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ORIGINAL

Modeling moisture absorption process of wood-based composites under over-saturated moisture conditions using two-part equations

Sheldon Q. Shi · Dongfeng Wu

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Abstract The objective of this study was to investigate the moisture absorption process for wood-based composites subjected to over-saturated moisture conditions. Two stages are comprised in the moisture transfer process at the over-saturated moisture conditions, an initial stage which is the moisture transfer process mainly under fiber saturation point (FSP), and a second stage which is the moisture transfer process beyond the FSP. A model was developed based on two-part equations to describe the process, from which three coefficients (k_1, k_{21}, and k_{22}) can be used to quantitatively describe the moisture transfer process under the conditions. Two different wood-based composites, wood fiberboard and wood fiber/polymer composites (polymer content: 30%), were used to test the model at four different ambient temperatures (30, 45, 62, and 80°C). It was shown that the two-part equation can accurately describe the moisture absorption process under over-saturated moisture conditions. The moisture absorption rate in the initial stage was about 30–60% greater than that in the second stage for most of the cases evaluated in this study. The higher the temperature, the greater moisture absorption parameters were obtained. At both moisture absorption stages (below FSP and above FSP), the calculated activation energy for the moisture

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S. Q. Shi (✉)
Forest Products Department,
Mississippi State University, Box 9820, Mississippi State, MS 39762, USA
e-mail: sshi@cfr.msstate.edu

D. Wu
Bioinformatics and Biostatistics Department, University of Louisville,
Louisville, KY 40292, USA

absorption rate of wood fiberboard was very close to that of wood fiber/polymer composites.

Introduction

Moisture movement in wood or wood-based materials is mainly controlled by diffusion if the moisture content of the wood is below fiber saturation point (FSP). Skaar (1958) indicated that the moisture diffusion was a combination of two movements: the vapor diffusion through the void structure and the bound water diffusion through the cell wall. It is shown that the moisture de-sorption process in wood (drying) can be successfully described by the diffusion model based on Fick's second law (Skaar 1958; Avramidis and Siau 1987; Liu 1989; Chen et al. 1995). However, when this diffusion model was applied to the moisture absorption process under water vapor conditions, systematic errors occurred at the initial moisture absorption process (Shi and Gardner 2006a) thanks to the hydroxyl groups on the wood surface accelerating the moisture absorption at the initial stage of the moisture absorption process as opposed to the delay during the moisture de-sorption process. Some researchers (Cloutier and Fortin 1993; Hartley and Schneider 1993; Cai and Shang 1992; Wu and Suchsland 1996) have conducted modeling the moisture absorption process in wood-based composites. Shi (2007a) developed a simple model describing the moisture absorption (WA) process as follows:

$$\mathrm{WA}(t) = \left(\frac{\frac{\mathrm{WA}_{1\infty}}{100}\left(1 - e^{-k_1 t^{1/2}}\right)}{1 + \frac{\mathrm{WA}_{1\infty}}{100} e^{-k_1 t^{1/2}}} \right) \times 100 \tag{1}$$

where $\mathrm{WA}_{1\infty}$ is the equilibrium water absorption (%), k_1 is the moisture absorption coefficient ($s^{-1/2}$), a constant referred to as intrinsic relative moisture absorption rate, and t is the time (s).

This equation has been successfully applied to model the moisture absorption process under water vapor conditions, from which k_1 can be used to quantify the rate of the moisture absorption in wood or wood-based materials. The similar function has also been used successfully to describe the hygroscopic thickness swelling process of wood-based composites (Shi and Gardner 2006a, b).

Over-saturated moisture condition is that when the relative humidity in the environment is 100% and the moisture condensation also occurs on the material surface. At this condition, the environment is filled with moisture mists, and the equilibrium moisture contents (EMC) of wood is higher than the FSP, but is lower than that under full saturated conditions (moisture occupies all the lumens and voids in wood-based material). This condition often occurs during the summer time in Gulf south of the United States, where the weather is humid and the ambient temperature is high. The objective of this research is to develop a mathematical model for moisture absorption process in over-saturated moisture conditions. In addition, through applying the developed model, the effect of the temperature on the moisture absorption process of wood-based composites was investigated.

Model development

Two-part equation model

Under the over-saturated conditions, the moisture transfer in wood-based materials can be considered to consist of two stages. The first stage is in the initial period of the moisture transfer process when most of the moisture absorption process is dominated by the bound water diffusion, of which the moisture content is below FSP. According to Shi (2007b), Eq. (1) can be used to describe the process for the first stage of the moisture transfer process.

The second stage of the moisture absorption process in over-saturated conditions is during the period when the moisture content of the materials is above the FSP. For modeling this process, the moisture absorption rate of wood-based composites ($\frac{\mathrm{d}W(t)}{\mathrm{d}t^{1/2}}$, in order to shorten the scale, a square root of time is used) can be assumed to be proportional to the specimen weight at the initial portion of the moisture absorption event, which is expressed as:

$$\frac{\mathrm{d}W(t)}{\mathrm{d}t^{1/2}} = k_{21}W(t) \tag{2}$$

where W is the weight of the specimen, t is the time, and k_{21} is the moisture absorption rate constant ($s^{-1/2}$).

During the second stage, the moisture in the cell wall maybe almost saturated, and free water movement in lumens of wood elements and voids in the composites might be dominating the moisture absorption process. Based on this consideration, one coefficient in the model is sufficient to describe the moisture transfer process. Another coefficient (k_{22}) is introduced in the model for adjustment. Since this adjustment coefficient can be a function of time, the initial moisture absorption rate can be expressed as:

$$\frac{\mathrm{d}W(t)}{\mathrm{d}t^{1/2}} = (k_{21} + k_{22}t^{1/2}) \times W(t) \tag{3}$$

where k_{22} is the adjustment coefficient for the moisture absorption rate ($s^{-1/2}$).

The relative moisture absorption rate declines linearly with an increase in the weight of the specimen. Therefore, the rate of change in specimen weight is then given by the differential equation:

$$\frac{\mathrm{d}W(t)}{\mathrm{d}t^{1/2}} = (k_{21} + k_{22}t^{1/2}) \times W(t) \times (1 - \frac{W(t)}{W_{2\infty}}) \tag{4}$$

where $W_{2\infty}$ is the equilibrium moisture content during the second stage of the moisture absorption process.

The analytical solution of Eq. (4) is:

$$W(t) = \frac{W_{2\infty}}{1 + \left(\frac{W_{2\infty}}{W_0} - 1\right)e^{-k_{21}t^{1/2} - \frac{k_{22}}{2}t}} \tag{5}$$

Moisture absorption of the board can be determined by the following equation:

$$\mathrm{WA}(t) = \frac{W(t) - W_0}{W_0} \times 100 \tag{6}$$

Combine Eqs. (5) and (6), after simplification, the following equation is obtained for WA (t) (%):

$$\mathrm{WA}(t) = \left(\frac{\frac{\mathrm{WA}_{2\infty}}{100}\left(1 - e^{-k_{21}t^{1/2} - \frac{k_{22}}{2}t}\right)}{1 + \frac{\mathrm{WA}_{2\infty}}{100} e^{-k_{21}t^{1/2} - \frac{k_{22}}{2}t}} \right) \times 100 \tag{7}$$

Equation (7) is used to describe the second stage of the moisture absorption process.

Therefore, the two-part equation model is a combination of Eqs. (1) and (7) of which Eq. (1) is for the first stage of the moisture absorption process under over-saturated conditions, and Eq. (7) is for the second stage. The optimal point (WA_1) between the Stage 1 and Stage 2 is obtained from the data set when the program seeks the minimum sum of square for the data fit with the non-linear curve fitting method. The coefficients k_1 from Eq. (1), and k_{21} and k_{22} from Eq. (7) can also be obtained.

The total equilibrium water absorption (WA_∞) can be calculated as:

$$\mathrm{WA}_\infty = \mathrm{WA}_1 + \mathrm{WA}_{2\infty} \tag{8}$$

Experimental

For the evaluation of the two-part equation model, the laboratory developed compression molded wood fiber based composites and wood fiber/polymer composites (30% polymer content), were used (Shi 1997). In the preparation of wood fiber based composites, hardwood fiber with 75% aspen and 25% other hardwoods were used for the wood fiberboard manufacture. The wood fiber/polymer composites were also made from hardwood fibers and the reclaimed automobile polymer mixtures. The polymer mixtures were processed from automobile shredder residual (ASR), also called automobile fluff, which contains a polymer mixture of about 27% polyurethane, 17% polypropylene, 12% polyvinyl chloride (PVC), 9% acrylonitrile butadiene styrene (ABS), and 35% other polymers. The mixed polymers were ground into particles at a size of 35 mesh (0.5 mm), and blended into the hardwood fiber furnish for making the wood fiber/polymer composites. Polymeric diphenylmethane diisocyanate (pMDI) was used as a binder. The board thickness was targeted as 3.2 mm. All the boards were processed at a press temperature of 130°C, a press time of 4 min, and a resin solids level of 4%. The target board density was 900 kg/m^3. Specimens with a dimension of $50 \times 50 \times 3.2$ mm^3 were prepared for the moisture absorption tests. Three replicates were used for each composite type. The average of the three WA measurements was used for the model evaluation. The edges of the specimens were sealed by aluminum foil bonded with epoxy to ensure moisture transport into the composites in one direction. To ensure the same moisture content for all the specimens, before each test, all the specimens were oven-dried at 103 ± 2°C until a constant weight was reached.

A humidity chamber, of which the wet bulb temperature was set higher than the dry bulb temperature, was used to control the moisture conditions. At this condition, moisture mist developed and moisture condensations were shown in the chamber, which is considered as over-saturated moisture conditions. The water droplets were also observed precipitating on the surface of the specimens. In order to evaluate the effect of temperature on the moisture absorption process, four different temperatures, 30, 45, 62, and 80°C, were used in the experiment.

This model with the two-part equations was applied to fit the experimental data. A program written in S-Plus® software (Professional Edition) was used to conduct non-linear curve fitting to the test data to find the parameters, k_1 and $WA_{1\infty}$ of Eq. (1), and k_{21}, k_{22}, and $WA_{2\infty}$ from Eq. (7). The optimal cutting point, WA_1, was found in the data set where to start applying the Eq. (7).

Results and discussions

It is seen from Fig. 1 that the two-part equation model fits the experimental measurement very well. The prediction error for wood fiber–polymer composites is usually lower than that for wood fiberboard (Table 1). It is shown in Fig. 2 that the higher the temperature, the greater the prediction error from the two-part equation model. This might be due to a greater measurement error for a higher temperature

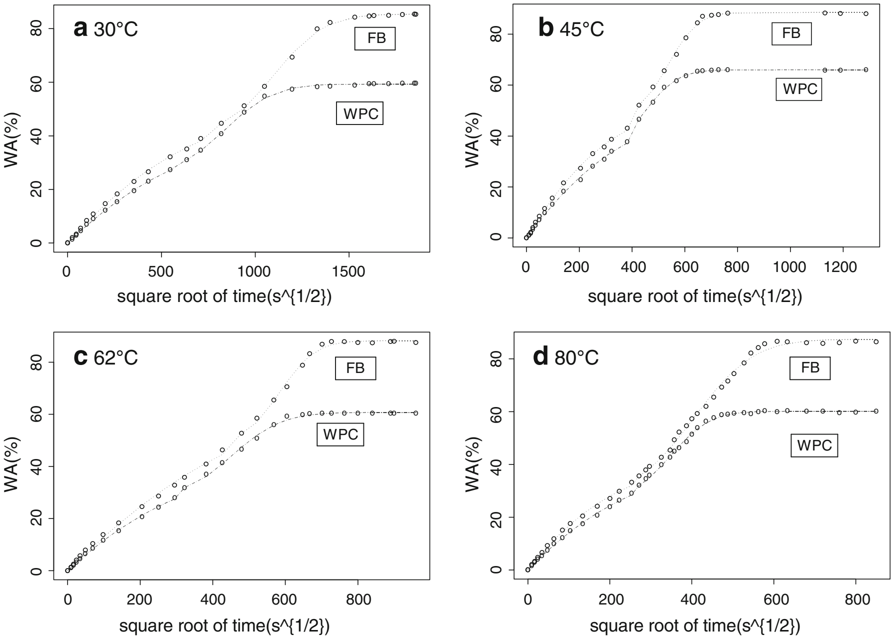

Fig. 1 Moisture absorption process for wood fiberboard (*FB*) and wood fiber/polymer composites (*WPC*) at different ambient temperatures. The effect of temperature on k_{21} for fiberboard (*FB*) and wood fiber/polymer composites (*WPC*)

Table 1 Calculated moisture absorption coefficients and the other parameters from the two-part equation model with the optimal fit

Temperature (°C)	Material	WA_1 (%)	k_1	$WA_{1\infty}$ (%)	k_{21}	k_{22}	$WA_{2\infty}$ (%)	WA_∞ (%)	SS
30	FB	39.0	0.00225	52.9	0.00090	1.286×10^{-5}	40.8	85.4	7.933
	WPC	27.4	0.00219	44.3	0.00151	1.470×10^{-5}	28.1	59.4	2.473
45	FB	43.1	0.00480	54.8	0.00255	7.190×10^{-5}	36.5	88.6	12.719
	WPC	37.8	0.00405	52.7	0.00815	6.072×10^{-5}	19.3	66.0	5.683
62	FB	46.3	0.00329	69.1	0.00185	9.712×10^{-5}	35.5	88.2	27.810
	WPC	28.1	0.00423	43.3	0.00187	5.062×10^{-5}	28.9	60.7	7.629
80	FB	33.2	0.00654	42.8	0.00268	4.416×10^{-5}	51.7	87.4	47.966
	WPC	29.0	0.00535	42.4	0.00406	1.040×10^{-4}	28.0	60.1	8.865

FB wood fiberboard, *WPC* wood fiber-polymer composites, WA_1 optimal cutting point in water absorption obtained from the optimal fit, $WA_{1\infty}$ calculated equilibrium water absorption from Eq. (1), k_1 moisture absorption coefficient from the first stage in Eq. (1), k_{21} moisture absorption coefficient from the second stage in Eq. (5), k_{22} moisture absorption coefficient adjusted parameter from the second stage in Eq. (5), $WA_{2\infty}$ equilibrium water absorption from second stage moisture absorption process in Eq. (5), WA_∞ overall equilibrium water absorption, *SS* sum of square

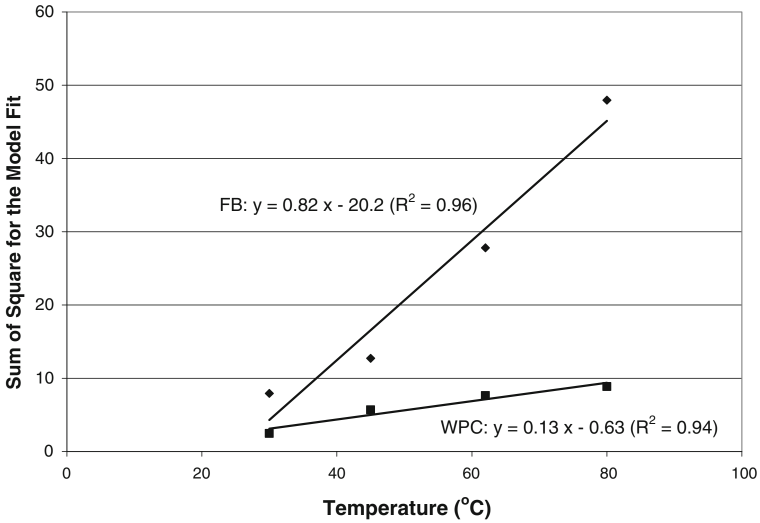

Fig. 2 The effect of temperature on sum of square for fiberboard (*FB*) and wood fiber/polymer composites (*WPC*)

testing. The specimen weight measurements were taken by moving the specimens in and out of the environment chamber, which would interrupt the moisture absorption process. The higher the temperature, the greater the degree of the interruption during the measurement, and the larger the measurement error. Figure 2 also shows that the effect of temperature on the prediction error was more significant for wood fiberboard (slope is 0.82) than that for wood fiber/polymer composites (slope is 0.13).

From the two-part equation model, it is seen that the first equation has one moisture absorption coefficient (k_1), which is similar to the bound water diffusion process (first stage of the process) since most of the diffusion occurs below fiber saturation point of wood-based materials. For the second equation in the model, a second coefficient (k_{22}) was used since it is to describe the moisture process with much more free water movement, in addition to having a moisture absorption coefficient (k_{21}). This second coefficient is the adjustment parameter which is used to adjust the prediction errors due to the free water movement in the lumens and voids. For most cases, the moisture absorption rate at the first stage (k_1) is about 30–50% greater than that at the second stage (k_{21}), as shown in Table 1. This is mainly due to the nature of the moisture absorption process. At the initial stage of the moisture absorption process, the moisture absorption is faster. As the time elapses, the moisture absorption rates slow, and tend to reach 0 at equilibrium. The adjustment coefficients for the second stage (k_{22}) are usually small, around only 1–5% of k_{21}.

Since the first equation is mainly describing the moisture transfer below FSP, technically, the optimal cutting point in water absorption values, $WA_{1,}$ obtained from the non linear curve fitting program should be close to the FSP of the composites. As shown in Table 1, the WA_1 values were in the range of 33–46% for wood fiberboard and 27–37% for wood fiber/polymer composites. They were about 9–17% higher than the FSP which is around 24–29% for wood fiberboard and 19–24% for wood fiber/polymer composites with 30% polymer content (Shi 2007b). While bound water diffusion dominates the moisture absorption process, some degree of free water movement also occurs. This may be part of the reason that the calculated starting points for the second moisture transfer stage are higher than the FSP.

As shown in Table 1, the overall equilibrium water absorption (WA_∞) was obtained as 85–89% for wood fiberboard, and 59–66% for wood fiber/polymer composites. This was about 60% higher than the FSP for wood fiberboard and 40% for wood fiber/polymer composites (existing in the lumens or voids of the composites as free water). It is also seen from the equilibrium water absorption data in Table 1, that wood fiber/polymer composites provided about 30% less moisture uptake than the wood fiberboard. This coincides with the polymer content used for the wood fiber/polymer composites (30%). Therefore, wood fiber is the main contributor to the water absorption in wood fiber/polymer composites.

It was also seen from Table 1 that both moisture absorption coefficients of two stages changed as a function of temperature. The higher the temperature, the greater the moisture absorption rate in the wood-based composite. This process occurs because water molecules move faster at higher temperature. As shown in Table 1, from 30 to 80°C, the moisture absorption rate increase for the initial stage was 191% for the wood fiberboard and 144% for the wood fiber/polymer composite. For the second stage, the rate was 198% for the wood fiberboard and 169% for the wood fiber/polymer composites. This shows that temperature has a greater effect on the wood fiberboard compared with the wood fiber/polymer composite. The Arrhenius plots in Figs. 3 and 4 show the relationship of ln k_1 versus 1/T and ln k_{21} versus 1/T, respectively, for both wood fiberboard and wood

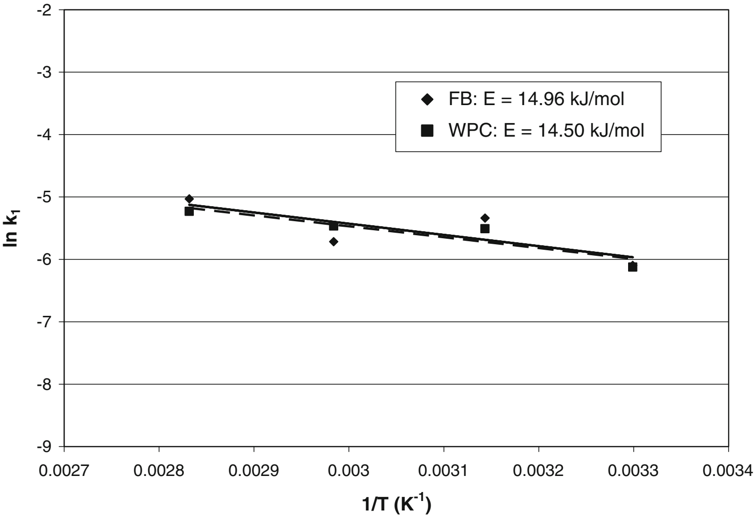

Fig. 3 The effect of temperature on k_1 for fiberboard (*FB*) and wood fiber/polymer composites (*WPC*)

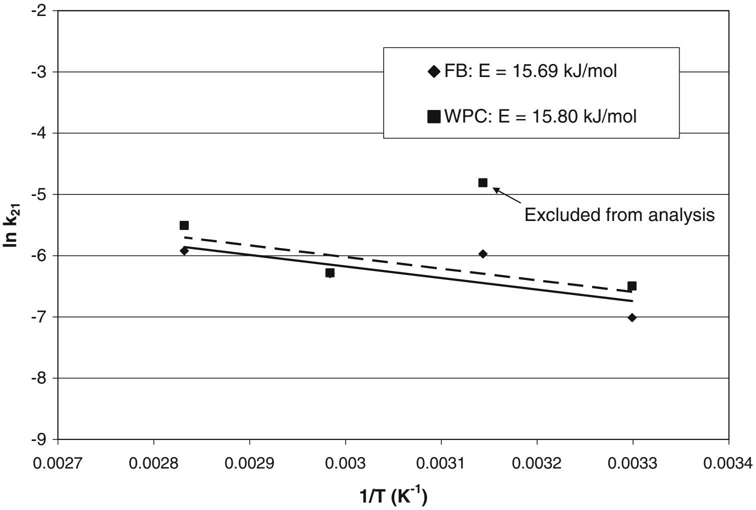

Fig. 4 The effect of temperature on k_{21} for fiberboard (*FB*) and wood fiber/polymer composites (*WPC*)

fiber/polymer composites. The activation energies (E_a) were calculated from the Arrhenius equation:

$$k_1 \,\text{or}\, k_{21} = Ae^{-E_a/RT} \tag{9}$$

where A is a constant, R is gas constant (8.314 J/mol K), and T is the temperature (degrees Kelvin, K).

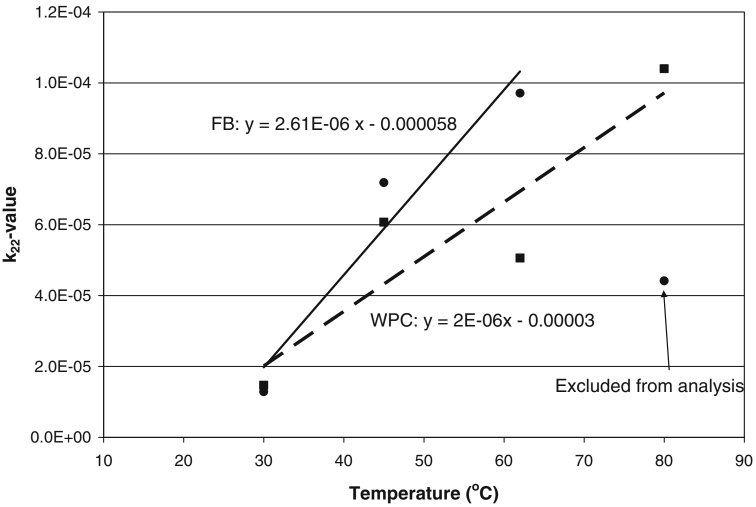

Fig. 5 The effect of temperature on k_{22} for fiberboard (*FB*) and wood fiber/polymer composites (*WPC*)

It is seen from Figs. 3 and 4 that the activation energies calculated from the plots of wood fiberboard and wood fiber/polymer composites are similar (14.96 vs. 14.50 kJ/mol for k_1 and 15.69 vs. 15.80 kJ/mol for k_{21}). This indicates that the degree of temperature effect on moisture absorption rate is similar between the wood fiberboard and wood fiber/polymer composites used in this study. Figure 5 shows the effect of temperature on the adjustment coefficient (k_{22}) for the second stage of the moisture absorption process. This adjustment coefficient was higher at higher temperature from experimental measurements in this study except for that at 80°C. This difference may be due to the fact that higher temperature may give more prediction error on the moisture absorption rate, which needs a greater adjustment coefficient.

Conclusion

The two-part moisture absorption model developed in this study can accurately describe the moisture absorption process under over-saturated moisture conditions. The model can be used to quantitatively compare the moisture absorption rates of different wood-based materials. For the two different wood-based composites used in the study, wood fiberboard and wood fiber/polymer composites (polymer content: 30%), the moisture absorption rate in the initial stage is about 30–60% greater than that in the second stage for most of the specimens used in this study. The higher the temperature, the greater moisture absorption coefficients were obtained. The calculated activation energies are very close between the wood fiberboard and wood fiber/polymer composites at both absorption stages (below FSP and above FSP).

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