites to absorb energy in impact conditions is directly related to presence of a continuous matrix which allows deformations and subsequently, energy absorption. Full embedment of fiber reinforcements is required for optimum performance versus impact. So that, as these flax:PP composites are characterized by high reinforcement contents (>

70 wt. %) the impact energy is relatively low. Impact energy evolution is similar to tensile and flexural strength thus showing high sensitiveness to fiber-polymer matrix interactions. As these composites are characterized by relatively low fiber embedment, the impact energy values are low, changing from 3.8 KJ m^{-2} for hot-pressed composites with 10 wt. % PP binder fiber up to values of about 5.0 KJ m^{-2} for hot-pressed composites with 30 wt. % PP binder fiber. Table 5 also shows Shore D hardness values for hot-pressed flax:PP composites showing an increasing tendency with total content of polypropylene

Table 5

An analysis of the fractured surfaces from impact tests can be useful to support previous results regarding Charpy impact energy and overall mechanical performance of hot-pressed flax:PP composites (Fig. 4). Independently of the PP binder fiber content we observe a typical fracture surface characterized by presence of randomly oriented flax fibers in the fracture plane while presence of a continuous polymer matrix (polypropylene) is not evident. For low PP binder fiber content (10 wt. %) we don't observe presence of polymer matrix. It is possible that some individual flax fibers are embedded by polypropylene but as the total amount of polypropylene is very low, it is difficult to observe in a clear way presence of polymer matrix areas (Fig. 4a and 4b). For composites with higher PP binder fiber content (20 wt. %) at high magnification (Fig. 4d) we observe some embedded flax fibers and some polypropylene fractured areas. This behavior is more intense for 30 wt. % PP binder fiber content (Fig. 4e and 4f). So that, we can conclude that fractured surfaces from impact tests show poor interaction between the fiber reinforcement and the polypropylene matrix. In fact, polypropylene doesn’t form a continuous matrix and it acts as a simple binder to provide cohesion to the composite material.

Figure 4

4. Conclusions.

In general terms we can conclude that the wet-laid process of flax and polypropylene fibers in aqueous dispersion leads to nonwovens with interesting properties for technical uses such as composite materials. The thermo-bonding process is useful to give enough cohesion to nonwovens thus enabling them for handling without breakage and subsequent processing operations by hot-press molding which requires adaptability to different shapes. The SEM study has revealed presence of embedded flax fibers and polypropylene aggregates which are responsible for nonwoven cohesion. Mechanical characterization of nonwovens shows great dependency of tensile strength on total content of PP binder fiber in the 10-30 wt. % range which is obvious as the melted polypropylene is the only component that is able to embed fibers. On other hand, the wet-laid process on a hydroformer is characterized by a preferential deposition direction so that, slight anisotropy on nonwoven sheets can be detected as mechanical performance on transverse direction are lower than those obtained on longitudinal (preferential) direction.

Regarding flax:PP composites obtained from stacking 8 individual nonwoven sheets and applying temperature and pressure (hot-press molding or thermo-compression), it is important to remark that interesting mechanical properties are obtained. The results show a remarkable increase in tensile and flexural strength values as the PP binder content increases. As it is impossible to obtain full flax fiber embedment with low amounts of PP (< 30 wt. %) and tensile and flexural strength are highly sensitive to fiber-matrix interactions, stress transfer is restricted. Similar behavior has been observed for Charpy impact energy. The SEM study on fractured samples from impact tests has revealed a fracture surface characterized by presence of randomly oriented fibers in the fracture plane thus evidencing the lack of polymer matrix which can contribute to stress transfer by shear.

In general terms this works confirms the usefulness of the wet-laid process of flax and polypropylene to obtain nonwoven structures with high flax fiber content (> 70 wt. %) being polypropylene a binder with relative low melting point which enables thermo-bonding at approximately 190 ºC. By stacking different flax:PP nonwoven sheets and applying moderate temperatures and pressures it is possible to convert nonwovens to composite engineering materials which can be useful for acoustic and thermal insulation panels with balanced mechanical properties. On other hand the high natural fiber content of these composites leads to obtaining high environmental efficiency or eco-friendly materials for technological sectors.

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Table 1.- General characteristics of flax and polypropylene fibres (PP) used as base (flax) and binder (PP) for nonwoven formation by the wet-laid process.

Property	**Flax fibre**	**PP fibre**
Fibre thickness [μm]	10 – 500	18
Density [g cm^{-3}]	1.4 – 1.5	0.91
Melt temperature [ºC]	--	160
Colour	Natural	White
Fibre length [mm]	6	6
Light resistance	Moderate	Moderate
Resistance to acids	Moderate	Only attacked by highly oxidizing agents
Resistance to alkalis	Moderate	Good
Water swelling value	Moderate	--

Table 2.- Mechanical properties of flax:PP nonwovens (longitudinal direction) in terms of the weight % of binder PP fibre.

	Tensile strength, F_l (N)		**Elongation at break, ε_l (%)**	
wt. % PP fibre	**Average**	**SD**	**Average**	**SD**
10	270	21.6	2.8	0.17
20	520	36.4	3.2	0.34
30	518	77.7	3.6	0.15

Table 3.- Mechanical properties of flax:PP nonwovens (transversal direction) in terms of the weight % of binder PP fibre.

	Tensile strength, F_t (N)		**Elongation at break, ε_t (%)**	
wt. % PP fibre	**Average**	**SD**	**Average**	**SD**
10	174	17.4	2.6	0.23
20	222	28.9	3.0	0.46
30	316	22.1	3.4	0.18

Table 4.- Surface mass and thickness values of flax-PP nonwovens in terms of the weight % of PP binder fibre.

wt. % PP fibre	Surface mass (g m^{-2})		Thickness (mm)	
	Average	**SD**	**Average**	**SD**
10	385.6	17.49	1.1	0.14
20	387.4	21.96	1.2	0.19
30	371.0	14.87	1.6	0.14

Table 5.- Charpy impact energy and Shore D hardness values of hot-pressed flax-PP composites in terms of the weight % of PP binder fibre.

wt. % PP fibre	Charpy impact energy (KJ m^{-2})		Shore D hardness	
	Average	**SD**	**Average**	**SD**
10	3.8	0.50	63	2
20	4.5	0.60	61	3
30	5.0	1.20	72	1

Figure legends

Figure 1.- SEM images of flax:PP nonwovens with different PP binder fiber weight % and magnifications, a) 10 wt. % PP; 200x, b) 10 wt. % PP; 400x, c) 20 wt. % PP; 200x, d) 20 wt. % PP; 400x, e) 30 wt. % PP; 200x, f) 30 wt. % PP; 400x.

Figure 2.-Variation of tensile strength and modulus of hot-pressed flax-PP composites in terms of the weight % PP binder fiber.

Figure 3.-Variation of flexural strength and modulus of hot-pressed flax-PP composites in terms of the weight % PP binder fiber.

Figure 4.- SEM images of fractured samples from Charpy impact tests of hot-pressed flax:PP composites with different PP binder fiber weight % and magnifications, a) 10 wt. % PP; 500x, b) 10 wt. % PP; 1000x, c) 20 wt. % PP; 500x, d) 20 wt. % PP; 1000x, e) 30 wt. % PP; 500x, f) 30 wt. % PP; 1000x.

Figure 1

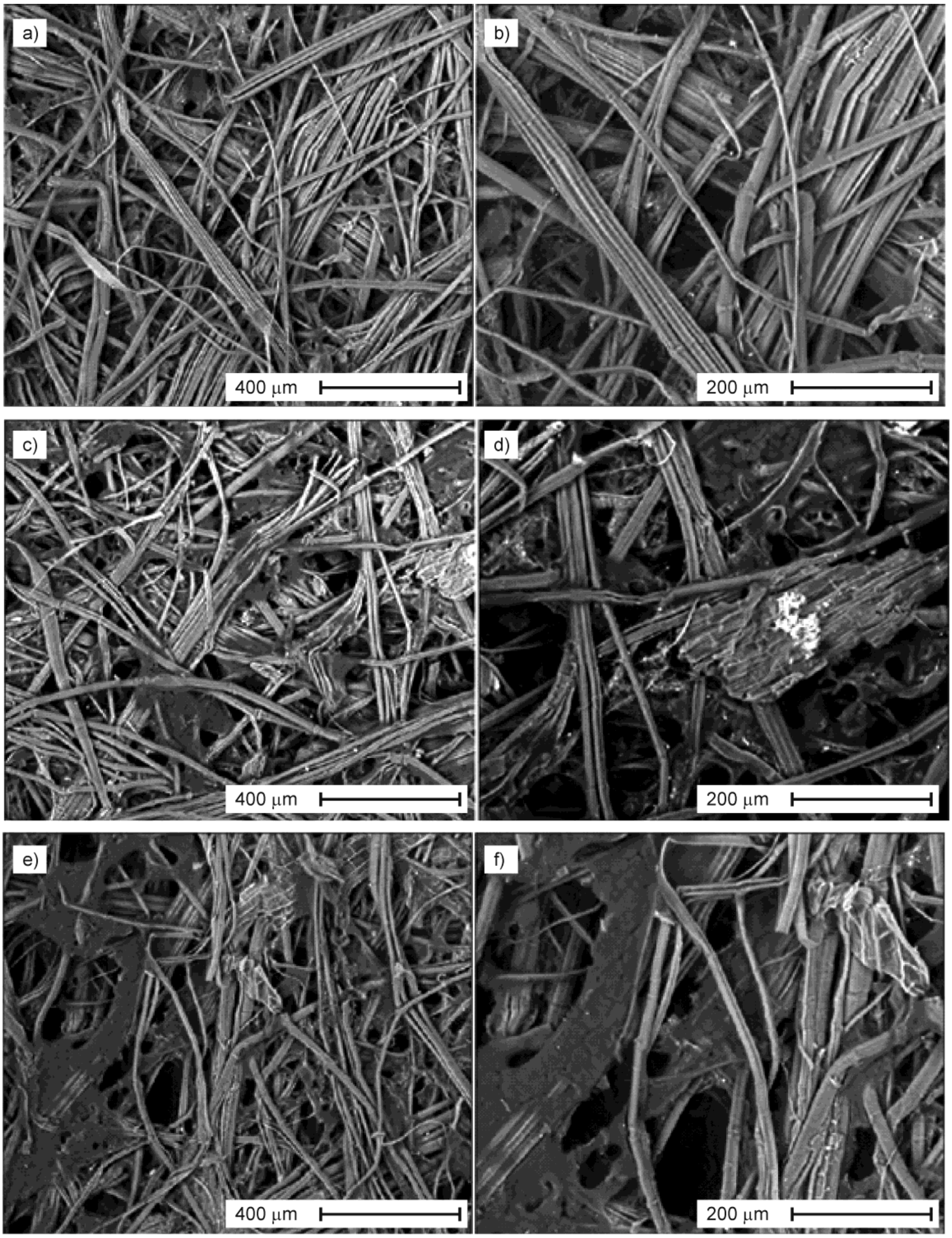
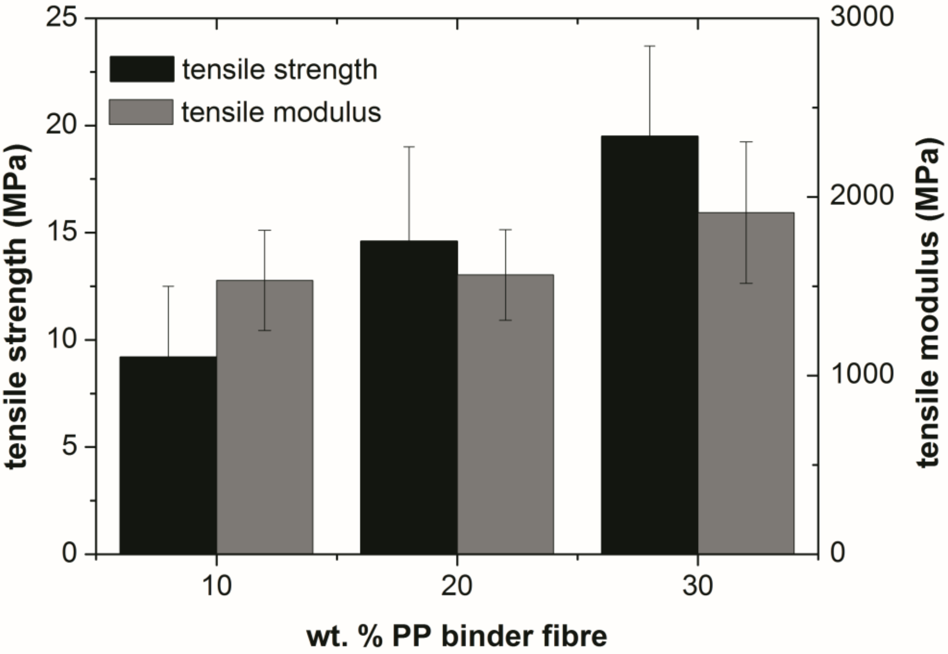
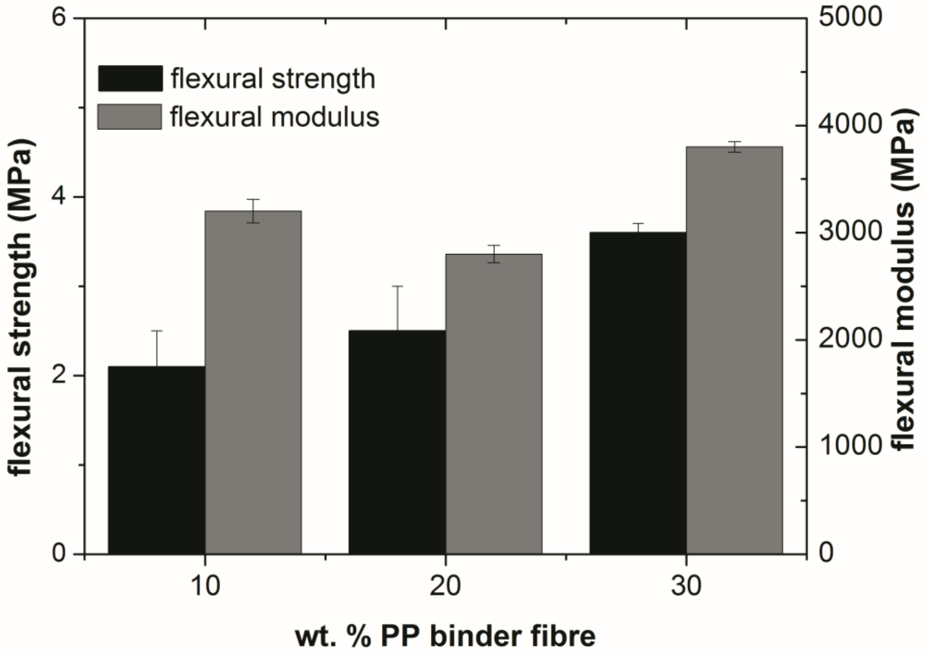


Figure 2



tensile strength
tensile modulus
tensile strength (MPa)
tensile modulus (MPa)
0
5
10
15
20
25
0
1000
2000
3000
10
20
30
wt. % PP binder fibre

Figure 3



flexural strength
flexural modulus
flexural strength (MPa)
flexural modulus (MPa)
wt. % PP binder fibre
0
2
4
6
0
1000
2000
3000
4000
5000
10
20
30

Figure 4