DENSITY RANGE OF COMPRESSION-MOLDED POLYPROPYLENE-WOOD COMPOSITES

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ABSTRACT

Wood and polypropylene fibers were mixed together in various proportions and compression-molded to boards of various specific gravities. The full theoretical specific gravity range could not be obtained even when the boards were cooled in the press. Voids surrounding the wood fibers possibly were due to the shrinkage of the wood fiber following pressing. Bending and tension properties were influenced more by the compression of the wood fibers than by the percentage of wood fiber addition.

Keywords: Thermoplastic, fiberboard, polypropylene, density, compression molding.

INTRODUCTION

Innovative ideas originating from the wood products industry have helped scientists develop many thermosetting-resin-bonded wood composites, from particleboard to medium-density fiberboard. Standard composite board technology prescribes a limited amount (3 to 9%) of thermosetting resin to bind boards to specific gravity (SG) levels from 0.55 to 1.00. Although resin quantity is accounted for in the fabrication specifications describing target board SG, it is not a major factor in considering the compaction of the wood particles. The individual wood cells in these composites are compressed from their effective SG of approximately 0.5 to various levels, depending on the target SG of the board, the voids left between the particles, and the cell's specific location within the horizontal density gradient.

Commercial products combining wood and thermoplastic resins have been developed primarily by the plastic industry. The wood is usually finely ground and added as a filler (Kokta et al. 1989) but may comprise as much as 50% by weight of the composite. The final SG of an extruded component of this type, made with a 0.9 SG polypropylene thermoplastic resin, is between 1.0 and 1.1, indicating that the wood cell walls were pulverized or that the cells were crushed nearly to the SG of solid wood substance (approximately 1.4 to 1.5) and

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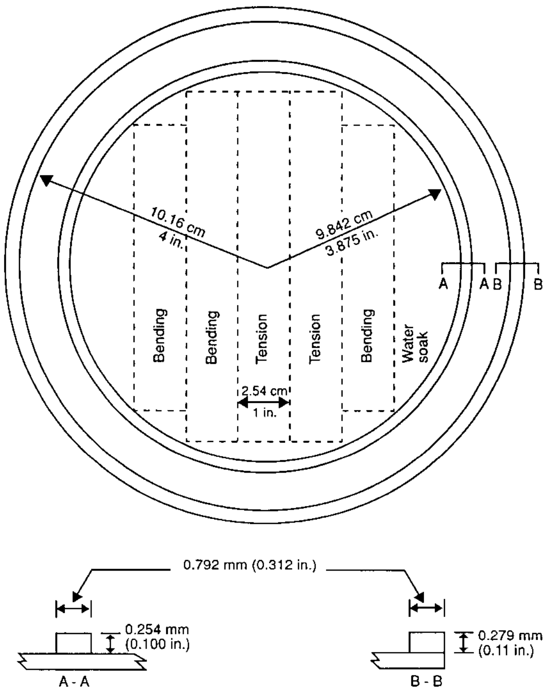

FIG. 1. Thickness gauge for compression molding polypropylene-wood composites and cut-up diagram of resulting board.

that the voids between and within the wood fiber structure were completely full of resin.

Research indicates that replacement of wood flour with wood fibers enhances certain physical properties of thermoplastic injection-molded, compression-molded, and extruded composites (Raj and Kokta 1989; Woodhams et al. 1990). The percentage of incompressible resin is relatively high in thermoplastic-wood fiber composites and must be considered in determining the actual SG to which the wood fiber is compressed. Objectives of this study were to determine (1) the effect of the resin/wood ratio on the range of SGs that could actually be achieved in a compression-molded polypropylene-wood composite, and (2) the effect of SG on bending and thickness swelling properties.

PROCEDURE

Short polypropylene (PP) Pulpex P-AD[2] (Hercules Inc., Wilmington, Delaware) fibers were mixed with aspen fibers, in specified proportions of 10 to 90% by weight of PP, by passing the fibers through a centrifugal blower. Moisture content of the aspen fibers, which were obtained from a commercial hardboard manufacturing plant, was 6% prior to mixing. Mats with a 178-mm (7-in.) diameter were formed on a screen using an air-forming device. A vacuum was drawn below the screen to settle the fibers. The mats were hot pressed at 190 C (375 F) for 3 min. This permitted the PP to melt and flow without incurring serious degradation of the wood fiber. Mats were pressed using a double-ring spacing bar (Fig. 1). The inner ring restrained and shaped the furnish, while the outer ring provided the necessary thickness control. Depending on the target density, pressures up to 10.34 MPa (1,500 lb/in.^{2}) were applied to compress the mats. Boards were fabricated to SGs defined in Fig. 2 for PP proportions of 10, 20, 40, 60, 80, 90, and 100% and to compacted wood SGs of 0.5, 0.9, and 1.4. Two boards were made for each condition. Because the expansion of the mats during pressing was a function of both the amount of material and the percentage of PP, problems were encountered in achieving uniform furnish distribution throughout the mats. By adjusting the diameter of the formed mats, the problems of underflow or overflow in the press mold were reduced. Initially, the boards were removed from the press while still hot and were cooled to room temperature under a force of 22.2 N (5 lb). The range of attainable board SGs was increased by cooling the boards in the press. All boards were trimmed to a uniform diameter of approximately 190 mm (7.5 in.), weighed, and measured for thickness. Following a minimum of 5 days' exposure to ambient conditions, samples were cut from one board from each condition (Fig. 1) and were tested for bending stiffness and strength, tensile strength, and 24-h water absorption and

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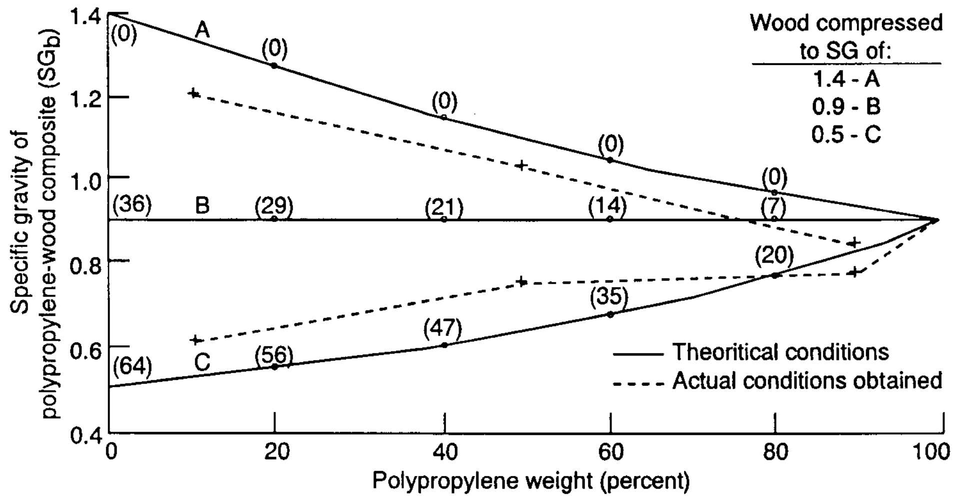

FIG. 2. Specific gravity (SG) of compression-molded polypropylene-wood composites at various levels of polypropylene additions and selected levels of wood compaction. Solid lines represent theoretical limits. Numbers in parentheses are volume of voids expressed as percentage of total board volume for specific theoretical values. Dashed lines represent maximum and minimum values obtained from boards cooled in press (two boards from each condition).

thickness swelling. The 25.4-mm- (1-in.-) wide bending specimens were tested for bending modulus of elasticity (MOE) according to ASTM D747-90 (ASTM 1990) procedures using a 50.8-mm- (2-in.-) span on a cantilever testing machine. Bending modulus of rupture (MOR) was determined according to ASTM D1037-87 (ASTM 1987) by center loading a 25.4-mm- (1-in.-) wide specimen on a 61-mm (2.4-in.) span. The 85.7-mm- (3.375-in.-) long by 25.4-mm- (1-in.-) wide tensile specimens were tested according to ASTM D638-84 (ASTM 1984) (type 1 specimen), except that the necked-down length was reduced to 12.7 mm (0.5 in.) to accommodate the smaller sample length. Weight and thickness of the irregularly shaped thickness swell specimens were measured immediately following removal from being fully immersed in water at ambient temperature for 24 h. Scanning electronic micrographs were taken of microtomed gold-plated cross sections of selected samples.

RESULTS AND DISCUSSION

Compression of plastic-wood composites is contingent upon the adjustment of the wood fibers and plastic to eliminate the voids between and within the fibers. Figure 2 shows the SG of plastic-wood composites when the mixture was pressed, compacting the wood to SGs of 0.5, 0.9, and 1.4. The calculations assume that the PP has an SG of 0.9 and is incompressible in the solid or liquid state and that no voids exist except the cell lumens. The wood fiber has a natural SG of 0.5 and can be crushed to the SG of the solid wood substance, assumed to be 1.4. The final wood SG (SG_w) is a function of the final board SG (SG_b), the polypropylene SG (SG_{pp}), and the proportion of the components:

$$SG_w = \frac{(1 - Pp)(SG_b)(SG_{pp})}{SG_{pp} - (Pp)(SG_b)} \qquad (1)$$

where Pp is the weight fraction of polypropylene. The volume of the voids (V_v) (i.e., the cell lumens) is calculated as a percentage of the total board volume according to

$$V_v = [1 - (SG_w/1.4)][1 - (Pp)(SG_b/SG_{pp})] \qquad (2)$$

These and other useful equations are developed in Appendix A.

Selected values of V_v are shown in paren-

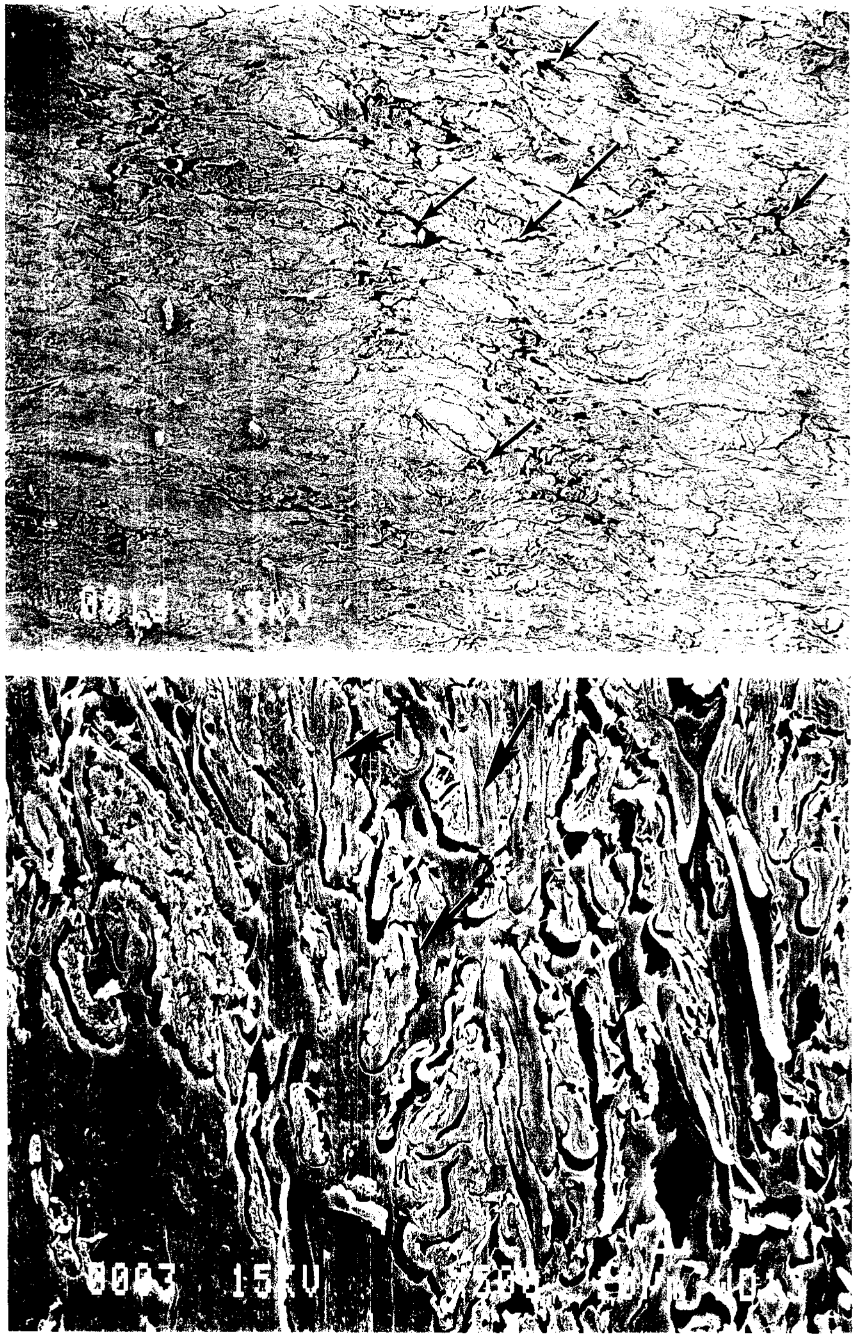

FIG. 3. Scanning electron microscope cross sections of 50% polypropylene/50% wood composite pressed to target specific gravity of 1.1. (a) Arrows point to void areas. Actual specific gravity is 1.07. Board was cooled in press. (b) Arrows numbered 1 point to collapsed cells. Arrow number 2 points to void between cell wall and polypropylene.

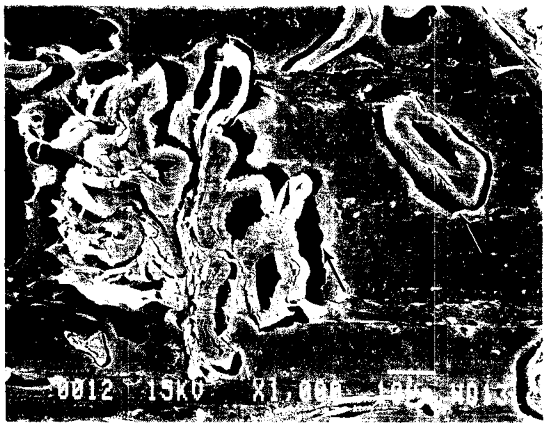

FIG. 4. Scanning electron microscope cross section of a 60% polypropylene/40% wood composite pressed to 1.0 specific gravity. Arrows point to voids between cell wall and polypropylene. Actual specific gravity is 0.695. Board was cooled after removal from press.

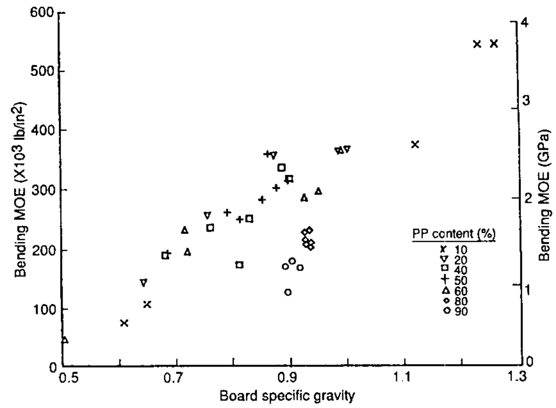

FIG. 5. Cantilever tests showing effect of board specific gravity and amount of polypropylene on bending MOE of polypropylene-wood composites. Data points represent single specimen.

theses in Fig. 2. The points connected with a dashed line indicate the range of board SGs we attained. Neither of the compression extremes, zero nor complete compression, was achieved, except with the 90% PP composite.

A board made with 50% by weight of aspen fiber and pressed to a target SG of 1.1 was examined microscopically. A cross section of this board magnified shows many voids (Fig. 3a). A closer view (Fig. 3b) shows that many of the wood cells were completely collapsed. However, poor bonding between the hydrophilic wood and the hydrophobic PP has allowed many separations to occur at the cell wall-PP interface. Wood and PP separating because of differential thermal shrinkage was unlikely since the coefficient of thermal expansion of the PP is greater than that of aspen (6.7 $\times$ 10^{-4} and 0.56 $\times$ 10^{-4} volumetric per °C, respectively). The 1.37% maximum tangential shrinkage of the wood caused by a 6% moisture loss was more than offset by an estimated 5% volumetric crystallization shrinkage of the PP [PP volumetric crystallization shrinkage varies from 1.5 to 10.5% depending on the degree of crystallization (Van Krevelan 1976)]. A possible explanation for the voids is movement of air from within the cell lumen to the cell wall-PP interface during compaction. Pressing-induced residual stresses in the collapsed wood should result in the expansion of the wood, after pressing, to fill any voids surrounding the fibers or fiber bundles. However, similar voids were evident in those boards that were cooled after removal from the press (Fig. 4), as well as in those boards that were cooled in the press. Perhaps most of the wood shrinkage caused by moisture loss occurred after removal from the press.

The results of bending MOE tests on individual specimens are shown in Fig. 5. A full complement of specimens was not obtained because of rescheduling of material use. However, the majority of the experimental design was completed and the data showed several important trends. Despite the poor bonding between the wood and the PP, the MOE clearly increased with an increase in board SG. This trend was also true for bending MOR and tensile strength. Bending MOE values depended more on the compression of the wood fibers than on the extent of wood fiber addition. When MOE was plotted as a function of the volume of wood substance within a board (Fig. 6), the data were well separated by board composition, showing the importance of wood compaction and the reduction of voids in improving bending stiffness of the composite.

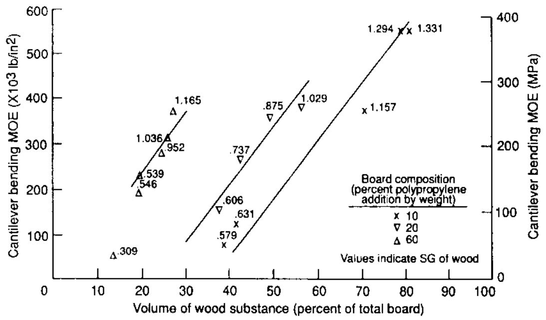

FIG. 6. Results of cantilever tests showing that compaction of wood fiber was more important than total wood addition in improving bending stiffness.

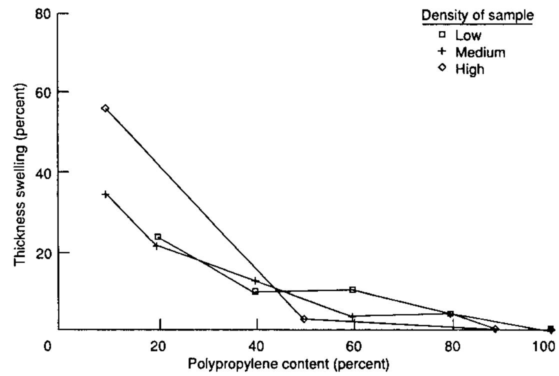

FIG. 8. Twenty-four-hour thickness swelling of polypropylene-wood composites. Data points represent single measurements.

Figures 7 and 8 show water absorption and thickness swelling response of samples to a 24-h water soak. Weight gain was greater in the low-density samples because the water had easier access to the wood fiber and the voids therein. At lower PP levels, thickness swelling was greater in the high-density samples because of the increased wood mass and its higher compression. When PP levels exceeded 40%, water absorption and thickness swelling properties began to level out at reduced values.

CONCLUSIONS

Compression-molding a polypropylene (PP)-wood composite without some compression of the wood fibers is difficult. However, over the range of press pressure used, complete collapse of all the wood fibers was not achieved. In a PP-wood composite, where the wood fibers are embedded in a void-free matrix of PP, the board specific gravity (SG) was increased by either reducing the amount of uncompacted wood or crushing the wood cells. In either case, the total volume of voids (cell lumens) was diminished. Bending stiffness, bending strength, and tensile strength increased with the addition of wood and with higher board SG. The extent of wood fiber compression had more effect on these properties than did the percentage of fiber addition. Micrographs show void areas surrounding many wood fibers and fiber bundles even though a significant proportion of the fibers were fully compressed. These voids appeared in boards cooled after removal from the press as well as in boards cooled in the press and may have been the result of air entrapped by the matrix. Water absorption and thickness swelling decreased significantly at PP levels above 40%.

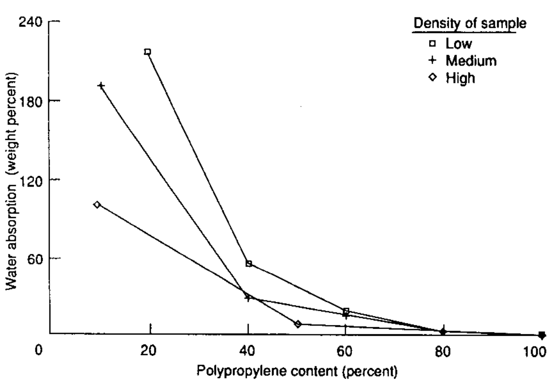

FIG. 7. Twenty-four-hour water absorption of polypropylene-wood composites. Data points represent single measurements.

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APPENDIX A—DETERMINING SPECIFIC GRAVITY AND VOLUME OF WOOD SUBSTANCE AND VOIDS

We wish to determine specific gravity of the wood (SG_w), the volume of the voids (cell lumens) (V_v), and the volume of the woody substance (V_{ws}) in a pressed plastic-wood composite, given specific gravity of a two-part polypropylene and wood mixture (SG_b), the weight fraction of polypropylene (Pp), and the specific gravity of the polypropylene (SG_{pp}).

We assume that the SG of the woody substance is 1.4 and no voids are present except the cell lumens.

Because SG_w is defined as the weight of the wood per unit volume,

$$SG_w = (1 - Pp)(SG_b)/V_w \tag{1a}$$

where V_w is the relative volume of the wood. However, the relative volume of the polypropylene (V_{pp}) is given by

$$V_{pp} = (Pp)(SG_b)/SG_{pp} \tag{2a}$$

and

$$V_w = (1 - V_{pp}) \tag{3a}$$

Substituting 3a and 2a into 1a gives

$$SG_w = (1 - Pp)(SG_b)/[1 - (Pp)(SG_b)/SG_{pp}] \tag{4a}$$

which converts to

$$SG_w = (1 - Pp)(SG_b)(SG_{pp})/[SG_{pp} - (Pp)(SG_b)] \tag{5a}$$

To determine V_{ws} and V_v as a percentage of the total composite,

$$V_{ws} = \text{(volume of the woody substance as a percentage of the wood)} \times \text{(volume of the wood as a percentage of the composite)} \tag{6a}$$

So,

$$V_{ws} = (SG_w/1.4)\{1 - [(Pp)(SG_b)/SG_{pp}]\} \tag{7a}$$

and

$$V_v = [1 - (SG_w/1.4)]\{1 - [(Pp)(SG_b)/SG_{pp}]\} \tag{8a}$$