

# EFFECT OF PANEL MOISTURE CONTENT AND DENSITY ON MOISTURE MOVEMENT IN MDF

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## ABSTRACT

This study examined the effect of medium density fiberboard (MDF) density and sorption state on the sorption isotherms and the effect of panel moisture content and density on the effective water conductivity and diffusion coefficient of MDF panels. A total of 39 laboratory-made MDF panels with dimensions 650 mm × 650 mm × 12 mm divided into 3 density groups (540 kg/m<sup>3</sup>, 650 kg/m<sup>3</sup>, and 800 kg/m<sup>3</sup>) was produced. The surface layers of each panel were removed, and the thickness of the remaining core layer of homogeneous density was reduced by sanding to 6 mm. The sorption isotherms were determined by exposing MDF samples to controlled relative humidities. The effective water conductivity was determined by the instantaneous profile method. Medium density fiberboard from all density levels displayed a marked sorption hysteresis. Both in adsorption and in desorption, the MDF specimens with higher density levels equilibrated at higher levels of moisture content. Moisture content had a stronger effect than density on the effective water conductivity. In desorption, the higher the moisture content level, the higher the effective water conductivity. Conversely, in adsorption, the effective water conductivity decreased as moisture content increased. The effective water conductivity in desorption and the diffusion coefficients both in desorption and adsorption were significantly higher for panels with a density of 540 kg/m<sup>3</sup> than for densities of 650 and 800 kg/m<sup>3</sup>. In adsorption, the effective water conductivity of panels with a density of 540 kg/m<sup>3</sup> was significantly higher than for a density of 800 kg/m<sup>3</sup>.

**Keywords:** Medium density fiberboard, effective water conductivity, diffusion coefficient, sorption isotherm, moisture content, density.

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## INTRODUCTION

As solid wood and other wood-based composites, medium density fiberboard (MDF) is a hygroscopic material. Therefore, its moisture content ( $M$ ) depends on the relative humidity (RH) and temperature of the surrounding air. It is common knowledge that  $M$  directly affects panel properties, e.g., thickness swell and linear expansion, surface smoothness (Fischer and Merkle 1963; Kehr 1966), thermal conductivity (Kamke and Zylkowski 1989), stiffness and strength (Planche 1999), and formaldehyde emissions (Jann and Deppe 1990) among other characteristics. During processing, finishing, and in service, MDF panels are exposed to large ambient relative humidity changes. The induced moisture movements and the resulting changes in dimensions and mechanical properties of the panel "layers" located at various distances from the surface can disturb panel balance. This causes deviations from the initial panel flatness (Suchsland and McNatt 1986). Deformed panels hinder further processing and affect the performance of final products such as furniture, cabinetry, and millwork.

The control of MDF properties and dimensional stability requires the ability to predict moisture movement in the panels. In fact, predicting and controlling moisture movements are important tools for maximizing MDF performance. In wood composites, equilibrium moisture content (EMC) depends on density (Vital and Wilson 1979), wood species, resin type, and resin content (Roffael and Schneider 1979; Greubel and Drewes 1987), temperature reached during pressing (Seifert 1972), specific treatments (e.g., with heat or chemicals) during production, and application of additives. Moreover, the rate of moisture diffusion in MDF panels is affected by the transient moisture level (Koponen 1984). In other words, the diffusion coefficient is a function of  $M$ . This must be taken into account when considering the development of warp over time since it affects the development of  $M$  gradients in the panels.

From all the factors affecting the development of warp in MDF panels, the overall density and the vertical density profile are routinely monitored by mill personnel and can be changed easily. It is therefore necessary to determine how these parameters impact panel warping.

There are only a few studies referring to the sorption behavior of MDF. Although the shape of the sorption isotherms produced by the different authors is very similar, the equilibrium moisture content (EMC) values corresponding to a specific RH level vary. Also, the effect of density on the EMC levels has not yet been established for MDF. As pointed out by Bolton and Humphrey (1994), most materials tested so far were characterized by a "systematic spatial variation of density," commonly called density profile, causing the actual relation between density and moisture diffusion over time to remain uncertain. The studies evaluating moisture diffusion in MDF have often been associated with conditions that are not typical for MDF in service. For example, Koponen (1984) determined the diffusion coefficient of MDF by water soaking. Samuelsson and Söderström (1994) and Rosenkilde and Söderström (1997) used MDF samples to model the drying of solid wood and consequently produced diffusion coefficients for MDF specimens exposed to temperatures higher than 50°C. For this reason, these data can not be used for modeling hygroscopic moisture diffusion and hygro-mechanical deformation in MDF at room temperature. For the above reason, it is necessary to determine sorption isotherms and diffusion coefficients in order to develop such a model for MDF.

The objectives of the current research are: 1) to determine sorption isotherms of MDF panels as a function of density at 20°C; and 2) to determine the effective water conductivity and diffusion coefficient of MDF panels as a function of moisture content and density at the same temperature.

## BACKGROUND

*Traditional methods for the characterization of moisture movement in wood and wood materials*

Sorption isotherms were determined by Greubel and Drewes (1987), Sekino et al. (1998), and Wu (1999) for MDF samples. However, these studies do not provide data on the effect of density on the EMC. Consequently, the research dedicated to particleboard and oriented strandboard (OSB) needed to be used as reference. It has been established that generally, the denser the composite panel, the lower its EMC at a given RH. Lundgren (1958) found that in adsorption (exposure to 90% RH), high-density fiberboard had an EMC from 8 to 12%, while for insulation board it was close to 17%. The density of the panels is not given in the article; however, the density of hardboard is at least two times higher than for insulation board. Schneider et al. (1982) established that for particleboard exposed to RH levels from 80% to 96%, a density increase of 300 kg/m<sup>3</sup> leads to an EMC decrease of 1%. Wu and Ren (2000) focussed their attention on the effect of density profile and the development of the sorption isotherm of OSB under cyclic RH exposure.

Although very useful as reference, the literature data do not provide specific information on the effect of density on the sorption isotherms of MDF. Given the potential impact of density, it is necessary to determine its relationships with the sorption isotherms from MDF panels with flat density profiles at various levels of overall density. The flat density profiles eliminate the effect of a vertical density variation.

The methodology necessary to determine sorption isotherms is well established (e.g., Wu and Suchsland 1996). It is usually achieved by determining the EMC of samples after exposure to various levels of RH maintained in conditioning chambers or in desiccators over saturated salt solutions. The specimens are periodically weighed until equilib-

rium is reached. The EMC is determined by the gravimetric method.

The interaction between M and RH in wood composites has been modeled similarly to the interaction in solid wood and other porous materials. Nelson (1983) developed a theoretical model (known as Nelson's sorption isotherm) of the sorption of water vapor by cellulose materials. The coefficients used in this model need to be experimentally determined based on linear regression analysis with the equilibrium moisture content as the dependent variable and the transformed RH as the independent variable. Wu and Suchsland (1996) validated the model for industrially produced particleboard.

The utilization of the sorption isotherm alone as was the case for most of the above studies is not a sufficient tool for the characterization of moisture diffusion in a wood composite panel since it does not provide any indication on the dynamics of water movement. A method for determining the rate of water vapor flow through a unit area of flat material induced by a unit vapor pressure gradient across a specimen has been standardized (ASTM E 96-94, 1994). The results from such tests (permeance in g·Pa<sup>-1</sup>·s<sup>-1</sup>·m<sup>-2</sup>) do not allow for conclusions on the moisture content profile inside the material at different points in time. It is an average number resulting from the completed trial, e.g., from equilibrium at 50% RH to equilibrium at 90% RH. This method can not provide indications on the effect of M or the density profile on moisture distribution; therefore it is not a convenient tool for analyzing the potential warping of wood composite panels. It is obvious that the determination of the diffusion coefficient of the material is necessary when transient moisture distribution has to be predicted.

Wu and Suchsland (1996) determined the M distribution based on a finite difference solution of Fick's second law:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left[ D(M) \frac{\partial M}{\partial x} \right] \quad (1)$$

where  $D(M)$  = diffusion coefficient as a function of  $M$ ,  $t$  = time,  $x$  = distance.

The authors calculated  $D$ , from the slope of the linear portion of the  $E$  versus  $\sqrt{t}$  curve as follows:

$$D = \left( \frac{\pi L^2}{4} \right) \left( \frac{E_2 - E_1}{\sqrt{t_2} - \sqrt{t_1}} \right) \quad \text{with} \quad (2)$$

$$E_i = (W_i - W_1)(W_E - W_1)$$

where  $W_i$  = specimen weight at time “ $i$ ,”  $W_1$  = initial specimen weight,  $W_E$  = specimen weight at equilibrium,  $L$  = half specimen thickness.

Wu and Suchsland (1996) observed that in adsorption, the particleboard core layer has a higher diffusion coefficient than the face layer and that the diffusion coefficient decreases with an increase in  $M$ . This observation is in contradiction with the results of Koponen (1984), who observed an increase of the diffusion coefficient with an increase in  $M$  in the range from 0%  $M$  to 25%  $M$  for MDF subjected to water soaking.

The utilization of Eq. (2) as a rule requires assuming a semi-infinite specimen, with the implication that the moisture content at the center does not change during exposure. Also, the initial  $M$ -profile is presumed uniform across the specimen thickness, and the surface is supposed to reach EMC immediately after the beginning of the exposure. An experiment can not fully create the assumed conditions, and the effect of this must be considered in the analysis of the results.

#### *The water potential concept*

Cloutier and Fortin (1993), Defo et al. (1999), and Tremblay et al. (1999) modeled moisture transport in wood based on a driving force derived from classical thermodynamics: the water potential gradient. Based on this theory, the water potential may be thought of as the sum of the separate contributions of the various force fields acting on water in a porous media such as wood (Fortin 1979; Cloutier and Fortin 1991):

$$\psi = \bar{G} - \bar{G}_0 \quad (3)$$

and

$$\psi = \psi_m + \psi_o + \psi_p + \psi_g + \psi_{ef} \quad (4)$$

where  $\bar{G}$  and  $\bar{G}_0$  = Gibbs specific free energy of water in the state considered and in the reference state,  $\psi_m$  = matrix potential due to the combined effect of the capillary and sorptive forces,  $\psi_o$  = osmotic potential due to the presence of solutes in water,  $\psi_p$  = pressure potential describing the effect of system bulk pressure either greater or smaller than the reference bulk pressure,  $\psi_g$  = gravitational potential accounting for gravity,  $\psi_{ef}$  = a component potential representing the integrated sum of the effects of all external force fields exclusive of gravity. For water movement in MDF in the hygroscopic range, only  $\psi_m$  and  $\psi_o$  can be considered as significant as is the case for solid wood (Cloutier and Fortin 1991). The same authors have shown that at constant temperature and pressure, the sum of the matrix and osmotic components of water potential can be written as follows:

$$\bar{G} - \bar{G}_0 = \psi_{m+o} = \frac{RT}{M_w} \ln \frac{p}{p_s} \quad (5)$$

where  $R$  = gas constant ( $8.3143 \text{ J mol}^{-1}\text{K}^{-1}$ ),  $T$  = absolute temperature (K),  $M_w$  = molecular weight of water ( $18.0153 \times 10^{-3} \text{ kg mol}^{-1}$ ),  $p$  = partial pressure of water vapor in MDF (Pa),  $p_s$  = partial pressure of water vapor in equilibrium with pure free water (Pa) at temperature  $T$ .

In the hygroscopic range, the  $M$ - $\psi$  relationship can be inferred from the sorption isotherms and Eq. (5).

The following conservation relation (Cloutier and Fortin 1993) can be used to describe the hygroscopic unsteady-state moisture movement in MDF in under isothermal conditions:

$$\frac{\partial C}{\partial t} + \vec{\nabla} \cdot \vec{q} = 0 \quad (6)$$

where  $C$  = moisture concentration ( $\text{kg}_{\text{water}} \text{ m}^{-3} \text{ moist MDF}$ ),  $\vec{q}$  = moisture flux vector (water

vapor + bound water) ( $\text{kg}_{\text{water}} \text{m}^{-2} \text{moist MDF s}^{-1}$ ),  
 $t$  = time (s).

The moisture concentration, can be defined as

$$C = G_m \rho_w \frac{M}{100} \quad (7)$$

where  $G_m$  = specific gravity of MDF ( $\text{kg}_{\text{oven-dry MDF}} \text{m}^3 \text{water}^{-1} \text{m}^{-3} \text{moist MDF} \text{kg}^{-1} \text{water}$ ),  $\rho_w$  = density of water ( $\text{kg}_{\text{water}} \text{m}^{-3} \text{water}$ ),  $M$  = moisture content in percentage ( $\text{kg}_{\text{water}} \text{kg}^{-1} \text{oven-dry MDF} \times 100$ ).

The total flux of moisture can be described by the following equation:

$$\vec{q} = -\underline{K}(M, T) \cdot \vec{\nabla} \psi \quad (8)$$

where  $\underline{K}(M, T)$  = effective water conductivity tensor ( $\text{kg}^2_{\text{water}} \text{m}^{-1} \text{moist MDF s}^{-1} \text{J}^{-1}$ ), a function of moisture content and temperature,  $\vec{\nabla} \psi$  = gradient in water potential ( $\text{J kg}^{-1} \text{water m}^{-1} \text{moist MDF}$ ).

In a large MDF panel, the proportion of the edges to the overall panel surface is low. In consequence the edge effect, which is the exchange between the panel edges and the environment as opposed to the exchange between the flat surfaces and the environment is not significant. Therefore large panels can be regarded as a plane isotropic material where only the flux through panel thickness is of importance. After substitution of Eq. (8) into Eq. (6), the following expression can be obtained for one-dimensional isothermal moisture movement:

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x} \left( K_x(M, T) \frac{\partial \psi}{\partial x} \right) = 0 \quad (9)$$

Equation (9) can be rewritten in a more classical way as follows:

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x} \left( D(C, T) \frac{\partial C}{\partial x} \right) = 0 \quad \text{with} \quad (10)$$

$$D(C, T) = K_x(M, T) \frac{\partial \psi}{\partial M} \frac{\partial M}{\partial C} \quad (11)$$

where  $K_x(M, T)$  = effective water conductivity function through the thickness,  $x$ ,  $D(C, T)$  = diffusion coefficient ( $\text{m}^2/\text{s}$ ),  $C$  = moisture concentration ( $\text{kg}/\text{m}^3$ ).

Equations (10) and (11) allow working with “D” instead of “K.” The term  $\partial \psi / \partial M$  can be obtained from the  $M - \psi$  relationship.

This approach can be seen as macroscopic since MDF is considered as a continuum. The physical variables involved are considered as continuous functions of space and time. In nonisothermal conditions, an equation should be added for energy conservation, and the effect of the temperature gradient on moisture movement should be taken into account in Eqs. (9) and (10).

Equation (9) can be used in the complete range of moisture content to describe water movement in hygroscopic porous media. With this approach, the gradient in water potential is considered as the driving force. It was applied successfully to both capillary and bound water movements in solid wood during drying by Cloutier et al. (1992), Tremblay et al. (1999), and Defo et al. (2000). In the current work, we consider water movement in MDF in the hygroscopic range. In this specific case, the gradient in moisture concentration can be considered as the driving force for water movement. Therefore, Eq. (10) should be satisfactory as long as the  $D(C, T)$  or  $D(M, T)$  relationship can be determined.

The effective water conductivity is obtained by integrating Eq. (9) (Cloutier and Fortin 1993):

$$K_x(M, T)_{x_i, t_j} = \frac{\frac{\partial}{\partial t} \int_{x_q=0}^{x_i} C \, dx}{\left[ \frac{\partial \psi}{\partial x} \right]_{x_i, t_j}} = \frac{\left[ \frac{\partial I}{\partial t} \right]_{x_i, t_j}}{\left[ \frac{\partial \psi}{\partial x} \right]_{x_i, t_j}} \quad (12)$$

where  $K_x(M, T)_{x_i, t_j}$  = effective water conductivity in the direction of flow  $x$  at position  $x_i$  and time  $t_j$ ,  $I$  = integral of the  $C$  profile,  $[\partial I / \partial t]_{x_i, t_j}$  = flux through the plane  $x_i$  at time  $t_j$ ,  $[\partial \psi / \partial x]_{x_i, t_j}$  = water potential gradient at  $x_i$  and  $t_j$ . The term  $[\partial I / \partial t]_{x_i, t_j}$  represents the actual moisture flux at position  $x_i$  and time  $t_j$ .

A similar approach can be used to obtain the coefficient of diffusion “D” from Eq. 10:

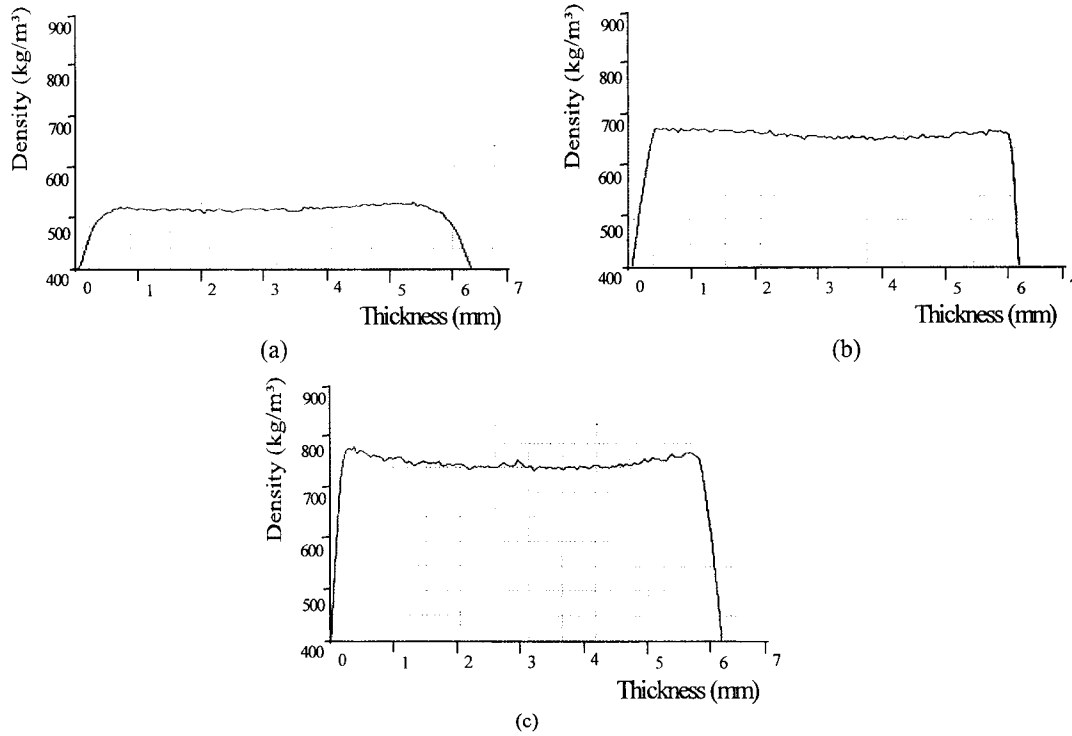


FIG. 1. Representative density profiles of the panels with uniform density distribution through the panel thickness: (a) panel with average density of 540 kg/m<sup>3</sup>; (b) panel with average density of 650 kg/m<sup>3</sup>; (c) panel with average density of 800 kg/m<sup>3</sup>.

$$D_x(M, T)_{x_i, t_j} = \frac{\frac{\partial}{\partial t} \int_{x_{q=0}}^{x_i} C \, dx}{\left[ \frac{\partial C}{\partial x} \right]_{x_i, t_j}} = \frac{\left[ \frac{\partial I}{\partial t} \right]_{x_i, t_j}}{\left[ \frac{\partial C}{\partial x} \right]_{x_i, t_j}} \quad (13)$$

#### MATERIALS AND METHODS

##### Materials

Green black spruce (*Picea mariana*) chips, a typical raw material for MDF in Eastern Canada, were provided by a local sawmill. The wood chips were reduced to fibers in an industrial grade Andritz refiner at Forintek Canada Corp., Eastern Laboratory. The fibers were dried to 2% initial M before resin blending. Commercial melamine urea formaldehyde (MUF) resin provided by Borden Canada was used.

A total of 39 laboratory MDF panels with

dimensions 650 mm × 650 mm × 12 mm divided into 3 nominal density groups (13 × 540 kg/m<sup>3</sup>, 13 × 650 kg/m<sup>3</sup>, 13 × 800 kg/m<sup>3</sup>) was produced. The components were mixed in a laboratory rotary blender. A 12% MUF resin content (solid resin/wood oven-dry weight) and 1% slack wax emulsion (solid wax/wood oven-dry weight) were supplied directly on the wood fibers using an air-pressure spray nozzle set parallel to the axis of the blender drum. No catalyst was applied, since the duration of hot-pressing was more than adequate to cure the resin. The blended fibers were formed into one-layer mats of 650 mm × 650 mm on steel caul-plates by a fiber-felting machine. A typical mat moisture content of 12.5% was obtained. The mats were first pre-pressed and then hot-pressed in a 900-mm × 900-mm Dieffenbacher hot-press. The press pressure was controlled by a PressMAN con-

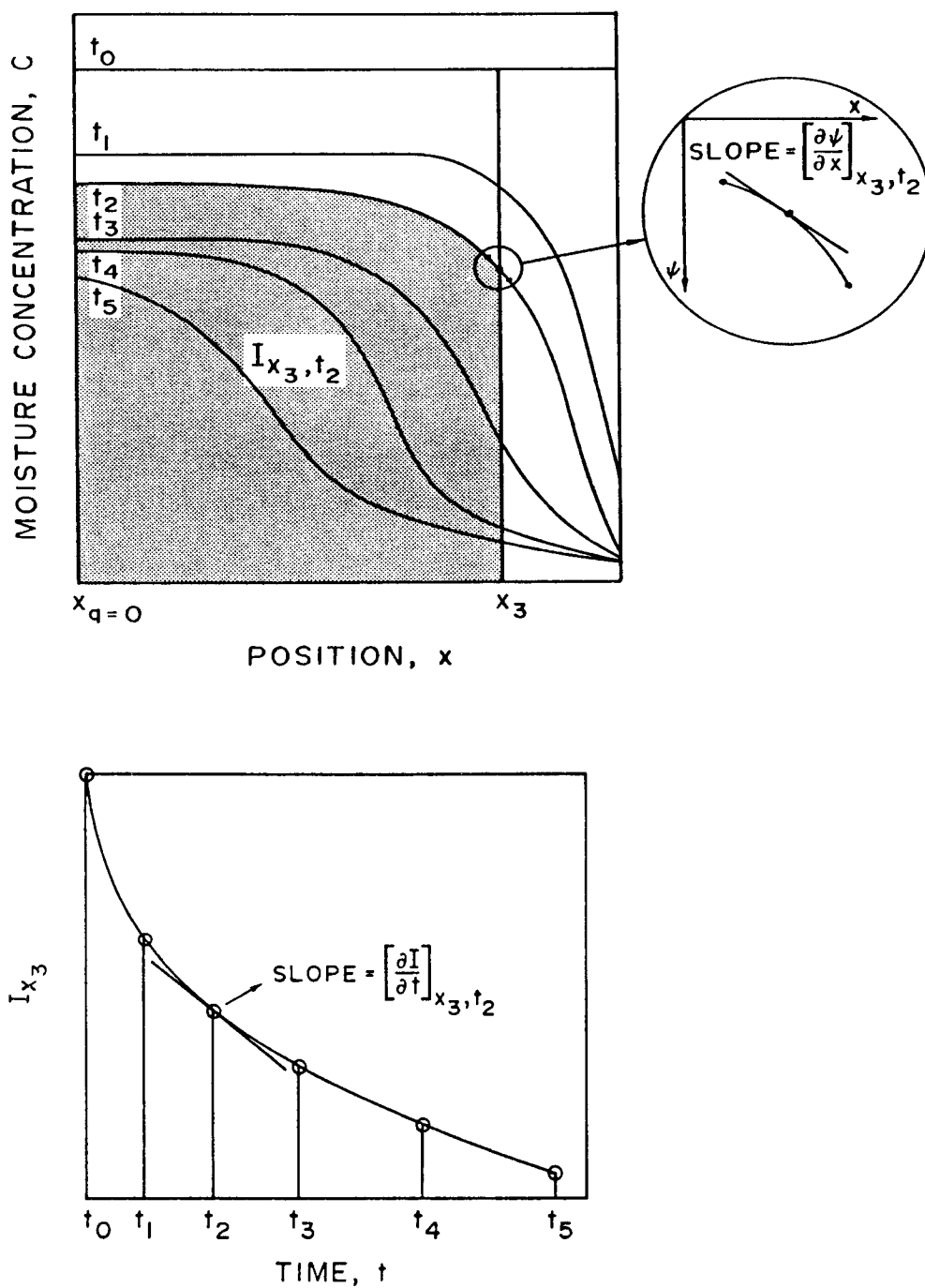


FIG. 2. Graphical representation of the instantaneous profile method: (a) The shaded area shows the integral "I" at  $x_3$  and  $t_2$ .  $\partial\psi/\partial x$  = water potential gradient; (b) Representative curve of I at  $x_3$  against time. The slope of the curve at  $t_2$  gives  $(\partial I/\partial t)_{x_3, t_2}$ . From Cloutier and Fortin (1993).

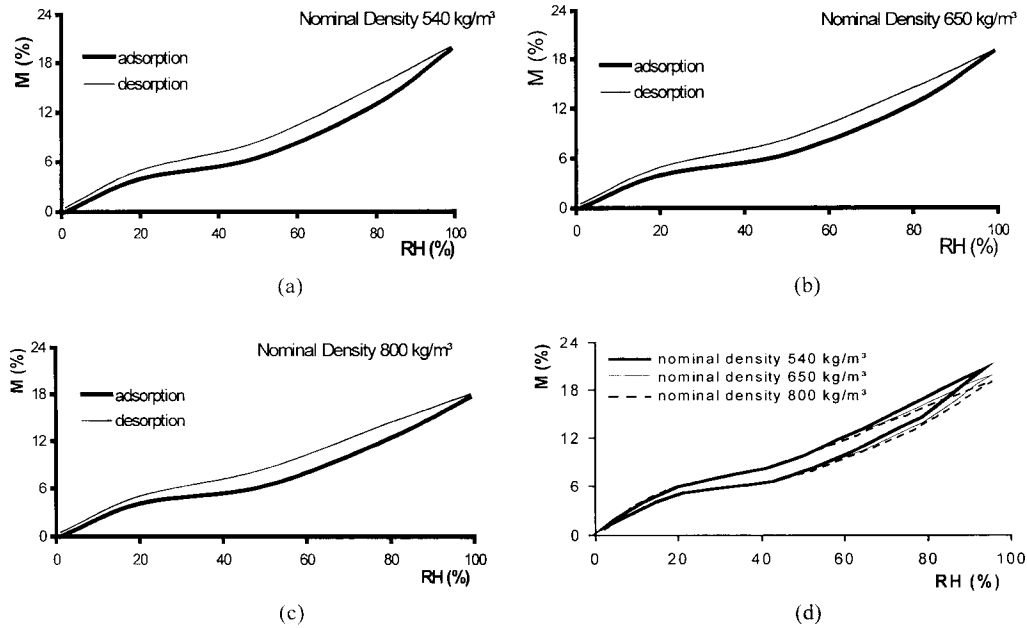


FIG. 3. Sorption isotherms for MDF samples at 20°C: (a) Nominal density of 540 kg/m<sup>3</sup>, (b) Nominal density of 650 kg/m<sup>3</sup>, (c) Nominal density of 800 kg/m<sup>3</sup>, (d) All nominal densities. (M = moisture content; RH = relative humidity)

trol system. Therefore, no thickness bars were used. Gas pressure, mat pressure, mat thickness, and core temperature were continuously monitored with the control system. The press closing time was 40 to 50 s at a maximum pressure of about 5.4 MPa. The pressure was then reduced to 0.9 MPa and kept constant for 190 s to achieve a core temperature of 120°C for 70 s and a target thickness of 12 mm. Finally, the pressure was gradually reduced to zero and the press opened within 15 to 20 s. Each panel was edge-trimmed (approximately 25 mm from each side) to discard the weak area next to the edges.

The surface layers of the panels were removed in a planer, and the thickness of the remaining core layer was reduced by sanding to 6 mm for the sorption trials. This resulted in specimens with uniform vertical density distribution through panel thickness with dimensions 600 mm × 600 mm × 6 mm. The average density of the panels with profile was approximately 100 kg/m<sup>3</sup> higher than that of the sanded specimens. Samples of the vertical density distribution of the sanded specimens

without profile used for the experiments are given in Fig. 1.

### Methods

The equilibrium moisture content of MDF specimens of the three densities was determined by equilibration after exposure to four RH levels at 20°C:

for adsorption starting at 0% RH: 50% RH, 65% RH, 80% RH, and 100% RH.

for desorption starting at 100% RH: 80% RH, 65% RH, 50% RH, and 0% RH.

Different specimens were used for the adsorption and desorption tests at RH exposure levels of 50%, 65%, and 80%, which were maintained in conditioning chambers. The level of 100% RH was obtained in a desiccator over distilled water. The drying to 0% M and the exposure to 0% RH were both done in a desiccator over phosphorus pentoxide P<sub>2</sub>O<sub>5</sub>. To speed up the drying, the adsorption specimens were dried in an oven at 40°C for 24 h. The specimens were periodically weighed until equilibrium (below 1% weight change per 24



TABLE 1. *Equilibrium moisture content and density of the 6-mm samples from the adsorption/desorption tests.*

Nominal density (kg/m <sup>3</sup> )	RH (%)	Adsorption				Desorption			
		EMC		Oven dry density		EMC		Oven dry density	
		Average (%)	Standard deviation (%)	Average (kg/m <sup>3</sup> )	Standard deviation (kg/m <sup>3</sup> )	Average (%)	Standard deviation (%)	Average (kg/m <sup>3</sup> )	Standard deviation (kg/m <sup>3</sup> )
540	0	0.52	0.015	541.3	44.4	0.52	0.015	541.3	44.4
	20	3.94	0.127	543.0	30.0	5.00	0.126	536.1	46.0
	50	6.44	0.273	537.2	24.4	8.46	0.336	540.5	18.6
	80	13.02	0.354	537.0	39.7	15.18	0.820	536.3	33.8
	100	19.58	0.714	543.2	14.7	19.58	0.714	543.2	14.7
650	0	0.51	0.021	644.9	28.3	0.51	0.021	644.9	28.3
	20	3.94	0.181	655.8	27.5	4.92	0.249	652.3	26.2
	50	6.49	0.152	650.7	15.7	8.34	0.140	647.3	13.5
	80	12.50	0.283	658.0	18.9	14.47	0.207	641.8	17.1
	100	18.32	0.624	647.3	18.0	18.32	0.624	647.3	18.0
800	0	0.52	0.018	803.5	13.6	0.52	0.018	803.5	13.6
	20	4.07	0.193	801.0	18.4	5.01	0.193	804.5	8.2
	50	6.33	0.103	792.5	6.4	8.47	0.276	808.5	15.1
	80	12.38	0.591	783.5	14.4	14.37	0.408	795.5	17.4
	100	17.60	0.620	782.3	20.6	17.60	0.620	782.3	20.6

h) was reached. The EMC was determined by the gravimetric method. Suchsland (1972) and Hernandez (1989) used similar methods.

For the determination of the effective water conductivity, 40 specimens for adsorption trials and 40 specimens for desorption trials with dimensions 45 mm × 35 mm × 6 mm were obtained from each density level. The specimens were glued with contact glue to a 6-mm-thick Plexiglas plate with dimensions 45 mm × 35 mm. The edges of the specimens were sealed with several layers of duct tape. As a result, only one surface of the specimens was exposed to the ambience. The adsorption spec-

imens were exposed to 50% RH until equilibrium was reached. The desorption specimens were equilibrated to 80% RH. Once equilibrium was reached for all specimens, the adsorption specimens were transferred to a chamber at 80% RH, while the desorption specimens were exposed to 50% RH. Four control specimens were used to monitor the average M of the sample. When a change in mass of about 2% was observed, four specimens were sliced with a microtome. Slice thickness was 1 mm. The M level of each layer was determined by the gravimetric method. The procedure was repeated with other specimens until the mass of the control specimens remained constant.

The data points for the averages of the "C"-values ("C" profiles) were obtained from the multiplication of the M-value and the density level (oven-dry weight/moist volume) of a given slice. Each point represented the average C value for the four slices of a group. From the average C profiles thus obtained,  $K_x(M, T)_{x_i, t_j}$  was evaluated using Eq. (12). The integral of the C profile "I" between the planes  $x_i$  and  $x_{q=0}$  was determined by the method of rectangles (Fig. 2a). The term  $[\partial I / \partial t]_{x_i, t_j}$  was determined by plotting I

TABLE 2. *Results of the analysis of variance for the impact of sorption state, density, and relative humidity on the equilibrium moisture content.*

Factor	F-value
sorption-state	304.7**
density	31.0**
relative humidity	12,431.0**
sorption-state × density	0.2 <sup>ns</sup>
sorption-state × relative humidity	61.3**
density × relative humidity	15.6**
sorption-state × relative humidity × density	0.1 <sup>ns</sup>

\*\* = significant at the 99% probability level.

<sup>ns</sup> = non-significant.

against  $t$  and calculating the slope at  $t_j$  by differentiation of the regression equation (Fig. 2b). The  $\psi$  gradient  $[\partial\psi/\partial x]_{x_i, t_j}$  was determined from the C-profiles and M- $\psi$  relationship obtained for MDF specimens from the same panels (Cloutier and Fortin 1993). The  $\psi$  profile at  $x_i$  and  $t_j$  was plotted and the  $\psi$  gradient was determined by calculating the slope at  $t_j$  by differentiation of the regression equation (Fig. 2a). Equation (12) was evaluated at 6 different positions in the specimens, namely 0.05, 0.15, 0.25, 0.35, 0.45, and 0.55 mm from the open surface. For comparison purposes, the diffusion coefficients were also calculated for the same data points based on Eq. (13). The difference with the effective water conductivity is that the C gradient  $[\partial C/\partial x]_{x_i, t_j}$  is used instead of the  $\psi$  gradient as the driving force.

In this study, MDF was assumed to be a non-swelling porous medium as was the case for the aspen sapwood used by Cloutier and Fortin (1993). To take shrinkage or swelling into account, a stress-strain model must be developed. This was beyond the scope of the present work.

## RESULTS AND DISCUSSION

### *Sorption isotherms*

Figure 3 displays the sorption isotherms obtained in adsorption and desorption at 20°C. The EMC and standard deviation obtained for each combination of the three factors considered (sorption state, density, and RH) are presented in Table 1. The EMC levels obtained for the three MDF density samples in the entire range of RH varied between 0% and 20%. An analysis of variance was performed on the data using the SAS PROC GLM procedure considering the impact of the sorption state (adsorption/desorption), panel density, and RH on the EMC. The F-values obtained are presented in Table 2. The linear effects of the three factors considered were all significant at the 99% probability level. The sorption-state\*RH and density\*RH interactions were

also found to be significant at the 99% probability level.

The EMC values obtained in the current work are somehow lower than those reported by Greubel and Drewes (1987), who found that at 20°C, the EMC of MDF vary from 5% at 20% RH to 17% at 80% RH. Our results show average EMCs for the two sorption states and three density levels of 4.5% at 20% RH and 13.7% at 80% RH. There is no clear indication for the differences in the EMC levels of the two studies. They may be due to differences in wood species, adhesive systems, resin levels, and press cycles of the industrial panels with density profile used by Greubel and Drewes (1987) and those of the laboratory panels without profiles used in the current research.

Significant differences were found between EMC means obtained in adsorption and desorption at 20, 50, and 80% RH, the values obtained in desorption being higher than in adsorption. The highest level of hysteresis, an average difference between EMC at adsorption and EMC at desorption of 2%, was observed for all density levels at about 45% RH.

The EMC means obtained at 540 kg/m<sup>3</sup> were found to be significantly higher than at 650 and 800 kg/m<sup>3</sup> for the 80 and 100% RH levels (Fig. 3d). This trend is in agreement with Lundgren (1958), who compared high-density fiberboard and insulation board, and with Vital and Wilson (1979) and Schneider et al. (1982) for particleboard. Our results show that the impact of density on EMC is significant at RH levels above 50%. A similar trend was reported by Wu and Ren (2000), who noticed a significant effect of density only above 32% RH.

The sorption isotherms are usually presented as curves of M as a function of RH. However, M can be presented as a function of water potential or chemical potential. Equation (5) is then used to convert RH values to  $\psi$  values. Figure 4 presents the M -  $\psi$  relationship obtained for MDF at a density of 540 kg/m<sup>3</sup>. The sorption hysteresis is visible in this figure as well as in Fig. 3.

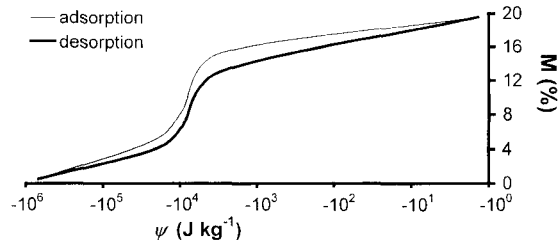


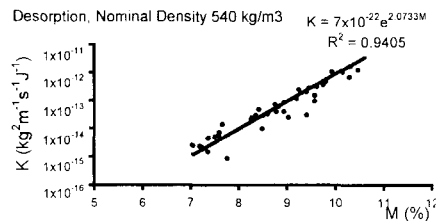
FIG. 4. Moisture content – water potential relationship at 540 kg/m<sup>3</sup>. M = moisture content;  $\psi$  = water potential.

### Effective water conductivity and coefficient of diffusion

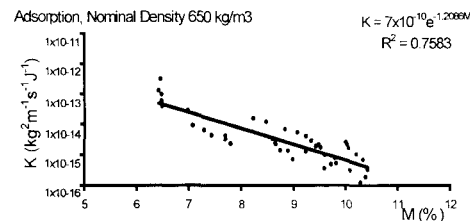
The results obtained for the effective water conductivity for the three density levels both in desorption and adsorption are presented in

Fig. 5. In desorption, K increases by several orders of magnitude as M increases from 8% to about 11%. There are no published results on the K (M) relationship for MDF. The trend we observed for K (M) in desorption for MDF is in agreement with that observed by Cloutier and Fortin (1993) for solid wood.

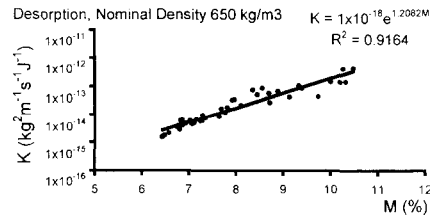
An inverted pattern is obtained in adsorption. The K values at low M levels (7 to 8% M) are several orders of magnitude higher compared to those at higher M levels (10 to 11% M). In other words, K decreases with an increase in M in adsorption. These results are in agreement with those obtained for particleboard by Wu and Suchsland (1996). According to them, while in solid wood bound water plays a more important role, in fiberboard and



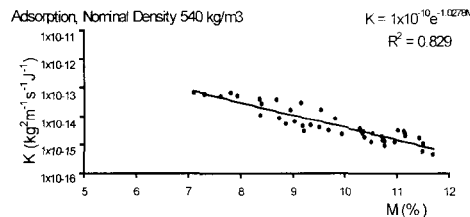
(a)



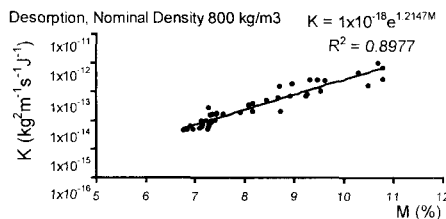
(d)



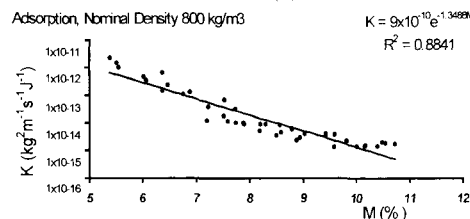
(b)



(e)



(c)



(f)

FIG. 5. Effective water conductivity for MDF panels as a function of moisture content: (a) MDF with nominal density of 540 kg/m<sup>3</sup> in desorption, (b) MDF with nominal density of 650 kg/m<sup>3</sup> in desorption, (c) MDF with nominal density of 800 kg/m<sup>3</sup> in desorption, (d) MDF with nominal density of 540 kg/m<sup>3</sup> in adsorption, (e) MDF with nominal density of 650 kg/m<sup>3</sup> in adsorption, (f) MDF with nominal density of 800 kg/m<sup>3</sup> in adsorption. (M = moisture content; K = effective water conductivity)

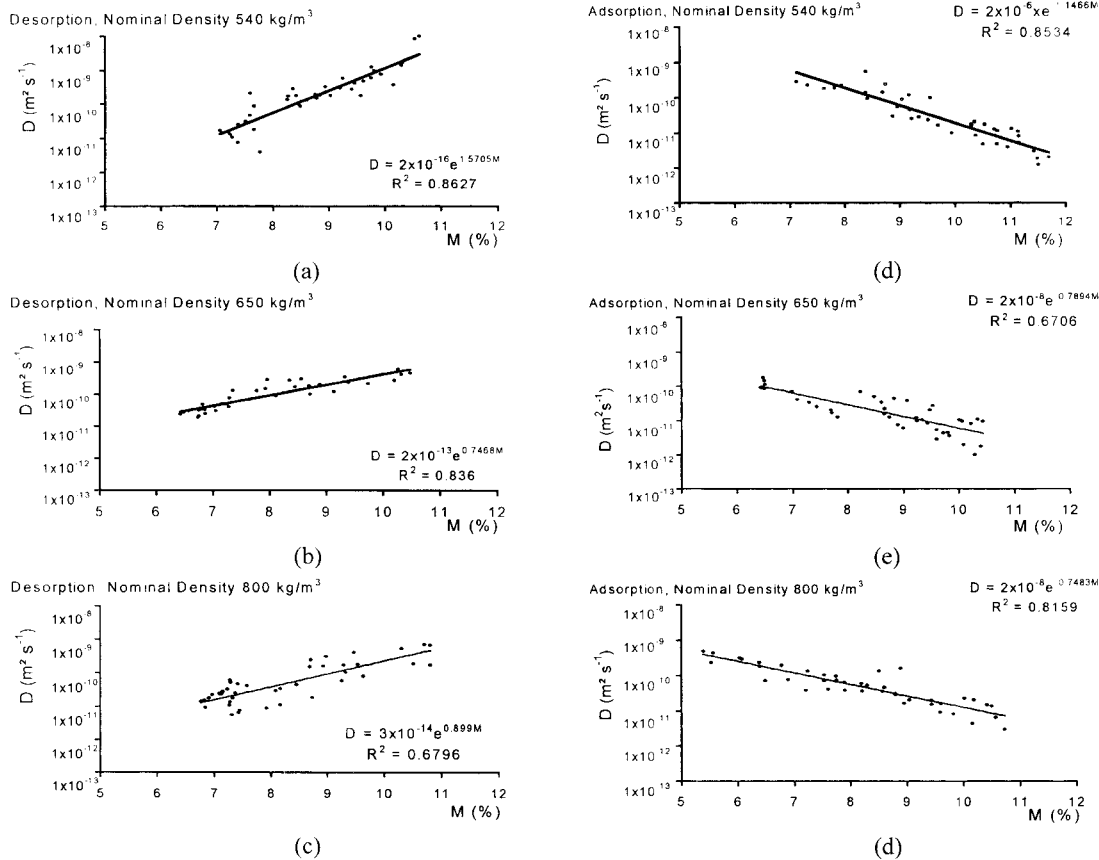


FIG. 6. Coefficient of diffusion for MDF panels as a function of moisture content: (a) MDF with nominal density of 540  $\text{kg/m}^3$  in desorption, (b) MDF with nominal density of 650  $\text{kg/m}^3$  in desorption, (c) MDF with nominal density of 800  $\text{kg/m}^3$  in desorption, (d) MDF with nominal density of 540  $\text{kg/m}^3$  in adsorption, (e) MDF with nominal density of 650  $\text{kg/m}^3$  in adsorption, (f) MDF with nominal density of 800  $\text{kg/m}^3$  in adsorption. ( $M$  = moisture content;  $D$  = coefficient of diffusion)

particleboard the dominant moisture transfer mechanism may be water-vapor diffusion through air-filled pore spaces. Siau (1995) also presents decreasing diffusion coefficients with an increase in  $M$  in the longitudinal direction of solid wood where water-vapor diffusion through air-filled pore spaces may be the dominant transport mechanism as well.

The corresponding diffusion coefficients are shown in Fig. 6. The general trend of the results is the same as for the  $K(M)$  relationships, but the actual  $D$  values are different. This shows that for moisture diffusion in MDF in the hygroscopic range, Eq. (9) or (10) can be used.

For analysis purposes, the  $K(M)$  and  $D(M)$  functions for all density samples are plotted in Fig. 7. The confidence intervals at the 95% probability level of the intercepts and slopes of the regression equations were calculated and are presented in Table 3. There was no significant effect of density on the intercept for  $K$  in adsorption; however, the slopes of the regression curves for 540  $\text{kg/m}^3$  and 800  $\text{kg/m}^3$  were significantly different. In desorption for  $K$  and in desorption and in adsorption for  $D$ , both the slope and the intercept of the regression curves for panels with a density of 540  $\text{kg/m}^3$  were significantly different from those of the panels with a density of 650  $\text{kg/m}^3$ .

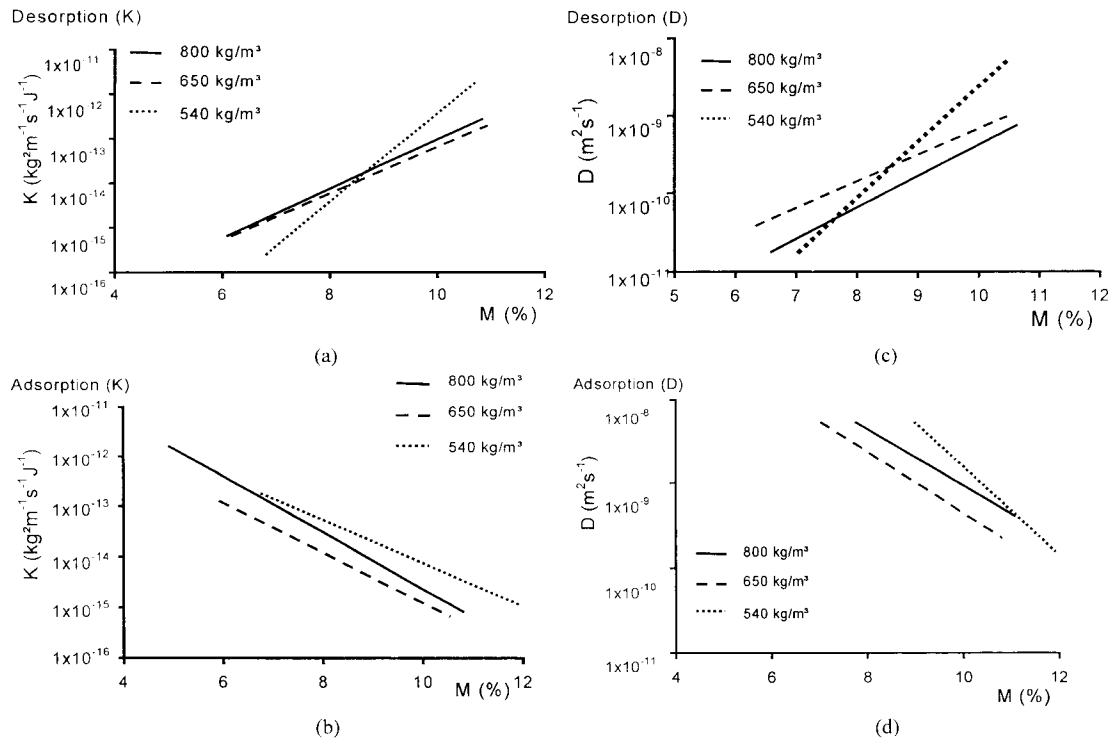


FIG. 7. Effect of density on K and D: (a) K in desorption for MDF panels with nominal densities of 540, 650 and 800 kg/m³, (b) K in adsorption for MDF panels with nominal densities of 540, 650 and 800 kg/m³, (c) D in desorption for MDF panels with nominal densities of 540, 650 and 800 kg/m³, (d) D in adsorption for MDF panels with nominal densities of 540, 650 and 800 kg/m³. (M = moisture content; K = effective water conductivity; D = coefficient of diffusion)

m³ and 800 kg/m³. Both in desorption and in adsorption, it appears (Fig. 7) that at high M, the K and D values are larger values for panels with a density of 540 kg/m³ than those for panels with a density of 650 kg/m³ and 800 kg/m³. These observations are similar to the results of Wu and Suchsland (1996), who stated that in particleboard the core layer (which is always associated with lower density) has a larger diffusion coefficient than the surface layer. The authors attributed the higher effective water conductivity of the particleboard samples with lower density to their larger percentage of voids, which plays an important role due to the significance of water vapor diffusion through air-filled pores at low M values in the wood composites.

#### CONCLUSIONS

The purpose of this study was to determine the effect of density and moisture content on the sorption isotherms and the effective water conductivity of MDF. The experiments were conducted using a standard technique to determine sorption isotherms and the instantaneous profile method to determine the effective water conductivity. The results show that in the interval between 0% RH and 100% RH, the equilibrium moisture content of MDF varies in the range of 0% to 20%. Medium density fiberboard from all density levels displayed a marked sorption hysteresis with a highest level of 2% M. Both in adsorption and in desorption, the MDF specimens with higher density levels equilibrated at lower levels of

TABLE 3. Summary of confidence limits for slopes and the intercepts of the curves characterizing the  $K(M)$  relation in adsorption.

Density level (kg/m <sup>3</sup> )	Intercept			Slope		
	Estimate	Standard error	Duncan grouping	Estimate	Standard error	Duncan grouping
Effective water conductivity (K) in adsorption						
540	-9.95	0.31	A	-0.45	0.032	A
650	-9.92	0.42	A	-0.53	0.047	A B
800	-9.03	0.28	A	-0.59	0.034	B
Effective water conductivity (K) in desorption						
540	-21.87	0.56	A	0.98	0.064	A
650	-17.99	0.20	B	0.53	0.025	B
800	-17.88	0.23	B	0.53	0.028	B
Coefficient of diffusion (D) in adsorption						
540	-5.74	0.32	A	-0.50	0.032	A
650	-7.79	0.34	B	-0.35	0.038	B
800	-7.65	0.20	B	-0.33	0.024	B
Coefficient of diffusion (D) in desorption						
540	-15.57	0.42	A	0.66	0.048	A
650	-12.65	0.18	B	0.33	0.022	B
800	-13.56	0.35	B	0.39	0.042	B

M. However, the impact of density was found to be relatively small and is proportional to the M level. The effective water conductivity in desorption and the diffusion coefficients both in desorption and adsorption were significantly higher for panels with a density of 540 kg/m<sup>3</sup> than for densities of 650 and 800 kg/m<sup>3</sup>. In adsorption, the effective water conductivity of panels with a density of 540 kg/m<sup>3</sup> was significantly higher than for a density of 800 kg/m<sup>3</sup>. The results obtained in this study provide a sound basis for the development of a model of panel hygro-mechanical deformation induced by moisture sorption.

#### ACKNOWLEDGMENTS

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