

Influence of Moisture Absorption on Mechanical Properties of Wood Flour–Polypropylene Composites

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ABSTRACT: Wood-plastic composites are being examined for a greater number of structural-type applications that may be exposed to different environments, some of them adverse. This paper discusses the influence of moisture absorption on the mechanical properties of wood flour–polypropylene composites. Composites filled with 20% or 40% wood flour (by weight) were placed in different environments, removed periodically, and tested for moisture content and mechanical properties. The composites filled with 20% wood flour (20% WF) absorbed moisture in all the environmental exposures, but no significant degradation of properties was observed. The 40% WF composites absorbed more moisture than did the 20% WF composites. The flexural properties of composites subjected to a water bath and to 90% relative humidity were lower than the flexural properties of the other composites. Tensile properties and notched impact strengths decreased only for composites placed in a water bath. Unnotched impact strengths did not change significantly with absorption of moisture.

KEY WORDS: wood, filler, reinforcement, polypropylene, composites, moisture, mechanical properties, modulus, strength.

INTRODUCTION

ALTHOUGH THE USE of wood-derived fillers for thermoplastics has become more accepted in recent years, the plastics industry is currently dominated by inorganic fillers. It is estimated that 2.3 billion ($\times 10^9$) kilograms (5.5 billion pounds) of fillers and reinforcements were used in plastics in the year 2000. Fiber-glass, calcium carbonate and other mineral fillers account for 93% of this market, while natural fibers account for 7% [1] Currently, building products account for

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70% of the total end market use of natural fibers in composites. Past research compares the mechanical properties of PP filled with inorganic fillers to PP filled with two wood-derived fillers: wood flour produced from post-industrial scrap such as planer shavings and sawdust, and wood fiber produced from post-consumer recycled sources such as old pallets and demolished buildings [2].

There are many advantages to using wood-derived fillers rather than mineral fillers in thermoplastics. Wood-derived fillers can range from a particle to a single fiber or fiber bundle, and they can serve as a filler or reinforcement for plastic. In particular, wood-filled systems have a lower specific gravity than do mineral-filled systems. Wood-derived fillers also have greater deformability when compared to mineral fillers, which results in less filler damage during processing and less abrasiveness to equipment [3]. From an economical point of view, wood-derived fillers come from a renewable resource and are typically less expensive than mineral fillers. The aesthetics of these products also is important; the addition of wood fiber to the higher growth forecast for natural fiber-polymer composites. The growth outlook for the natural fiber market in plastics is predicted to be 50% from 2000–2005[1].

The use of wood fillers for thermoplastics presents two main processing concerns for the plastics industry: temperature sensitivity and moisture uptake.

Past processing experience has shown that temperature sensitivity can be addressed by ensuring that processing temperatures of wood-filled thermoplastics are kept below 204°C (400°F) to prevent thermal degradation of fillers (4). This temperature adjustment due to temperature sensitivity has a positive aspect because wood-filled systems cool faster than do mineral systems. As a result, manufacturers who use these materials may observe lower cycle times, which can lead to higher production rates.

Moisture absorption poses another processing problem. The wood fiber itself may absorb moisture before compounding with polymer to form the composite. Moisture uptake also can be a processing problem if precompounded pellets are used as feedstock in a forming operation. In the field, the composites themselves can absorb moisture, which may adversely affect mechanical properties. It is sometimes claimed that moisture is not a problem for wood-plastic composites because the wood is totally encapsulated in polymer. In the case of total encapsulation, polymers would protect the wood from moisture because they are hydrophobic. At high percentages of wood flour, however, a composite still absorbs moisture [5]. In the work presented here, we investigated the influence of several environments, specifically of different humidities, on the mechanical properties of composites made from PP filled with 20% and 40% wood flour.

EXPERIMENTAL

The study material was wood-flour-filled PP at both 20% and 40% by weight

filler loadings. The 0.425-mm (40-mesh) wood flour was supplied by American Wood Fibers (Schofield, WI). This material is derived from clean post-industrial sources such as residue from window and door manufacturers. It is refined and screened to a specific particle size distribution. It was compounded with a homopolymer PP supplied by Huntsman Polypropylene Corporation (Woodbury, NJ).

Natural Fiber Composites, Inc. (NFC; Baraboo, WI) supplied the compounded wood flour and PP at 20% and 40% by weight filler loadings and the unfilled PP to be used as a control. The resulting pellets were oven dried for 24 hours at 105°C (221°F) at the Forest Products Laboratory (FPL) before being injection molded into tensile, flexural, and impact specimens in a 33-ton injection molder. The injection-molded specimens were again oven dried at the same temperature for 24 hours. Mechanical property tests were conducted before the specimens were placed in the test environments.

After preliminary property tests and measurements of the oven-dried specimens, approximately 100 flexural, 100 tensile, and 200 impact specimens of each filler loading were placed in three different humidity rooms. The exposure environments were 30%, 65%, and 90% relative humidity (RH) rooms maintained at 26.7°C (80°F). The same numbers of specimens were placed in a water bath at room temperature. Samples were removed periodically and tested for tensile, flexural, and impact properties. Molded specimens of unfilled PP also were placed in these environments after initial testing. The control specimens were tested less frequently than the test specimens. The tests were carried out on standard injection-molded samples according to corresponding ASTM methods for tensile properties (ASTM D638), flexural properties (ASTM D790), and impact properties (ASTM D256) [5]. Each test was performed on five replicate specimens.

RESULTS AND DISCUSSION

Moisture Uptake

Figures 1 and 2 present the average moisture uptake for each environmental exposure. Both of these plots report moisture uptake as a function of exposure time. Moisture uptake of injection-molded flexural specimens was determined by weighing the oven-dried samples before and during exposure. An increase in weight was assumed to represent moisture uptake. After exposure to the water bath, samples with 20% wood flour (20% WF) absorbed just over 1.4% moisture when equilibrium was reached, whereas 40% WF samples absorbed approximately 9.0% moisture. Equilibrium in the water bath was reached at approximately 1500 hours for 20% WF samples and 1200 hours for 40% WF samples. We expected that the material with the higher wood flour content would absorb more moisture, and this indeed was the case for each exposure level. What was some-

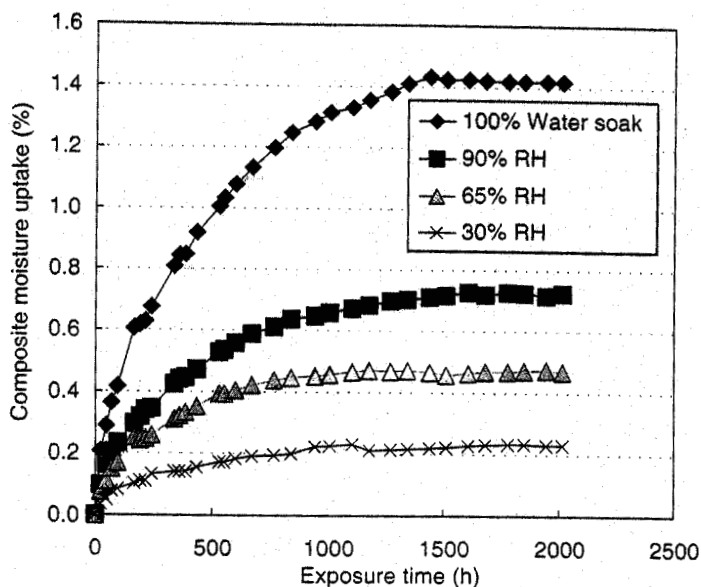


Figure 1. Moisture uptake of 20% WF composites as a function of exposure time.

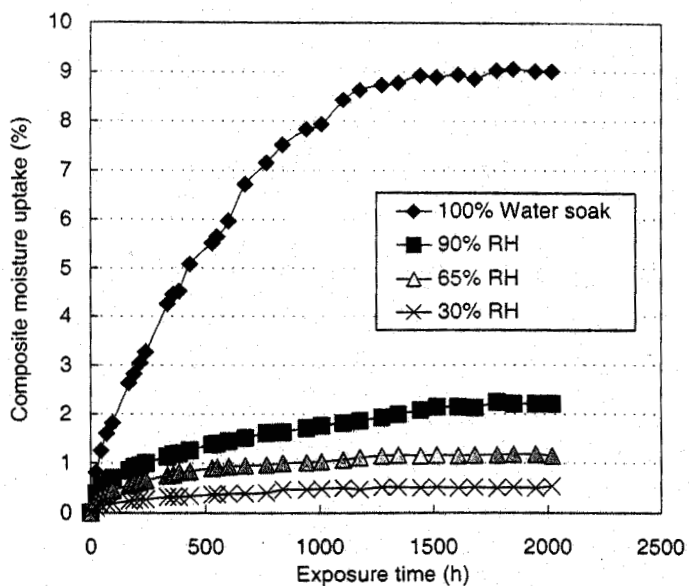


Figure 2. Moisture uptake of 40% WF composites as a function of exposure time.

what surprising was how much more quickly and how much more total moisture was absorbed by the 40% WF samples when exposed to the water soak as opposed to different humidity levels. This would seem to indicate that, particularly for the high wood flour content, wood was exposed on the surface of the samples. It is commonly believed that during injection molding and extrusion, a full skin of hydrophobic PP forms at the surface of the composite to provide a barrier against moisture absorption. Moisture can still be absorbed through surfaces where the wood is exposed as a result of breakage or cutting.

The control PP did not absorb any moisture as a result of exposure to the different test environments, indicating that moisture is absorbed by the wood component in the composite. Consequently, wood flour samples were placed in thin layers in wire trays and dried at 105°C (221°F) overnight. The samples were then placed in different RH (30%, 65%, 90%) rooms. As Figure 3 shows, the samples readily absorbed moisture. Wood flour in these environments reached equilibrium after 48 to 50 hours of exposure.

Because the PP did not absorb moisture, it can be assumed that all the moisture absorbed by the composite is absorbed by hydrophilic wood flour and not hydrophobic PP. Knowing the moisture absorption of the composite (Figures 1 and 2), the percentage of moisture in the wood flour component of the composite can be calculated (Figure 3). Figure 3 shows that for all exposures, higher wood flour content resulted in higher moisture content for the wood flour. Moreover, the amount

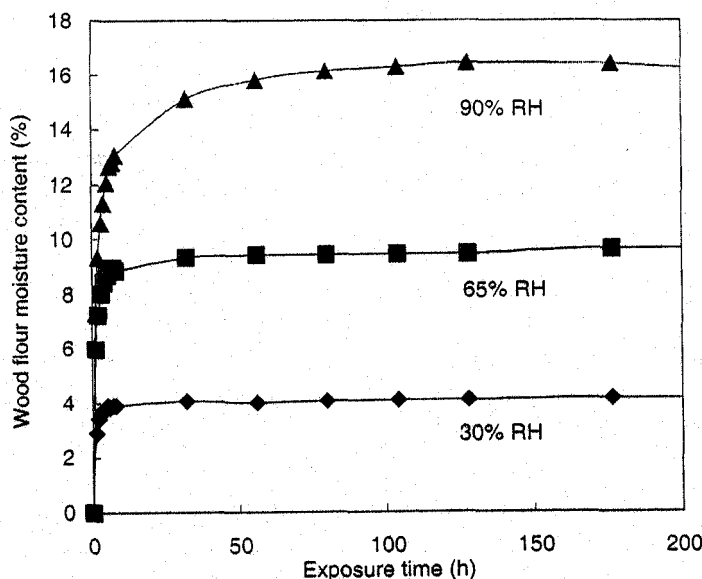


Figure 3. Moisture content of wood flour as a component of WF-PP composites.

of moisture absorbed by wood flour itself (Figure 4) was more than that absorbed by the wood flour in composites (Figure 3). For example, wood flour absorbs approximately 16% moisture when exposed to 90% RH. However, when wood flour is in a composite material, it absorbs only 3.6% moisture in a 20% WF composite or 5.5% moisture in a 40% WF composite for the same exposure. If the wood flour were completely encapsulated by the PP matrix, we would expect no absorption. If the wood flour were completely free to absorb moisture, we would expect 16% moisture gain for the wood flour in each composite. This indicates that in all the materials, the wood flour is inhibited from absorbing moisture due to encapsulation of the wood flour by the PP matrix. Furthermore, the degree of encapsulation is greater for the 20% WF composite.

Table 1 shows the trends in properties of WF-PP composites and unfilled PP. This table also shows the change in mechanical properties of each composite after exposure to the most extreme environment, the water soak.

Flexural Tests

Figures 5 and 6 show flexural modulus and strength, respectively, as a function of exposure time for 40% WF composites. To analyze the data, each data point was compared to the unexposed data for that composition. An alpha level of 0.01 was chosen to compare the data and determine the statistical significance of differ-

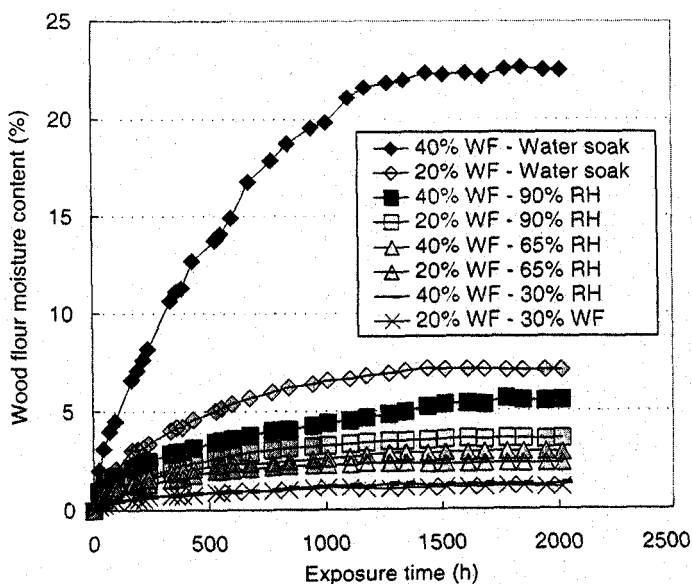


Figure 4. Moisture content of wood flour exposed to several humidity levels.

Table 1. Trends in properties of wood flour–polypropylenecomposites before and after exposure to a water bath at equilibrium.^a

Composite	Water Absorption (%)	Flexural Properties		Tensile Properties		Impact Energy	
		Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (MPa)	Notched (J/m)	Unnotched (J/m)
Control ^b	0	1.27	39.5	1.60	31.0	23	555
20% WF							
Before exposure	0	2.13	44.8	2.52	27.3	22	110
After exposure	+1.4	NA	NA	NA	NA	NA	NA
40% WF							
Before exposure	0	3.68	46.6	3.90	25.7	26	62
After exposure	+9.0	-39%	-22%	-29%	-14%	-7	NA

^aWF = wood flour filler. NA = no statistical difference in properties at alpha level of 0.01.

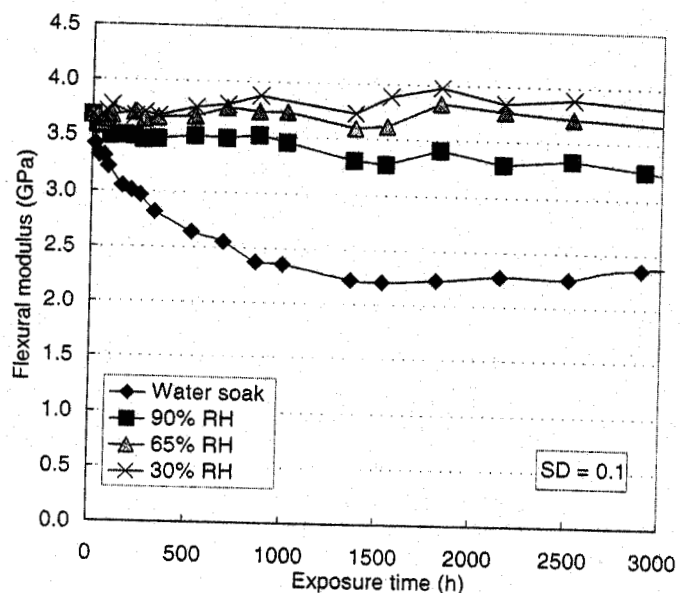


Figure 5. Flexural modulus of 40% WF composites as a function of exposure time.

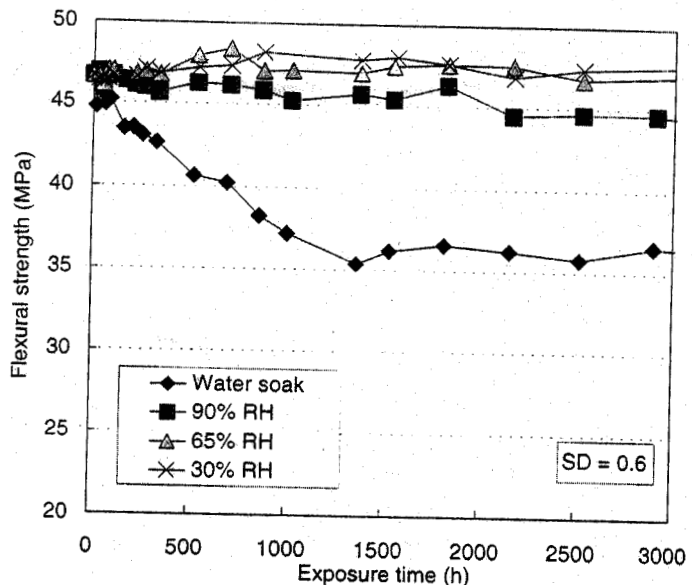


Figure 6. Flexural strength of 40% WF composites as a function of exposure time.

ences. For both flexural modulus and strength, no statistically significant decrease in properties occurred at any exposure level at the 20% filler level. At the 40% filler level, only the water soak and exposure to 90% RH resulted in significant decreases in properties. The last five data points for Figures 5 and 6 were each averaged to determine the loss in flexural properties. Flexural modulus decreased 39% and 11% for the water soak and 90% RH exposure, respectively. Exposure of the 40% WF composites to a water bath and 90% RH resulted in a decrease of flexural strength by 22% and 4%, respectively. The flexural properties of these composites reached a plateau at around 1200 hours of exposure, which corresponds to the point where equilibrium was reached in moisture uptake.

The modulus of a composite is determined in part by the modulus of each component. Generally, an increase in wood moisture results in a decrease in modulus [7]. With the modulus of one component of the composite decreasing, the modulus of the whole composite decreases. The strength of a composite is dictated in part by the quality of the bond at the interface, which allows stress transfer from the matrix to the filler. Improving the bonding at the interface results in an improvement in strength [8]. The absorption of water by the wood component of the composite may cause the wood to swell. This could lead to a degradation of the interfacial quality, resulting in a decrease in composite strength [5].

Tensile Tests

Results of tensile modulus and strength of 40% WF composites are shown in Figures 7 and 8, respectively. To determine the statistical significances among the data, the same procedure and alpha level were used as for the flexural tests. As for the flexural tests, the 20% WF composite showed no statistically significant decrease in either tensile modulus or strength. For the 40% WF composite, a decrease in tensile modulus and strength was observed for only the water soak test. In this case, tensile modulus decreased by 29% and tensile strength by 14%.

As with the flexural modulus, the loss in tensile modulus could be a result of the loss in modulus experienced by the wood component upon moisture absorption. The loss in tensile strength may be due to degradation of the PP/wood flour interface.

Impact Tests

The 20% WF composite exhibited no statistically significant change in notched or unnotched impact strength after exposure to the different environments. There was a significant change in notched impact energy at an alpha level of 0.01 for the 40% WF Composite placed in the water bath. The result was a 7% decrease in notched impact energy for this most extreme case.

Notched impact energy can be thought of as a measure of crack propagation,

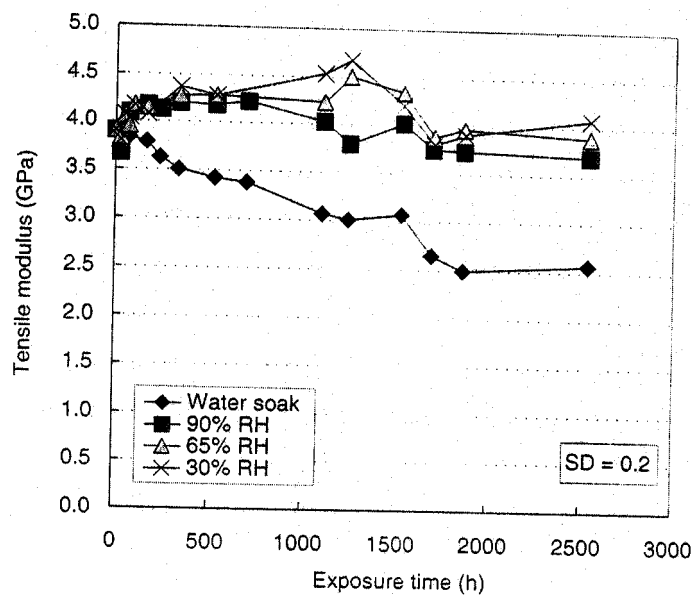


Figure 7. Tensile modulus of 40% WF composites as a function of exposure time.

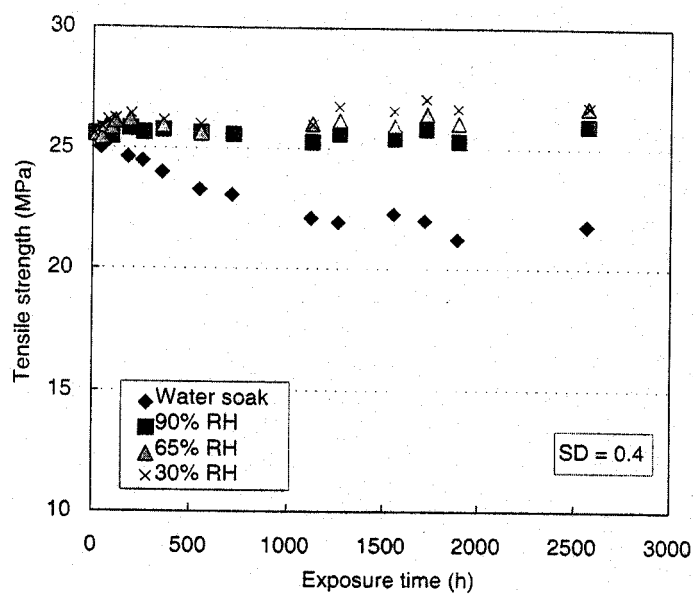


Figure 8. Tensile strength of 40% WF composites as a function of exposure time.

while unnotched impact energy measures the crack initiation. The crack propagation will occur along the path of least resistance, requiring as little energy as possible. In the case of composites, the crack may propagate at the matrix and fiber interface. Degrading this interface may result in lower notched impact strengths. Previous studies have reported increases in unnotched impact energy upon improvements in the bond between the PP and WF [4,8]. It was expected that upon exposure to moisture, the unnotched impact energy would decrease. However, in this study the unnotched impact energy remained unchanged after exposure. There are a number of things that may contribute to this: among them the plasticization or swelling of wood fiber, and surface changes occurring at the interface. There is too little information to determine if this can be explained by one of these phenomena.

CONCLUSION

The results of our study indicate that incomplete encapsulation of wood flour by the polypropylene (PP) matrix occurs in both 20% and 40% wood flour composites; less encapsulation occurs with the higher wood flour content. Thus, more moisture is absorbed by the wood flour at higher filler levels, which in turn may decrease mechanical properties. A composite with 20% wood flour absorbs a maximum of 1.4% moisture. This amount of absorption is not enough to significantly affect mechanical properties; flexural, tensile, and impact properties are not changed. For a composite with 40% wood flour, up to 9.0% moisture is absorbed. The PP affords less protection to the wood flour filler, and moisture is absorbed more rapidly and to a greater extent. This results in a decrease of tensile and flexural properties in the most extreme case, the water soak. A decrease in flexural properties also is observed for 40% wood flour composites exposed to 90% RH and 26.7°C (80°F). The decrease in strength may be due to a degradation of the interface between the PP and WF, while the decrease in modulus could be a result of the decrease in modulus of the wood upon moisture absorption. Unnotched impact energy remained unchanged upon exposure to moisture, while notched impact energy decreased only at the 40% filler level for specimens exposed to the water soak.

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