Effect of Maleated Polypropylene as Coupling Agent for Polypropylene Composites Reinforced with Hemp Strands

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ABSTRACT: New composites based on poly(propylene) as polymer matrix and hemp strands as natural reinforcement have been developed by injection-molding. The materials were previously mixed in a two roll mill to induce the dispersion of the fiber inside the polymer. To improve the adhesion between both components, maleated poly(propylene) was added as coupling agent, at 4% wt/wt with respect to hemp strands. The addition of this amount of this coupling agent to the formulation modified with 40 wt % of hemp strands increases the ultimate tensile strength (σ_t) and flexural strength (σ_f) up to 49 and 38%, respectively, compared with the composite without coupling agent. The interaction between the surface of hemp strands and the coupling agent was determined by FT-IR spectroscopy assuming that a covalent bond was established, avoiding the adverse effect of the poor compatibility at the interface for this kind of composites. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 833–840, 2006

Key words: composites; fibers; injection molding; interfaces; poly(propylene)

INTRODUCTION

Nowadays, polymer composites reinforced with fibers for obtaining materials with improved properties is one of the most important fields in material science. Within this field, the use of natural fibers, mainly based on cellulose, as reinforcement of polymer matrices is increasing due to their low cost and easy processability.[1] The renewable nature of their sources and their biodegradability are also interesting characteristics of natural fibers, which are an alternative to those nonbiodegradable inorganic reinforcements/fillers such as glass fiber and calcium carbonate.[2–4] But the addition of natural fibers to the polymer matrix has some disadvantages. The poor compatibility of this reinforcement with the polymer matrices derived from petroleum is one of the most important disadvantages.[5] In this sense, the improvement of compatibility between the polymer matrix and cellulose reinforcements in the preparation of composites is a big field under constant development.

One of the most often used thermoplastic groups for obtaining composites are the poly(olefins) such as poly(ethylene) and poly(propylene) (PP), but the adhesion of these matrices with natural fibers is rather low due to its different chemical structure. Poly(olefins) are very apolar materials because of their hydrophobic long aliphatic primary chain without any polar group.[6] On the other hand, the natural fibers based on cellulose have hydroxyl groups in their structure which promote the polarity of the materials having a high hydrophilic character. The combination of these two hydrophobic and hydrophilic components in the fabrication of composites involves negative interfacial effects related with the bad adhesion between both surfaces.

There are different ways to improve the adhesion at the interface of the composites. The modification of the surface of the fiber to change the polarity is one of them. In the case of cellulose fibers, the use of this way leads to the modification of the hydroxyl groups on the surface by reaction with different reactives to decrease the polarity of the surface or to increase the affinity of the surface of the fiber towards the polymer matrix.[7–9] Another way to improve the interaction between the reinforcement and the polymer is the addition of a coupling agent to bond chemically the surface of the fiber and the plastic matrix.[10] This is the case of the maleated poly(propylene) (MAH-PP) which is able to react with other materials with hydroxyl groups on the surface. This is a polymer modified with a polar group (maleic anhydride) grafted in the chain by a radical reaction in the presence of peroxides.[11] The coupling agent has functional groups which are able to react with other polar functional groups such as amines and alcohols. In the case of cellulose fibers, the hydroxyl groups on the surface of

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the fiber can react with the anhydride to form ester bonds.[12–15] This bond induces the compatibilisation and the transference of stresses from the polymer to the fiber, promoting better mechanical properties to the material.

In this work, PP-hemp strand (*Cannabis sativa*) composites have been modified by adding 4% wt/wt hemp strand of MAH-PP. Hemp strands are based on cellulose fibers which have been used as reinforcement of the polymer matrix because of its low production cost, extensive distribution and availability, and other factors such as recyclability, biodegradability and the renewable nature of its source. The materials were prepared by injection-molding after mixing in a two roll mill. The obtained materials were characterized by different mechanical tests, microscopic and spectroscopic techniques to determine the influence of MAH-PP on the final material.

EXPERIMENTAL

Materials

PP (Isplen 090 G2M, Repsol-YPF™) was used as polymer matrix. The hemp strands were provided by Agrofibra S. L., from crops of the regions of Solsonès and Bergada (Puigreig, Catalonia, Spain), and were physically treated before use. The raw hemp is based on long strands, with 50–150 μm in diameter, which were cut down to a nominal length of 10 mm by means of a manual guillotine (Metrotec). This process was carried out for inducing a better dispersion of the strands inside the composite. The strands were washed with water in a pulper machine at room temperature and slight stirring to remove the straw as well as the impurities. After this process, the hemp strands were stored during 24 h at 80°C prior use. To improve the compatibility between the polymer matrix and the hemp strands, poly(propylene)-co-maleic anhydride (MAH-PP) (Epolene G 3015, Eastman, [acid number: 15 mg KOH/g, M_n: 24.8×10^3 Da]), was used as coupling agent as received. Silanized glass fibers were used to compare the properties of the materials prepared by the addition of hemp strand with current fibers used in the market. These fibers have a surface treatment with silane derivatives to improve a better adhesion with the polymer matrix. On the other hand, to determine the nature of the improvement that MAH-PP involves, the surface of the hemp strands was chemically modified. This modification is based on the reaction of the surface —OH groups with a silane derivative (Octadecyl-trimetoxysilane, Dynasilan 9118, Degussa S.A.) to reduce the number of these groups.

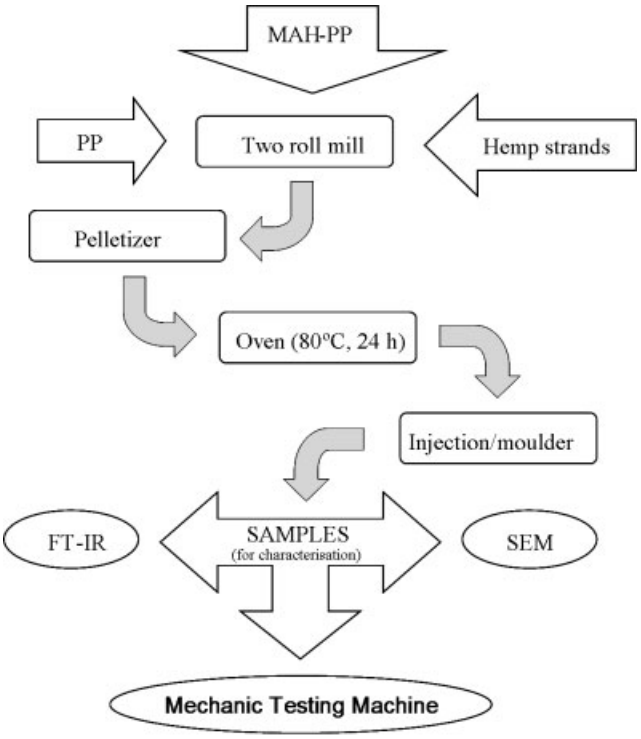

Figure 1 Flow chart for the preparation of composites based on PP and hemp strands coupled with MAH-PP.

Methods

Preparation of the composites

The composites were prepared as shown in Figure 1. PP and hemp strands and MAH-PP (for modified composites) were mixed at different wt/wt ratios in a two roll mill (IQAP LAB) at 185°C for 10 min to obtain a well-dispersed material. The mill is equipped with two parallel rolls, turning with two different speeds of 23 and 29 rpm. The dispersion depends on the processing time, temperature, and strand length. The blends were cut down to pellets with a particle size in the range of 10 mm using a pelletizer equipped with a set of knifes and different grids. The pellets were dried and stored at 80°C during 24 h. After this drying time the pellets were injected by an injection-molding machine (Meteor-40, Mateu & Solé). The processing temperatures of the three areas of the machine were 175, 175, and 190°C being the highest the corresponding to the nozzle. The first and second injection pressures were 120 and 25 $kg_f\ cm^{-2}$ respectively. By means of this procedure, specimens for tensile, flexural and impact tests were obtained with the corresponding shape according to the ASTM D638, ASTM D790, and ISO 178 respectively.

Mechanical analysis

Tensile and flexural tests were performed using an Universal Testing Machine (Instron 1122 according to

TABLE I
Tensile, Flexural Mechanical Properties, and Impact Strength of Reinforced Composites With and Without Addition of a Coupling Agent (MAH-PP)

	σ_t (MPa)		E_t (GPa)		ε_t (%)		σ_f (MPa)		E_f (GPa)		I (kJ/m^2)	
Strand content (wt %)	0% MAH-PP	4% MAH-PP	0% MAH-PP	4% MAH-PP	0% MAH-PP	4% MAH-PP	0% MAH-PP	4% MAH-PP	0% MAH-PP	4% MAH-PP	0% MAH-PP	4% MAH-PP
0	27.6 [0.5]	—	1.1 [0.1]	—	9.3 [0.2]	—	40.2 [1.0]	—	1.1 [0.1]	—	**	—
20	29.5 [0.7]	33.3 [0.4]	2.1 [0.2]	2.1 [0.2]	3.4 [0.1]	3.6 [0.2]	53.1 [0.8]	61.3 [0.3]	3.0 [0.1]	3.1 [0.2]	16.1 [1.5]	16.3 [1.0]
30	32.9 [0.5]	43.4 [1.0]	2.6 [0.2]	2.6 [0.2]	3.1 [0.1]	3.7 [0.2]	58.9 [0.7]	71.8 [1.1]	3.8 [0.2]	3.8 [0.1]	12.7 [0.7]	15.8 [1.4]
40	32.8 [0.9]	48.8 [1.8]	3.5 [0.1]	3.5 [0.1]	2.9 [0.1]	3.7 [0.1]	58.6 [0.4]	80.2 [2.7]	4.3 [0.2]	4.5 [0.2]	12.0 [0.7]	17.4 [1.4]

The percentage of coupling agent is referred to the hemp strand content. Values in square brackets indicate standard deviation; **, this formulation does not break.

ISO 527–1:2000 and UNE-EN ISO 179–1-2000 standard specifications respectively). Before use, the samples were stored at 23°C and 50% of relative humidity for 48 h, according to ASTM D618 standard specifications. A minimum of five specimens where used for obtaining each value, at room temperature and 50% of relative humidity. Ultimate tensile strength (σ_t, UTS), elastic modulus or Young modulus (E_t), flexural strength (σ_f), and flexural modulus (E_f) were the studied mechanical properties. Impact properties were studied in an Impact Charpy tester, obtaining the impact strength (I).

To determine the intrinsic tensile strength of the hemp strand (σ^F_t), a separation of the gags of half inch, in the tensile assay, has been used according to ASTM D3822/01 standard specifications. The strand was stuck on a frame made of paper to help its placement between the gags. Once the strand was lined up and attached between the gags, the frame was cut, to determine just the strength of the strand. The tensile assay was carried out using a rate of displacement of the gag of 1.27 mm min^{-1}, according to ASTM D3379/75 standard specifications. This rate is 10 times lower than the initial length between the gags.

Evaluation of the polarity

The methodology used for determining the polarity of the polymer matrix and the hemp strands is based on the titration of a finely powdered suspension of the material with MGCh (methyl-glycol-chitosan) (Wako Chemical GMBH, Neuss, Germany) as cationic reagent to interact with the polar groups of the surface of the material.[16] The cationic reagent is added in excess and the excess not interacted with the surface of the substrate (material) is titrated with a solution of potassium polyvinyl sulfate, using blue of *o*-toluidine (TBO) as indicator. The values of polarity are showed in terms of microequivalents of MGCh (methyl-glycol-chitosan) per gram of material.

Surface studies

The surface of the strands as well as the fracture area of the specimens for tensile test was observed by electron scanning microscopy (SEM) (Zeiss DMS 960). By means of this technique it was possible to determine qualitatively the adhesion degree between the matrix and the reinforcement.

Spectroscopic analysis

The chemical modification of the fibers was studied by Fourier Transformed infrared spectroscopy (FT-IR) (Matson Satellite FTIR). The spectrophotometer was connected to a computer with the software analyzer WinFirstTlite.

Surface modification of hemp strands

To confirm the covalent nature of the interaction between MAH-PP and the natural fibers, surface modified hemp strands were obtained to prepare reinforcement with the —OH groups on the surface blocked, to avoid the bond with the coupling agent. In this sense, the surface of the hemp strands was modified with octadecyl-trimetoxysilane (Dynasilan 9118, Degussa S.A.). A 2 wt % solution of the silane derivative in metoxypropanol was hydrolized at 40°C, pH 4 (acetic acid) at a stirring rate of 90 rpm for 2 h. The fibers were added to this solution and the reaction was stirred for two more hours. Once this time was elapsed the fibers were filtered and dried at 80°C for 24 h.

RESULTS AND DISCUSSION

Composites without addition of coupling agent (MAH-PP)

In this work, new composites based on PP as polymer matrix and hemp strands as reinforcement have been prepared following the procedure showed in Figure 1. Mechanical properties under tensile, flexural, and im-

TABLE II
Polarity of Different Materials Used in This Work

Material	Polarity (μeq MGCh)
Cellulose filament	114.7 (8.1)
Poly(propylene)	6.5 (0.8)
Modified glass fiber[a]	11.3 (0.8)

[a] Modified by silane derivatives. μeq-g MGCh, microequivalents of methyl-glycol-chitosan.

pact conditions have been evaluated and the results are summarized in Table I. In this table the results of the composites with and without MAH-PP are showed, observing interesting differences between the values. In the case of materials nonmodified with the coupling agent (0% MAH-PP in Table I), the increase in the amount of hemp strands produces a moderate increase in the ultimate tensile strength, which is even higher for the case of the flexural strength. Thus, for the formulation based on a 30 wt % of hemp strands, the values of flexural and ultimate tensile strength (σ_f and σ_t) increased up to 46 and 19% respectively, compared with nonreinforced PP.

These improvements in the static mechanical properties are obtained in spite of the fact that the interface between the hemp strands and the matrix does not present the best conditions to be an efficient reinforcement. It is well known that the high polarity of the lignocellulose strands is due to its chemical structure, and the low polarity of the thermoplastic matrices is derived from petroleum.[17] These values of polarity can be observed in Table 2, obtained by colloidal titration in terms of microequivalents of MGCh (methyl-glycol-chitosan) per gram of material. In this table, high differences between the polarity of natural fibers and polymer matrices can be observed. The experiment is based on the higher or lower amount of a cationic polymer (MGCh) that can be adsorbed on the surface of the material. Comparing the amount of MGCh adsorbed on the cellulose fibers and on the commercial silanized glass fibers, a higher polarity of the first ones can be assumed, which indicates that the second ones are more compatible with the PP matrix, from a polar point of view. But the polar factor is not the only parameter that can affect the interaction between the reinforcement and the polymer. There are other mechanisms that can improve the mechanical properties of the composites. As it can be seen from Figure 2, the hemp strands show an irregular surface and considerable porosity. Thus, the surface morphology of the strands also affects the interface allowing mechanical anchoring between the fiber and the PP. This effect is due to the coating and the interdiffusion of the polymer on the surface and in the pores of the reinforcement.[17–19] Some works developed by our group are related with the effect of a refining process of the strands on the mechanical properties of the final composite.[17,19,20] The refining process increases the specific surface leading a rise in the mechanical properties values because of a surface fibrillation, an increase in the flexibility and a slightly decrease in the strand length.

Therefore, a higher anchoring capacity is obtained because of the higher specific surface and flexibility of the strands. In the case of the composite with a 40 wt % of hemp strands, there is no increase in the tensile properties because of a saturation effect in the anchoring and the interdiffusion mechanism.

Nevertheless, the adhesion between the hemp strand and the polymer matrix is weak and it can be seen in the SEM microphotograph in Figure 3, where the fracture section of a tensile test specimen is shown. During the application of the tensile stress the strand was pulled out instead of broken, what indicates that there is not an effective interaction between strands and the matrix.

The Young modulus and flexural modulus were linearly increased with the increase in the percentage of reinforcement. Thus, for the formulation based on a 40 wt % of reinforcement, the Young and the flexural moduli were three and almost four times higher respectively, compared with the PP samples. These values are in agreement with an increase in the stiffness of the materials after the reinforcement. The rise in the value of the Young modulus involves a decrement of the tensile strain with the increase in the amount of hemp strands in the composite structure.

As far as the impact test is concerned, the composites showed typical decrease in the impact strength of

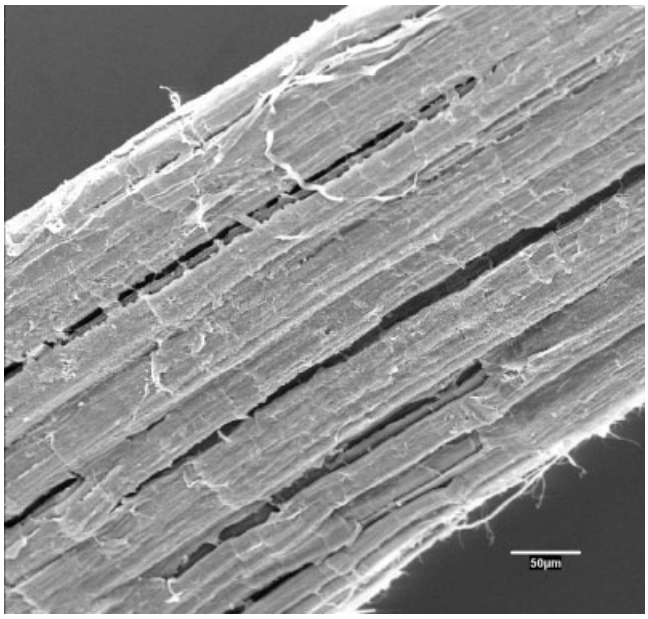

Figure 2 SEM microphotograph of the surface of a hemp strand.

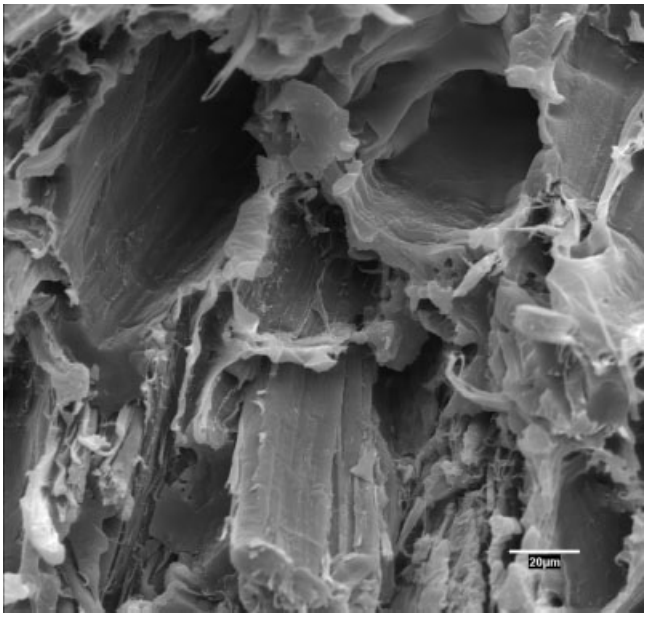

Figure 3 SE microphotograph of the area of fracture after the tensile test of a specimen of composite reinforced with a 30 wt % of hemp strand without coupling agent.

the reinforced materials compared to the polymer matrix because of the wettability of the system. The reinforced composites lose elasticity and they are more sensible to impact stresses.

But to consider an industrially competitive composite, the reinforcement must improve the values of the mechanical properties. From a chemical point of view, this improvement can be reached by the modification of the surface of the fiber. There are some works in the literature where the chemical modification of the surface of the cellulose fibers is considered.[21–23] The aim of this kind of modifications is the reduction of the polarity of the surface of the fibers or the branching of structures to simulate the nature of the polymer matrices improving a better compatibility in the interface. Another methodology is the establishment of a covalent bond between the fiber and the matrix.[24] One of the methodologies used for creating covalent bonds in the composite is the addition of a coupling agent, able to interact with both phases. In this sense, MAH-PP is the most often used coupling agent for the compatibilization of reinforcements and matrices with different polarity.

Composites with addition of coupling agent (MAH-PP)

The aim of the modification of the composition of the composite by adding MAH-PP is the improvement of the adhesion between the fiber surface and the polymer matrix by establishing covalent bonds.

To optimize the amount of MAH-PP added to the composite, the factor of compatibilization f_c of the "mixture rule" (eq. (1)) was studied for different reinforcement/matrix ratios. From a theoretical point of view, this parameter measures the degree of compatibility of fiber-matrix at the interface, where values close to 1 indicate an optimal interaction between the fiber and the polymer.

$$\sigma_t^{\mathrm{CM}} = f_c[\%V_F \cdot \sigma_t^F] + \%V_{\mathrm{PP}} \cdot \sigma_t^{\mathrm{PP}} \quad (1)$$

where $\sigma^{\mathrm{CM}}{}_t$ is the tensile strength of the composite material, f_c is the factor of compatibilization, $\%V_f$ and $\sigma^F{}_t$ are the volume percentage and the intrinsic tensile strength of the fibers, $\%V_{\mathrm{PP}}$ and $\sigma^{\mathrm{PP}}{}_t$ are volume percentage and tensile strength of polymer matrix. Knowing the values of the specific weights of the PP (0.90 kg/m^3) and hemp strands (1.48 kg/m^3) it is possible to calculate $\%V_F$ and $\%V_{\mathrm{PP}}$ for the formulations. In Figure 4, the factor of compatibilization f_c for various composites based on hemp strands is presented, for different amounts of MAH-PP. The formulations of 30 and 40 wt % of hemp strands show a value of f_c close to 1 when the amount of MAH-PP is approximately 4% wt/wt hemp strands.

The values of the mechanical properties of composites modified with MAH-PP (4%wt/wt hemp strand) are also summarized in Table I. This addition produced an increase of 20, 57, and 76% of the ultimate tensile strength (σ_t) for the formulations based on a 20, 30, and 40 wt % of hemp strands, compared with the control formulation (only PP without any reinforcement). If the values are compared with the values of the same formulation without MAH-PP the increases are lower, 13, 32, and 49%, which are significantly

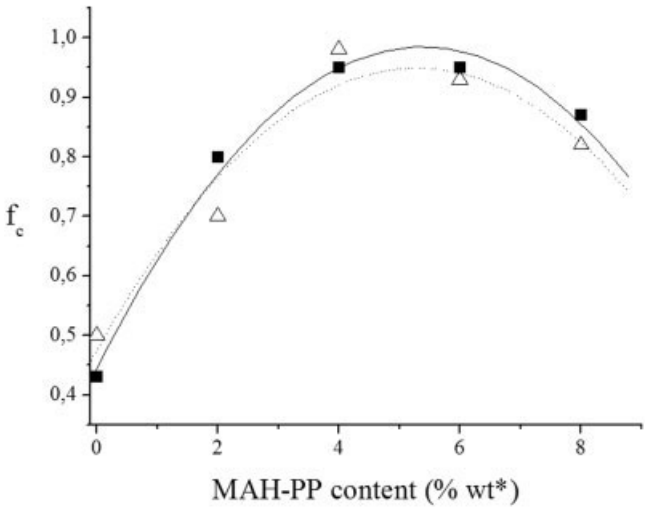

Figure 4 Dependence of the factor of compatibilization with the amount of MAH-PP in the composite. (····△····) 30 wt %, (—■—) 40 wt % of hemp strand. *, respect the hemp strand content.

TABLE III
Tensile, Flexural Mechanical Properties, and Impact Strength of Reinforced Composites with Glass Fiber Glass

Glass fiber content (wt %)	σ_t (MPa)	E_t (GPa)	ε_t (%)	σ_f (MPa)	E_f (GPa)	I (kJ/m^2)
0	27.6 [0.5]	1.1 [0.1]	9.3 [0.2]	40.2 [1.0]	1.1 [0.1]	**
20	50.9 [0.9]	2.9 [0.1]	3.1 [0.1]	78.0 [2.7]	3.2 [0.1]	19.5 [1.7]
30	57.4 [4.3]	3.2 [0.2]	3.0 [0.2]	88.1 [3.1]	4.7 [0.1]	17.7 [0.5]
40	61.0 [2.1]	4.3 [0.2]	2.3 [0.1]	97.2 [3.1]	6.4 [0.2]	18.5 [0.5]

Values in square brackets indicate standard deviation.

higher. On the other hand, if the values under flexural conditions are considered, the results are also favorable. Thus, the flexural strength is still enlarged 52, 78, and 99% for the formulations containing a 20, 30, and 40 wt % of hemp strands. If the values are compared with the values of the composites modified with 4% wt/wt hemp strands of MAH-PP the increase of the flexural strength rises up to 21.9% and 36.8% for the formulations modified with a 30 and 40 wt % of hemp strands, respectively. It means that the interaction between the fiber surface and the polymer matrix is improved compared with the formulations nonmodified with the coupling agent. In our case, the "mixture rule" has been used to evaluate the factor of compatibilization. Assuming the value $f_c = 1$, the theoretical value of $\sigma^F{}_t$ in the case of the formulations formed by 30 and 40 wt % of hemp strands is 103.9 and 100.7 MPa, respectively. These results are comparable with the experimental value of $\sigma^F{}_t$ of this hemp, which was 106 MPa, measured at a length of subjection of half an inch. Studying these results it can be affirmed that the composites made of PP and hemp strands, with 4% wt/wt hemp strands are according to the "mixture rule."

The results of the mechanical properties of the composites based on hemp strands and MAH-PP, summarized in Table I were compared with the values of the composites based on silanized glass fibers, collected in Table III. The value of the UTS of the materials prepared with a 20, 30, and 40 wt % of natural fibers represents 66, 77, and 80%, respectively, of the value of the formulations containing silanized glass fibers. In the case of the flexural strength, this result represents 80% of the value of the glass fiber composite, which indicates that the composites reinforced with the hemp strands show good wettability and some interactions between the matrix and the strands are expected.

The wettability of the composite system was improved, compared with the formulations nonmodified by MAH-PP, as it can be observed in Figure 5, where the fracture section of a tensile test specimen is shown. In this SEM microphotograph, no space between the polymer matrix and the reinforcement is observed. It means that during the tensile test the fiber is broken instead of pulled out, which indicates that there is some interaction between the polymer and the reinforcement. In the bibliography some mechanisms of covalent interaction because of the use of MAH-PP are reported. Mohanty et al.[25] assumed a mechanism of interaction based in the reaction between the hydroxyl groups of the natural fiber and the anhydride groups of the MAH-PP (Fig. 6). This interaction is interpreted as the formation of covalent bonds by the formation of ester groups between both phases and the establishment of hydrogen bond between the hydroxyl groups of the fiber and the remaining carboxylic group of the MAH-PP. To confirm this hypothesis, FT-IR spectra were obtained and are shown in Figure 7, where the spectrum of the strands inside the composite, spectrum of the natural fiber and the difference between them are included. The FT-IR spectra are recorded in the area where the double bond C═O of the ester group is assigned (around 1750 cm^{-1}). The intensity of the signal is very low due to the low modification degree. If the FT-IR spectrum of the fiber is subtracted to the spectrum of the fiber composite modified by MAH-PP, then a new band at 1750 cm^{-1} appears and

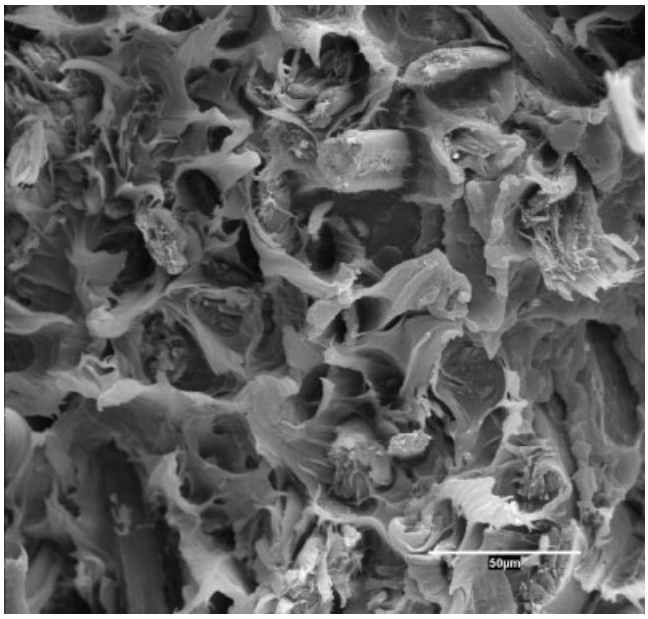

Figure 5 SEM micrograph of the area of fracture after the tensile test of a specimen of composite reinforced with a 30 wt % of hemp strand with coupling agent (4% wt/wt hemp strand of MAH-PP).

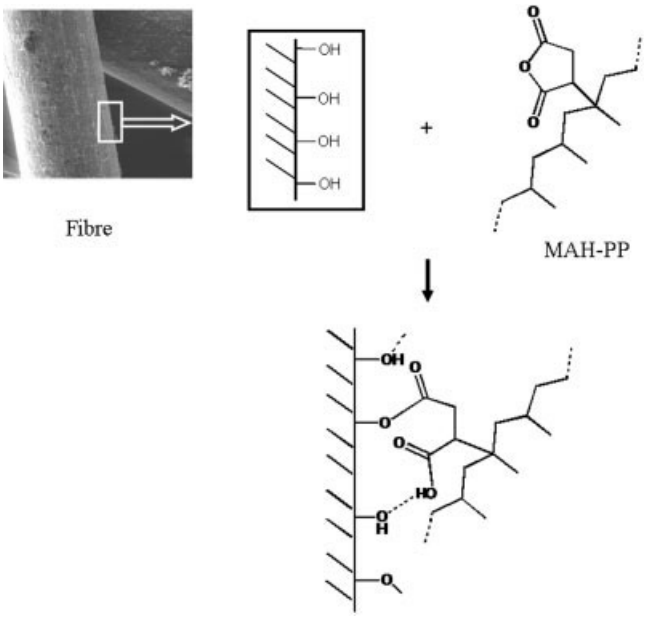

Figure 6 Mechanism of reaction between the hydroxyl groups on the surface of the natural cellulose fiber and the maleic anhydride groups of the coupling agent (MAH-PP).

is assigned, according to the literature,[26] to the new ester bond obtained by esterification reaction of the hydroxyl groups. This band in the FT-IR spectrum confirms the existence of covalent bonds between the hemp strands and the MAH-PP.

So, the increase in the mechanical properties in the materials modified by MAH-PP as coupling agent is related to the formation of new ester bonds between the natural fiber and the polymer matrix. In the case of fibers where the hydroxyl groups have been blocked or eliminated no interaction is expected. To demonstrate this hypothesis, modified hemp strands were obtained by reaction of the natural fibers with a silane derivative to block the hydroxyl groups accessible on the surface.[27] The hydrophobic character of the modified fiber was evaluated studying its behavior in an aqueous/organic mixture of solvents. Thus, a blend of nonsilanized and silanized fibers was introduced in a 50:50 hexane–water mixture. The nonsilanized fibers went down to the bottom of the flask whereas the silanized fibers remained floating in the interface between the organic and the aqueous phase as it can be seen in Figure 8. The silanized fibers are more hydrophobic compared to the nonsilanized fibers and are solvated by the organic phase. It means that the number of hydroxyl groups on the surface of the fiber has been decreased and if a composite is prepared, the number of —OH groups available for reacting with MAH-PP as coupling agent is lower and the mechanical properties should decrease. In the case of the formulation based on 40 wt % of silanized strand, coupled with a 4 wt % of MAH-PP, the value of the

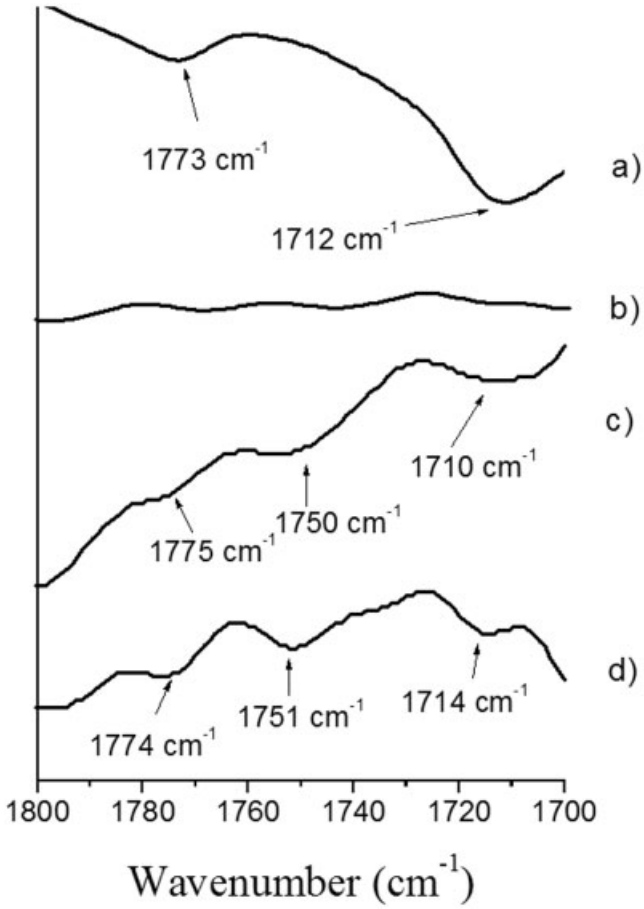

Figure 7 ATR-FT-IR of the surface of (a) MAH-PP, (b) hemp strand, (c) PP-hemp strand composite coupled with MAH-PP y (d) difference spectrum of (b) and (c).

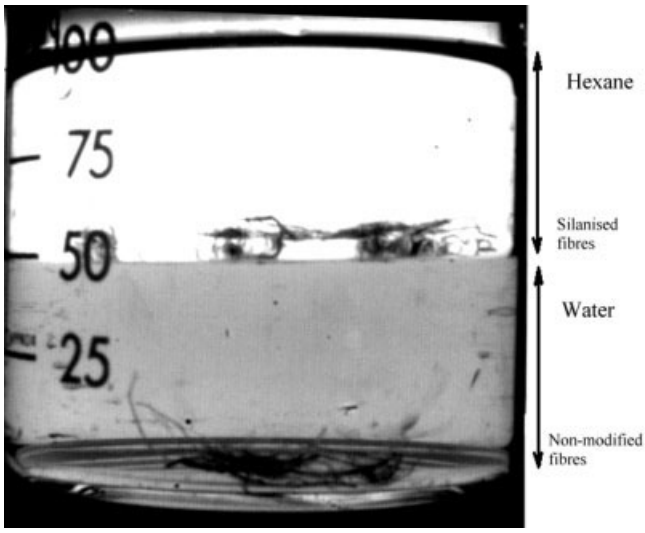

Figure 8 Digital picture of hemp strands modified with silane derivatives and without modification in contact with a mixture of solvents 50:50 hexane:water.

ultimate tensile strength was 26.5 MPa whereas this value for the formulation based on nonsilanized fibers is 48.8 MPa. The same trend was observed in the case of the flexural strength whose value was 44.6 MPa, very low compared with the value of the formulation based on nonsilanized strand that was 80.6 MPa, as was mentioned earlier. This decrease in the mechanical properties is related to the low degree of conversion in the reaction between the hydroxyl groups of the hemp strands and MAH-PP because of the low number of accessible —OH groups on the surface of the fiber. With all of these results it can be affirmed that there is an effective interaction between the hemp strands and the MAH-PP due to the formation of ester bonds in the structure.

CONCLUSIONS

New composites based on PP and hemp strands have been developed. The addition of the natural strands to the composite has induced better properties to the material although there is an interface between both components, observed by SEM, what indicates a low compatibility between them. To improve the interaction between the two components of the composite, MAH-PP was added as coupling agent. This addition has induced a significant increase in the mechanical properties, under tensile and flexural stresses. This improvement of properties has been explained as a covalent interaction between the surface hydroxyl groups of the natural fibers and the maleic anhydride of MAH-PP. This interaction decreases the interfacial effects of the composite.

With these results it can be concluded that the use of hemp strands without any prior chemical treatment in combination with MAH-PP is a good methodology to improve the properties of polymer matrices derived from petroleum.

References

1. Bledzki, A. K.; Gassan, J. Prog Polym Sci 1999, 24, 221.
2. Glasser, G. W.; Taib, R.; Jain, R.; Kander, R. J Appl Polym Sci 1999, 73, 1329.
3. Espert, A.; Camacho, W.; Karlson, S. J Appl Polym Sci 2003, 89, 2353.
4. Wambua, P.; Ivens, J.; Verpoest, I. Compos Sci Technol 2003, 63, 1259.
5. Daniel, F. C.; Daan, F.; Prabawa, S.; Young, R. A.; Anand, R. Sanadi Die Angew Makromol Chem 1999, 272, 57.
6. Keener, T. J.; Stuart, R. K.; Brown, T. K. Compos Appl Sci Manuf 2004, 35, 357.
7. Sreekala, M. S.; Thomas, S. Compos Sci Technol 2003, 63, 861.
8. Gustavsson, M. T.; Persson, P. V.; Iversen, T.; Hult, K.; Martinelle, M. Biomacromolecules 2004, 5, 106.
9. Herrera-Franco, P. J.; Valadez-Gonzalez, A. Compos Appl Sci Manuf 2004, 35, 339.
10. Harper, D.; Wolcott, M. Compos Appl Sci Manuf 2004, 35, 385.
11. Heinen, W.; Rosenmoller, C. H.; Wenzel, C. B.; de Groot, H. J. M.; Lugtenburg, J.; van Duin, M. Macromolecules 1996, 29, 1151.
12. Arbelaiz, A.; Fernandez, B.; Ramos, J. A.; Retegi, A.; Llano-Ponte, R.; Mondragon, I. Compos Sci Technol 2005, 65, 1582.
13. Singh, B.; Gupta, M.; Anchal, V.; Tyagi, O.S. Polym Int 2000, 49, 1444.
14. Kazayawoko, M.; Balatinecz, J. J.; Woodhams, R. T. J Appl Polym Sci 1997, 66, 1163.
15. Anglès, M. N.; Salvadó, J.; Dufresne, A. J Appl Polym Sci 1999, 74, 1962.
16. Terayama, H. J Polym Sci 1952, 8, 243.
17. Vilaseca, F.; López, A.; Llauró, X.; Pèlach, M. A.; Mutjé, P. Chem Eng Res Des 2004, 82, 1425.
18. Félix, J. Enhancing interactions between cellulose fibres and synthetic polymers, PhD Thesis, Chalmers University of Technology, Goteborg 1993.
19. Mutjé, P.; Gironès, J.; López, A.; Llop, M. F.; Vilaseca, F. J Reinforc Plast Compo 2006, 25, 313.
20. Carrasco, F.; Mutjé, P.; Pèlach, M. A. Wood Sci Technol 1996, 30, 227.
21. Pickering, K. L.; Abdalla, A.; Ji, C.; McDonald, A. G.; Franich, R. A. Compos Appl Sci Manuf 2003, 34, 915.
22. Yuan, X.; Jayaraman, K.; Bhattacharyya, D. Compos Appl Sci Manuf 2004, 35, 1363.
23. Marais, S.; Gouanve, F.; Bonnesoeur, A.; Grenet, J.; Poncin-Epaillard, F.; Morvan, C.; Metayer, M. Compos Appl Sci Manuf 2005, 36, 975.
24. Vilaseca, F.; Corrales, F.; Llop, M. F.; Pèlach, M. A.; Mutjé, P. Compos Interface 2005, 12, 725.
25. Mohanty, A. K.; Misra, M.; Hinrichsen, G. Macromol Mater Eng 2000, 1, 276.
26. Matías, M. C.; De La Orden, M. U.; González Sánchez, C.; Martínez Urreaga, J. J Appl Polym Sci 2000, 75, 256.
27. Biagiotti, J.; Puglia, D.; Torre, L.; Kenny, J. M.; Arbelaiz, A.; Cantero, G.; Marieta, C.; Llano, R.; Mondragón, I. Polym Compos 2004, 25, 470.