Repeated Humidity Cycling's Effect on Physical Properties of Three Kinds of Wood-based Panels

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Physical proprieties of particleboard, medium-density fiberboard, and wood-plastic composite board were studied by measuring the thickness and weight changes during repeated humidity cycling (RHC). The thickness stability, moisture absorbing capacity, and internal band strength of the control and treated specimens were measured for the three tested materials. The wood-plastic composite board showed the greatest stability, with only small changes in thickness and weight. Temperature is a key component of RHC treatment, with greater thickness changes after six cycles at 50 °C than after nine cycles at 20 °C. Compared with the control materials, the thickness stability of RHC-treated materials was decreased by 23.7 to 31.8%; RHC decreased the internal bond strength of specimens 22 to 23% for particleboard and medium-density fiberboard and 2.15% for wood-plastic composite board. Overall, thickness stability and internal bonding strength of the tested materials were highly correlated.

Keywords: Repeated humidity cycling; Wood-based panels; Hygroscopicity; Dimensional stability

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INTRODUCTION

In recent years, the increasing demand for wood composite products has decreased the worldwide per capita forest area (Gu *et al.* 2019). Wood-based panel production is an effective way to efficiently use wood resources, helping to ease the contradiction between wood supply and demand and protect the ecological environment. Double-sided, decorative wood-based panels are widely used for furniture and interior decoration, with convenient manufacture and without the requirement for finishing. These wood-based panels can be produced from particleboard, fiberboard, wood-plastic composite board, plywood, or other materials (Liu *et al.* 2019).

When these materials are used in interior conditions, they are subjected to fluctuations in relative humidity and temperature that may affect their performance. Therefore, it is essential to establish the long-term effects of environmental humidity and temperature fluctuations on the durability of these wood-based panels (Biblis and Lee 1979). The response of wood materials to variations of ambient humidity can be described as a type of ageing (Esteban *et al.* 2015), and this process has been studied since the1960s. Variations of humidity reduce the mechanical strength of particleboard (Biblis and Lee 1975) and change its dimensions and properties (Suchsland 1972, 1973). Laminated veneer lumber also exhibits reduced mechanical properties due to variations of humidity (Xue *et al.* 2010a, b). Medium-density fiberboards (MDF) lose their surface quality (*e.g.* increased roughness) when exposed to humidity and other weathering conditions (Perez *et al.* 2012).

Compared with other wooden materials, wood-plastic composite board (WPC) has a much smaller water absorption capacity and a slower water absorption process, resulting in better fungus resistance and dimensional stability (Wang *et al.* 2008). However, the behavior of different wood-based panels in response to humidity cycling has not been evaluated, and understanding potential changes in these materials in response to repeated humidity cycling (RHC) is required to assess overall material durability.

This paper focuses on the effect of repeated humidity cycling on properties of three types of decorative double-faced wood-based panels. The results will provide consumers and manufacturers with the scientific basis for material selection for specific uses of these materials.

EXPERIMENTAL

Materials

Three commercially manufactured decorative double-faced wood-based panels were provided from Kuka Home Co., Ltd. (Huzhou, China) and were used for the experiments in this study. The three panels were made of particleboard, medium-density fiberboard, and wood-plastic composite board (composed of 58% wood flour, 36% high density polyethylene, 4% maleic anhydride-grafted polyethylene and 2% lubricant), with dimensions of (2440 mm × 1220 mm ×20 mm). According to the Chinese national standard GB/T 17657(2013), the dimensions of the test specimens were 50 mm × 50 mm × 20 mm (length × width × thickness), and 120 pieces were cut from each wood-based panel. All specimens were conditioned in a chamber with a constant temperature of 20 °C and 65% relative humidity until reaching constant weight (7 days) prior to testing.

Methods

RHC procedure

To analyze the influence of temperature during RHC treatment, tests were conducted in a temperature-controlled chamber at 20 °C or 50 °C. Each cycle of variation of relative humidity (RH) consisted of four steps: 65%, 25%, 65%, and 85%. The specimens reached equilibrium moisture contents (EMC) for each condition of all cycles. After the second step (RH=25%) and the fourth step (RH=85%), the dimensions and weights of all specimens were measured. The 120 pieces were divided into four groups: the control group (group 0), a group treated with three cycles (group 3RHC), a group treated with six cycles (group 6RHC), and a group treated with nine cycles (group 9 RHC).

Estimation of thickness stability and moisture absorption

During RHC treatment, the thickness changes of specimens were evaluated after each condition treatment. Additionally, the moisture contents (MC) of samples were calculated from the measured weights and oven-dry weights after tests.

According to standard GB/T 17657 (2013), the control and treated groups were oven-dried and subsequently stored in a climate controlled chamber at a temperature of 20 °C with 65% relative humidity to reach the equilibrium moisture content (EMC). The thicknesses and weights of the specimens were measured before and after this conditioning.

The swelling coefficient was calculated using Eq. 1,

$$a = \frac{l_w - l_0}{l_0} \times 100 \tag{1}$$

where a is the swelling coefficient (%), l_0 denotes the initial thickness of the specimen (mm), and l_w represents the sample thickness (mm) after conditioning.

The moisture absorption (MA) after conditioning in the climate chamber was obtained by Eq. 2,

$$\mathrm{MA} = \frac{w_a - w_b}{w_b} \times 100 \tag{2}$$

where MA is obtained as a percentage (%), W_b denotes the weight (g) of the specimens before conditioning in the climate chamber, and W_a represents the weight (g) of the specimens after conditioning in the climate chamber.

Determination of internal bond strength

Humidity is an important factor affecting the internal adhesion and durability properties of wood materials. According to GB/T 17657(2013), prior to tests, the control and treated specimens were conditioned for at least three weeks at 20 °C and 65% relative humidity. Internal bond strength tests were completed using a mechanical testing machine AG-IC (Shimadzu, Kyoto, Japan) equipped a load cell with a capacity of 1000 kg. The load was continuously applied to the specimens throughout the tests at a uniform rate of motion of the movable cross-head of the testing machine of 1.2 mm/min until reaching failure. The internal bond strength of a specimen was determined according to Eq. 3,

$$\mathrm{f_v} = \mathrm{P/A} \tag{3}$$

where f_v is the internal bond strength (N/mm^2), P is the load at which the specimen failed (N), and A is the surface area of the specimen (mm^2).

RESULTS AND DISCUSSION

Thickness and Weight Changes During RHC Process

Wood-based panels exhibit changes in their thickness and weight in different humidity conditions due to absorbing or desorbing moisture. Table 1 presents the thickness and weight changes of the three tested materials during repeated humidity cycling at 20 °C and 50 °C. There were changes in the thickness and weight of all specimens during the nine humidity cycles. Among these tested materials, wood-plastic board showed the most stable thickness and weight, with average maximum thickness changes of 0.04 mm and average weight changes of 0.089 g. The specimens of medium-density fiberboard had changes of thickness and weight with a maximum of 0.56 mm and 0.071 g, respectively, and the particle board specimens had changes with a maximum of 0.34 mm and 1.284 g, respectively, in the last humidity cycle. The changes of specimen thickness and weight increased with increasing number of treatment cycles. Compared with the samples treated at 20 °C, repeated humidity cycling induced greater changes of specimen thickness and weight at 50 °C.

Table 1. Thickness and Weight Changes of the Three Tested Materials during Repeated Humidity Cycling at 20 °C

Materials→ Cycles↓	Particleboard		MDF		Wood-plastic Composite Board	
	Thickness (mm)	Weight (g)	Thickness (mm)	Weight (g)	Thickness (mm)	Weight (g)
Initial values	20.01 ±0.17	34.22 ±0.29	20.08 ±0.08	38.72 ±0.25	20.02 ±0.03	33.21 ±0.13
Cycle 1 25%	20.01 ±0.13	34.17 ±0.28	20.06 ±0.08	38.70 ±0.24	20.01 ±0.03	33.20 ±0.13
Cycle 1 85%	20.04 ±0.10	34.48 ±0.30	20.11 ±0.06	38.93 ±0.26	20.02 ±0.04	33.22 ±0.12
Cycle 2 25%	19.98 ±0.13	34.05 ±0.28	20.05 ±0.08	38.66 ±0.25	20.02 ±0.03	33.20 ±0.12
Cycle 2 85%	20.06 ±0.14	34.51 ±0.30	20.12 ±0.06	38.94 ±0.26	20.02 ±0.03	33.22 ±0.13
Cycle 3 25%	19.97 ±0.13	34.02 ±0.28	20.04 ±0.08	38.63 ±0.25	20.01 ±0.03	33.20 ±0.13
Cycle 3 85%	20.07 ±0.14	34.52 ±0.30	20.12 ±0.06	38.95 ±0.26	20.03 ±0.03	33.22 ±0.14
Cycle 4 25%	19.65 ±0.14	33.95 ±0.28	20.04 ±0.07	38.60 ±0.26	20.01 ±0.03	33.20 ±0.13
Cycle 4 85%	20.07 ±0.15	34.53 ±0.23	20.13 ±0.06	38.96 ±0.26	20.02 ±0.03	33.22 ±0.14
Cycle 5 25%	19.97 ±0.14	33.88 ±0.29	20.02 ±0.07	38.58 ±0.26	20.01 ±0.03	33.20 ±0.12
Cycle 5 85%	20.08 ±0.14	34.56 ±0.30	20.13 ±0.06	38.98 ±0.26	20.02 ±0.03	33.22 ±0.13
Cycle 6 25%	19.90 ±0.15	33.32 ±0.29	20.01 ±0.07	38.53 ±0.25	20.01 ±0.03	33.19 ±0.13
Cycle 6 85%	20.11 ±0.16	34.68 ±0.30	20.15 ±0.06	39.02 ±0.26	20.03 ±0.03	33.22 ±0.12
Cycle 7 25%	19.80 ±0.16	33.32 ±0.29	19.93 ±0.07	38.23 ±0.25	20.01 ±0.03	33.19 ±0.13
Cycle 7 85%	20.13 ±0.13	34.68 ±0.30	20.15 ±0.06	39.04 ±0.26	20.03 ±0.03	33.23 ±0.13
Cycle 8 25%	19.78 ±0.14	33.26 ±0.29	19.89 ±0.07	38.15 ±0.26	20.00 ±0.03	33.19 ±0.13
Cycle 8 85%	20.14 ±0.14	34.70 ±0.30	20.16 ±0.07	39.04 ±0.26	20.04 ±0.03	33.23 ±0.13
Cycle 9 25%	19.76 ±0.13	33.16 ±0.30	19.87 ±0.07	38.07 ±0.26	20.00 ±0.03	33.18 ±0.13
Cycle 9 85%	20.18 ±0.13	34.72 ±0.30	20.17 ±0.06	39.05 ±0.26	20.05 ±0.03	33.24 ±0.13

Values are the average of 30 samples ± standard deviation.

Table 2. Thickness and Weight Changes of the Three Tested Materials during Repeated Humidity Cycling at 50 °C

Materials → Cycles↓	Particleboard		MDF		Wood-plastic Composite Board	
	Thickness (mm)	Weight (g)	Thickness (mm)	Weight (g)	Thickness (mm)	Weight (g)
Initial values	20.024 ±0.140	34.645 ±0.212	20.037 ±0.055	38.758 ±0.307	20.077 ±0.034	33.232 ±0.137
Cycle 1 25%	19.828 ±0.142	33.710 ±0.213	19.922 ±0.064	38.049 ±0.228	20.074 ±0.034	33.211 ±0.136
Cycle 1 85%	20.106 ±0.144	35.336 ±0.202	20.197 ±0.044	38.812 ±0.360	20.079 ±0.032	33.264 ±0.133
Cycle 2 25%	19.778 ±0.134	33.659 ±0.214	19.905 ±0.060	37.979 ±0.225	20.071 ±0.029	33.205 ±0.137
Cycle 2 85%	20.114 ±0.144	35.442 ±0.204	20.217 ±0.040	38.933 ±0.307	20.081 ±0.031	33.269 ±0.134
Cycle 3 25%	19.767 ±0.137	33.622 ±0.215	19.891 ±0.061	37.952 ±0.227	20.067 ±0.027	33.201 ±0.139
Cycle 3 85%	20.125 ±0.143	35.548 ±0.210	20.247 ±0.040	39.090 ±0.267	20.091 ±0.029	33.284 ±0.135
Cycle 4 25%	19.762 ±0.136	33.590 ±0.215	19.879 ±0.065	37.936 ±0.225	20.060 ±0.026	33.197 ±0.139
Cycle 4 85%	20.145 ±0.140	35.692 ±0.222	20.346 ±0.595	39.241 ±0.343	20.097 ±0.031	33.292 ±0.135
Cycle 5 25%	19.751 ±0.133	33.526 ±0.214	19.857 ±0.062	37.900 ±0.232	20.056 ±0.028	33.193 ±0.136
Cycle 5 85%	20.257 ±0.191	35.745 ±0.223	20.414 ±0.630	39.274 ±0.333	20.105 ±0.031	33.303 ±0.135
Cycle 6 25%	19.726 ±0.147	33.438 ±0.197	19.856 ±0.063	37.840 ±0.232	20.055 ±0.029	33.188 ±0.136
Cycle 6 85%	20.288 ±0.210	35.775 ±0.222	20.414 ±0.630	39.444 ±0.339	20.105 ±0.033	33.317 ±0.135
Cycle 7 25%	19.716 ±0.142	33.411 ±0.213	19.843 ±0.064	37.841 ±0.360	20.049 ±0.027	33.184 ±0.136
Cycle 7 85%	20.321 ±0.144	35.786 ±0.202	20.513 ±0.044	39.456 ±0.225	20.106 ±0.032	33.318 ±0.133
Cycle 8 25%	19.698 ±0.134	33.397 ±0.214	19.836 ±0.060	37.842 ±0.307	20.046 ±0.028	33.187 ±0.137
Cycle 8 85%	20.334 ±0.144	35.793 ±0.222	20.576 ±0.062	39.462 ±0.227	20.109 ±0.026	33.320 ±0.134
Cycle 9 25%	19.678 ±0.137	33.361 ±0.214	19.829 ±0.630	37.839 ±0.333	20.041 ±0.030	33.183 ±0.134
Cycle 9 85%	20.419 ±0.142	35.802 ±0.223	20.598 ±0.063	39.469 ±0.232	20.101 ±0.027	33.321 ±0.136

Values are the average of 30 samples ± standard deviation.

Thickness and weight changes of samples are caused by a change in the moisture content. The moisture contents and thickness changes of all tested materials during the long-term humidity exposure were measured and are shown in Figs. 1 and 2, respectively. The MC was calculated from measured weights and oven-dry weights after tests. Before treatment, all specimens were conditioned at 65% RH and 20 °C with different initial levels of moisture due to their different constituent materials. The particleboard had initial moisture of 9.62%, desorbed moisture as 6.24% in the ninth treated cycle at 25% RH and 50 °C, and absorbed moisture as 13.16% at 85% RH and 50 °C. During the treatment process, MDF suffered moisture changes from 5.21% to 7.93%. The wood-plastic composite board showed the best resistance to humidity, with only 3.35% to 3.78% change in moisture. Moisture changes at 50 °C treatment were larger than those at 20 °C, for example, the particleboard absorbed 13.07% moisture in the 6th cycle at 50 °C, but only 11.23% in the 9th cycle at 20 °C.

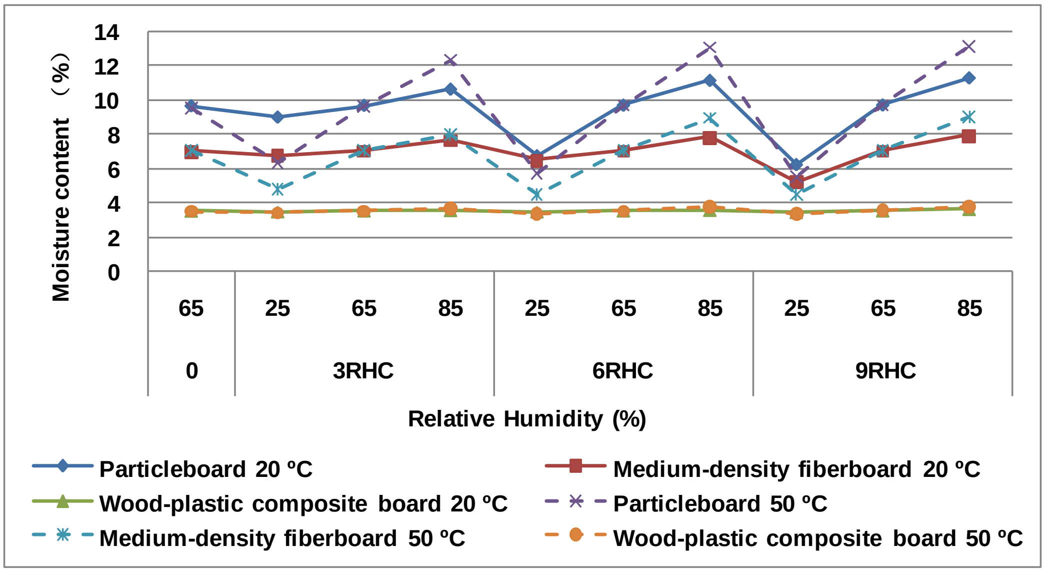

Fig. 1. Moisture content changes of the three tested materials during cycling

Thickness changes were expressed as the percentages of the original thickness at 65% RH, 20 °C. Moisture changes of specimens induced these thickness changes. As for the assessment of moisture changes, the wood-plastic composite board showed the highest stability, with thickness changes of only -0.2 to 0.1%. The MDF showed the greatest sensitivity to variations in humidity, with thickness changes ranging from -1.0 to 2.8%.

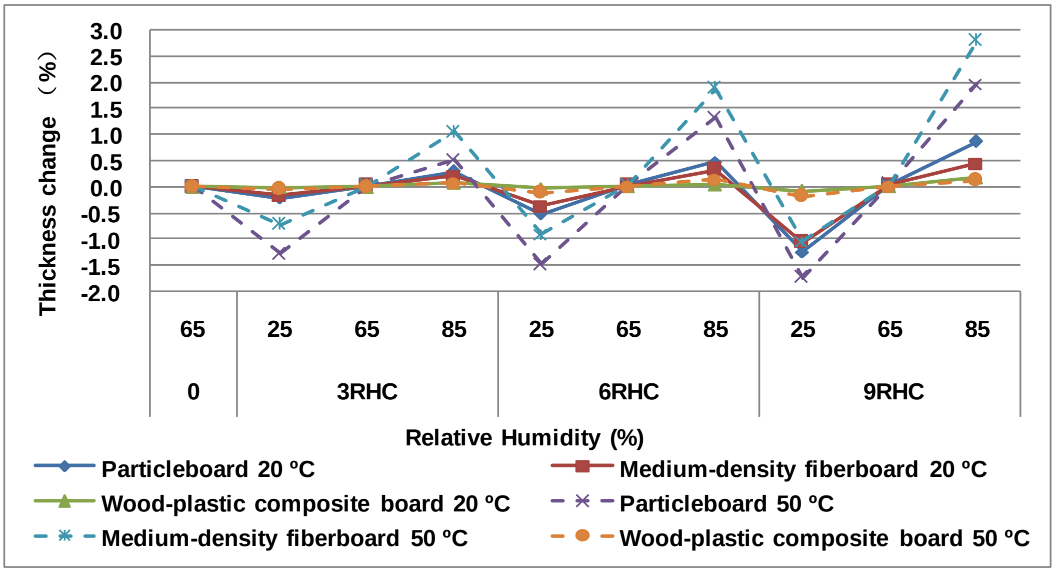

Fig. 2. Thickness changes of the three tested materials during cycling

Estimation of Thickness Stability and Moisture Absorption

The data presented in Fig. 3 illustrate that RHC treatment influences the thickness stability of wood-based materials. The average values of the swelling coefficient of particleboard, MDF, and wood-plastic composite board relative to that of the control group were 1.73%, 1.54%, and 0.11%, respectively. After nine cycles of RHC treatment at 50ºC, the swelling coefficient of particleboard increased 23.7%, the swelling coefficient of MDF increased 31.8%, and that of wood-plastic composite board increased 27.3% compared with the value for the control group. The decrease in thickness stability of the wood-based panels due to RHC treatment is because moisture affects the internal physical structure (Biblis and Lee 1975).

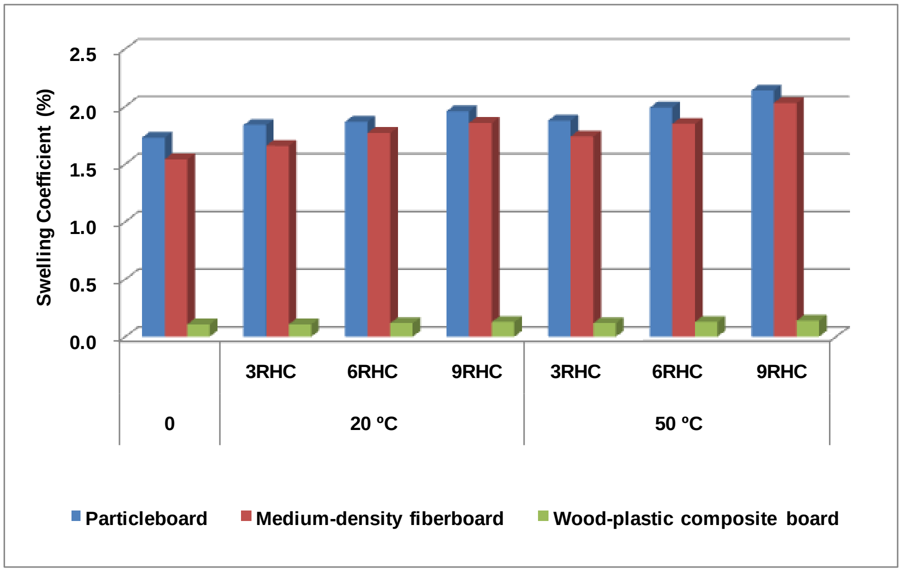

Fig. 3. Swelling coefficients in the thickness direction for the treatment and control groups

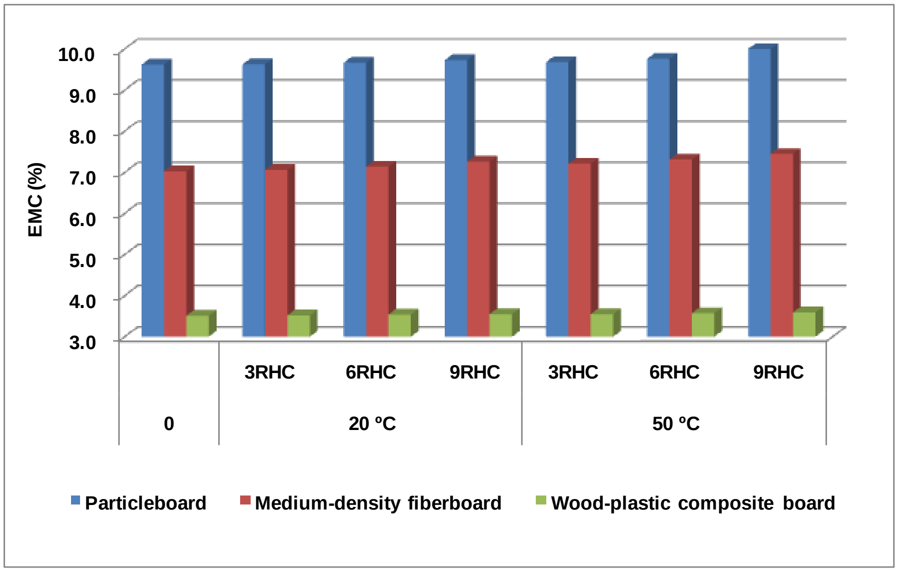

Fig. 4. Equilibrium moisture content at20ºC andRH65% for the treatment and control groups

The thickness stability of wood-based panels is largely determined by their hygroscopic capacity. Figure 4 depicts the equilibrium moisture of the specimens in the climate chamber at a temperature of 20 °C with 65% RH. The moisture absorption (MA) values of control groups were 9.62% for particleboard, 7.03% for MDF, and 3.51% for wood-plastic composite board. Compared with control groups, after RHC treatment the MA of all specimens increased: 10.08% for particleboard, 7.45% for MDF, and 3.59% for wood-plastic composite board. Therefore, RHC treatment increased the MA of wood-based panels, driving the increase in thickness stability of these panels.

Determination of Internal Bond Strength

The thickness stability and moisture absorption changes of the three tested materials during RHC treatment were discussed above, and these changes affected the internal bond (IB) strength. The results of control and treated groups after conditioning at a temperature of 20°C with 65% RH are summarized in Table 3. The RHC treatment induced different decreases in IB strength. The IB strength of the wood-plastic composite board decreased 2.16%, from 2.32 N/mm^2 to 2.27 N/mm^2. There were greater decreases in IB strength for particle board and MDF of 22.2% and 22.3%, respectively.

Table 3. Internal Bond Strength of the Specimens Before and After RHC Treatment

RHC→ Materials↓	0 (N/mm^2)	3RHC (N/mm^2)	6RHC (N/mm^2)	9RHC (N/mm^2)
Particleboard	0.63 ± 0.12	0.57 ± 0.17	0.53 ± 0.14	0.49 ± 0.16
MDF	0.87 ± 0.09	0.81 ± 0.19	0.73 ± 0.17	0.67 ± 0.13
Wood-plastic Composite Board	2.32 ± 0.14	2.29 ± 0.20	2.31 ± 0.18	2.27 ± 0.23

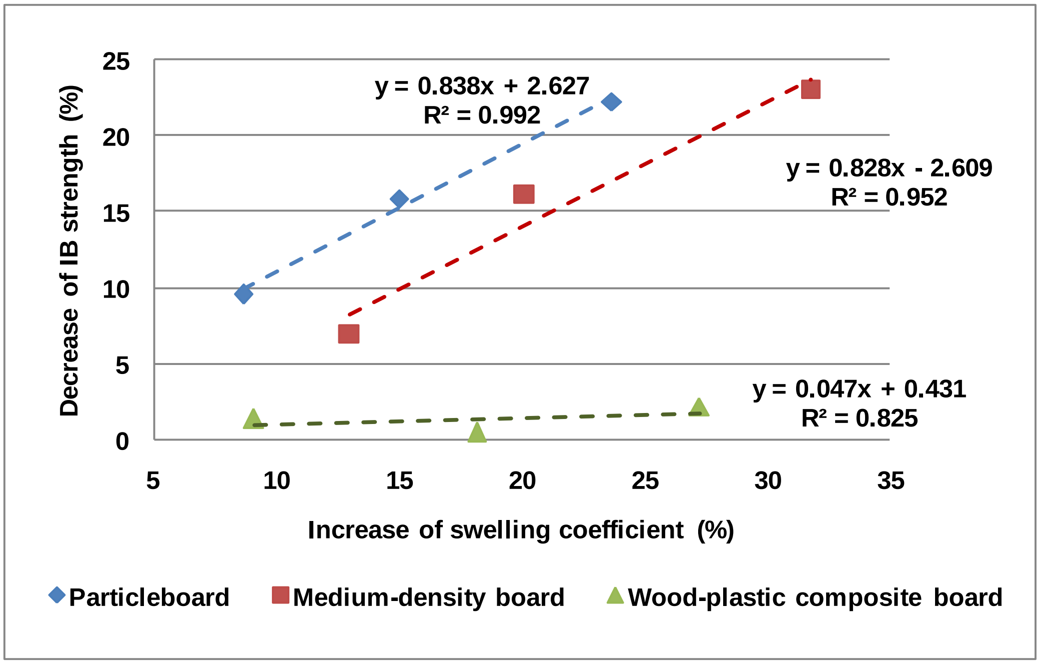

Fig. 5. Correlations between swelling coefficient and IB of specimens during RHC treatment at 50 °C

Using the measured thickness and moisture changes presented earlier, a combined analysis was performed next of the increase of swelling coefficient and decrease of IB strength, as presented in Fig. 5. These plots show a regular distribution, and the data trend suggests that IB strength change affected the thickness stability of these tested materials. Wood-based panel material with low thickness stability had a low IB strength, and material with high thickness stability had a high IB strength.

CONCLUSIONS

1. Particleboard, medium-density fiberboard, and wood-plastic composite board suffered thickness and weight changes during repeated humidity cycling (RHC) treatment. Among the three tested materials, the wood-plastic composite board material showed the highest stability, with small thickness and weight change values. Temperature is an important determinant of the effect of RHC treatment, with greater thickness changes after six cycles at 50 °C than after nine cycles at 20 °C.
2. There were differences in the moisture content of specimens conditioned at 20 °C and RH 65% due to differences in the internal structure of the materials. Compared with the control group, the thickness stability of RHC-treated materials was decreased by 23.7 to 31.8% and the moisture absorbing capacity increased 2.28 to 5.97%.
3. The internal bond strength of specimens decreased 22 to 23% for particleboard and MDF and 2.15% for wood-plastic composite board due to RHC treatment. There was a good correlation between the thickness stability and internal bonding strength of the tested materials.

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