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Agricultural waste can replace wood in plastic composites

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Waste wheat straw can be treated for use as an environmentally sustainable reinforcement in composite materials, with performance equal or better than wood-polymer composites.

Wood is a natural cellulose-based composite used for thousands of years in applications such as construction, tools, furniture, and paper. Recently, wood-polymer composites (WPCs) have emerged as wood substitutes, mainly for outdoor deck floors.[1–3] The wood used in WPCs usually comes from wood industry waste.[4] The WPC industry is continually seeking innovative lignocellulosic candidates as alternatives to wood because of ongoing concerns about the environmental impact of the exploitation of natural wood. A highly available source of renewable lignocellulosic fibers is agricultural waste (e.g., wheat straw).[5,6] This source is more sustainable and cheaper than waste wood.

However, the different chemical nature of natural fibers (which are hydrophilic) and common synthetic polymers (which are hydrophobic) impairs their compatibility. Moreover, hydrogen bonds among cellulose molecules, the main constituent of lignocellulosic fibers, hinder the fibers' dispersion within the polymer matrix, thus affecting the properties of the final material. To overcome these issues, the cellulose fibers must undergo pretreatments and surface modifications to improve their dispersion and their compatibility with the polymer matrix.[3,7,8]

We have therefore investigated a two-step approach to deal with these problems.[9] First, we use steam explosion to increase the fraction of cellulose in the wheat straw fibers. Steam explosion is an environmentally friendly process that separates the hemicellulose and lignin from the fibers and also defibrillates the fibers, increasing their aspect ratio and surface area. Second, we chemically modify the fibers' surface with a silane compound, either hexadecyltrimethoxysilane (HDS) or [3-(2-aminoethylamino) propyl] trimethoxysilane (AEAPS). We have measured the thermomechanical properties of composites made of polypropylene (PP) reinforced with these modified wheat straw fibers, and compared them to WPC. Our goal is to find a sustainable wood replacement for the WPC industry.

We thus studied four types of wheat straw fiber (see Table 1). We characterized the chemical surface modification of the fibers with attenuated total reflectance infrared spectroscopy (ATR-IR). We then used a twin compounder extruder to produce composites of PP and each of these fibers and also a composite of PP and commercial wood dust for comparison. In the case of PP and untreated wheat straw fiber, however, severe thermal degradation prevented processing of the composite. The composites consisted of 80wt% PP and 20wt% fiber. We used injection molding to make standard samples of these composites to study their thermomechanical properties.[9] Here we discuss the results of the tensile, flexural, impact, and rheological tests.

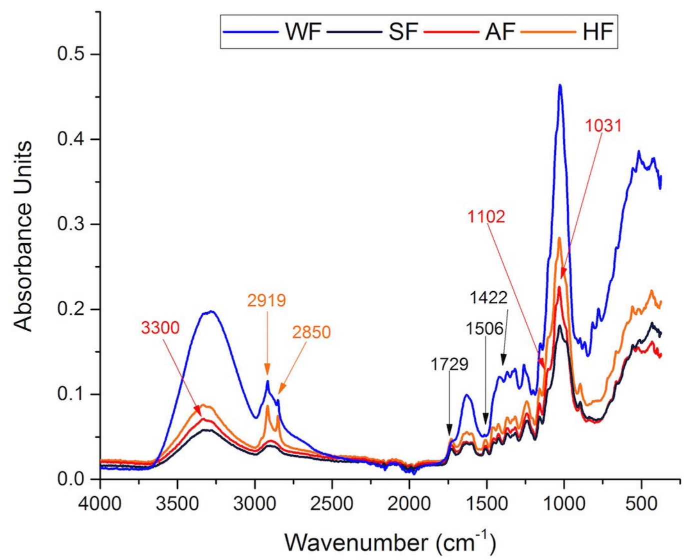

Figure 1. *Spectra obtained by attenuated total reflectance infrared spectroscopy (ATR-IR) of four types of wheat straw fiber (see Table 1 for key). The spectra confirm the chemical characteristics of the modified wheat straw fibers*

The ATR-IR results confirmed that the wheat straw fibers were modified as expected (see Figure 1). Steam explosion decreases the amount of lignin and hemicellulose in the straw configuration and consequently increases the percentage of cellulose fibers. This change is validated by the reduced intensity of the peaks at 1729, 1422, and 1506cm^{-1} in the spectra of steam-exploded fibers (SF) compared to that of untreated wheat fibers. The peaks at 2919 and 2850cm^{-1} indicate aliphatic chain

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Table 1. Types of wheat straw fiber studied. HDS: Hexadecyltrimethoxysilane. AEAPS: [3-(2-aminoethylamino) propyl] trimethoxysilane.

WF	Untreated wheat straw fibers
SF	Steam exploded
HF	HDS chemically modified
AF	AEAPS chemically modified

vibrations that were seen in steam-exploded wheat only after the HDS surface modification (HF fibers), confirming the presence of HDS in the HF fiber surface. Regarding the AEAPS-modified sample (AF), the characteristic peaks of cellulose and lignin overlap with those of the silane. Nevertheless, a minor peak at 3300cm^{-1} indicates the presence of the amine bond as previously confirmed.[10] Moreover, we observed absorptions associated with Si-O at 1240 and 1102cm^{-1} and with Si-O-Si at 1031cm^{-1}.

We summarize the mechanical properties of the composites in Figure 2. The stiffness (Young's modulus) of PP was improved both by wood powder (44% improvement compared to neat PP) and by wheat straw fibers (48% for the SF sample). We observed the best results for PP reinforced with AF (57%). The flexural modulus also improved for all the composites (20–50% improvement compared to neat PP).

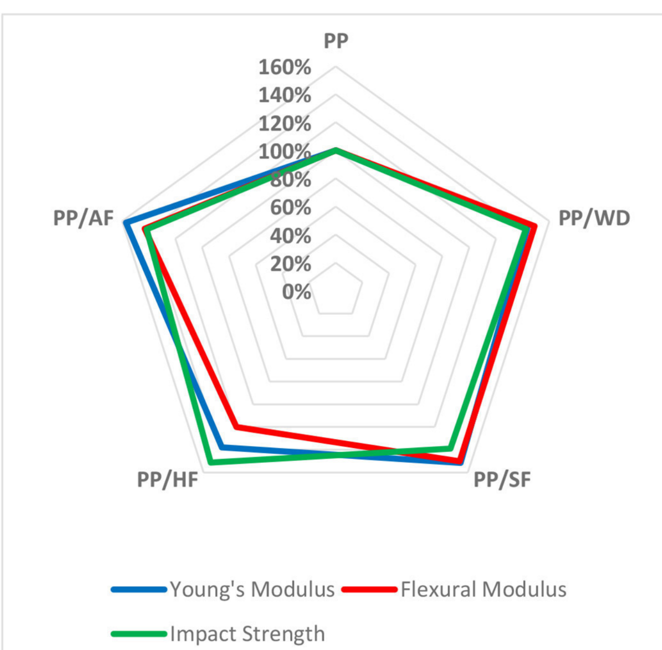

Figure 2. Mechanical characteristics of polypropylene (PP) were significantly improved when it was combined with either wood dust (WD) or wheat straw fibers. PP/X: Compound of 80wt.% PP and 20wt.% X.

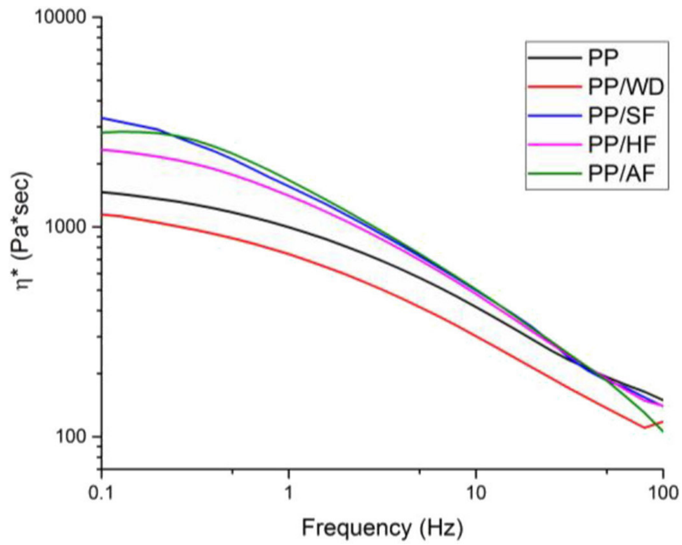

Figure 3. Complex viscosity (η^*) of the materials at 220°C measured by parallel-plate rheometry. Adding wheat straw fibers to PP increased the complex viscosity at lower shear rates (lower frequencies). By contrast, adding wood dust decreased the viscosity.

The best impact strength was exhibited by the HF composite (51%). Energy-absorbing mechanisms such as debonding and pull-out at the fiber/matrix interface may have contributed to this toughening effect.

We conducted rheological tests using a parallel-plate rheometer at 220°C (see Figure 3). Wood powder reduced the complex viscosity of the corresponding composite because the powder particles have a low aspect ratio. Conversely, the addition of wheat straw fibers of all three types increased the viscosity of the resulting composites because of the fiber–fiber and fiber–matrix interactions. This increase is more pronounced at lower shear rates (lower frequency in the graph). At higher shear rates, the influence of the fibers is reduced and the contribution of the matrix to the viscosity therefore increases (an effect called frequency thinning).

In summary, we have studied the reinforcement effects of steam-exploded, chemically modified wheat straw fibers obtained from agricultural waste. The short grow cycle of wheat makes the straw more environmentally friendly and sustainable than wood powder. The modified straw fibers are a cost-effective material with a reduced carbon dioxide footprint. We found that incorporation of 20wt% chemically modified straw in polypropylene led to an outstanding improvement of the material's thermomechanical properties. In particular, the increases in both the impact strength and Young's modulus were comparable or better than the effect of 20wt% wood powder. The next step in this line

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of research will be to vary the straw fiber concentration, in both PP and other polymer matrices, to evaluate the effect of these parameters on the thermomechanical properties, with the ultimate goal of expanding these composites' use in a variety of fields.

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