

SWELLING OF A CELL LUMEN FILLED AND A CELL-WALL BULKED WOOD POLYMER COMPOSITE IN WATER

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ABSTRACT

Liquid water swelling of lumen-filled and cell-wall bulked wood polymer composite (WPC) samples was measured at room temperature and 80 C. Ultimate swelling was greater (approximately that of untreated wood) and moisture diffusion coefficient lower for the lumen filled wood. The higher density, lumen filled sample had lower swelling than the lower density one. At 80 C, fiber saturation points (FSP) were 8% for the cell-wall samples and above 20% for the cell lumen samples. The FSP for more highly loaded cell lumen samples was lower than that for lower loading.

Keywords: Wood polymer composite (WPC), swelling, moisture diffusion, dimensional stability, maximum moisture content, fiber saturation point (FSP).

INTRODUCTION

Stamm (1964, 1977) and Meyer (1984) surveyed techniques that have been used to improve wood's dimensional stability. One technique is to polymerize a vinyl monomer, such as methyl methacrylate or styrene, in wood cell lumens to reduce rates of shrinkage and swelling. Another is to cure a chemical such as a phenolic resin in cell walls to reduce moisture-induced dimensional change. The work reported herein was designed to quantify the effects of immersion in liquid water at two temperatures on two wood polymer composites, one of the cell lumen type and the other of the cell-wall type.

MATERIALS AND METHODS

One type of sample used was sugar maple (*Acer saccharum* Marsh.) treated with a nonswelling monomer that polymerizes to a cross-linked polymer having properties similar to methyl methacrylate. The second sample type was sugar maple treated with a monomer that swells the wood, cures to a cross-linked polymer, and produces a dark-colored WPC. Wood Polymer Composites Processes Limited of Fredericton, New Brunswick produced the samples using heat and catalyst processes under the trademark WSTIWOOD®. The chemical formulations are proprietary. Three cell lumen samples and three cell-wall samples were machined to approximately 0.9 cm × 2.0 cm × 6.0 cm, radial, tangential, and longitudinal

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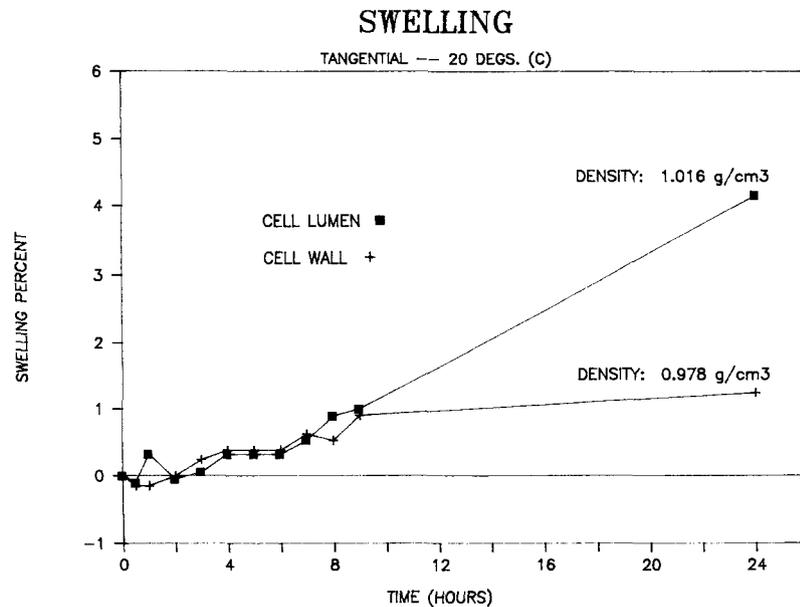


FIG. 1. Swelling of cell lumen and cell-wall wood polymer composite samples in room temperature water.

directions, respectively. The samples were carefully selected to give a true tangential width, since there is greatest swelling in the tangential direction giving easiest measurement of dimensional change. After machining, each sample was placed in an oven at 105 C to obtain oven-dry dimensions and weight. Oven-dry densities of the samples are reported in Table 1.

Two water baths were used to characterize the swelling behavior of the samples. The temperature of one bath was room temperature (20 C), and the other was 80 C. One cell-wall and one cell lumen sample were placed in the 20 C water bath. Two cell-wall and two cell lumen samples were placed in the 80 C water bath. Sample dimensions and weights were recorded after half an hour, after one hour, and then at one-hour intervals up to the 9th hour. Final measurements were taken at the 24th hour. Weights were measured to the nearest 0.01 g using a Mettler PC4400 balance, and dimensions were measured to the nearest 0.01 mm using a Mitutoyo digital caliper.

TABLE 1. Tangential swelling in water at two temperatures for cell lumen and cell-wall sugar maple WPC.

Temperature (C)	Sample ^a	Oven-dry density (gm cm ⁻³)	Swelling 24 hours (%)
20	CL	1.016	4.15
20	CW	0.978	1.24
80	CL	1.039	11.80
80	CL	0.988	15.57
80	CW	0.994	2.70
80	CW	0.966	2.19

^a CL and CW refer to cell lumen and cell-wall samples, respectively.

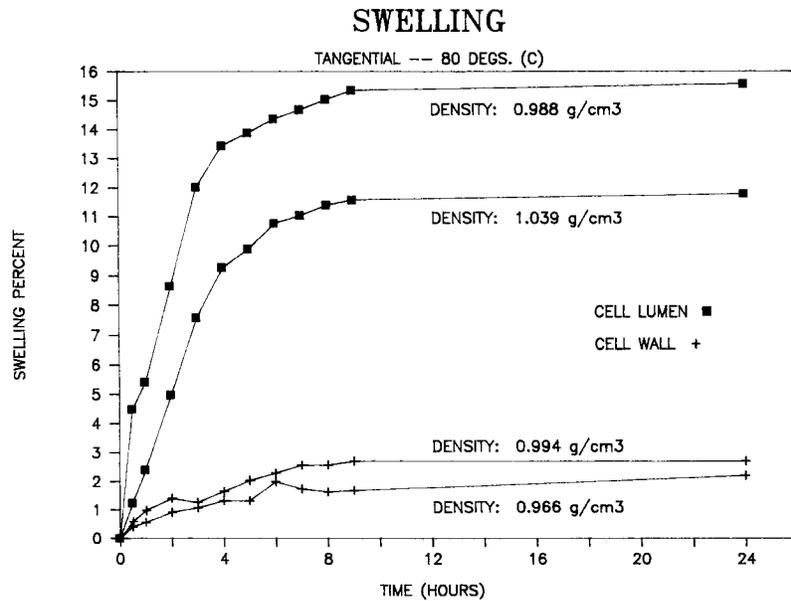


FIG. 2. Swelling of cell lumen and cell-wall wood polymer composite samples in hot (80 C) water.

RESULTS AND DISCUSSION

Figures 1 and 2 and Table 1 summarize the swelling results. Small measurement errors likely account for the small peaks in the lines connecting points in Figs. 1 and 2. The effect is more noticeable at lower swelling, where such error would be more obvious. The initial negative swelling (Fig. 1) is thermal shrinkage going from the 105 C oven to room temperature water.

The curves in Fig. 2 show that sample swelling at 80 C after 24 h had reached equilibrium with one cell lumen sample swelling 12% and the other 16% (Table 1). This is in the range that might be expected based upon: a) Meyer's (1984) statement that eventually a WPC with no cell-wall bulking will swell the same as untreated wood in the same moisture environment, and b) the average Wood Handbook (Forest Products Laboratory 1987) value of 10% for tangential sugar maple shrinkage.

The cell-wall samples had reduced swelling at both temperatures compared to the cell lumen samples. This is consistent with limited cell-wall water accessibility.

The lower density cell lumen sample at 80 C moisture equilibrium (24 h) had noticeably greater swelling than the higher density sample. There are at least two possible reasons for this. As monomer polymerizes, it shrinks. In WPC, this shrinkage typically causes the wood to contract during polymerization. In this study, shrinkage of the gross sample during cure was noted, with the denser (more heavily loaded) samples shrinking more than the less dense samples. If the connections between polymer and cell walls and polymer in one lumen with polymer in the next are sufficiently strong, the polymer could mechanically restrain the wood from swelling. The effect should be greater with greater amounts of polymer in the cell lumens, as observed. A second possibility is that some cell-wall pen-

TANGENTIAL SWELLING vs MOISTURE CONTENT

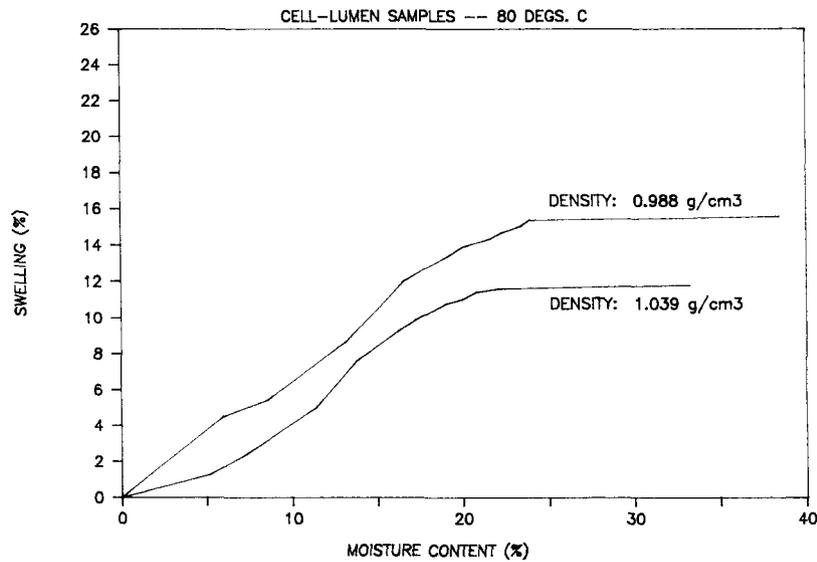


FIG. 3. Swelling of different density cell lumen wood polymer composite samples in 80 C water. Fiber saturation point appears to be 20% MC for the higher density sample and 25% MC for the lower density sample.

etration by the monomer occurred, with more occurring at the higher loading. A small amount of swelling from this could easily be masked by the polymerization shrinkage and the water loss associated with polymerization heat. The swelling and density differences in the cell-wall samples are the opposite of the cell lumen samples. Differences in the cell-wall samples are small, however, making inferences difficult.

Plotting swelling against moisture content (Figs. 3 and 4) and taking the levelling-off point indicate that the fiber saturation points (FSP) of the WPC samples at 80 C are lower than for untreated wood. In Fig. 3, the cell lumen treatment has an FSP of 20% for the higher density sample and near 25% for the lower density sample. This is consistent with the swelling results and has the same possible causes. The cell-wall samples (Fig. 4) have an FSP near 8% for both samples, consistent with moisture-excluding effects of cell-wall bulking.

Calculating moisture diffusion coefficients in the samples requires a moisture

TABLE 2. Theoretical and experimental maximum moisture contents of cell lumen sugar maple WPC.

Sample ^a	O.D. [wood] (g cm ⁻³)	O.D. [WPC] (g cm ⁻³)	P	F _p	F _v	Theor. MC _{max} (%)	Exper. MC _{max} (%)	Percent diff. (%)
1	0.681	0.836	0.142	0.162	0.838	69.4	67.6	2.7
2	0.681	1.002	0.368	0.421	0.579	39.2	45.5	16.1
3	0.675	0.924	0.273	0.307	0.693	53.8	53.2	1.1
4	0.675	1.078	0.485	0.546	0.454	31.8	34.7	9.1

^a Based on Fig. 3, an FSP of 25% MC was used for samples 1 and 3, and 20% MC was used as FSP for samples 2 and 4.

TANGENTIAL SWELLING vs MOISTURE CONTENT

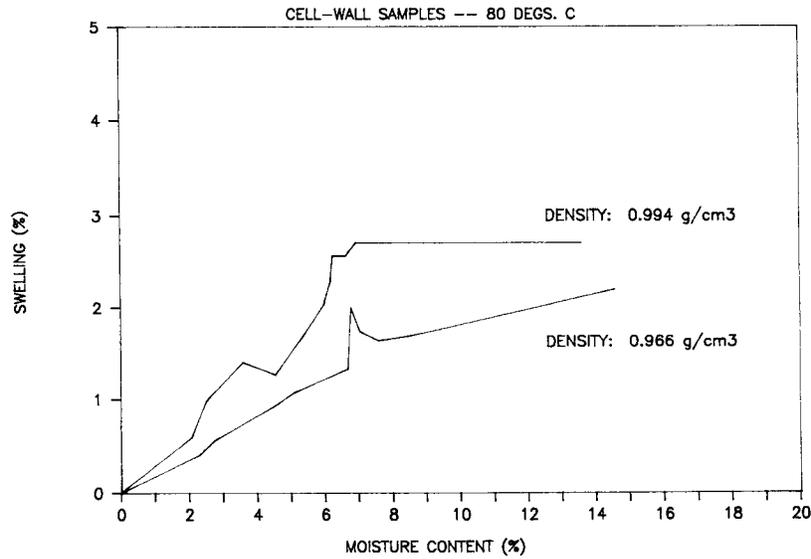


FIG. 4. Swelling of different density cell-wall wood polymer composite samples in 80 C water. Fiber saturation point appears to be 8% MC.

content fraction based on maximum moisture content (MC_{max}). One approach to calculating MC_{max} is (Skaar 1972):

$$MC_{max} = MC_{fsp} + (1/G_o)[1 - (G_o/G_o')] \quad (1)$$

where MC_{fsp} is the FSP, G_o is the specific gravity of the dry wood and G_o' is the dry specific gravity of the cell wall. Siau and Meyer (1966) developed:

$$F_p = \frac{d_{cw}d_{od}P}{xd_{cw}d_p - d_{od}d_p} \quad (2)$$

to calculate the fraction of voids filled with polymer. In (2), d_{cw} is the cell-wall density (1.54 g cm^{-3}), d_{od} is the dry density of untreated wood, d_p is the polymer density, x is the factor by which the WPC decreased/increased in volume compared to the untreated wood, and P is the polymer retention, calculated by:

$$P = \frac{xd}{d_{od}} - 1 \quad (3)$$

where d is the oven-dry density of the WPC.

The fraction of voids that is not filled with polymer (F_v) and that will therefore be filled with water at MC_{max} is:

$$F_v = 1 - F_p. \quad (4)$$

Equation (1) can be rewritten to calculate the MC_{max} of the WPC:

$$MC_{max} = MC_{fsp}^* + F_v(1/G_o^*)[1 - (G_o^*/G_o')] \quad (5)$$

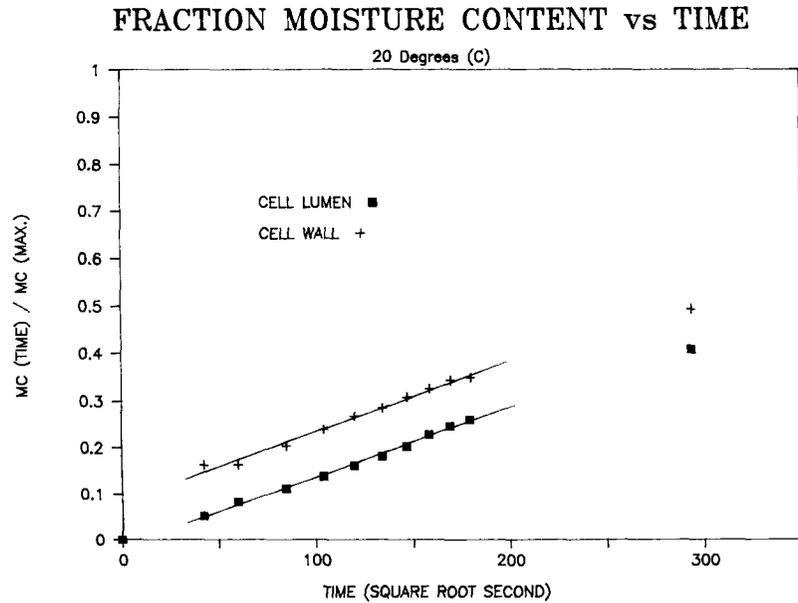


FIG. 5. Fraction of maximum MC vs. time for cell lumen and cell-wall wood polymer composite samples in room temperature water. Lines are linear regressions.

where MC_{fsp}^* is the FSP of the WPC and G_o^* is the dry relative density of the WPC.

Reliable values for the maximum moisture content at different polymer loadings are critical to the usefulness of this approach. Thus an experiment was used to confirm the applicability of Eq. (5) to this study. Four cell lumen samples were placed in water, and a vacuum was drawn until the weights stabilized (after 96 h). Each sample's maximum moisture content was calculated from its final weight. Table 2 shows that there is reasonable agreement between maximum moisture contents from Eq. (5) and experimental values.

The samples' diffusion coefficients given in Table 3 were calculated using the sample thickness (L) and the slopes of the regression equations for Figs. 5 and 6 by (Siau 1984):

$$D = (\text{slope})^2(L^2/5.10). \quad (6)$$

Values for maximum moisture content used in calculating D were obtained using Eq. (5). For cell lumen samples, the value was 50% MC, and for the cell-wall samples it was 15% MC.

TABLE 3. Slopes of fractional MC vs. square root time curves, sample thickness and diffusion coefficients for cell lumen and cell-wall sugar maple WPC.

Temperature (C)	Sample ^a	Thickness [L] (cm)	Slope	Diffusion coefficient (cm ² s ⁻¹)
20	CL	0.941	0.0015	3.33×10^{-7}
20	CW	0.869	0.0015	3.85×10^{-7}
80	CL	0.804	0.0026	8.31×10^{-7}
80	CW	0.958	0.0028	1.45×10^{-6}

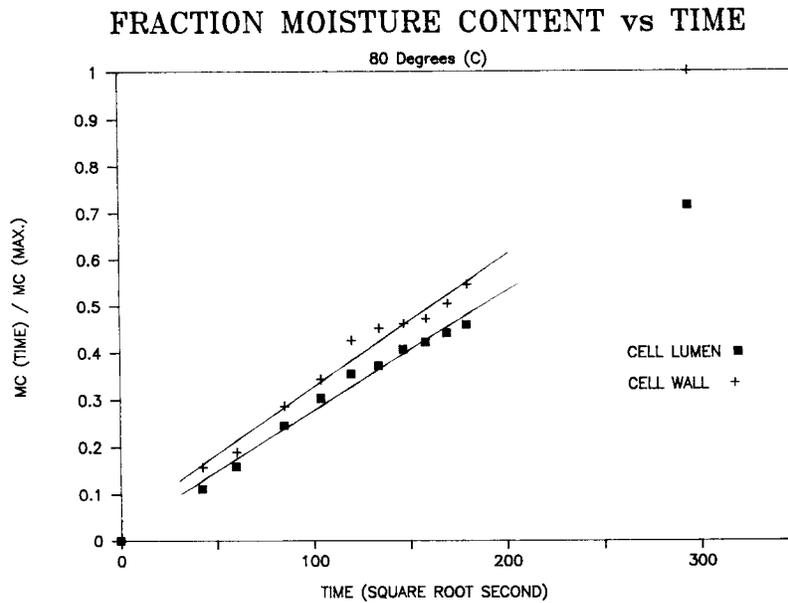


FIG. 6. Fraction of maximum MC vs. time for cell lumen and cell-wall wood polymer composite samples in hot (80 C) water. Lines are linear regressions.

The diffusion coefficients of the cell-wall samples are about 14% higher than the cell lumen samples at 20 C and approximately 1.7 times greater at 80 C (Table 3). Rowell et al. (1982) observed a 4.8 times higher value for a propylene oxide cell-wall treatment than for a methyl methacrylate lumen treatment at room temperature. The more dramatic difference for Rowell et al. is probably because that work measured longitudinal diffusion and this work measured radial. A more dramatic reduction in longitudinal diffusion upon filling cell lumens is expected than for radial because of the greater contribution of cell lumens to longitudinal movement.

The Rowell et al. (1982) cell lumen and cell-wall treatments had diffusion coefficients approximately 5 times greater than cell lumen and cell-wall treatments in the present work. This is within the expected range of radial and longitudinal differences for wood (Siau 1984).

CONCLUSIONS

Cell-wall treated wood polymer composites had low equilibrium swelling in liquid water at both room temperature and 80 C. Moisture diffusion coefficients were higher at both temperatures in the cell-wall samples than in the cell lumen samples. Results appear consistent with the diffusion work of Rowell et al. (1982) when the differences in moisture movement direction between the two experiments are considered. Cell lumen treated samples' ultimate swelling was in the range of untreated wood and the cell-wall samples considerably reduced compared to untreated wood. The higher density cell lumen sample had lower ultimate swelling than the lower density sample.

Calculated maximum moisture contents (required for calculating diffusion coefficients) agreed well with experimentally measured values.

The fiber saturation point, developed from the moisture content–swelling relationship at 80 C, was approximately 8% for the cell-wall samples and similar to untreated wood in the cell lumen samples. The fiber saturation point appeared to decrease with increasing density in the cell lumen treated samples.

REFERENCES

- FOREST PRODUCTS LABORATORY. 1987. Wood handbook. U.S. Dept. of Agriculture, Agriculture Handbook 72. U.S. Govt. Printing Office, Washington, DC.
- MEYER, J. A. 1984. Wood-polymer materials. Pages 257–289 in R. Rowell, ed. The chemistry of solid wood. Advances in Chemistry Series 207, American Chemical Society, Washington, DC.
- ROWELL, R. M., R. MOISUK, AND J. A. MEYER. 1982. Wood polymer composites: Cell-wall grafting with alkylene oxides and lumen treatments with methyl methacrylate. *Wood Science* 15(2): 90–96.
- SIAU, J. F. 1984. Transport processes in wood. Springer-Verlag, Berlin and New York. 245 pp.
- , AND J. A. MEYER. 1966. Comparison of the properties of heat and radiation cured wood-polymer combinations. *For. Prod. J.* 16(8):47–56.
- SKAAR, K. 1972. Water in wood. Syracuse Univ. Press. 218 pp.
- STAMM, A. J. 1964. Wood and cellulose science. Ronald Press, New York. 549 pp.
- . 1977. Dimensional changes of wood and their control. In I. S. Goldstein, ed. Wood technology: Chemical aspects. Advances in Chemistry Series 43, American Chemical Society, Washington, DC.