A PROCEDURE TO DETERMINE WATER ABSORPTION DISTRIBUTION IN WOOD COMPOSITE PANELS[1]

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ABSTRACT

A procedure is presented to determine the water absorption distribution of wood composite panels. The procedure is based on the direct measurement of the vertical density distribution before water soak, the vertical density distribution after the water-soaked specimens have been reconditioned to pre-soak weights, and the construction of the vertical density distribution for the specimens immediately after water soak. The separation of "wood mass" and water was achieved through the application of radiation absorption principles involving the two elements. The procedure was used to examine the water absorption distributions of medium density fiberboard, oriented strandboard, and particleboard. A good agreement was obtained between the estimated average water absorptions and measured water absorptions. Water absorption distribution in relation to the layer density and layer thickness swell was discussed.

Keywords: medium density fiberboard, oriented strandboard, particleboard, thickness swell distribution, vertical density distribution, water absorption.

INTRODUCTION

The water absorption (WA) and the thickness swell (TS), measured by the water soak method (24-h exposure is the most common practice), are usually taken as the primary measures of the water resistance ability of wood composite panel materials (ASTM 1994). The water soak method accelerates WA and is often a preferred procedure for laboratory analysis; cyclic relative humidity tests are also used to evaluate moisture up-take of many interior-use panel materials. American Society for Testing and Materials (ASTM) specified the WA test when it first published the tentative test standard for wood-base fiber and particle panel materials (ASTM 1949).

Two mechanisms of water inclusion are normally involved in the WA test: adsorption (bound water within the cell wall) and absorption (free water in the cell lumens). The bound water is responsible for the hygroscopic swell and triggers the release of set-in compressive stress (or strain) of composite products. Bound water reaches its maximum when the cell wall

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is fully saturated (about 25% if no alteration of cell-wall material is assumed to have occurred because of hot pressing). The two mechanisms of water inclusion and the two types of water are not separately accounted for in the WA test, and both free and bound water may be present at any time during the WA test. Total WA and also the relative amounts of bound water and free water are probably controlled by the structure-related factors such as wood cell-wall collapse during consolidation, the vertical density distribution (VDD), and the horizontal density distribution in the panels (Xu 1993). The complicated phenomenon of WA has not been well understood due to the lack of understanding of wood composite structure.

In a previous study (Xu and Winistorfer 1995b), we found that TS was not uniformly distributed through the thickness dimension of composite panels, and layer TS was positively correlated to layer density. The finding of layer density proportional TS distribution prompted us to examine the WA distributions in these wood composite panels. We believe that an improved understanding of WA as influenced by layer density will help us better understand and improve WA and TS of wood composite panel materials. This paper describes a technique to estimate WA distribution using vertical density distribution measurement of composite material, as well as radiation absorption characteristics of wood and water.

MATERIALS AND METHODS

The materials consisted of three commercial composite products: 1) medium density fiberboard (MDF) (adhesive: urea-melamine-formaldehyde, density: 760 kg/m^3, thickness: 15.8 mm); 2) oriented strandboard (OSB) (adhesive: phenol-formaldehyde, density: 670 kg/m^3, thickness: 14.9 mm); and 3) particleboard (adhesive: urea-formaldehyde, density: 660 kg/m^3, thickness: 15.9 mm). These commercial materials were procured from a commercial supply house, and a history of manufacturing processing conditions is not known. The materials were conditioned at a room temperature of approximately 23°C and 50% relative humidity, and an equilibrium moisture content of 7% was maintained before test. For each material, specimens measuring 100 mm × 100 mm were prepared, and their VDDs were measured using the scanning gamma ray densitometer according to the procedures previously described by Winistorfer et al. (1986). Specifically, counts (transmitted radiation at the detector) were taken for 20 s at each step, with a scan step size of 0.254 mm. A detector window slit with a width of 0.20 mm and a height of 10 mm was used.

Specimens of MDF, OSB, and particleboard were subjected to water soak exposure times of 24 and 168 h; three specimens were used for each exposure treatment. The use of 168-h water soak treatment, together with the standard 24-h water soak practice, was primarily for validation of the technique. The use of a specimen size of 100 mm × 100 mm rather than the standard 150 mm × 150 mm to measure WA was determined by the configuration of the densitometer. However, recent studies have indicated that a TS and WA specimen size of 100 mm × 100 mm is appropriate and provides consistent test results as compared to the 150-mm × 150-mm specimens (Xu and Steiner 1995). These specimens were then gamma ray scanned immediately after the water soak test and again after the specimens had equilibrated (dried) to their original, pre-soak weights.

DEVELOPMENT OF THE WATER ABSORPTION DISTRIBUTION PROCEDURE

Let A represent the state of a composite specimen before water soak (thickness: l), B represent the state of the same composite specimen immediately after the water soak test (thickness: m), and C represent the state after the water-soaked specimen has been reconditioned to its pre-soak weight (thickness n). Further, let $f(x)$ stand for the density values (unit: kg/m^3, thickness increment: 0.254 mm) at state A, and $h(z)$ stand for the density values (unit: kg/m^3, thickness increment: 0.254 mm) at state

C. The VDD values at states A and C were used to determine the layer TS distribution in our previous investigation (Xu and Winistorfer 1995b).

The VDDs at states A and C were determined by the direct scanning gamma ray densitometry method using a mass attenuation coefficient of 0.0185 (m^2/kg) (Winistorfer et al. 1986). However, the VDD at state B can not be directly determined by the same method, as the mass attenuation coefficient was variant and unknown (affected by a variant, unknown amount of water across the panel thickness). At this state, the layer density would be the weighted average density of water and "wood mass." (We acknowledge that some resin, wax, and about 7% equilibrium moisture content at room condition were also present when the composite panel density was measured at states A and C; therefore we put quotation marks around wood mass.) If the VDD of "wood mass" at state B can be determined, the amount of water, therefore the WA, can be determined by the radiation absorption measurement technique.

Constructing the VDD of "wood mass" at state B

Theoretically, TS of the composite specimen at state B contains both the unrecoverable swell and hygroscopic swell, while TS at state C contains only the unrecoverable swell component. The hygroscopic swell can be approximated as the difference in board thicknesses between states B and C: m-n. This hygroscopic swell was probably not uniformly distributed through the panel thickness. For the purpose of simplicity, however, it was assumed in this investigation that this hygroscopic swell was uniformly distributed through the thickness dimension of the panel. (We understand that certain assumptions are unavoidable; if we need to estimate WA distribution, this assumption of uniformity in hygroscopic swell may not be too much in error as hygroscopic swell is usually small compared to the permanent unrecoverable swell.)

Using the above assumption, the VDD of "wood mass" at state B can be constructed. This construction was performed simply by increasing the thickness increment in VDD at state C with a factor of m/n, and by decreasing the density values by a factor of n/m (the same board weight was observed). Obviously, the same number of density points in VDD of "wood mass" at state B existed as in the VDD at state C.

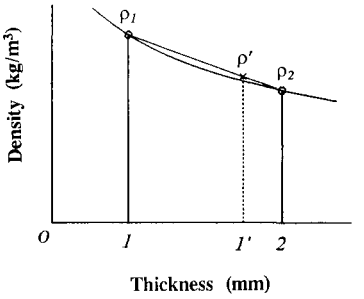

FIG. 1. A schematic showing the density estimation by linear interpolation.

The VDD constructed above had a different thickness increment (0.254*m/n mm) than VDDs at states A and C (thickness increment: 0.254 mm). To generate the VDD at the same thickness increment of 0.254 mm, a linear assumption was made between adjacent density data points in the VDD, as in our previous investigation (Xu and Winistorfer 1995b). For example, as shown in Fig. 1, the density value at point *1'*, which is 0.254 mm away from point *1*, can be estimated as

$$p' = p_1 + (p_2 - p_1)n/m \qquad (1)$$

where p_1, p_2, and p' are the density values at locations of *1*, *2*, and *1'*.

In this study, a FORTRAN algorithm was written to construct this VDD with a thickness increment of 0.254 mm. Function $g(y)$ was used to designate the generated density values of "wood mass" at state B (density: kg/m^3, thickness increment: 0.254 mm).

Estimating the water absorption at state B

The basic radiation absorption equation to determine material density is expressed as

$$I = I_0 e^{-pu_m t} \quad (2)$$

where:

- I = intensity of the radiation beam after passing through a material (counts)
- I_0 = intensity of the radiation beam without passing through a material (air counts)
- u_m = material mass attenuation coefficient (m^2/kg)
- t = material distance (m)
- p = material density (kg/m^3)

At state B, u_m was not constant as the panel material at any measurement location contained an unknown amount of water. Using the elemental analysis (Olson and Arganbright 1981; Coppola and Reiniger 1974), Eq. (2) was changed to

$$I = I_0 e^{-(u_w p_w + u_a p_a)t} \quad (3)$$

in which u_w and u_a are the attenuation coefficients of "wood mass" and water, respectively, and p_w and p_a are the respective densities of "wood mass" and water mass.

Our laboratory densitometer system uses an americium-241 (Am^{241}) radiation source with a photon energy of 60 KeV. At this energy level, u_w was determined to be 0.0185 (m^2/kg) for our routine density measurement of commercial wood composite panels (Laufenberg [1986] has shown that a small amount of resin and wax has very limited influence on the mass attenuation coefficient of wood composite panels; the small amount of resin and wax has been accounted for in establishing the mass attenuation coefficient), and u_a was determined to be 0.0207 (m^2/kg) according to Olson and Arganbright [1981]). Using the density values of "wood mass" constructed above as the input for p_w, the density of water mass was determined by the following equation

$$p_a = 1/(tu_a)\cdot\ln(I_0/I) - u_w p_w/u_a \quad (4)$$

There are two methods to calculate the layer WA distribution. One method involves the estimation of actual layer WA based on the *in situ* weights (or densities) of water and "wood mass" at the same layer location as

$$WA(\%) = 100\cdot p_a/p_w \quad (5)$$

An alternative method estimates the layer WA based on the *in situ* water mass (density) and overall average board density ($\bar{p}$) as

$$WA(\%) = 100\cdot p_a/\bar{p} \quad (6)$$

Since the average of all layer WA calculated by Eq. (6) equals the overall WA theoretically, and the layer WA calculated by Eq. (6) provides the relative amount of water through the panel thickness, Eq. (6) was used in this investigation to calculate the layer WA.

Water absorption based on state A

The layer WA distribution estimated above was based on the thickness reference at state B (board thickness m at state B was larger than the original board thickness l). To express the layer WA distribution in reference to state A (original state), the following procedure was developed.

Let $f(x_1)$, $f(x_2)$, and $f(x_3)$ stand for the density values at locations of x_1, x_2, and x_3 at state A, and $g(y_1)$, $g(y_2)$, and $g(y_3)$ stand for the density values of "wood mass" at locations of y_1, y_2, and y_3 at state B (Fig. 2). Suppose layer $L_{y_1y'}$ (y' is somewhere in between y_2 and y_3) at state B originated from layer $L_{x_1x_2}$ at state A, and further suppose the equal weight of "wood mass" before and after layer swell (Xu and Winistorfer 1995b), the following equation was established as

$$ax^2 + bx + c = 0 \quad (7)$$

in which, $a = [f(x_1)+f(x_2)]/0.254$, $b = f(x_1)$, $c = [g(y_1)+g(y_2)]\cdot 0.254$, x is the distance from point y_2 to y'.

The solution of Eq. (7) determines the location at state B to estimate the layer WA at state A. For example, using the linear interpolation assumption, the layer WA at location x_2, $WA(x_2)$, at state A was estimated by

$$WA(x_2) = WA(y_2) + [WA(y_3) - WA(y_2)]\cdot x/0.254 \quad (8)$$

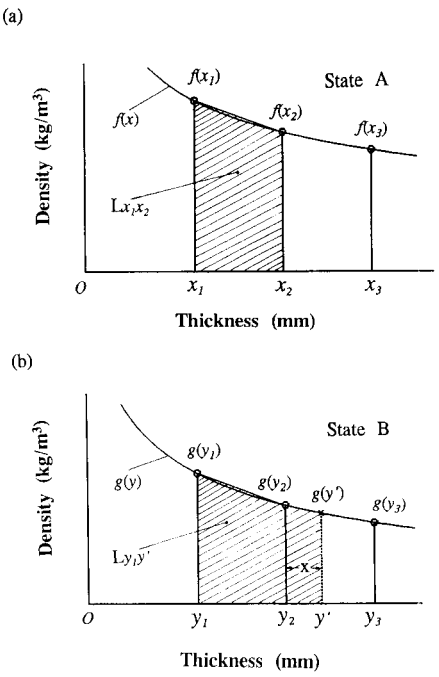

FIG. 2. A schematic showing the procedure to determine the swollen thickness of individual horizontal layers.

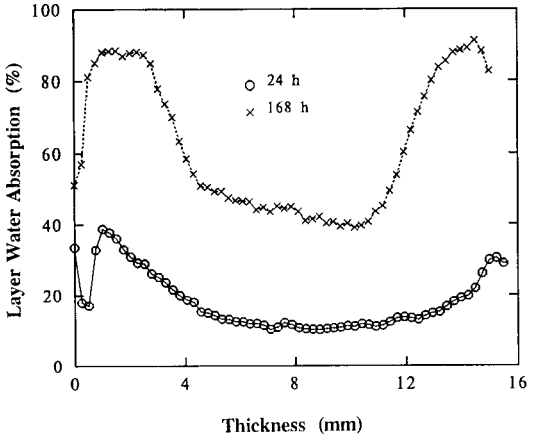

FIG. 3. Layer water absorption distributions of the medium density fiberboard after two water soak exposure times.

while WA(y_2) and WA(y_3) are the layer WA at locations of y_2 and y_3 (state B).

The layer TS of layer $L_{x_1x_2}$ can be calculated as

$$TS = x*100/0.254 \quad (9)$$

The procedure for estimating the swollen thickness of individual horizontal layers by Eq. (7) was exactly the same as the procedure used in our previous investigation of layer TS development (Xu and Winistorfer 1995b). The FORTRAN algorithm developed in the previous investigation was used for the present study.

NUMERICAL EXAMPLES AND DISCUSSION

General

For the three materials tested and two water soak treatments used, the hygroscopic swells or the differences in specimen thicknesses between states B and C were minimal. Specifically, for the 24-h and 168-h water exposure treatments, the hygroscopic swells (relative to the board thicknesses at state B) were 4.8% and 10.4% for the MDF samples, 4.9% and 8.2% for the OSB samples, and 2.9% and 7.5% for the particleboard samples, respectively. The small differences in the thicknesses between states B and C do not necessarily validate the assumption of uniformity in hygroscopic swell, but they do suggest that the assumption and the construction of VDD for state B do not necessarily result in too much error.

Case 1: medium density fiberboard

The WA distributions predicted from the model for the MDF material based on the average of three specimens at a layer resolution thickness of 0.254 mm are shown in Fig. 3. The average WA values from these distributions were 18.3% and 61.1% for the 24-h and 168-h water soak exposures, respectively. These values differed slightly from the measured average WA values (21.2% and 66.4%, respectively). The small differences in these average WA values indicate that the procedure for determining the WA distribution is feasible.

Similar to the layer TS distribution reported in our previous investigation (Xu and Winistorfer 1995b), the surface regions of the panel

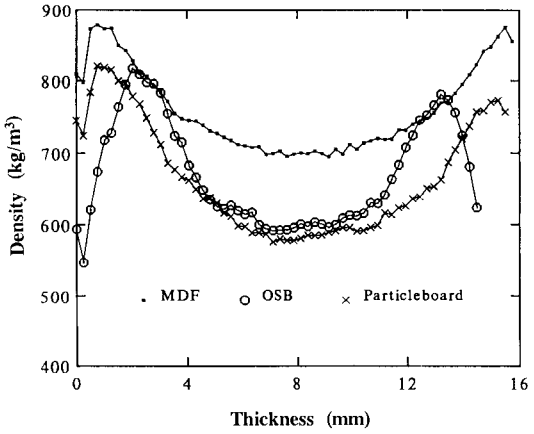

FIG. 4. The relationship between layer water absorption and layer density of the medium density fiberboard.

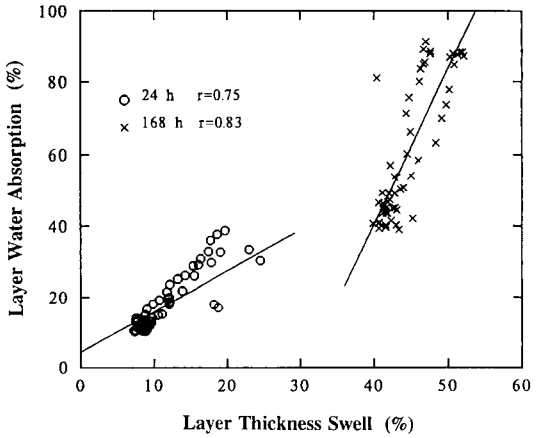

FIG. 6. The relationship between layer water absorption and layer thickness swell of the medium density fiberboard.

exhibited higher WA than the center layers. Many processing treatments can contribute to this distribution phenomenon. For example, changing the resin and wax distributions or using different furnish materials through the panel thickness can result in a WA distribution. However, it is believed that the VDD through the thickness dimension in the MDF material (Fig. 4) was the single most important factor in the layer WA distribution for this study. More water was taken up in the high density regions because more wood material was available in these regions for water adsorption. Figure 5 shows the scatterplot between the layer density and layer WA, together with the result of the correlation analysis (r = linear correlation coefficient). The data indicate that the layer WA was positively correlated to the layer density in this MDF material.

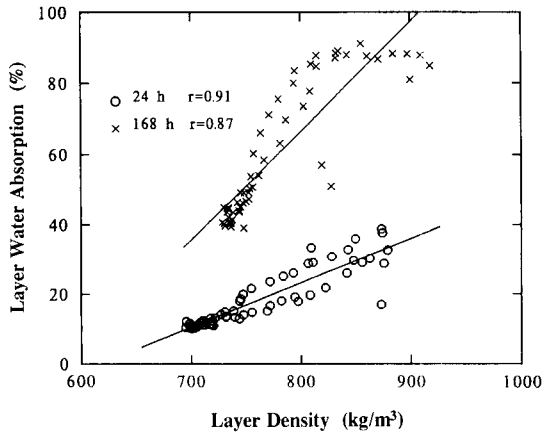

FIG. 5. Vertical density distributions of the medium density fiberboard, oriented strandboard, and particleboard materials.

Since layer TS was also positively correlated to the layer density (Xu and Winistorfer 1995b), the layer WA was expected to be positively correlated to the layer TS (Fig. 6). It is generally believed that water up-take is the prerequisite for thickness expansion; a linear relationship between TS and WA has been reported for many commercial and laboratory composite products (Suchsland 1973; Suchsland et al. 1978; Winistorfer et al. 1996).

Case 2: oriented strandboard

The predicted layer WA distributions across the thickness of the OSB are shown in Fig. 7; these distributions were also based on the average of three specimens and were generated at a resolution thickness increment of 0.254 mm. The layer WA distributions yielded average WA values of 13.4% and 41.5% for the 24-h and 168-h water soak exposures, respectively, which also differed slightly from the measured values (16.5% and 47.2%, respectively).

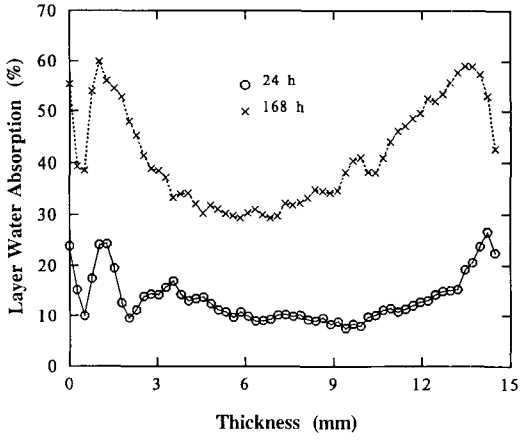

FIG. 7. Layer water absorption distributions of the oriented strandboard after two water soak exposure times.

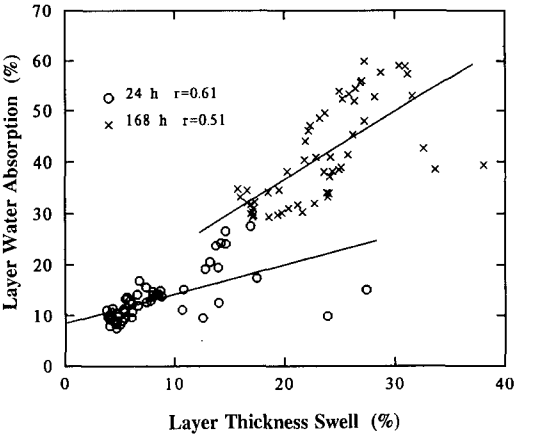

FIG. 9. The relationship between layer water absorption and layer thickness swell of the oriented strandboard.

Similar to the MDF material, layer WA at the surface regions of the OSB was also generally higher than that in the center. Figure 8 shows the positive correlation between the layer density and layer WA for both 24-h and 168-h water soak exposures.

The layer WA distribution of OSB was also believed to be correlated to the layer TS. The scatterplot between the layer TS and layer WA (Fig. 9) demonstrated a positive correlation ($r > 0$) for both water soak exposure times.

Case 3: particleboard

The predicted WA distributions at a layer resolution thickness of 0.254 mm for the particleboard samples based on the average of three specimens are shown in Fig. 10. The average WA values given by these distributions were 30.5% and 77.2% for the 24-h and 168-h water soak exposures, respectively. These average values also agreed well with the measured values (32.1% and 82.3%, respectively),

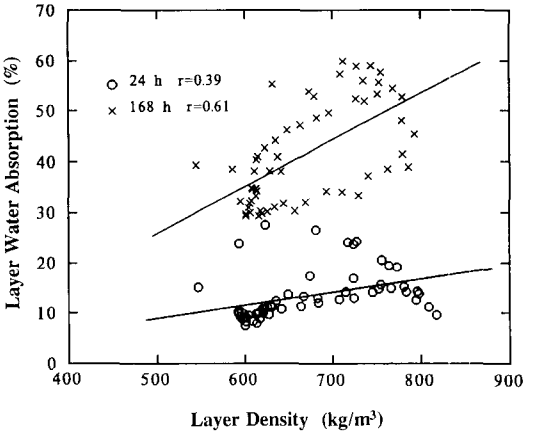

FIG. 8. The relationship between layer water absorption and layer density of the oriented strandboard.

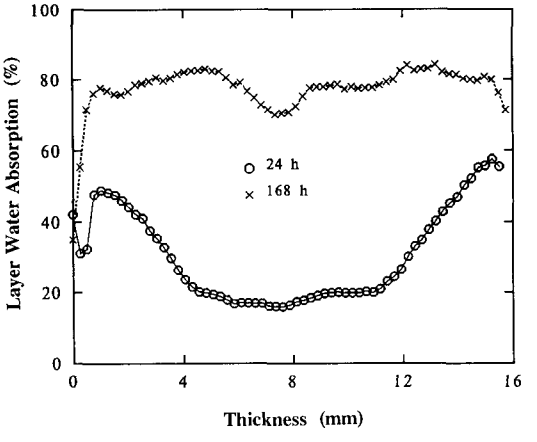

FIG. 10. Layer water absorption distributions of the particleboard after two water soak exposure times.

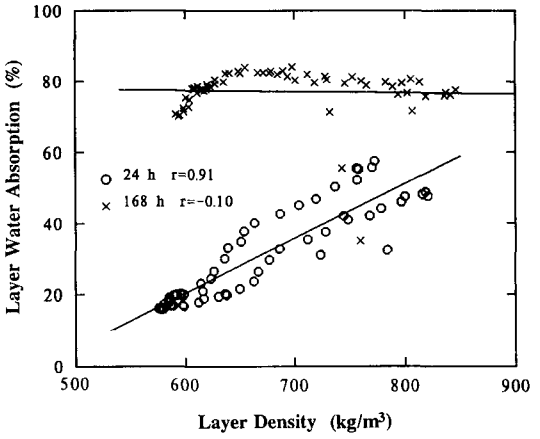

FIG. 11. The relationship between layer water absorption and layer density of the particleboard.

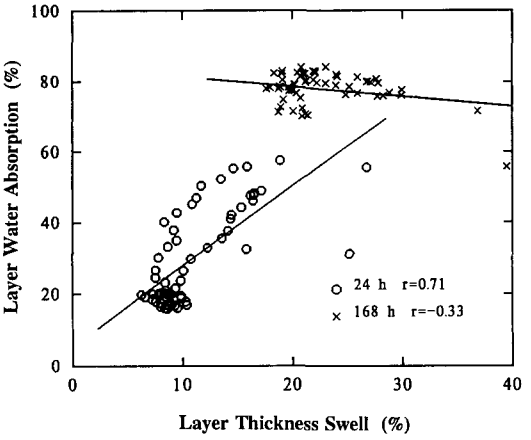

FIG. 12. The relationship between layer water absorption and layer thickness swell of the particleboard.

which suggests that the procedure to estimate the WA distribution is appropriate.

The layer WA distribution of particleboard after 24-h water soak exposure showed a response similar to the MDF and OSB specimens, i.e., positively correlated to layer density and to layer TS (Figs. 11 and 12). However, the 168-h soak treatment resulted in somewhat "abnormal" response for the layer WA. At this treatment level, the layer WA was either non-sensitive or negatively correlated to the layer density or layer TS (Figs. 11 and 12). A possible explanation for this behavior is that the particleboard materials used in this study were manufactured with urea-formaldehyde adhesives, while MDF and OSB panels were bonded with more water-resistant adhesive systems. The prolonged water soak might have severely deteriorated the water resistance performance of the urea-formaldehyde adhesive in the core of particleboard (low compaction zone), which contributed to an increased WA in this region.

For all the three panel products (MDF, OSB, and particleboard), the average WA values yielded from the predicted layer WA distributions were slightly lower than those values measured. This is probably because the WA values at surrounding edges of WA specimens are slightly higher than those in the center portions. The layer WA distributions were generated using the VDD measurements in the center portions of the specimens, which is the standard procedure in density measurement.

We have also developed a layer removal technique (slicing) to measure layer properties of these wood composite panels (Xu and Winistorfer 1995a). This slicing technique involves the mechanical sectioning of composite specimens into thin horizontal layers and measuring the properties on these layers. Using the slicing technique, layer WA was also found to be positively correlated to layer density and layer TS (Winistorfer and Xu 1996). Although these two techniques cannot be compared directly, they are complementary in studying the layer properties of wood composite panels.

SUMMARY AND CONCLUSIONS

Modern wood composite technology employs a fast press closure rate, high press temperature, and/or other techniques to achieve high density surface–low density core panel constructions. This high density face–low density core scenario is desired for improved bending properties of composite panel products for many applications. The present study, together with our previous investigation (Xu and Winistorfer 1995b), has shown clearly that the high density surface regions contributed

more to the overall water absorption (except the particleboard after 168-h exposure) and thickness swell of these panel materials. While this finding of the layer density effect on layer water absorption and layer thickness swell may not lead us to forgo the high density face–low density core structure concept, it nevertheless clearly points out that future research and manufacturing operations to improve the dimensional stability should be focused on the high density surface regions. For example, more adhesive/wax or improved adhesive/wax systems could be applied to the surface furnish to improve the dimensional stability of high density surface regions, therefore improving the stability of the whole panel. Similarly, low density wood species could be used solely as the surface furnish, or certain treatments (acetylation etc.) could be performed to alter the compressive rheological characteristics of surface furnishes.

The procedure developed in this study to determine the water absorption was based on the direct measurement of vertical density distributions before and after water soak, the construction of vertical density distributions for the specimens immediately after water soak, and the application of radiation absorption principles. A more detailed discussion of the procedure, a description of our densitometer system, and the FORTRAN algorithms are available from the authors.

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