

# Thermal and Mechanical Properties of Wood Flour–Polystyrene Blends from Postconsumer Plastic Waste

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**ABSTRACT:** Polystyrene (PS) from packing materials and plastic cups was reinforced with 30 and 50% wood flour through a blending process with and without a commercial compatibilizing agent. The processability of the pure recycled polystyrene (rPS) and wood–rPS composites was studied in terms of the torque of the mixing process; this was then compared with that of a commercial virgin multipurpose PS. The physical and mechanical properties were compared with those of the virgin PS reinforced with 30 and 50% wood flour. The results show that the mechanical properties of the pure and reinforced rPS did not decrease with respect to the virgin PS, and in terms of the impact strength, the rPS was superior to the virgin plastic. The mechanical properties were not affected by the commercial compatibilizing agent, but the torque of the blends was significantly lower with the compatibilizer. Differential scanning calo-

rimetry (DSC) and dynamic mechanical analysis were used to study the glass-transition temperature ( $T_g$ ) of both the pure virgin PS and pure rPS and the wood flour–PS composites. The  $T_g$  values of the rPS and wood–rPS composites were higher than those of the virgin PS and wood–virgin PS composites. The use of rPS increased the stiffness and flexural modulus of the composites. Thermogravimetric analysis revealed that the thermal stability of rPS and its composites was slightly greater than that of the virgin PS and its composites. These results suggest that postconsumer PS can be used to obtain composite materials with good mechanical and thermal properties. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 119: 443–451, 2011

**Key words:** composites; mechanical properties; polystyrene; recycling; thermal properties

## INTRODUCTION

Worldwide, polystyrene (PS) is the third most used thermoplastic after polyethylene (PE) and polypropylene (PP). The applications or uses of PS differ greatly from those of PE and PP because the former's glass-transition temperature ( $T_g$ ) is approximately 90–100°C; below this temperature (environmental conditions), PS is rigid, brittle, and easily cracked or shattered.

The copolymerization of PS with elastomeric materials give it a greater impact resistance compared to the pure polymer; this allows its extensive use in packaging, containers, electronics, computers, and many other disposable products.<sup>1–3</sup> The resulting polymer is a high-impact polystyrene (HIPS) and may be regarded as a two-phase blend of materials with different viscoelastic properties.<sup>4,5</sup>

The use of PS has increased significantly; this has led to growing concern over its effects on the environment and the dwindling space in landfills.

One way to minimize this adverse amount of waste is by reusing and recycling PS products. Two problems emerge during the recycling of plastics: how to characterize postconsumer plastics and how to increase the mechanical properties of recycled polystyrene (rPS).<sup>6–8</sup>

Several methods for increasing the use of rPS have been investigated. Some of this research has focused on the replacement of virgin PS in the manufacture of final products.

Reports have shown that the incorporation of large amounts of rPS into blends does not decrease the mechanical and rheological properties of virgin HIPS.<sup>9</sup>

The use of rPS in blends with other virgin thermoplastics that have a low PS contents (5%), such as polyurethane, has been reported. The addition of rPS was found to change the mechanical behavior and the final morphology of the compositions.<sup>10</sup>

The mechanical properties of rPS have also been improved by the addition of other thermoplastic polymers, such as PP,<sup>11,12</sup> poly(methyl methacrylate),<sup>13</sup> PE, and polyamide (PA).<sup>14,15</sup> These blends

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increased the impact strength of the rPS without decreasing its tensile strength too much.

The effects of compatibilizers such as poly(styrene-*b*-ethylene-*co*-butylene-*b*-styrene) (SEBS) in a 6 : 3 PP/HIPS composition have also been studied. This recycled blend (with 5 wt % SEBS) was reported to present the highest reduction in the dispersed-phase particle size, with average diameters of 0.04–0.12  $\mu\text{m}$ ; this led to a higher average interfacial area of the HIPS particles.<sup>16</sup>

Other researchers have focused on the production of plastic materials based on rPS and the use of several types of compatibilizers for binary or ternary blends with high-density polyethylene (HDPE), PP, and poly(vinyl chloride) (PVC). The impact strength of 8 : 1 : 1 HDPE/PS/PVC ternary blends was noticeably increased with the addition of styrene-ethylene-propylene block copolymer as a compatibilizer.<sup>17</sup>

The reinforcement of rPS with cellulosic materials has also been studied, with reports of the thermal and mechanical properties of a simulated waste plastic fraction composed of HDPE, PP, PS, and PVC with SEBS grafted with maleic anhydride as a compatibilizing agent.<sup>18</sup> The addition of 12.5% cellulose to the commingled blends was found to be very effective for enhancing the mechanical properties of both the virgin material and the recycled blends.

Cellulose acetate from sugar cane bagasse has also been used as a reinforcing agent in postconsumer PS. Different analysis techniques were used to confirm the existence of miscibility microregions, although there were not enough to generate blend compatibility.<sup>19</sup>

A study of a mixture of recycled HDPE/PS (65/35) reinforced with wood flour revealed that the addition of wood filler to recycled plastics increased their stiffness.<sup>20</sup>

Natural zeolite has also been used to study the effect of recycled PP, HDPE, low-density PE, and 5% PS on the flow behavior, mechanical properties, and morphology of immiscible multicomponent systems. Zeolite was reported to have a compatibilizing effect at low concentrations (1–2 wt %).<sup>21</sup>

Incompatible polymer blends, such as wood-PS, are very complex because of the different morphologies of their components. Moreover, the subsequent interaction between the component phases is a critical feature of immiscible blends that can transform their thermal properties (e.g., melting point,  $T_g$ ).<sup>22,23</sup>

Researchers have used dynamic mechanical analysis (DMA) to reveal a shift of the loss factor ( $\tan \delta$ ) to higher temperatures when untreated wood fiber at 50% (w/w) content is added to a 65/35 PE-PS blend.<sup>20</sup>

The dynamic mechanical behavior of atactic PS and HIPS has been also studied. For HIPS, Young's storage modulus ( $E'$ ) was lower than that of PS, and the  $T_g$  of HIPS shifted to lower temperatures with respect to the PS.<sup>1</sup>

Relatively little information exists about the mechanical and thermal behavior of pure or reinforced postconsumer PS as compared to the mechanical properties of virgin PS.

A recent article<sup>24</sup> reported that a decline in the thermal diffusivity of HIPS was more pronounced than that of recycled HIPS when the temperature was greater than the  $T_g$ .

Findings from other articles<sup>25,26</sup> have shown that recycled expanded polystyrene (EPS) tended to have poorer material properties than raw PS; this hampered the demand for the former material.

The main goal of this study was to investigate the mechanical and thermal behavior and the processing conditions of postconsumer PS from plastic cups, food trays, and packing when reinforced with two different wood flour compositions. The mechanical and thermal properties of the recycled materials were compared with those of commercial virgin PS and wood flour-virgin PS composites.

## EXPERIMENTAL

### Materials

This study used a 1 : 1 blend of the waste of EPS from packing materials and that of plastic cups collected from supermarkets and restaurants. The plastic waste was washed with hot water and dried for 8 h at 80°C. Afterwards, the EPS and cups were pressed at 120°C and 4 bar of pressure, in laboratory press (HP, Bs. Aires, Argentina), to eliminate the high air content in EPS. Then, the material was pre-ground in a knife mill (Ming Lee Industrial Limited, Strong Crusher, Hong Kong, China) to an average size of 1–2 cm and oven-dried at 80°C for 24 h.

Virgin PS (PS STYRON 678 D) with a melt flow index value of 10 g/10 min and a density of 1.05 g/cm<sup>3</sup> was supplied by Dow Chemical Co (Midland, Michigan)

*Pinus radiata* wood flour was obtained from an industrial sawmill, dried overnight at 105°C, and screened at 60 mesh.

A commercial resin (Struktol TR065) was supplied by the Struktol Co. (Stow, Ohio) and was used as a compatibilizing agent (2 wt %).

Struktol TR065 is a mixture of light colored aliphatic resins with a molecular weight below 2000, a specific gravity of 0.97 g/cm<sup>3</sup>, and a softening point of 95–105°C; it is commonly used as a compatibilizing agent for PS and PVC.

### Melt-blending process

Wood flour-virgin PS and wood flour-rPS composites were prepared at ratios of 30/70 and 50/50 wt %.

Table I lists the compositions of the wood-PS composites.

**TABLE I**  
**Composition of the Wood-PS Composites**

Sample	Virgin PS (%)	rPS (%)	Wood flour (%)	Compatibilizer (%)
1	100	—	—	—
2	100	—	—	2
3	70	—	30	—
4	70	—	30	2
5	50	—	50	—
6	50	—	50	2
7	—	100	—	—
8	—	100	—	2
9	—	70	30	—
10	—	70	30	2
11	—	50	50	—
12	—	50	50	2

To evaluate the influence of wood on the mechanical properties of the composites, virgin PS and rPS were also prepared without flour.

The mixes were prepared in a Thermo Haake Polydrive Rheomix 600 (Thermo Electron Co., Hamburg, Germany) supplied with a roller blade mixer and set at a heating temperature of 190°C with the rotational speed of the mixer's rollers at 60 rpm for 15 min.

The components of each sample were added sequentially to the mixer. PS and the compatibilizer were added first, followed by wood flour. Filler loadings of 30 and 50 wt % were prepared for each kind of PS. The mixing continued for 10 min after all of the components were added.

The extrudates were then molded in a laboratory press at 190°C and 120 bar of pressure to produce dog-bone shaped tensile, flexural, and impact bar specimens for the property evaluations of the wood-PS composites.

The effect of the commercial compatibilizer on the flow behavior of the composites was studied during the experimental mixing process.

### Physical and mechanical testing

The physical properties of the composites shown in Table I were tested for water absorption and thickness swelling according to ASTM D 1037-96a. Ten 50 × 50 mm<sup>2</sup> specimens were evaluated in the soaked condition after they were immersed in water at 20 ± 3°C for 24 h.

The specific gravity of the composites was also tested with a density profiler (Amersham model AMCK 6693, Buckinghamshire, England) supplied with Am-241. The density profile and the mean density were obtained.

The tensile and flexural tests of the two kinds of PS (virgin and recycled) and the wood flour-PS composites were carried out with an Instron model 4468 testing machine (Barcelona, España) with a 5000-kg capacity. The test speeds for the tensile and flexural properties were 5 mm/min according to ASTM D 638-

03 and 1.28 mm/min according to ASTM D 790-03, respectively. All of these tests were performed at room temperature (23°C) and 60% relative humidity. At least 10 samples of each formulation were tested. The averages and standard deviations were determined for 10 test pieces of each blend.

The Izod impact test was performed at room temperature according to ASTM D 256-03 for 10 pieces with notched test samples in a DYNISCO-API pendulum impact test machine (Dynisco Instruments, Madison).

A parametric analysis of variance was performed on the data collected from the physical and mechanical tests to distinguish statistical differences ( $p \leq 0.05$ ) among the sample properties. All of the statistical analyses were performed with Statgraphics Plus software (Statistical Graphics Manugistics Group Inc, Rockville, MA).

### Thermal analysis

The  $T_g$  values of the virgin PS and rPS extruded from the Rheomix were determined with a differential scanning calorimeter (DSC 822<sup>e</sup>, Mettler Toledo, Greifensee, Switzerland) equipped with a thermal analysis data STAR<sup>e</sup> software system.

Samples of about 5–10 mg were run at a heating rate of 10°C/min under a nitrogen atmosphere between 30 and 150°C to remove any previous thermal history.

For  $T_g$  determinations, a heating rate of 20°C/min was used because the  $T_g$  was more pronounced at faster heating rates.

A dynamic mechanical analyzer (DMA-7e, Perkin Elmer, Waltham, Massachusetts) was used to determine the  $T_g$  values of the wood-PS composites.

The sample dimensions were 4 × 2 × 20 mm<sup>3</sup>. The samples were tested by bending at three points with a 15-mm support span. The test was dynamic with a temperature range of 30–150°C at a heating rate of 5°C/min. A load frequency of 1 Hz was used.

The thermal stability of the pure PS (virgin and recycled) and PS-wood flour composites was investigated by nonisothermal thermogravimetric analysis (TGA) with a TA Instruments TGA Q 50 (New Castle, Delaware).

Measurements were conducted at a heating rate of 10°C/min in a nitrogen atmosphere with a temperature range of 25–600°C. The average sample mass was about 4 mg.

## RESULTS AND DISCUSSION

### Physical properties

Absorption and swelling were only measured for the wood-PS composites because the virgin PS and rPS did not absorb water.

**TABLE II**  
Physical Properties of the Virgin PS and rPS Composites with Wood Flour

Wood (%)	Virgin PS (%)	rPS (%)	Compatibilizer (%)	24-h absorption (%)	24-h swelling (%)	Specific gravity (kg/m <sup>3</sup> )
30	70	—	2	1.05	0.67	1052
30	70	—	—	0.61	0.55	1140
50	50	—	2	2.45	2.91	1140
50	50	—	—	1.79	1.34	1136
30	—	70	2	0.83	0.98	1076
30	—	70	—	0.87	0.86	1090
50	—	50	2	2.12	3.20	1164
50	—	50	—	1.65	3.09	1170

Table II shows the results of the thickness swelling, water absorption, and mean density for the wood–PS composites with and without the compatibilizing agent.

As shown in Table II, it was reasonable to expect increased water absorption and swelling of the composites with higher wood contents. The values were greatest for the 50/50 wood–PS compositions. The compatibilizer did not influence these composite properties, and the differences between the virgin PS and rPS composites were not significant.

### Mechanical and processing results

We studied the influence that the commercial compatibilizer had on the torque of the pure virgin PS, rPS, and wood–PS composites.

Figure 1 shows the results of the torque obtained from the mixing process for the pure virgin PS and their composites with 30 and 50% wood with and without the compatibilizer TR065.

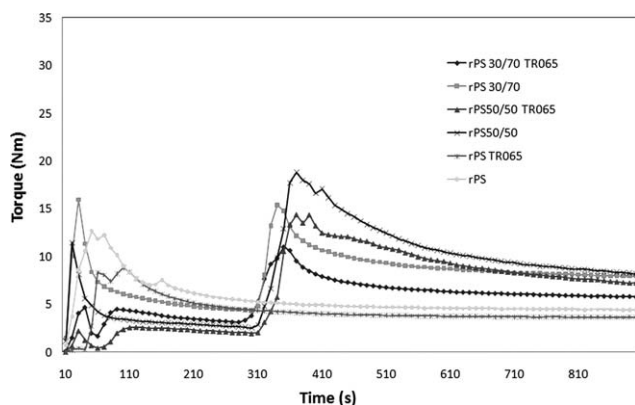
As shown in Figure 1, the torque values increased sharply when the wood flour was incorporated into the mixer 5 min after the addition of the polymer and compatibilizer. Moreover, the torque of the virgin PS stabilized at approximately 5 Nm. When the compatibilizing agent was added, the torque

declined strongly during the first 10 min of mixing and then rose to some 4 Nm at the end of the process. The addition of 30% wood to the virgin PS increased the torque, which stabilized at 7 Nm at the end of the mixing. The 50% wood composite stabilized at 9 Nm. The torque of the wood–virgin PS composites dropped only slightly in the presence of the compatibilizing agent.

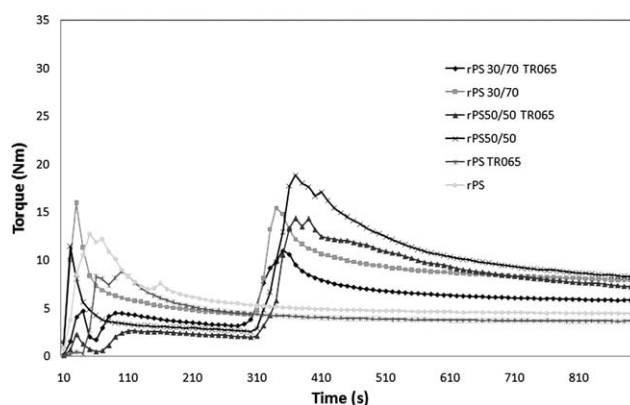
Figure 2 shows the results of the torque obtained for the mixtures of rPS with the compatibilizer and with composites having 30 and 50% wood flour. The diminished torque of the pure rPS was not highly significant when the compatibilizing agent was added, as shown in Figure 2. On the other hand, the addition of 50% wood to the rPS raised the initial torque to values over 15 Nm; these stabilized after 10 min of mixing at 8 Nm. The presence of the compatibilizing agent caused the most significant decline in the torque of the 30/70 wood–PS composite.

In general, Figures 1 and 2 present fairly similar behavior in terms of the torque of the virgin PS, rPS, and their derived composites.

The presence of lignocellulosic materials clearly increased the torque of the pure polymers. Similar torque values (ca. 10 Nm) were reported for recycled plastics reinforced with 20% cellulose.<sup>18</sup> In general, the shear and viscosity of a nonpolar polymer such

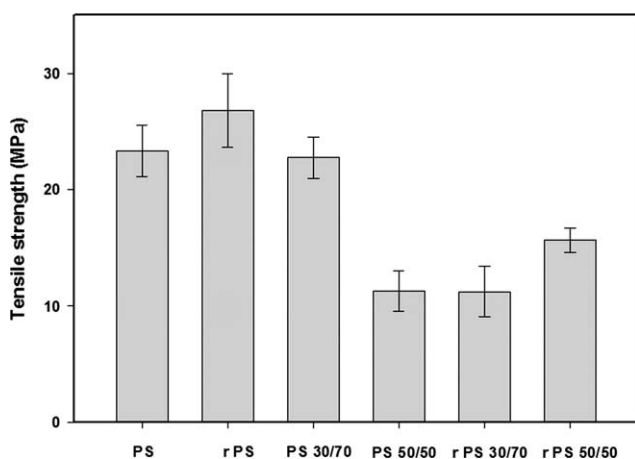


**Figure 1** Torque curves of the virgin PS and wood–PS composites without and with the compatibilizer TR065.



**Figure 2** Torque curves of the rPS and wood–rPS composites without and with the compatibilizer TR065.





**Figure 3** Tensile strength of the virgin PS, rPS, and 30/70 wood-PS composites, 50/50 wood-PS composites, 30/70 wood-rPS composites, and 50/50 wood-rPS composites.

as PS increase when it is reinforced with a polar lignocellulosic filler such as wood flour. The higher viscosity of the blends increase the torque during the mixing process.

On the other hand, there was no appreciable change in the torque between PS, rPS, and their derived composites, which might have implied a low-molecular-weight degradation of PS in the recycling process.

Figure 3 shows the effect of wood flour on the tensile strength of the virgin PS and rPS.

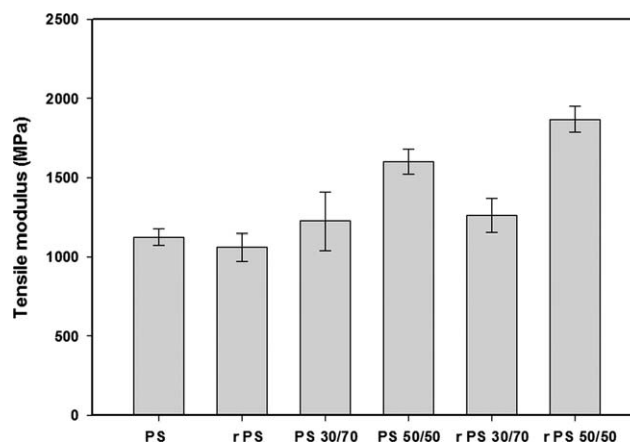
Of the composites shown in Figure 3, rPS had the highest tensile strength value. When 30% wood was added to the virgin PS, its tensile strength was not significantly altered, but the tensile strength of the rPS did drop significantly under this condition. The incorporation of 50% wood produced the greatest decline in the tensile strength of the virgin PS.

The statistical analyses showed that the compatibilizing agent Struktol TR065 did not affect the tensile properties of the pure virgin PS, rPS, or wood-PS composites, and so it was not included in the figure.

Figure 4 shows the tensile modulus values of the virgin PS, pure rPS, and wood-PS composites. The 50/50 wood-rPS blends presented better moduli than the virgin materials; the same was true for the tensile modulus values of the other blends. Figure 4 show that the 30/70 blends (wood-PS) of both the virgin PS and rPS had slightly higher tensile moduli than the pure virgin PS and rPS. The presence of the compatibilizing agent did not have any statistical influence on the tensile modulus of the composites and was not included in the figure.

Figure 5 shows the flexural strength of the pure virgin PS, rPS, and wood-PS composites.

rPS had higher flexural strength values than the virgin PS. The incorporation of 30% wood slightly augmented the flexural strength of the virgin PS, but



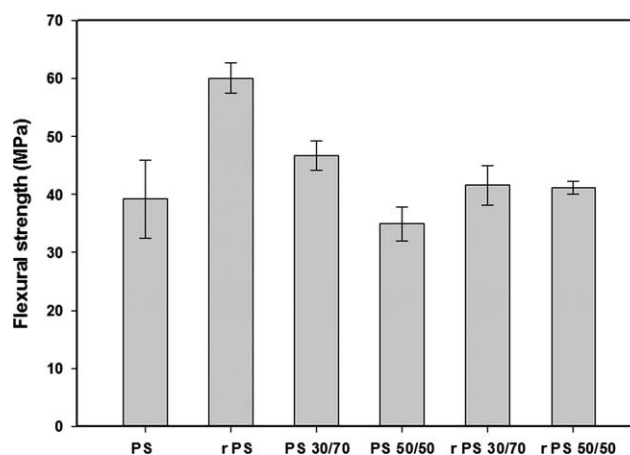
**Figure 4** Tensile modulus of the virgin PS, rPS, and 30/70 wood-PS composites, 50/50 wood-PS composites, 30/70 wood-rPS composites, and 50/50 wood-rPS composites.

at 50%, this decreased to values just below those of the virgin PS.

Likewise, the incorporation of 30 or 50% wood caused the flexural strength of the rPS to drop.

Some publications have reported a slight increase in the flexural strength of mixtures with recycled PP, PE, and PS when 12.5% cellulose was incorporated. In these mixtures, the virgin polymers always showed greater flexural strength than their recycled counterparts;<sup>18</sup> the recycled polymers may have been mixed with pollutants that deteriorated their mechanical properties.

This study showed that postconsumer PS can contain additives from the recycling process that have a favorable influence, improve the interaction and interfacial adhesion with the wood flour, and increase the mechanical properties of rPS versus the virgin PS.



**Figure 5** Flexural strength of the virgin PS, rPS, and 30/70 wood-PS composites, 50/50 wood-PS composites, 30/70 wood-rPS, and 50/50 wood-rPS composites.

Xu et al.<sup>9</sup> reported similar behavior when rPS was blended with virgin HIPS. Moreover, in our study, we was found that the tensile and flexural strengths of rPS were similar for the 30/70 and 50/50 composites. However, for virgin PS, the tensile and flexural strengths clearly decreased when the filler content was increased from 30/70 to 50/50, as shown in Figures 3 and 5.

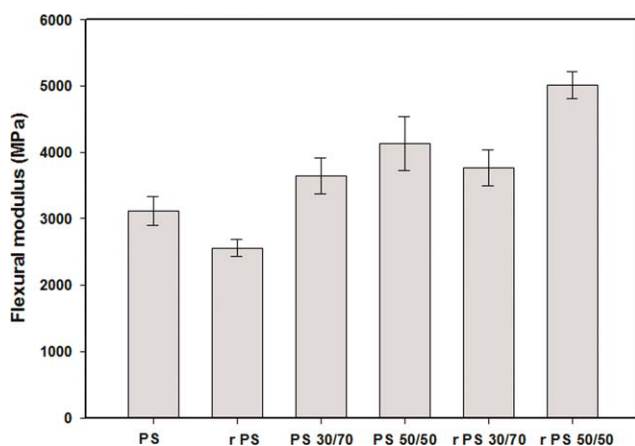
The flexural modulus values of the virgin PS, rPS, and wood-PS composites are shown in Figure 6.

As shown in Figure 6, the incorporation of wood strongly increased the flexural modulus values of the composites. The greatest increment was produced in the 50/50 wood-rPS mixtures. The 30/70 and 50/50 virgin PS mixtures also had increased modulus values with respect to the pure polymer. The presence of the wood in the polymeric matrix of PS augmented the polymer's rigidity, increasing the value of the modulus in relation to the pure polymer. This phenomenon has also been reported by other researchers who studied the effect of wood flour on mixtures of rPS and PE<sup>20</sup> and virgin PS.<sup>7</sup>

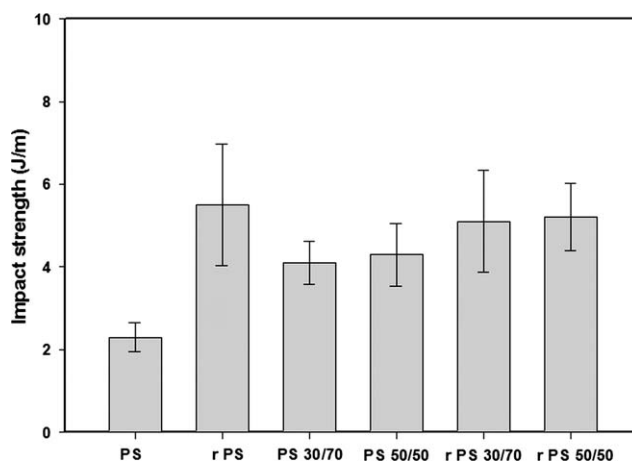
Figure 7 shows the notched Izod impact strength of the pure PS (virgin and recycled) and wood-PS composites. As shown in Figure 7, the impact strength values of the pure rPS and 30/70 wood-rPS composite increased significantly with the recycling process. The 50/50 blends with rPS also had higher impact strength values than the virgin PS.

Again, the results show a similar trend for the mechanical properties (tensile, flexural, and impact) of the composites. Compared to the pure PS samples, all combinations of wood flour loaded in rPS resulted in higher average tensile and flexural moduli and greater impact strengths.

The incorporation of additives into the pure rPS obtained from expanded packing and plastic cups increased the viscoelastic behavior of the material,



**Figure 6** Flexural modulus of the virgin PS, rPS, and 30/70 wood-PS composites, 50/50 wood-PS composites, 30/70 wood-rPS, and 50/50 wood-rPS composites.



**Figure 7** Impact strength of the virgin PS, rPS, and 30/70 wood-PS composites, 50/50 wood-PS composites, 30/70 wood-rPS composites, and 50/50 wood-rPS composites.

decreasing its flexural modulus (Fig. 6) and increasing its impact strength. When wood flour was added to rPS, the stiffness of the composites increased, and the 50/50 blends had higher flexural modulus values.

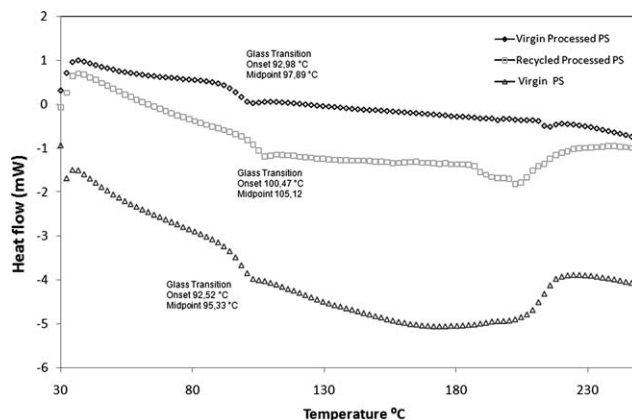
The same phenomenon occurred when rPS was used to replace virgin PS in different compositions. The impact strength increased along with the weight percentage of rPS in the blends.<sup>9</sup>

In another study, recycled blends of PP/PS from plastic waste presented better impact strengths than the virgin material.<sup>16</sup>

### DSC, DMA, and TGA results

Figure 8 shows the DSC thermograms of the virgin PS and rPS extrudates from the Rheomix 600 (processed polymers).

This figure shows that the  $T_g$  of the virgin PS did not change when it was processed but remained at 92°C. According to the literature,<sup>27</sup> changes are



**Figure 8** DSC curves for the glass transition of the rPS and virgin PS.

**TABLE III**  
 $T_g$  Values of the Virgin PS, rPS, and Wood-PS Composites Obtained from  $E''$ ,  $E'$ , and  $\tan \delta$

Sample	Compatibilizer (% w/w)	$E''$ ( $^{\circ}\text{C}$ )	$E'$ ( $^{\circ}\text{C}$ )	$\tan \delta$ ( $^{\circ}\text{C}$ )
PS	—	95	88	100–120
PS	2	91	82	100–118
rPS	—	98	93	105–125
rPS	2	94	89	95–120
PS (30/70)	—	98	92	100–125
PS (30/70)	2	91	85	96–120
PS (50/50)	—	98	94	100–130
PS (50/50)	2	92	88	100–120
rPS (30/70)	—	100	99	105–130
rPS (30/70)	2	91	85	98–120
rPS (50/50)	—	102	98	105–133
rPS (50/50)	2	94	90	98–128

produced in the rheological properties of some thermoplastic polymers with the number of processing cycles; in particular, there is a decrease in the melt flow index. The rPS had a  $T_g$  of  $104^{\circ}\text{C}$ , which was also found in the assays done with DMA on the pure polymers and their composites.

A comparison between the two kinds of PS showed a higher  $T_g$  for rPS (ca.  $8^{\circ}\text{C}$  above that of the virgin PS). The behavior of  $T_g$  in wood-PS composites was complicated to study with DSC because wood is a complex composite material and it is difficult to determine  $T_g$  with this technique.<sup>28–30</sup>

$T_g$  of wood-PS composites was better analyzed by DMA.

The dynamic mechanical properties [the loss modulus ( $E''$ ),  $E'$ , and dumping  $\tan \delta$ ] are shown in Table III.

$T_g$  of the samples was determined by the peak of the  $E''$  curve and the decline of the  $E'$  curve. For all samples,  $\tan \delta$  showed two maxima in a range of higher temperatures.

As shown in Table III,  $T_g$  was  $6$ – $8^{\circ}\text{C}$  higher for all samples of rPS with respect to the virgin PS and wood-virgin PS composites.

The higher  $T_g$  values of rPS and their derived composites with respect to virgin PS were probably due to the additives used in the manufacture of the foams and cups. These additives had some degree of physical adhesion with PS, which suggests that the chain mobility was restricted, which increased  $T_g$ .

The  $T_g$  values of the pure virgin PS, rPS, and wood-PS composites decreased by about  $5$ – $6^{\circ}\text{C}$  when 2% compatibilizer was added to the sample. The compatibilizer produced a plasticization effect in the PS and wood-PS composites.

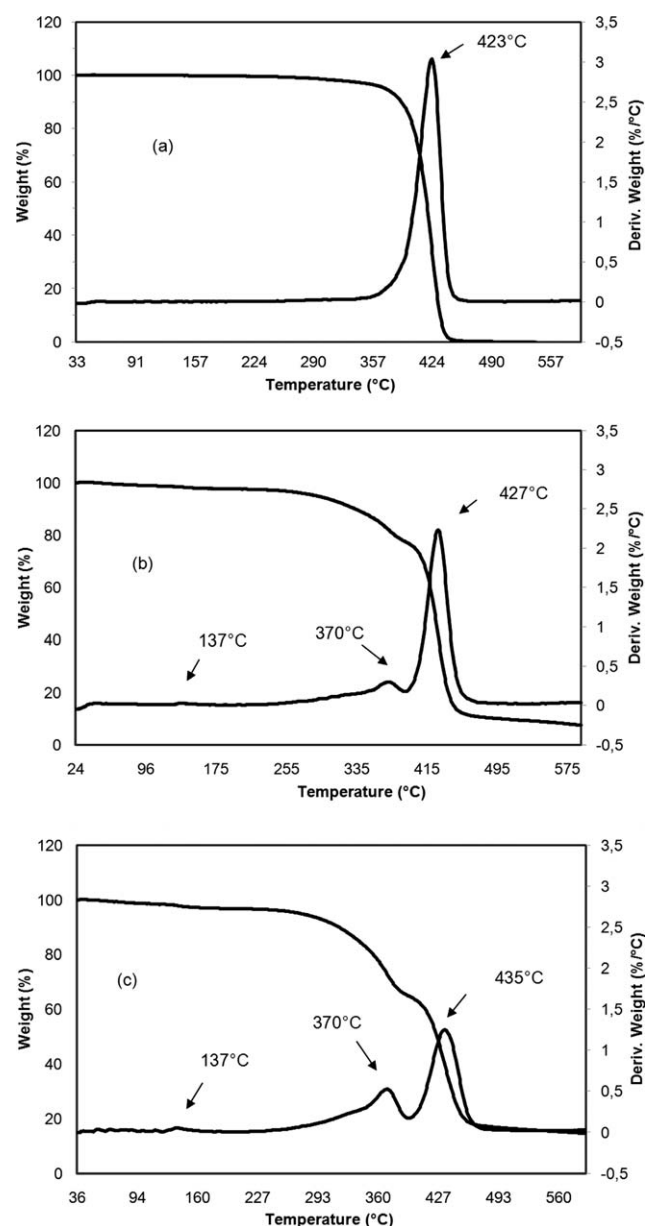
An analysis of the DMA data with increased wood contents in the composites from 30 to 50% (w/w) showed that the  $T_g$  values were not significantly affected.

Table III also shows slightly greater  $T_g$  values for the wood-PS composites compared to the virgin PS

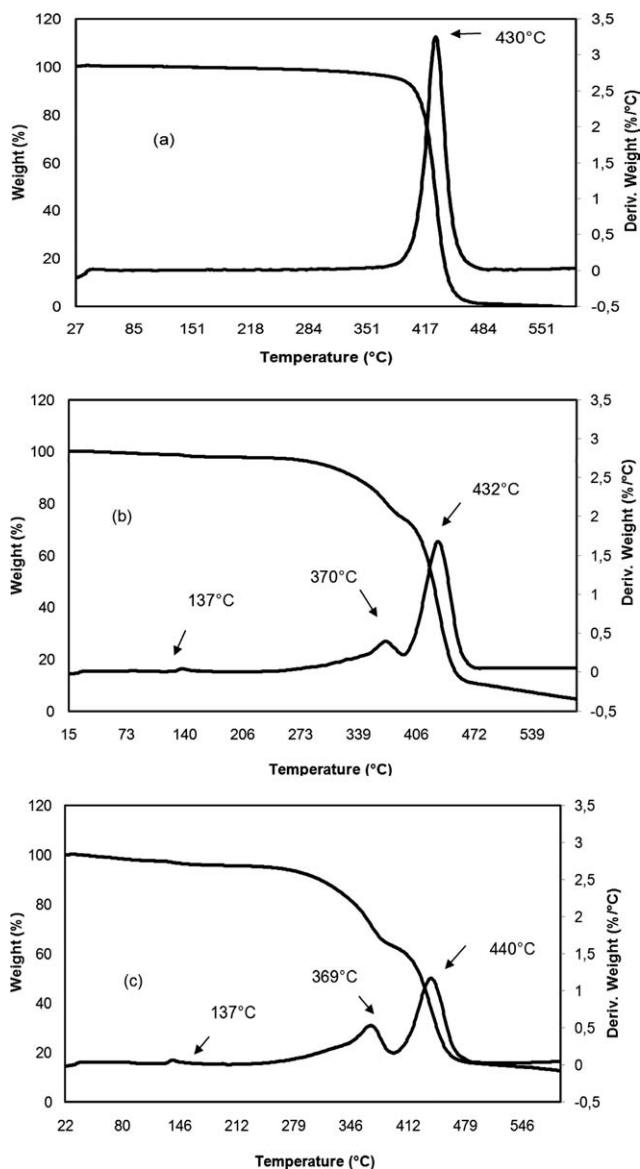
and rPS. Wood-plastic composites are often stiffer than plastics alone, and this could be seen in the increase in the flexural modulus values of the wood-PS composites.

As shown in Figures 9 and 10, the decomposition of the pure PS and rPS occurred in one step between  $370$  and  $440^{\circ}\text{C}$  (for the virgin PS) and  $390$  and  $475^{\circ}\text{C}$  (for the rPS) with maximum weight loss rates [derivative thermogravimetric (DTG)] of  $423^{\circ}\text{C}$  (for the virgin PS) and  $430^{\circ}\text{C}$  (for the rPS).

Figure 9 shows that the decomposition profiles of the wood-PS composites were characterized by three peaks. The first one was very weak for 30/70 composites and occurred at  $130$ – $140^{\circ}\text{C}$ ; it was attributed to the evaporation of water.



**Figure 9** TGA and DTG curves of the (a) PS, (b) 30/70 wood-PS composite, and (c) 50/50 wood-PS composite.



**Figure 10** TGA and DTG curves of the (a) rPS, (b) 30/70 wood-rPS composite, and (c) 50/50 wood-rPS composite.

For the 50/50 wood-PS composites, this peak was more pronounced, and DTG showed a maximum at 137°C.

The second step, which corresponded to the degradation of the wood components (e.g., hemicellulose, cellulose, lignin), started at about 240°C with DTG at 370°C for the 30/70 and 50/50 composites.

In the third step, PS degradation occurred between 390 and 450°C with DTG at 427 and 435°C for the 30/70 and 50/50 blends, respectively.

The rPS and wood-rPS composites showed similar behavior (Fig. 10), although DTG of the wood and rPS degradation shifted to higher temperatures (432°C for the 30/70 composite and 440°C for the 50/50 composite); this revealed a slight increase in the thermal stability of PS in the composites.

This phenomenon has also been reported for other polymers reinforced with lignocellulosic fibers.<sup>31,32</sup>

## CONCLUSIONS

The results of this study show that the mechanical properties of the rPS were not lower than those of multipurpose virgin PS. Furthermore, some properties, such as impact strength, were significantly superior in the rPS compared to the virgin PS.

The addition of high contents (50%) of wood flour also increased the flexural modulus of recycled and virgin PS.

The results of the tensile modulus showed a decreasing trend with higher wood contents.

The best results for the Izod impact strength were for the 30/70 wood-rPS.

In general, the improved mechanical properties could be explained by the better dispersal of wood in the rPS, which may have been due to the additive contents used in cups, trays, and packing materials, which produced better adherence of the wood within the polymeric matrix.

On the other hand, the mechanical properties of the PS and wood-PS composites were not affected by the presence of a commercial compatibilizing agent. It may be necessary to incorporate a higher percentage of compatibilizer or to research the use of another coupling agent to produce a change in the mechanical properties of the wood-PS composites.

The  $T_g$  values of the rPS and wood-rPS composites studied by DMA shifted to higher temperatures compared to those of the virgin PS and wood-virgin PS composites. The 50/50 wood-rPS blend had the highest  $T_g$  value (Table III) and the highest flexural modulus (Fig. 6).

The TGA study revealed that the thermal stability of the rPS and its composites was slightly greater than that of the virgin PS and its composites.

These results suggest a preferential association between the rPS and wood.

In general, the use of rPS increased the stiffness of the composites.

Finally, this study showed that it is feasible to obtain composite materials with good thermal and mechanical properties with recycled polymers in an attempt to reduce the disposal of postconsumer PS into the environment.

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