Dimensional Stability of Fire-Retardant-Treated Laminated Veneer Lumber

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Abstract

Test of fire-retardant-treated (FRT) laminated veneer lumber (LVL) indicated moisture gain under adsorption and moisture loss under desorption conditions. The moisture content of FRT specimens increased considerably under adsorption conditions compared with control specimens, while it was not found to be a significant difference under desorption conditions. The statistical findings revealed that impregnation with chemical salts had significant effects on the expansion properties. Fire-retardant treatment also had meaningful effects on the swelling properties. However, the expansion and swelling properties of the LVL were not affected significantly by the veneer drying temperature. Generally, equilibrium moisture content of LVL decreased with increasing veneer drying temperature. The interactions between fire-retardant chemicals and veneer drying temperature were also found to be insignificant.

Wood and wood-based materials are of great importance in both residential and nonresidential building construction. Engineered composite materials represent one of the fastest growing segments of the wood products industry. Laminated veneer lumber (LVL) is a structural material made from veneer sheets that are bonded together with an adhesive system (Shi and Walker 2006). As the name implies, it is an alternative material to solid-sawn or glued-laminated lumber. Wood composites are used as a construction material in more than 40 percent of new residential construction in North America, and LVL is the primary flange material in the manufacture of I-joists. Some believe that LVL may be used as a substitute for solid-sawn wood because it retains the structural properties of wood (Haygreen and Bowyer 1996).

Dimensional properties, in response to loss of moisture of the materials, are one of the most important properties for wood-based products. The dimensional changes become important when large panel sizes are used or when the expansion is totally or partially restrained. The in-plane movements can cause high internal stresses due to the restraint offered by fastening such as nails. These stresses may be large enough to cause buckled panels, pushed-out nails, and separation of the panel from the structure (Wu and Suchsland 1996). Hence, the level of expansion and contraction values of LVL can be important for suitable design applications.

The fire performance of wood-based materials can be significantly improved by chemical treatments, thereby widening their utility (Anonymous 1999, Shi and Walker 2006, Ayrilmis et al. 2007, Kartal et al. 2007). Fire-retardant-treated (FRT) wood products provide a viable alternative to traditional noncombustible materials where a higher level of fire safety is desired. The most common fire-retardant chemicals used for wood and wood-based panels are the inorganic salts: phosphoric acid, monoammonium phosphate (MAP), diammonium phosphate (DAP), ammonium sulfate, nitrogen, zinc chloride (ZnCl), and boron compounds, namely, borax (BX) and boric acid (BA; LeVan

and Winandy 1990). Phosphates and boron compounds are among the oldest known fire-retardant systems, and they are usually included in proprietary systems used for wood. Because of its high preservative effectiveness and lower impact on mechanical properties compared with other chemicals, boron compounds are often considered good fire retardants (LeVan and Tran 1990, Winandy 1997, Anonymous 1999).

Wood treated with inorganic flame-retardant salts is usually more hygroscopic than untreated wood, especially at high relative humidity (RH) values. In particular, boron compounds and phosphates may have adverse effects on hygroscopicity (Alexiou et al. 1986, LeVan and Winandy 1990, Hashim et al. 1994, Shi and Walker 2006). Increases in the equilibrium moisture content (EMC) of such treated wood will depend on the type of chemical, level of chemical retention, and size and species of the wood (Anonymous 1999). In addition, variation in chemical composition of wood can influence sorption properties. In general, hemicellulose is the most hygroscopic constituent, followed by cellulose and lignin (Zhang and Datta 2004, Salin 2008). Typically, an increase in moisture content (MC) from 2 to 8 percent occurs in the treated wood at 27°C, 65 percent RH; and at 80 percent RH, it further increases from 5 to 15 percent compared with untreated samples (Holmes 1977).

An extensive literature search did not reveal any information about the effect of fire-retardant chemicals such as boron compounds and phosphates and redrying on dimensional stability of FRT LVL. Impregnation with water-soluble salts can adversely affect dimensional stability of wood composites (Akbulut et al. 2004, Ayrilmis et al. 2005, Ayrilmis 2006, Ayrilmis et al. 2007, Kartal et al. 2007). The veneers in an LVL panel are aligned in the same grain direction, while in plywood panels the veneers are bonded with the grain at right angles. For this reason, the dimensional behavior of LVL is closer to lumber under changing environment conditions compared with other wood composites such as plywood and oriented strand board (OSB; Haygreen and Bowyer 1996). Waterborne inorganic salts, such as boron compounds and phosphates, adversely affect swelling and expansion properties of wood and wood composites because of their hygroscopic characteristics and possible interaction between the deposition of boron and phosphate crystals and the monomer in the cell wall. The objective of this study was to investigate the influence of various fire-retardant treatments on linear and thickness variations of LVL made from redried wood veneer sheets.

Materials and Methods

Rotary cut veneers obtained from beech (*Fagus orientalis* Lipsky) logs were used to make LVL under laboratory conditions. Each veneer sheet was 500 by 500 by 2.7 mm thick. The veneers were almost free from defects, and the sheets were kept in a conditioning chamber maintained at 25°C and 37 percent RH (7% MC) until they equilibrated. Three different fire-retardant chemical formulations were used in treatments: a mixture of BX and BA ($Na_2B_4O_7 \cdot 10H_2O$ and H_3BO_3; BX/BA, 1:1 by weight), MAP ($NH_4H_2PO_4$), and DAP [$(NH_4)_2HPO_4$].

The veneers were pressure impregnated with the fire-retardant chemicals using a full-cell process. A vacuum of 0.086 MPa was pulled for 30 minutes, chemicals were added, and pressure of 1.1 MPa was then applied for 60 minutes. The concentration of the chemical solutions was adjusted to provide 56 kg of chemical retention on 1 m^3 ovendry wood weight.

Following the impregnation, the treated veneer sheets were dried in an industrial jet dryer of four different temperatures, namely, 120°C, 140°C, 160°C, and 180°C, for 15 minutes. A total of 36 five-ply, 13-mm-thick experimental panels were manufactured from veneer sheets with the dimension of 500 by 500 by 2.7 mm. An exterior phenol-formaldehyde resin (47% solid content) was applied on a single bond line at a rate of 200 g/m^2. The individual veneers were then assembled, with the grain of all veneers oriented in the lengthwise direction of the billet, and hot pressed for 15 minutes under a pressure of 1.5 MPa and temperature of 140°C. The resulting LVL panels were allowed to cool for 48 hours in a controlled environment room maintained at 20°C, 65 percent RH before cutting into test specimens.

The linear and thickness variations of the panels were determined following procedures outlined in TS EN 318 (Turkish Standards Institute 2005). The linear and thickness variations for LVL, samples between two EMC conditions (65% to 85% for adsorption condition, 65% to 30% for desorption condition, both at 20 ± 2°C), were calculated as a percentage of the initial specimen length and thickness. Linear expansion (LE) or contraction (LC) and thickness swell (TS) are induced by changes in moisture content. Changes in length and thickness were monitored under adsorption conditions between 65 and 85 percent RH and desorption conditions between 65 to 30 percent RH.

The specimens with dimensions of 300 by 50 by 13 mm parallel to fiber direction of the LVL were tested. The numbers of specimens tested for each treatment group are given in Table 1. The specimens were equilibrated to constant weight in climate chambers. Half of the LVL specimens were randomly used for adsorption regime and the other half for desorption regime. The LE, linear expansion coefficient (LEC), LC, and linear contraction coefficient (LCC) were calculated as follows:

$$LE_{65\,to\,85} = (L_{85\,final} - L_{65\,initial}) \times 100 / L_{65\,initial}$$
$$(\text{adsorption regime}) \quad (1)$$

$$LEC = LE_{65\,to\,85} / \Delta M_{65\,to\,85} \quad (\text{adsorption regime}) \quad (2)$$

$$LC_{65\,to\,30} = (L_{65\,initial} - L_{30\,final}) \times 100 / L_{65\,initial}$$
$$(\text{desorption regime}) \quad (3)$$

$$LCC = LC_{65\,to\,30} / \Delta M_{65\,to\,30} \quad (\text{desorption regime}) \quad (4)$$

where

LE = linear expansion (%),

LEC = linear expansion coefficient (%),

LC = linear contraction (%),

LCC = linear contraction coefficient (%),

ΔM = Increase or decrease in moisture content ($\Delta M = M_2 - M_1$) (%),

M_{85} = MC at 85 percent RH (%),

M_{65} = MC at 65 percent RH (%), and

M_{30} = MC at 30 percent RH (%).

Table 1.—Fire-retardant treatment and drying temperature effects on the equilibrium moisture content (EMC) and changes of moisture content of LVL panels.

Treatment chemical	No. of specimens	Retention (kg/m³)	Drying temperature (°C)	EMC (%)				Change of moisture content (%)	
				Adsorption		Desorption		Adsorption	Desorption
				65% RH[a]	85% RH	65% RH	30% RH	(EMC$_{85\%}$ − EMC$_{65\%}$)	(EMC$_{65\%}$ − EMC$_{30\%}$)
Untreated	8	—	120	11.6	20.0	15.6	8.5	8.4	7.1
	8		140	11.1	19.1	15.3	8.5	8.0	6.8
	8		160	11.2	19.1	15.2	8.2	7.9	7.0
	8		180	11.1	19.6	15.2	8.0	8.5	7.2
	32							*8.3*[b]	*7.0*
MAP	10	56.2	120	11.9	24.4	15.9	9.0	12.5	6.9
	10		140	11.6	24.0	15.8	8.5	12.4	7.3
	10		160	11.5	23.9	15.8	8.5	12.4	7.3
	10		180	11.1	23.4	15.3	8.3	12.3	7.0
	40							*12.4*	*7.1*
DAP	7	56.6	120	12.4	26.0	18.1	9.3	13.6	8.8
	7		140	12.5	26.1	18.3	9.5	13.6	8.8
	7		160	12.6	26.3	17.8	9.4	13.7	8.4
	7		180	11.9	25.5	18.0	9.0	13.6	9.0
	28							*13.6*	*8.8*
BX/BA	7	57.8	120	13.0	27.1	16.8	10.2	14.1	6.6
	7		140	12.6	26.1	16.4	10.3	13.5	6.1
	7		160	12.8	26.6	16.6	10.0	13.8	6.6
	7		180	12.8	26.6	16.6	10.1	13.8	6.5
	28							*13.8*	*6.5*

[a] RH = relative humidity.
[b] The bold italic numbers are average values of moisture content changes for all drying temperatures.

The thickness swelling and shrinkage properties were calculated as follows:

$$\text{TS}_{65\,\text{to}\,85} = (T_{85\,\text{final}} - T_{65\,\text{initial}}) \times 100/T_{65\,\text{initial}}$$
$$\text{(adsorption regime)} \quad (5)$$

$$\text{TSC} = \text{TS}_{65\,\text{to}\,85}/\Delta M_{65\,\text{to}\,85} \quad \text{(adsorption regime)} \quad (6)$$

$$\text{TSh}_{65\,\text{to}\,30} = (T_{65\,\text{initial}} - T_{30\,\text{final}}) \times 100/T_{65\,\text{initial}}$$
$$\text{(desorption regime)} \quad (7)$$

$$\text{TShC} = \text{TSh}_{65\,\text{to}\,30}/\Delta M_{65\,\text{to}\,30} \quad \text{(desorption regime)} \quad (8)$$

where

TS = thickness swelling (%),

TSC = thickness swelling coefficient (%),

TSh = thickness shrinkage (%), and

TShC = thickness shrinkage coefficient (%).

Results and Discussion

Table 1 shows comparative changes in the MC of LVL samples, under adsorption (65% to 85%) and desorption (65% to 30%) conditions, produced from FRT veneers dried at the test temperatures.

As shown in Table 1, under adsorption condition of 65 to 85 percent RH, the highest moisture uptake occured in BX/BA-treated LVL samples (with average of 13.8%) followed by DAP (13.6%), MAP (12.4%), and control (8.3%). Water-soluble fire retardants have an adverse affect on hygroscopicity. Under desorption conditions of 65 to 30 percent RH, it appears that FR treatments have a minor effect on moisture loss of the treated panels as compared with the control panels. The maximum moisture loss occurred with the DAP-treated samples, with average decrease of 8.8 percent, followed by MAP (7.1%), control (7.0%), and BX/BA (6.5%) treatments (Table 1). The moisture loss (%) in the desorption samples was lower than moisture uptakes (%) in adsorption samples. Figure 1 shows sorption hysteresis curves of the FRT and control LVL groups at 120°C. Similar trends were observed in the other drying temperatures. As shown in Figure 1, the moisture uptake and moisture loss at the higher RH (between 65% and 85%) were higher than at the lower RH (between 30% and 65%). The moisture uptake values in Table 2 are for 65 to 85 percent, while the moisture loss values are for 65 to 30 percent. Fewer effects of chemicals on moisture loss properties of treated samples could be realized at RH ranging from 30 to 65 percent under desorption conditions (Fig. 1). In addition, drying temperature had no considerable effect on the moisture intake or loss of FRT or control LVL groups (Table 1).

Previous studies reported that wood treated with inorganic flame-retardant salts is usually more hygroscopic than untreated wood, particularly at higher relative humidities. Above 80 percent RH, veneers treated with chemical salts reached moisture equilibrium faster (Holmes 1977, LeVan and Winandy 1990, Leao 1993, Repellin and Guyonnet 2005, Kartal et al. 2007, Lesar et al. 2009). Increased water sorption can be attributed to the new adsorption sites that were formed as a result of the treatments. However, structural and chemical modifications of cell-wall constituents may lead to the formation of additional hydrogen-bonding sites for water. Increases in the equilibrium moisture content of such treated wood will depend upon the type of chemical, level of chemical retention, size of the wood, and species of the wood involved (Anonymous 1999). A number of studies also verified a definite correlation between chemical treatments and water uptake properties of wood (Alexiou et al. 1986, LeVan and
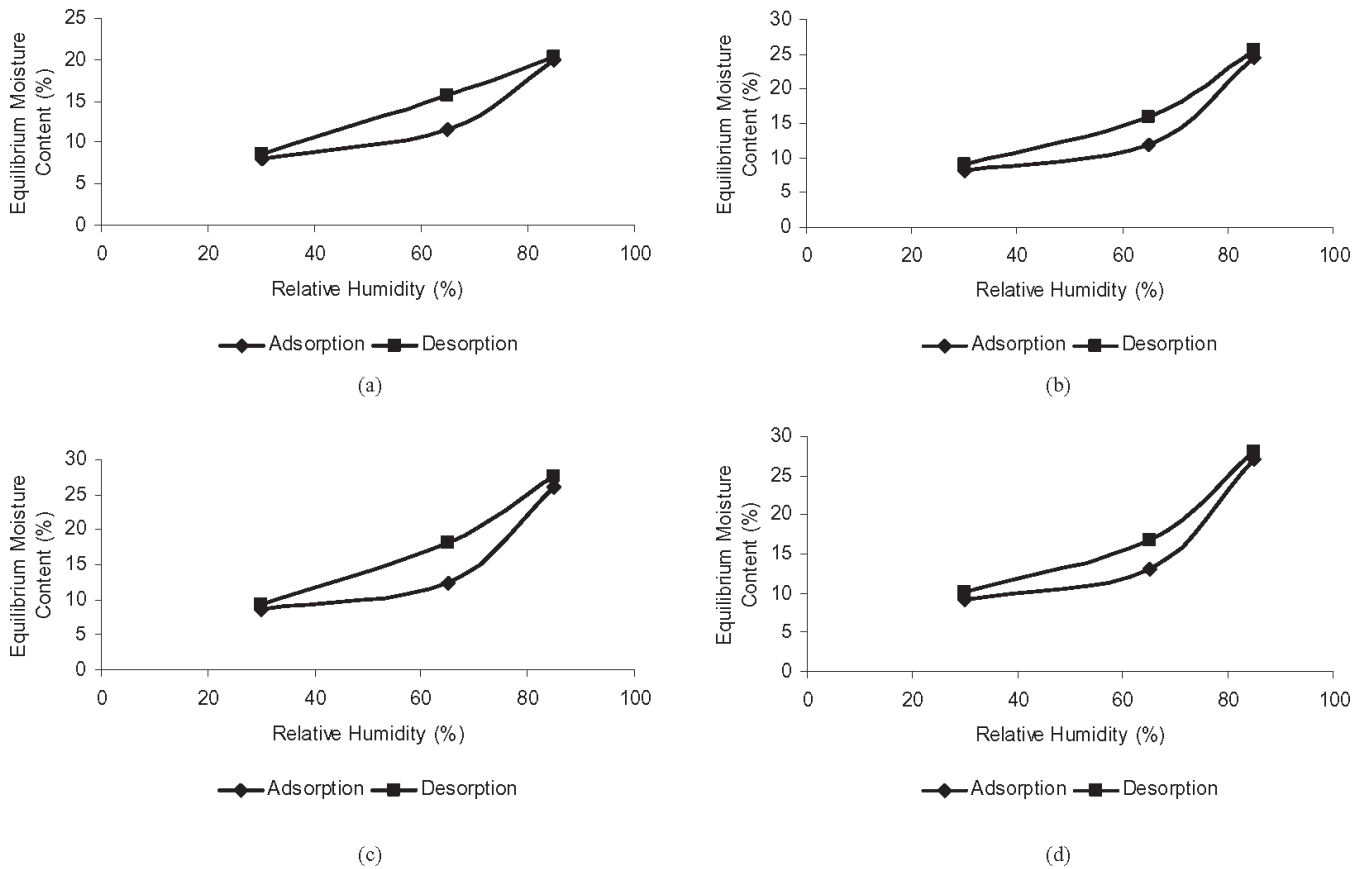
Figure 1.—Sorption hysteresis curves of the FRT and control LVL groups at 120°C: (a) control, (b) MAP, (c) DAP, (d) BX/BA.

Winandy 1990, Hashim et al. 1994, Lesar et al. 2009). Ammonium and boron-based fire-retardant chemicals have been reported to have a negative effect on the dimensional stability of wood and wood-based panels such as particleboard, medium-density fiberboard, and OSB (Yalinkiliç et al. 1998; Akbulut et al. 2004; Ayrilmis et al. 2005, 2007; Ayrilmis 2006; Kartal et al. 2007).

Under adsorption conditions, BX/BA and DAP had higher water sorption values than the others. However, under desorption conditions, BX/BA-treated samples had the lowest moisture loss while DAP-treated samples had the highest moisture loss. It is probably related to BA–water interaction that is a typical Lewis acid–base reaction to form hydrated BA molecules. Water acts in some reactions as a base and in others as an acid and is therefore referred to amphoteric (Frihart 2005). BA can form a coordinate covalent bond with a Lewis base (e.g., OH^- from water) to form hydrated BA molecules that have high bond energies. Water cannot react in a similar way with the other fire-retardant chemicals examined in this study. The BA–water reaction proceeds more easily during adsorption, and therefore higher water uptake values were observed compared with the other fire-retardant chemicals. Moreover, during desorption, due to high bond energies, it can be more difficult to remove water from hydrated BA compared with the FRT samples. The lower moisture losses in the desorption samples produced from BX/BA-treated panels clearly support this information.

The average LE/LC values and the TS and TSh values of the experimental LVL panels are presented in Tables 2 and 3, respectively. The statistical comparison results for treatment types are presented in Table 4. Duncan's multiple range test results showed that the BX/BA-treated samples had significantly higher LE values than MAP- and DAP-treated panels, while it was in the same group as the control. Similarly, the LC of BX/BA-treated samples was significantly higher than the control and MAP samples, but not different from the DAP samples.

The fire-retardant treatment also had a significant effect on TS and TSh (Table 4). The TS values of BX/BA and untreated panels were significantly higher than those of the MAP- and DAP-treated samples. In MAP-treated samples, TS values were significantly lower than those of others. However, in the DAP-treated samples, TS values were between the BX/BA- and DAP-treated samples. Moreover, TSh values were significantly higher in the control and DAP-treated samples. However, BX/BA-treated samples, which had a lower moisture loss under desorption conditions, had significantly lower TSh values than other treatments. MAP-treated samples were intermediate between these two groups.

These results indicate that the phosphate and the boron compounds did not have a significant negative effect on the dimensional stability of LVL samples, even though the water uptake significantly increased with fire-retardant treatment above 65 percent RH (Tables 1 through 3). These results indicate that phosphate compounds can be used as fire retardants in LVL manufacture.

Analysis of variance (ANOVA) results indicated that drying temperature did not significantly affect EMC or

Table 2.—Average values of linear expansion/contraction.[a]

| Treatment chemical | Temperature (°C) | Linear expansion/contraction parameters | | | |
		Linear expansion	Linear contraction	Linear expansion coefficient	Linear contraction coefficient
Untreated	120	0.10 (0.04)	0.07 (0.02)	0.012	0.011
	140	0.09 (0.04)	0.04 (0.03)	0.011	0.006
	160	0.10 (0.04)	0.04 (0.03)	0.012	0.006
	180	0.10 (0.03)	0.06 (0.04)	0.012	0.009
MAP	120	0.07 (0.04)	0.05 (0.02)	0.006	0.007
	140	0.06 (0.03)	0.04 (0.02)	0.005	0.006
	160	0.07 (0.03)	0.06 (0.02)	0.006	0.008
	180	0.07 (0.03)	0.05 (0.02)	0.006	0.008
DAP	120	0.08 (0.04)	0.07 (0.02)	0.006	0.008
	140	0.09 (0.04)	0.06 (0.03)	0.007	0.007
	160	0.08 (0.03)	0.07 (0.03)	0.006	0.008
	180	0.08 (0.03)	0.05 (0.02)	0.006	0.006
BX/BA	120	0.11 (0.05)	0.07 (0.04)	0.008	0.010
	140	0.11 (0.04)	0.08 (0.04)	0.008	0.012
	160	0.10 (0.04)	0.08 (0.03)	0.007	0.013
	180	0.10 (0.04)	0.06 (0.02)	0.007	0.010

[a] Values are percentages with standard deviations in parentheses.

Table 3.—Average values of thickness swelling/shrinkage.[a]

| Treatment chemical | Temperature (°C) | Thickness swelling/shrinkage parameters | | | |
		Swelling	Shrinkage	Swelling coefficient	Shrinkage coefficient
Untreated	120	2.68 (0.32)	1.72 (0.16)	0.318	0.244
	140	2.95 (0.37)	1.82 (0.36)	0.368	0.268
	160	2.86 (0.27)	1.90 (0.18)	0.361	0.273
	180	2.90 (0.33)	1.87 (0.09)	0.339	0.260
MAP	120	2.20 (0.20)	1.39 (0.18)	0.175	0.205
	140	1.93 (0.25)	1.56 (0.14)	0.155	0.211
	160	1.88 (0.36)	1.46 (0.17)	0.153	0.200
	180	1.71 (0.26)	1.31 (0.14)	0.141	0.192
DAP	120	2.58 (0.51)	1.75 (0.28)	0.192	0.199
	140	2.31 (0.44)	1.86 (0.24)	0.171	0.211
	160	2.37 (0.44)	1.71 (0.12)	0.174	0.205
	180	2.48 (0.50)	1.89 (0.26)	0.184	0.212
BX/BA	120	3.03 (0.59)	1.32 (0.24)	0.217	0.201
	140	3.03 (0.55)	1.25 (0.20)	0.225	0.203
	160	2.96 (0.48)	1.29 (0.28)	0.214	0.196
	180	2.90 (0.53)	1.27 (0.25)	0.210	0.191

[a] Values are percentages with standard deviations in parentheses.

dimensional stability of the LVL, even though EMC decreased with increasing veneer drying temperature. Similar results were also found for the EMC of plywood panels (Aydin and Colakoglu 2005). Kollmann and Schneider (1963) reported that the sorption capacity of beech wood decreased with increasing thermal treatment temperature and time. This was attributed to the degradation of the most hygroscopic compounds, hemicelluloses and amorphous cellulose, but dehydration reactions during heat treatment were also reported (Holmes 1977, Zhang and Datta 2004, Esteves et al. 2007, Salin 2008). Previous studies have shown that the hygroscopicity of wood materials was affected by temperature and resulted in a decrease in EMC (Tabarsa 1995, Gunduz et al. 2008). The MC of wood materials thermally modified using a hot press decreased with increasing press temperature (Tabarsa and Chui 1997, Unsal and Candan 2008). Hemicelluloses are hydrolyzed during heat treatment, and this decreases the hygroscopity of heat-treated wood (Winandy and Smith 2006). The temperature and duration of exposure are two important factors affecting the degradation of hemicelluloses (LeVan and Winandy 1990). However, heat treatment of wood usually required longer time, typically more than 2 hours. In the present study, however, all veneer sheets used for producing

Table 4.—Statistical analysis results of expansion and swelling properties of LVLs as a function of treatment type.[a]

| Treatment type | Expansion properties | | Swelling properties | |
	Linear expansion	Linear contraction	Thickness swelling	Thickness shrinkage
MAP	A	A	A	A
DAP	AB	AB	B	B
BX/BA	C	B	C	C
Control	BC	A	C	B

[a] Groups with the same letters in each column indicate that there is no statistical difference ($P > 0.05$) between the samples according to the Duncan's multiple range test.

LVL panels were dried in a very short time (15 min) and pressed at a constant temperature (140°C). This may be the major reason for the insignificant effect of drying temperature on EMC and dimensional stability of LVL panels. The interactions between fire-retardant chemicals and drying temperature of veneer were found to be insignificant.

Conclusions

Water-soluble fire retardants have a negative effect on the hygroscopic behavior of LVL panels. Under adsorption conditions, it was found that the highest moisture intake occured in BX/BA-treated LVL panels, with an average increase of 13.8 percent, followed by DAP (13.6%), MAP (12.4%), and control (8.3%). However, under desorption conditions, it appears that FR treatments have a minor effect on moisture loss of the treated panels compared with the control panels. The maximum moisture loss was observed with the DAP treatment with an average of 8.8 percent, followed by MAP (7.1%), control (7.0%), and BX/BA (6.5%) treatments. The moisture intake and moisture loss at the higher RH (between 65% and 85%) were higher than at the lower RH (between 30% and 65%). The moisture intake values are for 65 to 85 percent, while the moisture loss values are for 65 to 30 percent. Fewer effects of chemicals on moisture loss properties of treated samples could be realized at RH ranging from 30 to 65 percent under desorption conditions. Treatments with water-soluble fire retardants also influence dimensional stability of LVL. Generally, BX/BA-treated samples had significantly higher LE and TSh values than other fire retardants and control in adsorption. All the veneer sheets used for producing LVL panels were dried in a very short time (15 min) and pressed at a constant temperature (140°C) under dry conditions. This may be the major reason for the absence of any effect of drying temperature on EMC and dimensional stability of LVL panels. The interactions between fire-retardant chemicals and drying temperature of veneer were found to be insignificant in terms of moisture intake or loss of FRT and control LVL groups.

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