EFFECT OF DENSITY AND POLYMER CONTENT ON THE HYGROSCOPIC THICKNESS SWELLING RATE OF COMPRESSION MOLDED WOOD FIBER/POLYMER COMPOSITES

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ABSTRACT

The effects of polymer content and board density on the hygroscopic thickness swelling rate of compression-molded wood fiber/polymer composites were investigated in this study. A swelling model developed by Shi and Gardner (2005) was used to study the thickness swelling process of wood fiber/polymer composites exposed to water vapor conditions in which a parameter, K_{SR}, was used for the comparison of the swelling rates. The polymer materials used to process the wood fiber/polymer composites were from a reclaimed automobile plastic mixture, also called polymer fluff. Polymeric diphenylmethane diisocyanate (pMDI) resin was used as a binder. Six polymer contents (0, 15, 30, 45, 60, and 100%) and four target specific gravities (0.55, 0.75, 0.90, and 1.00) were evaluated in the experiments using the swelling model. It was shown that the swelling model successfully fit the empirical swelling rate data as impacted by different board densities and polymer contents. Board density has a significant effect on the swelling rate of the composites. The swelling rate increased linearly as board density decreased. The effect of polymer content on the swelling rate depends partially on board density. Polymer content did not show a significant effect on swelling rate at an oven-dry density of 900 kg/m^3. It was also confirmed from this study that the accuracy of the swelling model prediction is a function of the magnitude of the swelling rate parameter. The lower the thickness swelling rate of the composites, the more accurate the prediction obtained from the swelling model.

Keywords: Swelling rate, compression molding, thickness swelling, wood fiberboard, wood fiber/polymer composites.

INTRODUCTION

The hygroscopic thickness swelling rate is an important parameter for wood-based composites. Apparently, a higher hygroscopic swelling rate often causes fatigue when the relative humidity fluctuates due to the more rapid rate of change in the induced internal stress of the composite. Also, a high swelling rate would induce a high decay rate as the wood composites are exposed to the environment. Therefore, swelling rate can be one of the indices for the durability of wood-based composites since it relates to the rate of decay, dimensional stability, and other durability concerns. Many methods have been investigated to improve the dimensional stability

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of wood composites (Hsu et al. 1988; Geimer et al. 1992; Youngquist et al. 1986; Lehmann 1964; and Hujanen 1973). Several studies have focused on the thickness swelling rate of wood composites (Clemons et al. 1992; Vital et al. 1980; Cooper 1996; Ellis 1994; Shi and Gardner 2005). The thickness swelling rate typically depends on board density. Vital et al. (1980) found that the effect of density on the thickness swelling in particleboard depends on the relative humidity (RH). At low relative humidity, thickness swelling was independent of board density. At high relative humidity, an increase in density resulted in a greater thickness swelling. Swelling rate may also depend on the material composition of the composites. Ellis (1994) studied the moisture sorption and swelling of wood-polymer composites at 27°C and 90% relative humidity and concluded that compared to neat wood composites, the wood-polymer composites swelled at a slower rate. However, the swelling rate in the previous research was based only on the observation of test data since no quantitative method had been developed. Shi and Gardner (2005) developed a swelling model describing the hygroscopic thickness swelling process of wood-based composites. A swelling rate parameter (K_{SR}), as determined using the test data, can be used to quantify the swelling rate. The swelling model is expressed in the following equation:

$$TS(t) = \left(\frac{T_\infty}{T_0 + (T_\infty - T_0)e^{-K_{SR}t}} - 1 \right) \times 100 \qquad (1)$$

TS(t) is the thickness swelling at time t. T_o and T_∞ are the initial and equilibrium thickness of the board, respectively. K_{SR} is a constant referred to as the intrinsic relative swelling rate.

The values of the intrinsic relative swelling rate parameter, K_{SR}, in Eq. (1) depend on how fast the composites swell, and also on their equilibrium thickness swelling. To obtain the K_{SR}-value, a nonlinear regression curve-fitting method was used to fit the empirical data in the swelling model, using computer software with curve-fitting routines. This non-linear curve-fitting algorithm seeks the parameter values that minimize the sum of the squared differences between the observed and predicted values of the dependent variable.

$$SS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad (2)$$

where y_i and $\hat{y}_i$ are the observed and predicted values of the dependent variable, respectively.

The asymptotic standard errors (StdErr) and the coefficients of variation (CV%) of the parameter were calculated based on the fitting results.

$$CV\% = StdErr \times \frac{100}{K_{SR}} \qquad (3)$$

The effect of ambient environments, including the RH and temperature, on the swelling rate of both wood fiberboard and wood fiber/polymer composites was investigated using the model. It was concluded that the swelling rate increased as temperature increased. However, a weak relationship was found between the swelling rate and RH. The explanation for this phenomenon was provided by Shi and Gardner (2005). The higher the RH, the greater the concentration gradient for the moisture diffusion in the material, while on the other hand, the lower the RH, the lower the amount of water vapor in the ambient environment, and the material may be equilibrated in moisture quicker. It was also found in this study that a possible interaction existed between the density and polymer content of the wood fiber/polymer composite. It would be helpful to have a good understanding of how the polymer content in wood fiber/polymer composites affects the swelling rate, and also how it interacts with board density. The objectives of this study are: 1) to investigate the effect of polymer content and board density on the hygroscopic thickness swelling rate of wood fiber/polymer composites; 2) to test the applicability of the swelling model by Shi and Gardner (2005) to the swelling data of different polymer contents and board densities generated in this study.

MATERIALS AND METHODS

The experiment was conducted to investigate the effect of polymer content and board density on the swelling rate of the composites. Hardwood fiber (75% aspen, 25% other hardwood) and polymer particles of 35 mesh (0.5 mm) were used in producing the wood fiber/polymer composites. The polymers used in the wood fiber/polymer composites were processed from reclaimed automobile polymer mixtures, also called polymer fluff. This material consists of both thermoplastic and thermosetting polymers, mainly polyurethane, polypropylene, poly(vinyl chloride) (PVC), acrylonitrile, butadiene, and styrene (ABS). These polymer mixtures were ground into particles of 35 mesh (0.5 mm) before they were mixed into the wood/fiber furnish. Polymeric diphenylmethane diisocyanate (pMDI) resin was used as a binder. A blender was used to blend the pMDI adhesive into the wood fiber and polymer particle furnish. All the wood fiber/polymer composites were manufactured at a press temperature of 150°C, press time of 4 min, and resin solids level of 4% based on the oven-dry weight of the panel. Composites with a target specific gravity of 0.90 and six different polymer contents (0, 15, 30, 45, 60, 100%) based on the oven-dry weight of the materials, and four different target specific gravities (0.55, 0.75, 0.90, and 1.0) for polymer contents of 0 and 30% were manufactured. The specimen used for the hygroscopic thickness swelling tests had dimensions of 76.2 × 76.2 × 3.18 mm. After compression-molding out of the hot press, specimens were cut and placed in a sealed container with dessicant in the bottom to prevent the specimens from absorbing moisture from the environment. All the specimens were conditioned in the container for over one month. In addition, before each test, all the specimens were oven-dried at 103 ± 2°C. The oven-dry board density was measured. Three replicas were used for the hygroscopic thickness swelling test measurements. Specimens were placed in a sealed desiccator with distilled water on the bottom in which the relative humidity can be regarded as 100%. The ambient room temperature was measured as 17 ± 3°C. The board thickness was also measured as a function of time to obtain the thickness swelling process. The swelling model (Shi and Gardner 2005) was applied to these measured data, and the swelling rate parameter (K_{SR}) was obtained using a nonlinear curve fitting method.

RESULTS AND DISCUSSION

Figure 1 shows the hygroscopic thickness swelling process for wood fiber/polymer composites with different polymer contents at a target oven-dry density of 900 kg/m^3. The thickness swelling processes of the composites manufactured with different board densities at two polymer loading levels, 0% and 30%, are shown in Figs. 2 and 3, respectively. Table 1 sum-

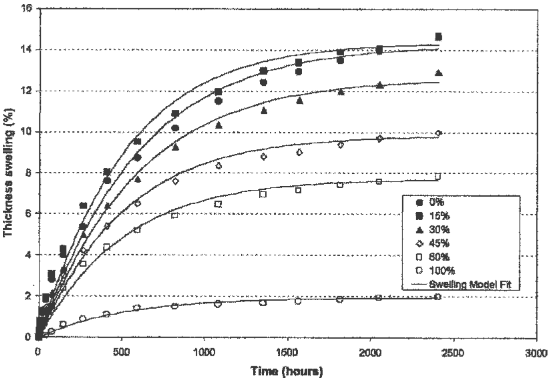

FIG. 1. Thickness swelling rate of composites manufactured with different polymer contents.

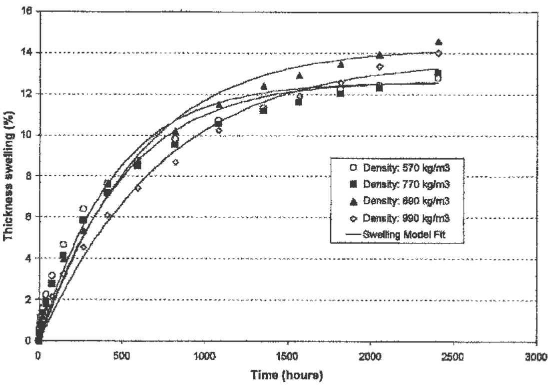

FIG. 2. Thickness swelling rate of wood fiberboard with different board densities.

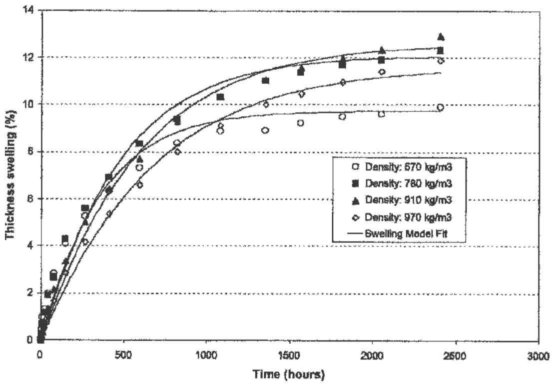

FIG. 3. Thickness swelling rate of wood fiber/polymer composites with different board densities.

marizes the results of the swelling measurements, swelling rate parameters determined by the nonlinear curve-fitting procedure using the swelling model, their standard errors, and the coefficient of correlations of the model fit. As shown in Figs. 1, 2, and 3, the swelling model fit the experimental data quite well. It is seen in Table 1 that the correlation coefficients of the model are over 0.98 for all the specimens.

As shown in Fig. 1, polymer content has a significant effect on the hygroscopic thickness swelling of the wood fiber/polymer composites. Less equilibrium thickness swelling was obtained for the composites with higher polymer content. This is because the hydrophobic nature for most of the polymers used in the wood fiber/polymer composites tends to reduce the hygroscopic thickness swelling of the composites. It is noticed that the thickness swelling for 100% polymer composites is about 2%. This little swelling may be caused mainly by the relaxation of the stresses generated during the hot-pressing process of the boards, in addition to the minor swelling from some hydrophilic polymer materials, such as nylon, etc. From the plot of swelling rate parameter vs. polymer content for the wood fiber/polymer composite shown in Fig. 4, polymer content does not have a significant effect on the hygroscopic thickness swelling rate of the composites at an oven-dry board density of about 900 kg/m^3. From Fig. 1, it shows that the initial thickness swelling rate (slope of swelling curve at the initial stage) decreases as the polymer content increases. However, since the swelling rate parameter in the swelling model was obtained considering the whole thickness swelling process until it was equilibrated, it is dependent not only on the initial rate of swell, but also on the equilibrium thickness swelling of the composites. For those materials with lower equilibrium thickness swelling (such as composites with higher polymer content), it will take less time to attain the equilibrium thickness, for

TABLE 1. *Results of thickness swelling and swelling rate parameters for wood fiber/polymer composites manufactured with different densities and polymer contents.*

Polymer content (%)	Oven-dry density (kg/m^3)	T_0 (mm)	T_4 (mm)	TS_4 (%)	Swelling rate parameter (K_{SR}) (hr^{-1}) Value (H10^{-3})	StdErr (H10^{-3})	CV (%)	R^2
0	570	2.92	3.28	12.6	2.463	0.190	7.7	0.98
	770	2.96	3.33	12.7	2.144	0.135	6.3	0.98
	890	3.33	3.80	14.3	1.843	0.087	4.7	0.99
	990	3.53	4.02	13.7	1.490	0.059	4.0	0.99
15	840	3.41	3.90	14.4	2.117	0.105	5.0	0.99
30	570	2.81	3.09	9.8	2.998	0.237	7.9	0.98
	780	2.94	3.29	12.1	2.275	0.131	5.8	0.99
	910	3.23	3.64	12.6	1.836	0.062	3.4	1.00
	970	3.67	4.10	11.7	1.615	0.047	2.9	1.00
45	910	3.21	3.53	9.9	2.065	0.097	4.7	0.99
60	910	3.19	3.44	7.7	2.077	0.090	4.3	0.99
100	920	3.31	3.37	2.0	1.956	0.143	7.3	0.98

T_0: initial thickness; T_4: final thickness; TS_4: equilibrium thickness swelling; StdErr: asymptotic standard errors of the parameter; R^2: coefficient of correlation; CV: coefficients of variation for the parameter K_{SR}.

which, it will contribute a greater magnitude of swelling rate parameter.

Figure 5 shows a comparison of the swelling rate parameter between the wood fiberboard and wood fiber/polymer composites (polymer content: 30%) as a function of the board density. A linear relationship was fit between the swelling rate and the oven-dry board density. As the board density increases, the swelling rate decreases linearly. Linear regression functions can be established as:

$$\text{0\% polymer content: } Y = 3.807 - 2.263\ X \quad (R^2 = 0.922) \qquad (4)$$

$$\text{0\% polymer content: } Y = 4.962 - 3.444\ X \quad (R^2 = 0.999) \qquad (5)$$

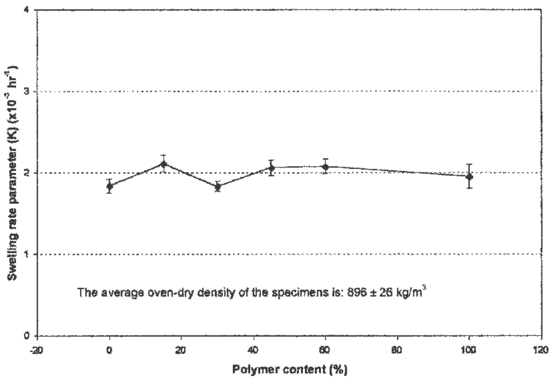

FIG. 4. Thickness swelling rate parameter vs. polymer content.

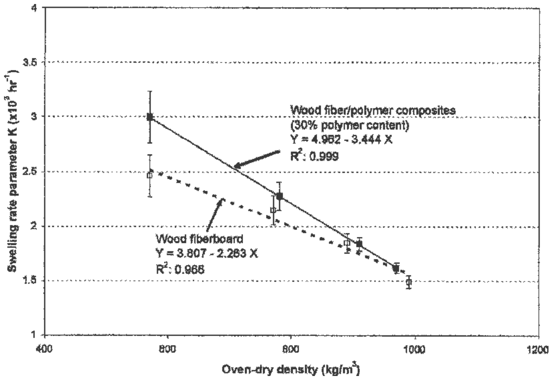

FIG. 5. Thickness swelling rate parameter vs. oven-dry density.

This result is expected since the higher the board density, the more difficult it becomes for water vapor to penetrate into the composites, and subsequently, the slower the hygroscopic thickness swelling rate. Figure 5 also shows the comparison of the swelling rate parameter between wood fiberboard (0% polymer content) and wood fiber/polymer (30% polymer content). It seems that the addition of polymers has an effect on the swelling rate, but is dependent on the density level of the composites. It is shown in Eqs. (4) and (5) that the slope of the regression line for wood fiber/polymer composites (3.444) is greater than that of the wood fiberboard (2.263). This behavior indicates that there is an interaction between the polymer content and the board density in regard to their effect on the swelling rate. At higher board densities, the polymer content has a smaller effect on the thickness swelling rate. Because of the significant effect from board density, when the density increases at a certain level, the contribution from the polymer content to the swelling rate can be negligible. It is shown in Fig. 5 that wood fiber/polymer composites may have a higher swelling rate compared to the wood fiberboard when the oven-dry density is below 900 kg/m^3. As the oven-dry board density is over 900 kg/m^3, the swelling parameters of both wood fiberboard and wood fiber/polymer composites are nearly identical. This is why the polymer content does not show an effect on the swelling rate as shown in Fig. 4, since the density of these specimens was approximately 900 kg/m^3.

Analysis of the prediction accuracy of the swelling rate model was also conducted. The results are shown in Figs. 6, 7, and 8. It is seen in Fig. 6 that the standard error of swelling model has a weak relationship with the polymer content ($R^2 = 0.45$). This is partially explained because the polymer content doesn't show an effect on the swelling rate. It shows in Fig. 7 that excellent correlations exist between the standard error and the board density ($R^2 > 0.99$). The higher the density, the lower the standard error of the model obtained. Again, this may be due to the linear relationship between the density and swelling rate parameter. The model prediction

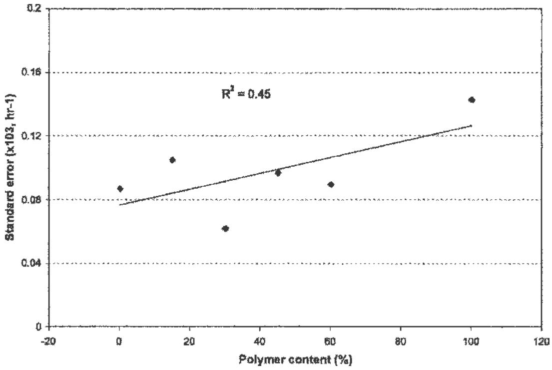

FIG. 6. Standard error of the swelling model vs. polymer content.

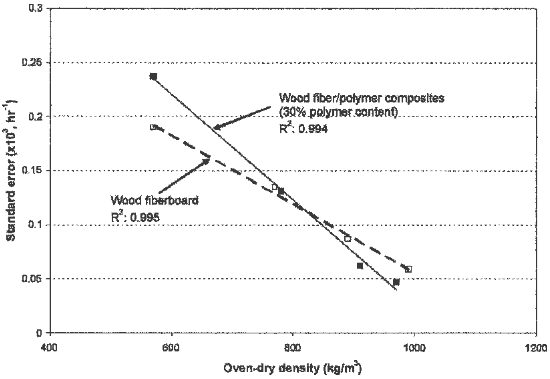

FIG. 7. Standard error of the swelling model vs. density

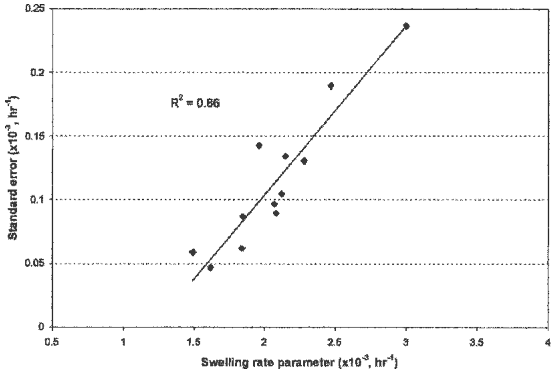

FIG. 8. Standard error of the swelling model vs. swelling rate parameter

error has a high correlation with the magnitude of the swelling rate parameter. From the previous results (Shi and Gardner 2005), the lower the swelling rate, the better the model prediction obtained. A relationship between the standard error vs. swelling rate parameter was also plotted and shown in Fig. 8 using the data in this study. It confirms that the prediction error of the swelling model has good correlation with the swelling rate parameter ($R^2 = 0.86$). The explanation of this phenomenon can be that more inner de-bonding or damage occurs for the specimen with a higher swelling rate, which will change the mode of moisture uptake. Therefore, it would change from a pure diffusion controlled swelling to a swelling including fracture inside the specimen, which may induce more error in the swelling model prediction (Shi and Gardner 2005).

CONCLUSIONS

The effect of board density and polymer content on the swelling rate was investigated, and the swelling model developed by Shi and Gardner (2005) was tested using the data generated in this study. The results of the study indicated that the swelling model provided a very good prediction of the hygroscopic swelling process of wood composites as a function of board density and polymer content. It is confirmed from this study that the lower the swelling rate, the more accurate the prediction from the model. Board density had a significant effect on the swelling rate. The swelling rate increased linearly with a decrease in board density. The effect of polymer content on the swelling rate is dependent on the board density. At an oven-dry board density of 900 kg/m^3, polymer content appears to have no effect on the thickness swelling rate.

REFERENCES

CLEMONS, C., R. A. YOUNG, AND R. M. ROWELL. 1992. Moisture sorption properties of composite boards from esterified aspen fiber. Wood Fiber Sci. 24(3):353–363.

COOPER, P. A. 1996. Rate of swelling of vacuum-impregnated wood. Wood Fiber Sci. 28(1):28–38.

ELLIS, W. D. 1994. Moisture sorption and swelling of wood-polymer composites. Wood Fiber Sci. 26(3):333–341.

GEIMER, R. L., S. E. JOHNSON, AND F. A. KAMKE. 1992. Response of flakeboard properties to changes in steam injection pressing environments. USDA Forest Service Research Paper FPL-RP-507.

HSU, W. E., W. SCHWALD, J. SCHWALD, AND J. A. SHIELDS. 1988. Chemical and physical changes required for producing dimensionally stable wood-based composites. Part 1: Steam pretreatment. Wood Sci. Technol. 22:281–289.

HUJANEN, D. R. 1973. Comparison of three methods for dimensionally stabilizing wafer-type particleboard. Forest Prod. J. 23(6):29–30.

LEHMANN, W. F. 1964. Retarding dimensional changes of particle boards. Information Circular 20. Forest Research Laboratory, Oregon State University, Corvallis, OR.

SHI, S. Q. AND D. J. GARDNER. 2006. Hygroscopic thickness swelling rate of compression molded wood fiberboard and wood fiber/polymer composites. Composites Part A: Applied Science and Manufacturing (In press).

VITAL, B. R., J. B. WILSON, AND P. H. KANAREK. 1980. Parameters affecting dimensional stability of flakeboard and particleboard. Forest Prod. J. 30(12):23–29.

YOUNGQUIST, J. A., A. KRZYSIK, AND R. M. ROWELL. 1986. Dimensional stability of acetylated aspen flakeboard. Wood Fiber Sci. 18(1):90–98.