# Effect of Species and Particle Size on Properties of Wood-Flour-Filled Polypropylene Composites

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Ms. Nicole Stark
Chemical Engineer
USDA Forest Products Lab
One Gifford Pinchot Drive
Madison WI 53705 USA
Tel: 608-231-9392 Fax: 608-231-9582

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# Effect of Species and Particle Size on Properties of Wood-Flour-Filled Polypropylene Composites

Nicole M. Stark, Chemical Engineer
USDA Forest Service
Forest Products Laboratory
Madison, Wisconsin

Mark J. Berger, Technical Sales Representative
American Wood Fibers
Schofield, Wisconsin

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## Abstract

Research on wood-flour-filled polypropylene has primarily focused on one species of wood flour and one or two broad particle-size distributions. To fully exploit the use of wood flour as a filler, the effects of species and particle size need to be examined. This study focused on the effects of both of these variables on the properties of polypropylene filled with wood flour. To examine the effects of species, wood flour derived from four species, ponderosa pine, loblolly pine, maple, and oak, was used as a filler for polypropylene at 20,30,40,50, and 60% by weight wood flour. With increasing wood flour content, flexural and tensile modulus, density, heat deflection temperature, and notched impact energy increased, while flexural and tensile strength, tensile elongation, mold shrinkage, melt flow index, and unnotched impact energy decreased. In general, the hardwoods exhibited slightly better tensile and flexural properties and heat deflection temperatures than did the softwoods. Four commercially available wood flours and four screened wood flours with discrete, narrow particle-size distributions were used to study the effects of particle size on wood-flour-filled polypropylene. In this case, the composite material was 40% by weight wood flour. Particle size did not affect specific gravity, but it did affect other properties. Melt flow index, heat deflection temperature, and notched impact energy increased with increasing particle size, whereas unnotched impact energy decreased. For particles smaller than about 0.25 mm, mold shrinkage decreased. Flexural and tensile modulus and strength increased with increasing particle size.

## Introduction

The use of scrap-wood-derived fillers for thermoplastics has been accepted by the plastics industry in recent years. Wood-derived fillers have several advantages compared with their inorganic counterparts, such as lower density and lower volumetric cost. They also are less abrasive to processing equipment and are derived from a renewable resource. To facilitate the use of wood-derived fillers, the USDA Forest Service, Forest Products Laboratory (FPL) supplied injection molders with precompounded pellets (1). In an FPL research study, polypropylene (PP) filled with several inorganic fillers commonly used by the plastics industry was compared with PP filled with wood flour or wood fiber derived from demolition wood (2). The results suggested that wood-derived fillers do have a place in the

filler market. The performance characteristics of plastics with wood fillers were similar to those of talc-filled plastics.

One of the most common wood-derived fillers is wood flour. Wood flour is commercially produced from postindustrial sources such as planer shavings and sawdust. The scrap wood is sourced for species purity and then ground to specific particle-size distributions, which are typically fairly large.

There are several variables to consider when using wood flour as a filler. Among them are moisture content, purity, particle size, and species. While the first three variables can be controlled by raw material selection and the manufacturing process, species availability is often regionally influenced. This creates a geographic variable for the plastics processor to consider.

Most research using wood flour as a filler for thermoplastics has been conducted with a limited number of wood species, and only a few grades of broad particle-size distributions. To fully exploit the use of wood flour fillers, the full effect of wood species and particle-size distributions must be determined. The wood species examined in this paper are ponderosa pine *(Pinus ponderosa* Dougl. ex Laws.), loblolly pine *(Pinus taeda* L.), oak *(Quercus* spp.), and maple *(Acer* spp.). This represents both softwoods (the pines) and hardwoods (the oaks and maples) from different regions of the United States.

Commercially produced wood flour has a broad particle distribution. As a result, a comparison of mesh sizes from a commercial supplier of wood flour results in an overlap of particle sizes. Extra screening of the wood flour to narrow the particle-size distribution generally results in a more expensive wood flour; therefore, typical commercial grades include a mixture of particle sizes. Because of the size overlap, particularly at larger mesh sizes (smaller particle sizes), it is difficult to chacterize properties based on specific particle sizes using commercial grades of wood flour. This study examines four different mesh sizes of wood flour that are commercially produced as well as four discrete sizes of wood flour, each with a narrow particle-size distribution.

## Experimental

### Materials

The wood flours for the species examinations were standard 40 mesh (0.42-mm openings) grades manufactured by American Wood Fibers (AWF), Schofield, WI. The species examined were ponderosa pine, loblolly pine, maple, and oak.

Commercial grades 2020,4020,8020, and 12020, which AWF corresponds to 20- (0.841 mm), 40-, 80- (0.177 mm), and 120- (0. 125 mm) mesh ponderosa pine, were used to examine particle-size effects of wood flour as a filler in PP. Wood flours screened to discrete, narrow particle-size distributions by AWF were also examined. Figure 1 compares the particle-size ranges of the screened to the commercial wood flours. Figure 1 demonstrates the overlap of the size ranges for the commercial wood flours and the discreteness of size ranges for the screened wood flours. For the wood flour codes, C designates commercial particle-size distribution, with the number following corresponding to the mesh size of the wood flour set by AWF. The screened particle-size distribution is designated with an S followed by the average mesh size in the wood flour sample.

An injection molding grade of homopolymer PP, Fortilene 3907, was supplied by Solvay Polymers, Inc. (Deer Park, TX). This material has a melt index (MI) of 36.5 g/10 min. The four species of 40-mesh wood flour were filled at 20,30,40,50, or 60% by weight wood flour. The eight sizes of ponderosa pine wood flour were filled at 40% by weight wood flour.

### Sample Preparation

The wood flour and PP were dry blended at 60% by weight wood flour for the species portion of this study and 40% by weight wood flour for the size portion. The pre-blend was compounded using a 32-mm Davis Standard (Pawcatuck, CT) co-rotating, intermeshing twin-screw extruder with a 32:1 length-to-diameter ratio. Eight electrically heated and water-cooled barrel sections provided the temperature control. The temperature profile for all of the samples was consistent, and a vacuum was applied at the fourth and seventh section. The melt temperature was kept under 190°C to prevent thermal degradation of the wood flour. Extrudate strands were cooled in a water trough and pelletized. The resulting pellets were

dried at 105°C before being injection molded into American Society for Testing and Materials (ASTM) test specimens. All the materials were molded using a 33-ton Cincinnati Milacron (Batavia, OH) reciprocating screw injection molder at the appropriate wood flour percentages.

### Testing

The tests were conducted using ASTM standards (3) for plastics (Table 1). Each test was run with five replicates. Melt index tests were conducted at 190°C because the standard temperature (230°C) is well above the thermal degradation point of wood, and only one test was run per formulation for the melt index tests. The specific gravities are estimates that were obtained by weighing flexural specimens and dividing by the volume. Heat deflection temperature (HDT) tests were performed by Plastics Technologies Laboratory (Pittsfield, MA).

## Results and Discussion

### Species Effects

Table 2 provides the specific gravities, the MI, the percentage mold shrinkage, and the heat deflection properties of composites made from wood-flour-filled PP using ponderosa pine, loblolly pine, oak, and maple at 20,30,40,50, or 60% by weight wood flour. Results of tests for impact, tensile, and flexural properties are shown in Table 3.

#### *Specific Gravity*

The high pressure wood flour encounters during processing compresses it to the point where the cells collapse. At that point, the specific gravity of the wood flour is similar to that of the cell walls. Because this density is larger than that of pure PP, it was expected that the specific gravity would increase with increasing concentrations of wood flour. This was indeed the case. For each species, the specific gravity increased by ~0.05 for each 10% increase in wood flour content.

#### *Melt Index*

The test for MI was conducted at 190°C instead of the 230°C typically used for PP. The lower temperature was chosen to prevent thermal degradation of the wood flour. Filler restricts the mobility of the polymer molecules; therefore, it was no surprise that the MI

decreased with increasing filler concentration. This happened at a rate of between 2.2 and 2.6 g/10 min for every 10% increase in filler content for all of the species.

### *Mold Shrinkage*

As expected, percentage mold shrinkage decreased with increasing filler concentration. This occurred at an overall rate of 1.3% for every 10% increase in filler content for all species (Fig. 2). The highest mold shrinkage was observed when loblolly pine was used as a filler, followed by maple, oak, and ponderosa pine.

### *Heat Deflection*

At 20% wood flour content, all of the species reported a similar HDT, which was greater than that of the unfilled PP. With increasing wood flour content, the HDT increases at a greater rate for the hardwoods than for the softwoods. At 60% filler, the average reported HDT for the hardwoods is 33% higher than for the softwoods.

### *Impact Energy*

For all the species, notched Izod impact energy increased with increasing wood flour content (Fig. 3). However, at around 50% wood flour content, the notched impact energy for all the species experienced a leveling off or a decline. The notch acts as a crack initiator; therefore, the notched Izod impact test is a measure of crack propagation.

The unnotched impact energy decreased with increasing filler content. This was expected and can be observed with many fillers (2). Unnotched impact energy includes crack initiation and propagation. Fillers provide stress concentrations, at which point less energy is required to initiate a crack. As filler concentrations increase, the energy required to initiate the crack decreases; thus, the unnotched impact energy decreases.

### *Tensile Propetiies*

As observed elsewhere, the maximum tensile strength (NITS) decreased with increasing filler content (4). Figure 4 shows that although oak, maple, and ponderosa pine performed similarly, loblolly pine performed slightly worse. The tensile modulus of elasticity (MOE) increased linearly with increasing filler content while the percentage elongation decreased. Overall, the hardwoods exhibited higher tensile MTS and MOE properties and lower percentage elongation values than the softwoods.

### *Flexural Properties*

The flexural MOE increased linearly with increasing wood flour content (Fig. 5) This occurred at a rate of between 0.53 to 0.54 GPa for the hardwoods and 0.61 to 0.66 GPa for the softwoods per 10% increase in filler content. It is common knowledge that the addition of fillers to thermoplastics increases the modulus, and this has been observed elsewhere with oil palm wood flour (4). Slightly higher values for flexural MOE were observed with the hardwoods.

For ponderosa pine, the maximum flexural strength increased with increasing wood flour content for up to 40% filler content, at which point the flexural strength decreased. This decrease in maximum flexural strength occurred after 30% filler content with the other three wood flours. Again, the strength values were determined to be higher for the hardwoods.

## Size Effects

Tables 4 and 5 summarize the performance and mechanical properties of 40% ponderosa pine wood-four-filled polypropylene along with the average coefficient of variation.

### *Specific Gravity*

Specific gravity was not affected by differences in particle size of the wood flour. This was due to the high pressures during processing that led to the collapse of the cells. Since this phenomenon is not dependent on particle size, the overall specific gravity is likewise not dependent on particle size.

### *Melt Index*

The MI data, determined at 190°C, demonstrated that as particle size increased, the MI increased for the range of wood flours examined. As particle size increased, the size of the unfilled regions within the polymer increased, resulting in greater flow mobility for the polymer and higher MI values.

### *Mold Shrinkage*

For the commercial wood flours, the mold shrinkage decreased with increasing particle size and then increased at 40 mesh. This trend was also observed with the screened wood flours. Figure 6 shows this trend with particle size compared with mold shrinkage for the screened wood flows.

### *Heat Deflection*

Although the HDT initially did not appear to follow any discernible trend, comparison of the screened flour composites with the commercial flour composites suggests that the HDT increased with increasing particle size. Previous work on 40-mesh ponderosa-pine-filled PP at 40% by weight reported a HDT of 90°C (2). These results seem to indicate that the value obtained for S-35 is low and that HDT increases with increasing particle size.

### *Impact Energy*

Figure 7 demonstrates the effect of particle size on notched impact energy. Generally, notched impact energy is a measure of crack propagation, while unnotched impact energy is a measure of both crack initiation and propagation. For the range of particle sizes examined, notched impact energy increased with particle size. The reverse was true for unnotched impact energy. As particle size increased, unnotched impact energy decreased, mainly as a result of crack initiation. The larger particle sizes provide higher stress concentrations where a crack can be initiated more easily; i.e., less energy is required to initiate the crack, which dominates over the higher energy needed to propagate the crack.

Results from the impact tests have been confirmed by other sources. Previously reported data for wood-flour-filled PP demonstrated that notched impact energy increases with increasing particle size. Zaini and others (4) investigated the effects of several mesh sizes of oil palm wood flour on the properties of PP filled at 20%, 30%, 40%, and 50% by weight. Between 230 (0.063 mm) and 60 mesh (0.25 mm), notched impact energy increased with increasing particle size. Myers and others (5) also found that notched impact energy increased with increasing particle size in examining the effects of 40- and 20-mesh sizes on PP filled with 45% and 55% by weight wood flour.

### *Tensile Properties*

The MTS for the commercial wood flours reached a maximum at 80 mesh. Similarly, for the screened wood flours, MTS increased with increasing particle size until reaching -0.25 mm, at which point MTS decreased (Fig. 8). This result corresponds well with reported data. Zaini and others (4) reported increasing MTS with increasing particle size for PP filled with between 230- and 60-mesh oil palm wood flour. Myers and others (5) reported decreasing MTS with increasing particle size for 40-to 20-mesh wood-flour-filled PP.

Tensile MOE exhibited trends similar to those for MTS for both the commercial and the screened wood flours. The values for these properties increased with increasing particle size up to a particle size of around 0.25 mm, at which point the property values began to decrease. There was little difference in percentage tensile elongation between the wood flours.

### *Flexural Properties*

Like the tensile properties, flexural MOE appeared to increase with increasing particle size and then to decrease at an average particle size of about 0.25 mm (Fig. 9). These results also correspond with previously reported data. Zaini and others (4) reported an increase in flexural modulus with increasing particle size for composites made with 230- to 60-mesh oil palm wood flour, and Myers and others (5) reported decreasing flexural MOE with increasing particle size for PP filled with 40- to 20-mesh wood flour.

Maximum flexural strength exhibited the same trends as did flexural MOE, MTS, tensile MOE, and percentage of tensile elongation. Maximum flexural strength increased with increasing particle size when average particle size was smaller than about 0.25 mm. For particles larger than 0.25 mm, maximum flexural strength decreased.

## Summary and Conclusions

This study focused on two variables of wood flour, species and mesh size, and determined the effects of these two variables on wood-flour-filled PP. It is important for the end user to be aware of the differences that species variations may have on their product, because species can be regionally influenced. Based on the results of this study, the following statements can be made:

- With increasing wood flour content,
  - melt index decreased,
  - mold shrinkage decreased,
  - notched impact energy increased while unnotched decreased,
  - flexural and tensile strength decreased, while modulus of elasticity increased, and
  - tensile percentage elongation decreased.

- The hardwoods exhibited slightly higher values for flexural and tensile strength and modulus, higher heat deflection temperature, and lower percentage tensile elongation than did the softwoods.
- Specific gravity was species independent.

Based on the data from this study and elsewhere, particle size apparently does have an effect on property performance of wood-flour-filled PP. The variances in property performance will help an end user choose an appropriate mesh size of wood flour based on performance needs and cost considerations. The results led to the following statements for the AWF-prepared ranges of particle sizes examined:

- The trends in property performance observed for screened wood-flour-filled PP are the same as those for commercial wood-flour-filled PP. Specifically, for increasing particle size,
  - melt index increased,
  - mold shrinkage decreased (for particles smaller than about 0.25 mm),
  - notched impact energy increased and unnotched impact energy decreased,
  - flexural and tensile modulus and strength increased (for particles smaller than about 0.25 mm), and
  - percentage of tensile elongation increased.
- Specific gravity was independent of particle size.

These data represent preliminary work on the effects of species and particle-size differences on wood-flour-filled PP. Further characterization of the wood flour, such as characterization of aspect ratios, and study of the effects of additives on different sizes of wood flours represent just a portion of the work still required to understand and fully exploit the use of wood flour as a filler in thermoplastics.

## Acknowledgments

The material used in this study was supplied by Solvay Polymer, Inc., and American Wood Fibers. Funding was provided by the University of Wisconsin-Madison Solid Waste Management Research Program.

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Table 1. The tests and ASTM standards used.

| Property test | ASTM standard (3) |
|---|---|
| Izod impact | D256 |
| Flexural | D790 |
| Tensile | D638 |
| Melt index | D1238[a] |
| Mold shrinkage | D955 |
| Heat deflection | D648 (264 $lb/in^2$) |

[a]The melt index tests were performed at 190°C.

Table 2. Summary of performance of several species of wood-flour-filled polypropylene at different weight percentages along with the average coefficient of variation (COV).

| Material[a] | Specific gravity ($g/cm^3$) | Melt index[b] (g/10 min) | Mold shrinkage (%) | Heat deflection (°C) |
|---|---|---|---|---|
| PND-20 | 0.95 | 9.5 | 0.76 | 69 |
| PND-30 | 0.98 | 6.3 | 0.59 | 76 |
| PND-40 | 1.04 | 3.2 | 0.41 | 85 |
| PND-50 | 1.09 | 2.6 | 0.36 | 89 |
| PND-60 | 1.13 | 0.01 | 0.26 | 91 |
| LBL-20 | 0.94 | 9.1 | 0.94 | 64 |
| LBL-30 | 1.00 | 7.5 | 0.70 | 72 |
| LBL-40 | 1.04 | 3.6 | 0.60 | 78 |
| LBL-50 | 1.09 | 2.0 | 0.49 | 79 |
| LBL-60 | 1.12 | 0.1 | 0.34 | 77 |
| MPL-20 | 0.94 | 10.1 | 0.88 | 69 |
| MPL-30 | 0.98 | 6.2 | 0.65 | 88 |
| MPL-40 | 1.04 | 3.2 | 0.47 | 104 |
| MPL-50 | 1.09 | 0.4 | 0.37 | 111 |
| MPL-60 | 1.13 | 0.0 | 0.35 | 110 |
| OAK-20 | 0.94 | 8.9 | 0.84 | 74 |
| OAK-30 | 1.01 | 4.4 | 0.56 | 98 |
| OAK-40 | 1.02 | 1.1 | 0.51 | 100 |
| OAK-50 | 1.09 | 0.1 | 0.35 | 112 |
| OAK-60 | 1.13 | 0.0 | 0.29 | 114 |
| PP | 0.87 | 15.7 | 1.46 | 55 |
| COV (%) | 1 | -- | 6 | 2 |

[a]PND, ponderosa pine; LBL, loblolly pine; MPL, maple; OAK, oak; PP, unfilled polypropylene. Number refers to the weight percentage of filler in the composite.

[b]The melt index measurements were taken at 190°C.

Table 3. Summary of mechanical property performance of several species of wood-flour-filled polypropylene at different weight percentages along with the average coefficient of variation (COV).

| Material | Izod impact | | Tensile properties | | | Flexural properties | |
|---|---|---|---|---|---|---|---|
| | Notched (J/m) | Unnotched (J/m) | Strength (MPa) | Elongation (%) | Modulus (GPa) | Strength (MPa) | Modulus (GPa) |
| PND-20 | 15.4 | 128 | 26.5 | 5.65 | 1.99 | 41.6 | 1.89 |
| PND-30 | 19.0 | 95 | 24.6 | 3.12 | 3.24 | 43.1 | 2.58 |
| PND-40 | 20.8 | 76 | 25.5 | 2.29 | 3.71 | 44.2 | 3.22 |
| PND-50 | 20.5 | 58 | 23.0 | 1.67 | 4.25 | 41.8 | 3.66 |
| PND-60 | 21.1 | 41 | 20.1 | 1.44 | 4.56 | 38.8 | 4.04 |
| LBL-20 | 12.4 | 120 | 24.9 | 4.83 | 2.14 | 40.6 | 1.71 |
| LBL-30 | 12.7 | 75 | 23.7 | 3.45 | 2.53 | 41.2 | 2.28 |
| LBL-40 | 13.7 | 49 | 21.4 | 1.76 | 3.28 | 39.3 | 2.84 |
| LBL-50 | 13.8 | 42 | 19.7 | 1.32 | 3.97 | 37.1 | 3.40 |
| LBL-60 | 10.4 | 31 | 17.8 | 0.92 | 4.32 | 34.1 | 3.81 |
| MPL-20 | 12.8 | 113 | 27.9 | 4.11 | 2.87 | 46.2 | 2. |
| MPL-30 | 15.0 | 87 | 27.1 | 3.26 | 3.33 | 46.5 | 2.47 |
| MPL-40 | 16.5 | 63 | 25.6 | 2.03 | 4.72 | 45.4 | 3.23 |
| MPL-50 | 17.7 | 49 | 24.0 | 1.44 | 5..20 | 42.1 | 4.16 |
| MPL-60 | 17.9 | 44 | 19.9 | 1.13 | 4.77 | 38.0 | 4.35 |
| OAK-20 | 14.6 | 87 | 27.2 | 4.66 | 2.48 | 44.1 | 1.83 |
| OAK-30 | 17.5 | 63 | 25.7 | 2.43 | 3.81 | 45.9 | 2.87 |
| OAK-40 | 18.6 | 68 | 25.2 | 2.09 | 4.19 | 44.8 | 3.39 |
| OAK-50 | 20.9 | 46 | 23.4 | 1.51 | 4.79 | 42.8 | 3.99 |
| OAK-60 | 18.8 | 33 | 19.8 | 1.20 | 5.05 | 38.1 | 4.60 |
| PP | 15 | 600 | 28.5 | 10.44 | 1.31 | 34.7 | 1.03 |
| COV (%) | 12 | 6 | 2 | 8 | 10 | 2 | 4 |

[a]PND, ponderosa pine; LBL, loblolly pine; MPL, maple; OAK, oak; PP, unfilled polypropylene. Number refers to the weight percentage of filler in the composite.

Table 4. Summary of performance of 40% ponderosa pine wood-flour-filled polypropylene along with the average coefficient of variation (COV).

| Material[a] | Specific gravity ($g/cm^3$) | Melt index[b] (g/10 min) | Mold shrinkage (%) | Heat deflection (°C) |
|---|---|---|---|---|
| S-35 | 1.05 | 4.13 | 0.49 | 75 |
| S-70 | 1.05 | 1.50 | 0.47 | 86 |
| S-120 | 1.04 | 2.03 | 0.52 | 81 |
| S-235 | 1.04 | 1.20 | 0.58 | 77 |
| C-20 | 1.05 | 3.00 | 0.44 | 93 |
| C-40 | 1.05 | 2.50 | 0.41 | 89 |
| C-80 | 1.04 | 1.60 | 0.45 | 81 |
| C-120 | 1.04 | 2.03 | 0.53 | 85 |
| PP | 0.87 | 15.7 | 1.46 | 55 |
| COV (%) | 1 | -- | 2 | 2 |

[a]S, screened particle-size distribution, number corresponds to average mesh size in wood flour sample; C, commercial particle-size distribution, number corresponds to mesh of wood flour set by American Wood Fibers; PP, unfilled polypropylene.

[b]The melt index measurements were taken at 190°C

Table 5. Summary of mechanical property performance for 40% ponderosa pine wood-flour-filled polypropylene along with the average coefficient of variation (COV).

| Material[a] | Izod impact | | Tensile properties | | | Flexural properties | |
|---|---|---|---|---|---|---|---|
| | Notched (J/m) | Unnotched (J/m) | Strength (MPa) | Elongation (%) | Modulus (GPa) | Strength (MPa) | Modulus (GPa) |
| S-35 | 22 | 54 | 21.8 | 2.27 | 3.20 | 38.7 | 2.69 |
| S-70 | 20 | 79 | 25.5 | 2.27 | 3.61 | 42.6 | 3.15 |
| S-120 | 19 | 84 | 24.9 | 2.29 | 3.47 | 42.9 | 3.00 |
| S-235 | 16 | 91 | 24.3 | 2.11 | 3.46 | 41.4 | 2.89 |
| C-20 | 27 | 60 | 23.3 | 1.97 | 3.04 | 42.7 | 2.98 |
| C-40 | 21 | 65 | 24.4 | 2.29 | 3.56 | 42.4 | 3.10 |
| C-80 | 19 | 75 | 24.8 | 2.17 | 3.55 | 41.9 | 3.12 |
| C-120 | 17 | 86 | 24.2 | 2.23 | 3.48 | 41.8 | 2.84 |
| PP | 15 | 600 | 28.5 | 10.44 | 1.31 | 34.7 | 1.03 |
| COV (%) | 5 | 10 | 1 | 6 | 7 | 1 | 2 |

[a]S, screened particle-size distribution, number corresponds to average mesh size in wood flour sample; C, commercial particle-size distribution, number corresponds to mesh of wood flour set by American Wood Fibers; PP, unfilled polypropylene.

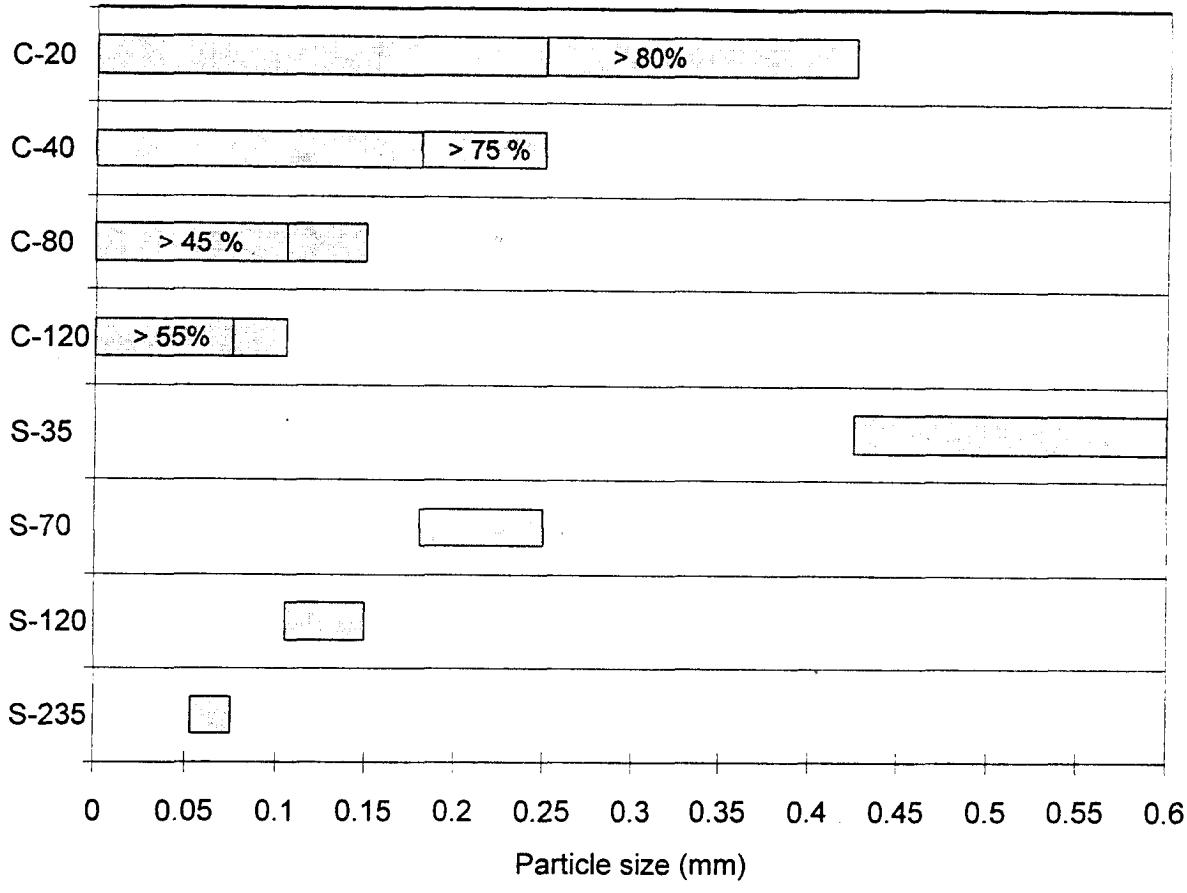


Figure 1. Particle-size distributions of ponderosa pine wood flours (C, commercial particle-size distribution with number corresponding to mesh of wood flour set by American Wood Fibers; S, screened particle-size distribution with number of average mesh size in wood flour sample).

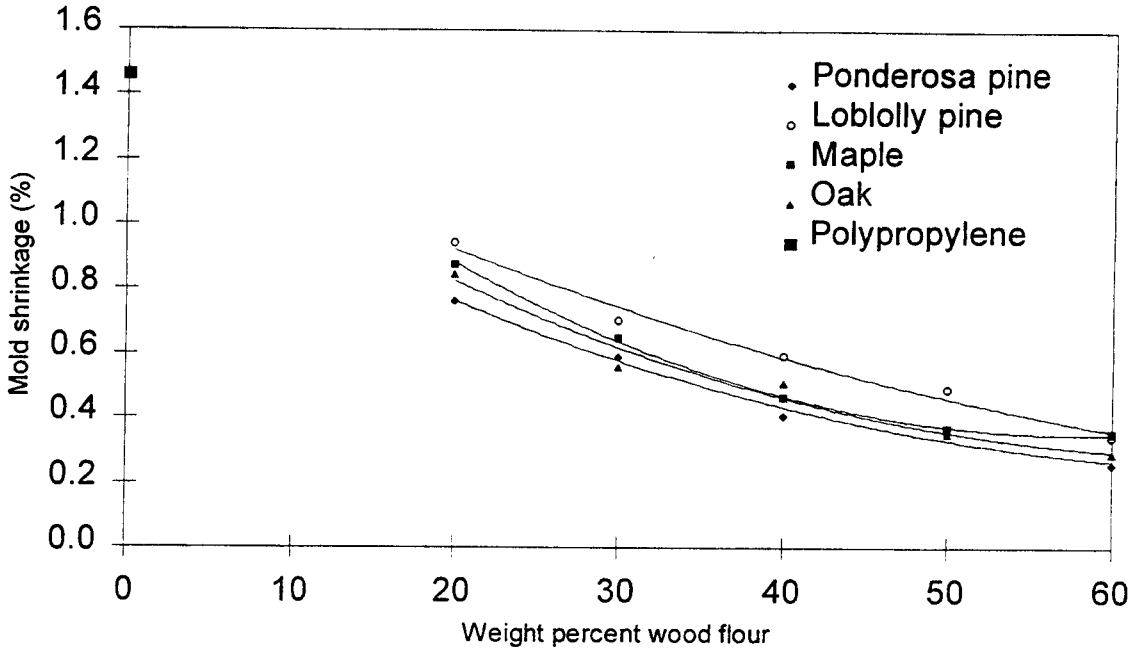


Figure 2. Effect of wood flour species and content on mold shrinkage.

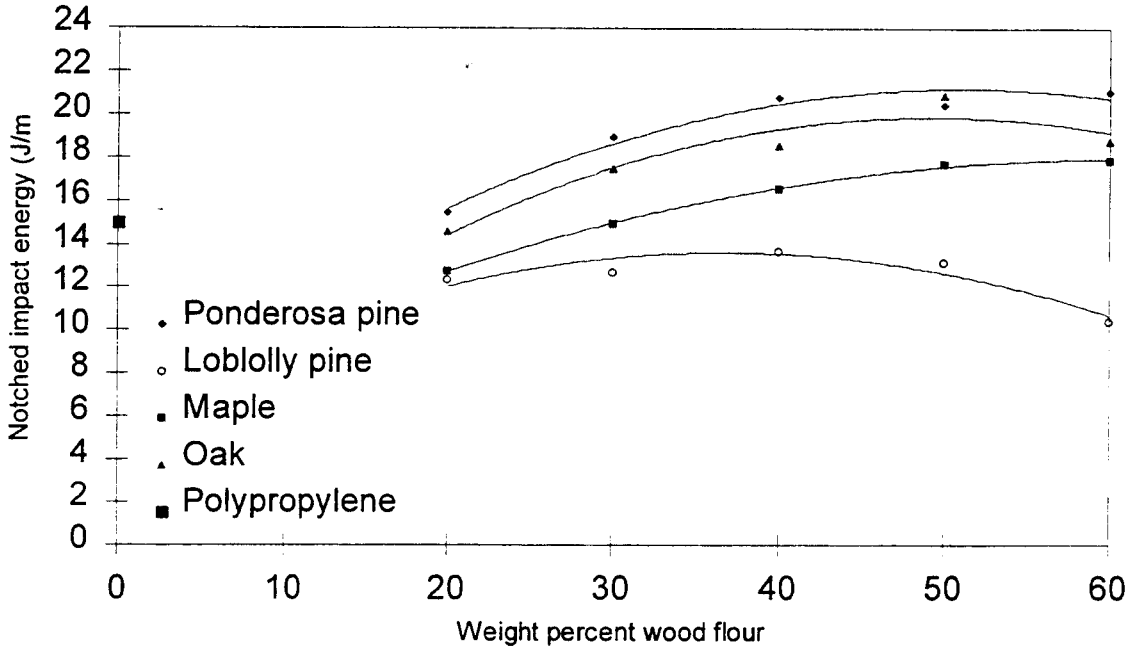


Figure 3. Effect of wood flour species and content on notched impact energy.

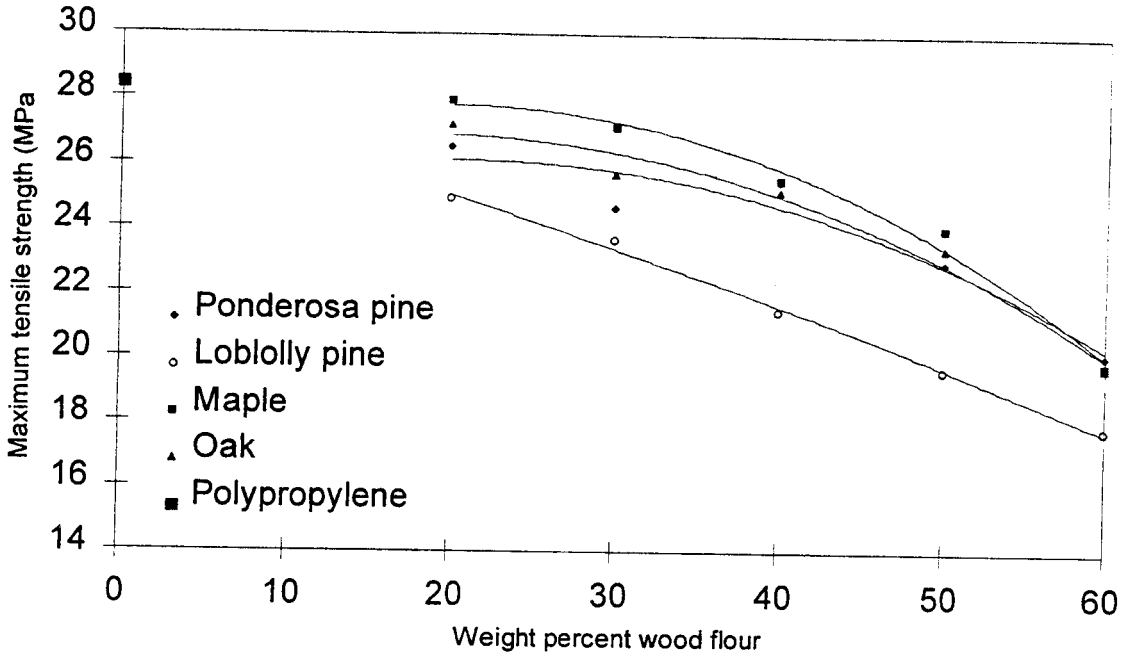


Figure 4. Effect of wood flour species and content on maximum tensile strength

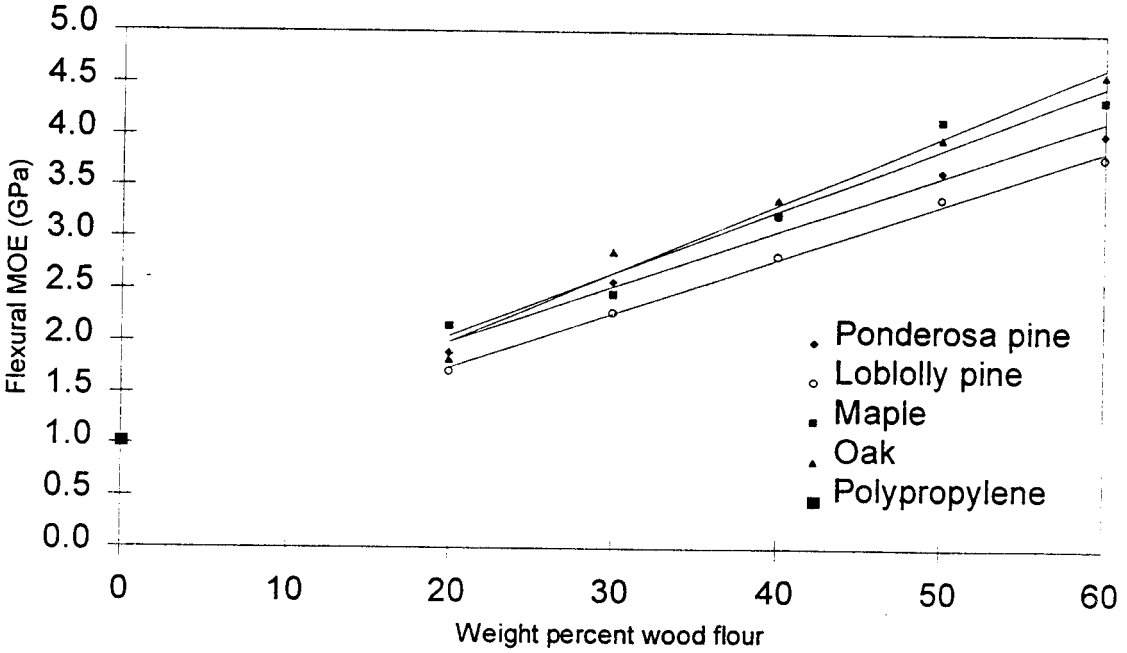


Figure 5. Effect of wood flour species and content on flexural modulus of elasticity (MOE).

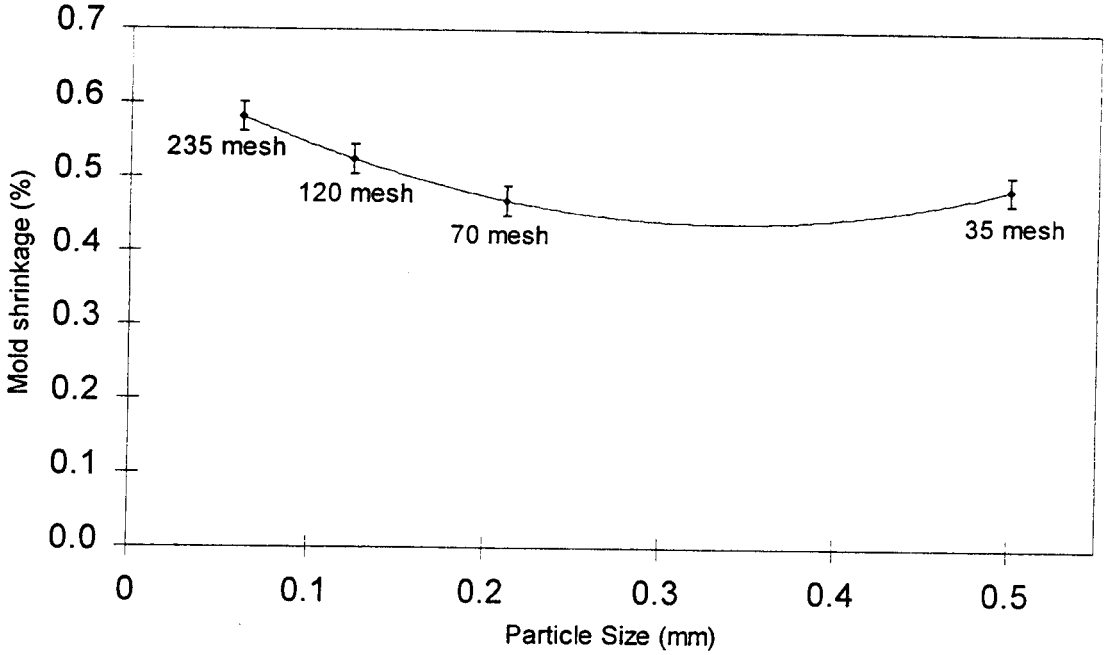


Figure 6. Effect of ponderosa pine wood flour size on percent mold shrinkage.

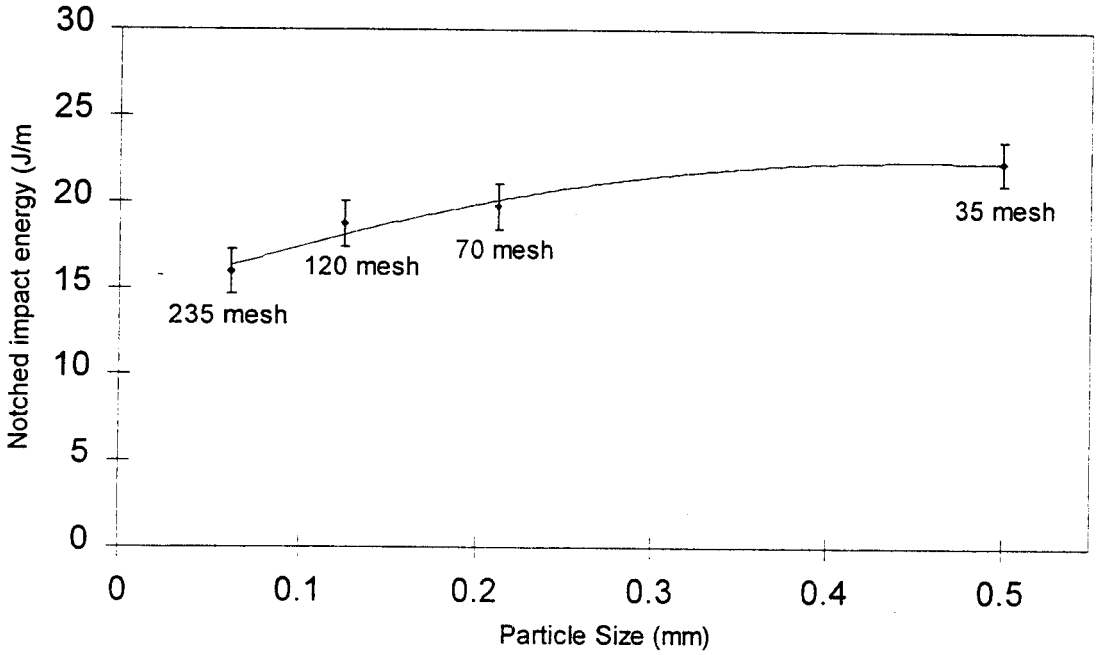


Figure 7. Effect of ponderosa pine wood flour size on notched impact energy.

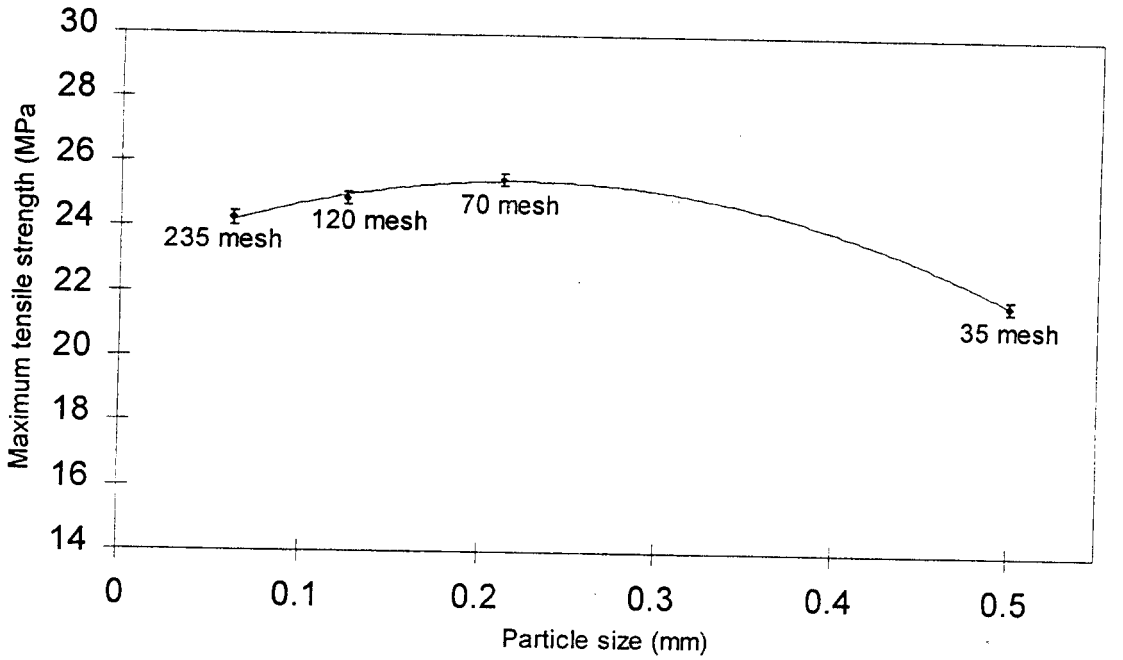


Figure 8. Effect of ponderosa pine wood flour size on maximum tensile strength.

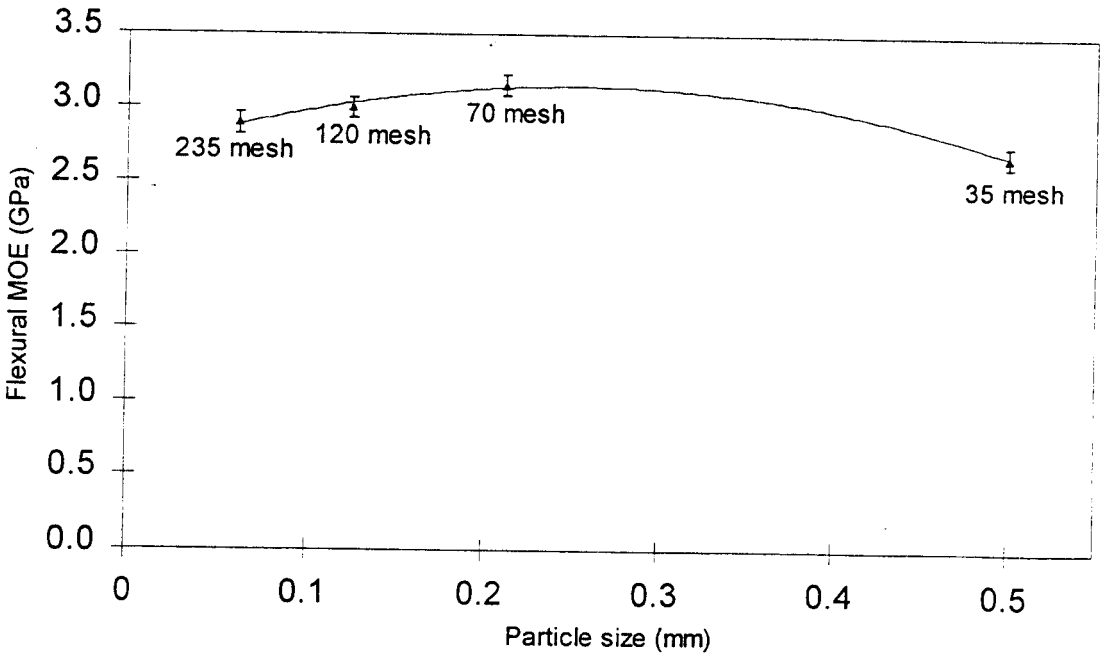


Figure 9. Effect of ponderosa pine wood flour size on flexural modulus of elasticity (MOE).