SOUTHERN PINE WOOD AND STRANDS IMPREGNATED WITH LOW LEVELS OF BUTANETETRACARBOXYLIC ACID AS STABILIZING AGENT FOR ORIENTED STRANDBOARD[1]

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ABSTRACT

Southern pine wood specimens were impregnated with butanetetracarboxylic (BTCA) acid at 1.0–5.0% levels using a vacuum/pressure method and hot-pressing at 150°–210°C in the radial direction. The acid treatments gave anti-swelling efficiency (ASE) values up to 57% in an exhaustive first water-soak cycle. The ASE values were higher in the radial than tangential direction, and higher for irreversible than reversible components. Laboratory strandboards made with wood strands impregnated with 0.5°–1.0% BTCA levels under vacuum showed ASE values of up to 53%, but internal bond and modulus of elasticity and rupture values decreased somewhat excessively. The strength values of boards were modest, higher than the minimum industry requirements for commodity-type oriented strandboard. The various effects of BTCA on wood and board properties were discussed. Use of BTCA at less than 0.5% level and optimization of hot-pressing and resin binder and wax levels may result in a method of manufacturing oriented strandboard with significantly improved dimensional stability.

Keywords: Butanetetracarboxylic acid, acid wood stabilization, dimensionally stable oriented strandboard.

INTRODUCTION

Oriented strandboard (OSB) is manufactured from southern pine (SP) and aspen and various other soft hardwoods using phenol-formaldehyde or isocynate resins as binders. One major problem with OSB is its low dimensional stability, specifically thickness swelling values that range from 15% to 30% in 24-h water-soak test. Currently, paraffin wax is added to boards up to about 1.5% by weight of wood as water barrier, but the effectiveness is somewhat limited. Higher levels of wax cannot be used because it interferes with adhesion of binders. In a companion paper, we showed impregnation of l% and 2% low molecular weight PF resins in wood strands by a vacuum method to improve the dimensional stability of boards, but the method deemed to be of high cost due to the vacuum impregnation process (Wan and Kim 2006). In this paper, we investigated butanetetracarboxylic acid (BTCA) as an acid crosslinking agent

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for improving the dimensional stability of oriented strandboard with the possible acidic adverse effects being kept in mind.

Various chemical/physical methods have been explored to improve the dimensional stability of wood and wood composites besides the low molecular weight PF resin approach (Hon and Bangi 1996). Acetylation of hydroxyl groups of wood makes wood less hygroscopic and improves dimensional stability of strandboard (Goldstein et al. 1961; Gomez et al. 1999), but the method is expensive for commodity-type OSB since the chemical loading level is relatively high and the process entails an acetic acid recycling step. For OSB bonded with liquid-type PF resins, the binder level can be increased to improve the dimensional stability, from the current 3.5% level up to about 10% level, to achieve a low thickness swelling and increased strength properties; but the increased binder cost becomes substantial. Another approach is the steam injection pressing method, where plasticization of wood occurs more effectively due to the hot steam injected into board mat during pressing (Gomez et al. 1999), but the method is also expensive for commodity-type panels. Another approach is the use of a polycarboxylic acid resin where thickness reductions up to 45% were obtained for aspen wood with up to 17% resin solids loading levels (Peyer et al. 2000). Although some crosslinking reactions were suggested, bulking effect was the major contributor to the stabilization probably because of the relatively small number of carboxylic acid groups available in large resin molecules. The effectiveness was very small at 1%–2% of resin loading levels, making the resin material cost high for commodity-type OSB panels.

Plasticization, increased hydrophobicity, and degradation of wood structures occur in hotpressing of wood composites because of various chemical/physical changes that occur due to the heat and moisture (Inoue et al. 1993). The chemical/physical changes include dehydration of hydroxyl groups, de-acetylation, and polymer chain rearrangement and depolymerization of hemicelluloses and lignin components (Seborg et al. 1953; Humphrey 1982; Salmen 1982; Rofael 1987; Hsu et al. 1988). These changes can relieve stresses incurred in compaction of wood mats but also result in weakening of wood structures. On the other hand, various acids accelerate these chemical/physical changes especially at elevated temperatures, and often the reactions would progress beyond the useful extent to harm the structural integrity of wood (Gomez et al. 1999). On the other hand, using a weak acid that can crosslink the hydroxyl groups in wood may offer a low-cost approach to the manufacture of dimensionally stable wood composites such as OSB. Butanetetracarboxylic acid (BTCA) and several other polycarboxylic acids, with sodium dihydrogenphosphate (NaH_2PO_4) catalyst, have been explored as crosslinking agents for wood and cotton (Caufield 1994). At a 9% loading level in *Chamaecyparis lawsoniana* (Oregon cedar) and *Picea sitchensis* (Western spruce) the BTCA approach showed an anti-swelling efficiency (ASE) of 57.2% and 55.5%, respectively (Fang et al. 1998). The compression recovery of treated Oregon cedar specimens in 5-h boiling water test was only 27.0%. In the treatment of cotton with BTCA, ester bonds were found to form with cellulose hydroxyl groups (Yang and Andrews 1991; Yang 1993; Teal 1994; Zhou et al. 1995; Yang and Wang 1996, 1997), indicating crosslinking covalent bonds formed in the cellulose/wood structures due to the multiple functional groups involved. If all the carboxylic groups would react to form ester bonds, no acid residues would remain in wood except the catalyst. However, the esterifcation reactions can be incomplete or reversed to result in some free acids remaining in the products. Although the possible acid degradation effect of polycarboxylic acids was not mentioned in these reports, BTCA would offer an avenue to a potentially low-cost method in stabilizing wood and wood composites. This study examined several BTCA/catalyst combinations at low loading levels under various hot-pressing conditions. SP wood specimens were used in the preliminary study and, then, 60:40 SP and mixed hardwood strands were treated and strandboards were made and tested.

EXPERIMENTAL METHODS

Materials

End-matched SP wood specimens (40 mm × 19 mm × 5 mm; longitudinal, tangential, radial) were cut from commercial kiln-dried lumber. Ten replicate samples were used for each treatment and control experiment. The wood specimens were conditioned in a room at 25°C and 60% relative humidity (RH) for up to three weeks. General properties of prepared wood specimens met the requirement of the American Wood-Preservers' Association Standard M10-77 section 5.1 (AWPA 1988). Butanetetracarboxylic acid (Ortec, Inc.) was dissolved in water with sodium dihydrogenphosphate (NaH_2PO_4) (Aldrich Chemical Co.) catalyst to make treatment solutions. The pH of 1% BTCA water solution was 2.9. Green OSB strands (60% SP and 40% mixed hardwoods) were obtained from Norbord Corp., Guntown, Mississippi.

Impregnation of wood specimens with BTCA solution, drying, and hot-pressing

Using the typical vacuum and pressure method used in the wood preservation treatment industry, a set number of wood specimens were weighted down in a pan and placed in a treating cylinder, a vacuum of 98 kPa was applied for 15 min, and then a BTCA solution introduced until the wood specimens were fully submerged while under vacuum. Then, vacuum was released and an air pressure of 690–828 kPa was applied for 30 min. The wet specimens were taken out and weighed to determine the weight gains of treating solution, aired in hood for 12 h, and then dried in an oven at 103°C for 24 h. BTCA loading levels in wood specimens were calculated using the concentration of BTCA solution and the wet weight gains. The wet weight gains were approximately 100%, and therefore, for a target BTCA loading level of 1.0%, for example, a 1.0% BTCA solution was used in treatment.

The treated, dried wood specimens were then put side by side in a 150-mm × 150-mm Carver laboratory press and hot-pressed in the radial direction to reach 4-mm thickness from the ini-

tial 5-mm thickness (20% thickness compression) with selected press temperatures and times. The compressed, heat-treated wood specimens were equilibrated at 25°C in 60% RH conditioning room for three weeks. Control samples were treated with water instead of a BTCA solution in the treatment cylinder and dried and similarly hot-pressed.

Determination of anti-swelling efficiency

ASE measurements were carried out by subjecting wood specimens to an exhaustive water-soak treatment according to Rowell and Ellis (1978; FPL 1999). The hot-pressed and equilibrated specimens were dried at 103°C for 24 h, cooled in a desiccator for 3 h, and the oven-dry dimensions (Vd) measured. The specimens were then weighted down in a pan and placed in a treatment cylinder, a vacuum of 98 kPa was applied for 15 min, and then distilled water was introduced until specimens were fully submerged. Vacuum was then released and an air pressure of 690–828 kPa was applied for 30 min, and the specimens were taken out and placed in distilled water at 20°C for 24 h. The dimensions of the water-saturated specimens (Vw) were measured, and the volumetric swelling of treated specimens (St) relative to that of control (Sc) was calculated using Eq. (1). The volumetric anti-swelling efficiency (ASEv) value was calculated using Eq. (2).

$$St \text{ or } Sc \ (\%) = ((Vw - Vd)/Vd) \times 100 \tag{1}$$

$$ASEv \ (\%) = ((Sc - St)/Sc) \times 100 \tag{2}$$

After drying at 103°C for 24 h, the wood specimens were subjected to the same water-soak treatment two more times, resulting in three consecutive ASE values, i.e., $ASEv_1$, $ASEv_2$ and $ASEv_3$. This procedure also led to reversible and irreversible ASE values, ASEre and ASEir, obtained by comparing the recovered and unrecovered swelling values after drying of wet specimens. Furthermore, since the wood specimens were cut to have their thicknesses in the radial direction, thickness and width changes led

to the respective radial and tangential ASE values: ASEr and ASEt. Experimental parameters for BTCA treatments of wood specimens were BTCA loading level, hot-press temperature and time, and NaH_2PO_4/BTCA ratio as shown in Table 1.

BTCA treatments of strands and manufacturing and testing of strandboards

Green wood strands, 18 kg, were impregnated with BTCA solutions using the vacuum procedure, following the same method used for wood specimen treatments but without the pressure application step. The impregnated strands were dried in a kiln at 110°C until about 4% MC content, screened through an 8-mm × 8-mm screen to remove fines, and stored in a sealed plastic bag until used in the board preparation. For the spraying method of BTCA application, a measured amount of aqueous BTCA solution was sprayed on green wood strands using a compressed-air sprayer in a tumbling blender. Then the strands were kept in a plastic bag for 24 h to help BTCA solution to diffuse, dried and screened similarly, and kept in a sealed plastic bag until used. For strandboard experiments, the following three parameters were studied as a 2 × 3 × 4 factorial experiment: BTCA loading levels of 0%, 0.5%, 0.75%, and 1.0%; press temperatures of 200° and 220°C; press times of 3, 5, and 7 min. Then, the catalyst-only boards were made at a 2.0% loading level. Finally, the spraying method for application of BTCA solution on wood strands was examined to see if a simpler impregnation step was possible.

TABLE 1. *BTCA/sodium dihydrogenphosphate (SDHP) ratio and level and hot-pressing parameters used for impregnating and hot pressing SP wood specimens.*

BTCA/SDHP	BTCA level (%)	Press Time (min)	Press Temp (°C)
1:1	1.0	20	150, 180, 210
	2.5	20	150, 180
	3.0	20	150, 180
	5.0	20	150, 180, 210
1:2	1.0	5	180, 210
	1.0	20	180
0:1	0.0	20	150

The treated wood strands were blended with GP®169C09 (Georgia-Pacific Resins Inc.), a liquid OSB core-layer PF resin, at 4% resin solids loading level based on the weight of the board at 8% MC. The resin blender was equipped with a Coe spinning-disc sprayer. The mat (533 mm × 560 mm) was manually formed to obtain a 12.7-mm target board thickness at 641kg/m³ (42.0 pcf) density. Two replicate boards were made on a 2 ft × 2 ft William White hot press using 45s closing time and a maximum pressure of about 4830 kPa at selected press temperature and press time. Maximum temperatures attained in the core layer are shown in Table 2. Pressed boards were weighed, kept in an insulated box overnight (hot stacking), cut into test specimens, and conditioned in 60% RH room at 25°C for three weeks prior to testing. Internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) were measured according to ASTM 1037. Average IB values were obtained by normalizing the test results at 641kg/m³ within the sample group against sample densities where generally good correlations were obtained. Thickness and volumetric swelling values of boards were obtained by soaking two 75.9-mm × 75.9-mm samples in water for 24 h, followed by drying at 105°C for 24 h. Reversible and irreversible swelling values were also calculated.

RESULTS AND DISCUSSION

BTCA-treated wood specimens in the first water-soak cycle

High ASE values were obtained for most BTCA-treated wood specimens in the first water-soak cycle (Table 3), indicating high extents of retention for the 20% thickness compaction

TABLE 2. *Maximum temperatures (°C) attained in the core layers of board at indicated hot-pressing temperatures and times.*

Hot-press temperature	3 min	5 min	7 min
200°C	141	151	186
220°C	140	190	200

TABLE 3. *ASE values of SP wood specimens treated with butanetetracarboxylic acid (B) and sodium dihydrogenphosphate (S) combinations and controls' volume expansion (Cv) (%) (replication = 10).**

B:S ratio and level		Temp °C	Time min	Dry/1st water soak				Dry/2nd water soak				Dry/3rd water soak			
				$ASEv_1$	$ASEr_1$	$ASEt_1$	Cv_1	$ASEv_2$	$ASEr_2$	$ASEt_2$	Cv_2	$ASEv_3$	$ASEr_3$	$ASEt_3$	Cv_3
0:1	1.0%	150	15	1.1	—	—	32.5	−12.2	—	—	17.2	−9.6	—	—	16.9
	5.0%	150	20	51.4	59.0	25.8	32.0	18.0	20.0	13.2	19.1	13.6	14.0	13.1	17.9
		180	20	57.5	65.8	26.1	32.5	27.3	31.3	18.1	18.8	22.2	16.0	25.2	17.7
		210	20	57.1	65.3	34.5	23.6	46.7	54.8	27.7	20.7	46.3	54.1	28.2	20.6
1:1	3.0%	180	20	34.6	—	—	19.9	10.2	—	—	14.2	6.8	—		13.9
	2.5%	150	20	21.1	—	—	29.7	−6.4	—	—	16.8	−11.0	—		16.3
	1.0%	150	20	13.2	15.9	1.4	26.5	−10.4	−18.0	−1.0	15.5	−6.3	−14.5	3.4	15.9
		180	20	29.0	34.9	0.7	34.7	−1.8	−0.4	−4.4	18.7	2.0	5.6	−3.9	17.3
		210	20	23.8	28.3	9.9	23.1	10.9	16.2	−1.4	19.8	2.1	16.1	2.6	19.3
1:2	1.0%	180	20	14.1	15.9	9.5	23.4	−5.5	−10.4	2.2	17.6	−7.5	−15.8	2.6	15.6
		180	5	17.3	20.9	7.6	25.1	−12.4	−23.7	3.4	16.5	−12.9	−25.0	3.3	16.4
		210	5	30.4	35.8	15.6	21.3	14.9	18.5	6.8	17.9	2.2	14.0	7.6	18.0

* Wood specimens were hot pressed in the radial direction at indicated temperatures and times with a 20% thickness compression. ASE_{1-3} values indicate ASE values of 1–3 water wet-dry cycle tests. ASEv, ASEr, and ASEt represent ASE values calculated from the volumetric, radial, and tangential direction changes, respectively. Standard deviation values were relatively small but omitted for simplification of table.

effected in hot-pressing. $ASEv_1$ values were 51%–57% for 5% BTCA loading level and decreased to 14%–30% for 1% acid loading level. The hot-pressing time was the same for all samples, but the different hot-pressing temperatures resulted in differing effects especially for lower acid loading levels, leading to equations relating $ASEv_1$ values to acid loading levels (X) (1–5%) at each hot-pressing temperature:

$$ASEv_1 = 0.17 + 9.95X \ (R^2 = 0.84) \ (150°C) \tag{3}$$

$$ASEv_1 = 18.22 + 7.23X \ (R^2 = 0.53) \ (180°C) \tag{4}$$

$$ASEv_1 = 15.40 + 8.34X \ (R^2 = 0.86) \ (210°C) \tag{5}$$

The coefficients of equations are relatively large at all temperatures, indicating the increasing ASE values obtained as the BTCA loading level increased as expected. Overall, Eqs. (2) and (3) are similar to each other and Eq. (1) is also similar to them except the intercept. The intercept value at 150°C is negligible, as expected from the nature of correlation, but the intercept values for higher hot-pressing temperatures became significant in Eqs. (2) and (3). The significant intercept values would indicate that BTCA approach results in a 'bonus' effect when

the treatment involves a hot-pressing at above a certain threshold temperature. The threshold temperature appears to be at somewhere between 150°–180°C. Furthermore, Eqs. (2) and (3) indicate that ASE values would be reasonably high at BTCA levels below 1% if the hot-pressing temperature is kept at least above the threshold temperature. The hot-pressing temperature used in the oriented strandboard industry is near 200°C, although the pressing time is far shorter than the time used here. Since acidic degradation effects on wood were considered to be important criteria, the correlation results led to choose 0.5%, 0.75%, and 1.0% BTCA levels in the subsequent strandboard study to find the minimum necessary loading level with an ASE values ranging in 20%–30%.

The hot-pressing time used in the wood specimen experiments, 20 min, is relatively long, and the overall thermal effect could be more than what is attained in the industrial OSB manufacture, although the latter would be relatively comparable to the former considering the fact that industry hot-pressing is followed by a hot-stacking procedure that ends often when stacks of boards are broken in the place of use. In this regard, an attempt made to correlate the $ASEv_1$ values to the hot-pressing temperatures did not give any meaningful equations:

$$ASEv_1 = A + BT \qquad (6)$$

The coefficient values were very small as well as the R^2 values. A relatively high temperature effect of BTCA levels was reported in previous results (Yang and Andrews 1991), but it is likely that the long hot-pressing time used had swamped the differing temperature effects. The strandboard results, discussed below, showed hot-pressing temperature/time effects clearly. Overall, although an ASE_1 value of 50% or higher at 5% chemical loading level has been considered significant in the past from the materials cost standpoint (Rowell and Ellis 1978), commodity-type OSB should use a significantly lower level of BTCA not only from the high entailing material cost but also to reduce the wood degradation effects.

BTCA-treated wood specimens in the second and third water soak cycles

$ASEv_2$ and $ASEv_3$ values were all still high for 5.0% BTCA loading levels for all press temperatures, with only slight decreases observed at 210°C (Table 3). Considering the rather exhaustive water-soak/drying steps used in these ASE measurements, the 5.0% BTCA loading level results suggest that ester (Yang and Andrews 1991) and other chemical bonds had formed with crosslinking and a good amount of them survive the water-soak/drying test procedures. At 1%–3% BTCA loading levels, on the other hand, $ASEv_2$ and $ASEv_3$ values decreased to small positive values for higher press temperatures or to small negative values for lower press temperatures, indicating that the levels of such

bonds survived were minimal. Also, $ASEv_1$ values of sodium dihydrogenphosphate-only treatments were essentially zero and the corresponding $ASEv_2$ and $ASEv_3$ values slightly negative, indicating the acidic catalyst's small negative effect. Increasing the BTCA/sodium dihydrogenphosphate ratio to 1:2 at the 1.0% BTCA loading level at 180°C pressing temperature showed an increased negative effect on $ASEv_{2-3}$ values. Since $ASEv_{2-3}$ values reflect relatively long-term durability, the results obtained indicate that such a durability or stabilization would be possible only by using 5% or higher BTCA loading levels. However, 5% BTCA level appeared to be excessive to use in commodity-type OSB manufacture because of cost and wood degradation reasons.

Radial and tangential ASE of BTCA-treated wood specimens

The radial ASE (ASEr) values were about twice the tangential ASE (ASEt) values in most cases at 5% BTCA level for all hot-pressing temperatures (Table 3). Both ASEr and ASRt values decreased at lower BTCA levels, but the decreases were less for ASEr values than for ASEt values, indicating the greater effectiveness of the acid in the radial direction at low loading levels. The different ASEr and ASEt values and behaviors appear to reflect BTCA acid effects on the earlywood and latewood layers of wood specimens, respectively, an observation enabled by the tangential-face cutting pattern used in the preparation of wood specimens. Earlywood layers, likely to absorb more BTCA solution than

TABLE 4. *Reversible and irreversible swelling and corresponding ASE_1 values (%) of SP wood specimens treated with BTCA/sodium dihydrogenphosphate (SDHP) combinations at indicated loading levels followed by hot-pressing at 210°C for 20 min in the radial direction to 20% thickness compaction.*

Treatment	Irreversible swelling (%)	Reversible swelling (%)	ASE_{1ir} (irreversible)	ASE_{1re} (reversible)
5% 1:1 BTCA/SDHP, 20 min	0.27	6.0	93.6	55.9
Control	4.29	13.7	—	—
1% 1:1 BTCA/SDHP, 20 min	2.24	10.6	61.1	18.2
Control	4.93	13.0	—	—
1% 1:2 BTCA/SDHP, 5 min	0.96	9.7	79.7	17.5
Control	4.73	11.7	—	—

TABLE 5. *Volumetric swelling and ASE values (%) of strandboards made from strands treated with 1:1 BTCA/sodium hydrogenphosphate by hot-pressing at 200 and 220°C for 3, 5, and 7 min (24 h water-soak test).*

Temperature	Volumetric swelling						Irreversible swelling						Reversible swelling					
	200°C			220°C			200°C			220°C			200°C			220°C		
Time (min)	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7
Control	27.8	30.2	29.3	26.5	24.8	23.0	19.7	21.4	18.9	14.8	16.7	13.5	8.6	9.3	10.5	12.1	8.0	9.7
0.5% BTCA	25.5	24.1	23.9	21.2	17.8	13.5	17.2	15.6	14.1	12.2	8.5	5.2	8.4	8.7	10.2	9.5	8.9	8.4
(ASEv)	9.4	19.3	16.8	19.9	24.9	41.0	12.7	27.1	25.4	17.6	49.1	61.5	2.3	6.5	2.9	21.5	−11.3	13.4
0.75% BTCA	22.6	24.5	21.8	16.3	14.3	11.8	14.3	15.8	11.9	6.7	6.1	3.8	8.6	9.3	10.2	9.3	8.2	7.9
(ASEv)	19.8	18.2	25.0	38.6	40.2	48.6	27.4	26.2	37.0	54.7	63.5	71.9	0.0	0.0	2.9	23.1	−2.5	18.6
1.0% BTCA	28.7	24.5	22.3	12.1	11.6	10.8	19.7	15.5	12.5	4.2	3.8	3.1	9.3	9.4	10.0	8.0	7.6	7.4
(ASEv)	−2.5	18.1	23.0	54.2	51.3	53.1	0.0	27.6	33.9	71.6	77.2	77.0	−8.1	−1.1	4.8	33.9	5.0	23.7

Note: Control strandboards were made without BTCA treatment. ASE values (%) were calculated for irreversible swelling and reversible swelling components measured after drying soaked samples.

latewood layers and also preferentially to compact in the radial direction in hot-pressing, would determine ASEr values. On the other hand, latewood layers, likely to absorb less BTCA solution and not much compacted in the radial direction and not at all in the tangential direction, would determine ASEt values. Since the overall stabilization effects are found to be significantly higher for radial direction and also more effective at low loading levels, an approach of stabilizing earlywood layers appears to be the key in applications like OSB manufacture where the BTCA level would be tightly limited.

Reversible and irreversible swelling of BTCA-treated wood specimens in the first water soak cycle

Reversible and irreversible swelling values were obtained by comparing the volumes of wet and dried wood specimens in the $ASEv_1$ measurement and subsequent drying steps for specimens hot-pressed at 210°C (Table 4). The control specimens swelled approximately 75% reversibly and 25% irreversibly. Specimens with 1.0% and 5.0% BTCA treatments showed overall lower reversible and irreversible swelling values, and reversible values were similarly higher than the irreversible swelling. In general, the resultant ASE values were higher for irreversible swelling (ASE_1ir) than for reversible swelling (ASE_1re), indicating that BTCA treatments more effectively reduce irreversible swelling. Reversible swelling is related to hygroscopicity of wood cell walls and irreversible swelling to compaction stresses remaining in wood structures. The relatively high ASEre values, pronounced only at 5.0% BTCA loading level, suggest that the hygroscopicity of wood cell walls was decreased by BTCA treatments, possibly by esterification or dehydration of hydroxyl groups, as discussed above. However, the ASEir values were the major contributor to the stabilization and high values even at 1.0% BTCA loading level to indicate that compaction stresses were effectively relieved. This result inevitably brings up the question of degradation of

TABLE 6. *Thickness swelling (TS) values of strandboards made from strands treated with 1:1 and 0:1 BTCA/sodium dihydrogenphosphate (SDHP) solutions and hot-pressed at 200 and 220°C for 3, 5, or 7 min (24h water-soak test).*

Temperature	200°C			220°C		
Time (min)	3	5	7	3	5	7
Control	28.3	30.7	29.4	26.9	24.7	23.2
0.5% 1:1 BTCA/SDHP	25.6	24.3	24.3	21.7	17.4	13.6
% decrease	9.5	20.9	17.4	19.3	29.6	41.4
0.75% 1:1 BTCA/SDHP	22.9	25.1	22.1	16.0	14.3	11.7
% decrease	19.1	18.2	24.8	40.5	42.1	49.6
1.0% 1:1 BTCA/SDHP	29.0	24.9	22.5	12.2	11.4	10.5
% decrease	−2.5	18.9	23.5	54.6	53.9	54.7
2.0% 0:1 BTCA/NaH$_2$PO$_4$						23.8
% decrease						−2.6

Note: % decrease is calculated by $100 \times (TS_{control} - TS_{treated})/TS_{control}$

wood, a parameter considered in the outset as needed to be carefully controlled for this approach, as discussed above.

Swelling of strandboards made with BTCA treatments

The (volumetric) ASE values (Table 5) and the decreases in thickness swelling (Tables 6) of BTCA-treated strandboards in 24 h water-soak tests were similar in magnitude due to the fact that volumetric changes were determined mostly by thickness changes. ASE values and thickness decreases ranged from 17%–23% at 200°C and 41%–53% at 220°C of press temperature with longer press times showing higher ASE values as expected. Statistical analyses indicate that the press temperature, BTCA loading level, press time, and interaction of press temperature and BTCA loading level all influenced the ASE values. The thickness swelling values of treated boards, obtained without adding paraffin wax, are below the thickness swelling requirement (25%) of Product Standards PS2–92 (APA 1992). Overall, therefore, this approach appears to offer a way of significantly reducing the thickness swelling of OSB.

The ASE values showed interesting trends. ASE values are higher for higher BTCA levels in the loading range of 0.5%–1.0% at 220°C in agreement with the trend observed in wood specimen results discussed above. However, ASE values are small at 200°C especially for short press times to indicate the presence of a minimum press temperature/time parameter necessary. Also, the ASE values of boards consisted mainly of irreversible swelling components with only minor contribution coming from reversible swelling components, agreeing with data obtained in the wood specimen experiments with low BTCA loading levels. Thus, BTCA at low loading levels appears to effectively reduce the compaction stresses possibly by degradation of wood structures or chemical bonds. On the other hand, the reversible ASE values were not only small in comparison to the irreversible values but also erratic or became negative in some cases, indicating that the esterification or dehydration of hydroxyl groups does not contribute much. This result also is similar to the results obtained in the wood specimen experiments

Physical strengths of strandboards made with BTCA treatments

Internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) values of treated strandboards significantly decreased in comparison to those of control boards (Table 7). The extents of strength decreases are more severe for higher press temperatures, longer press times, and higher BTCA levels: IB value decreases ranged from 5.0%–34.8% at 200°C and 7.0%–43.8% at 220°C; MOR value decreases ranged from 21.9%–52.3% at 200°C and 44.9%–59.8% at 220°C, and MOE value

TABLE 7. *Average strength values of strandboards made from strands treated with 1:1 BTCA/sodium hydrogenphosphate by hot-pressing at 200 and 220°C for 3, 5, 7 min and corresponding % decreases in comparison with control values.*

	Internal bond strengths (kPa)*						Modulus of rupture values (MPa)						Modulus of elasticity values (GPa)					
Temperature	200°C			220°C			200°C			220°C			200°C			220°C		
Time (min)	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7
Control	751	812	814	800	966	839	38.3	40.7	37.2	36.3	32.2	35.2	4.0	4.6	4.2	4.8	4.5	5.3
0.5% BTCA	707	680	748	744	716	742	29.9	24.0	19.9	20.0	17.4	18.9	4.0	3.6	3.4	3.3	3.2	4.1
(% decrease)*	5.9	16.3	8.1	7.0	25.9	11.6	21.9	41.0	46.5	44.9	46.0	46.3	0.0	21.7	19.0	31.3	28.9	22.6
0.75% BTCA	727	708	798	589	660	582	24.3	25.8	21.1	18.0	16.6	19.4	3.6	4.2	3.8	3.7	3.9	4.8
(% decrease)*	3.2	12.8	2.0	26.4	31.7	30.6	36.6	36.6	43.3	50.4	48.4	44.9	10.0	8.7	9.5	22.9	13.3	9.4
1.0% BTCA	490	721	691	450	719	654	22.8	19.4	23.6	14.6	14.4	14.2	3.6	3.5	3.8	4.1	3.3	3.7
(% decrease)*	34.8	11.2	15.1	43.8	25.6	22.1	40.5	52.3	36.6	59.8	55.3	59.7	10.0	23.9	9.5	14.5	26.7	30.2
2.0% NaH₂PO₄						836						24.4						4.6
(% decrease)*						0.0						30.7						13.2

* IB values were normalized to a 725 kg/m³ density.

TABLE 8. *Strength and 24 h water-soak thickness swelling and ASE values of strandboards made by spraying 1:1 BTCA/sodium dihydrogenphosphate (SDHP) solutions on strands and hot-pressing at 220°C for 7 min.*

1:1 BTCA/SDHP level	0.5%	0.75%	1.0%
Thickness swell (%)	22.4	20.5	20.5
Internal bond (KPa)	772	854	894
Modulus of elasticity (GPa)	4.3	4.6	4.4
Modulus of rupture (MPA)	26.3	23.6	24.1
Anti-swelling efficiency (%)	1.2	10.3	0.0

decreases ranged 0.0%–23.9% at 200°C and 9.4%–30.2% at 220°C. The 2.0% sodium dihydrogenphosphate catalyst only treatment showed 30.7% MOR and 13.2% MOE strength decreases at 220°C and 7-min press time, indicating that BTCA itself has significant strength degradation effects. It is also possible that the curing of the PF resin binder is inhibited by the acid due to neutralization of the sodium hydroxide in the resin to result in a less satisfactory resin cure and poor adhesive bonds. On the other hand, the strength values of BTCA-treated boards showed increasingly smaller standard deviation values (not shown) as the press temperature, press time, and BTCA loading level were increased. This increasing uniformity of boards in parallel to the strength decreases as well as decreases in the irreversible swelling values points to the increasing degradation of wood structures as the major cause of strength degradations. Overall, the BTCA-treatments resulted in somewhat excessive decreases in board strengths, especially MOR. Therefore, although the strength values of the laboratory boards met the R-1 grade requirements of R-1 grade of CSA 0437.0-93 (CSA 1993), the BTCA approach appears impractical at least within the acid level range used in the study.

The spraying method of BTCA application was investigated to see if this low-cost application method could replace the vacuum impregnation method. The test results of boards (Table 8) showed that the spraying method is ineffective with little effects on ASE values.

CONCLUSIONS

Southern pine wood specimens impregnated with 1–5% BTCA and catalyst and compressed

in the radial direction in hot-pressing showed a high anti-swelling efficiency. The dimensional stabilization effects of BTCA treatment entailed reversible and irreversible swelling components ascribed to the formation of crosslinking/dehydration-type bonds and wood structure degradation, respectively. The decrease in reversible swelling, the main thesis of this work, was clearly noticeable at 5% BTCA level but became smaller and less well defined at 1% BTCA level in comparison to decreases in irreversible swelling. Similarly treated and manufactured strandboards at 0.5%–1.0% BTCA/catalyst levels also showed decreases in thickness swelling up to a 50% in 24 h water-soak test. However, the strength values of strandboards, although modest and above the industrial requirements, decreased somewhat excessively in comparison to control values. Decreases in strength values and increases in ASE values were generally proportional to severity of treatments, i.e. BTCA loading level, press temperature, and press time. Also, ASE values were mostly of irreversible swelling components to indicate that the underlying mechanism would be some acidic degradation of wood structures or chemical bonds that resulted in relieving the compaction stresses. Therefore, the BTCA approach in the acid level range chosen in this study appears impractical for OSB manufacture. On other hand, the modest strength values of treated strandboards and high effectiveness of BTCA/catalyst system in decreasing the irreversible swelling indicated that further research with acid levels below 0.5% would yield useful results. Adjusting the binder resin and wax loading levels at the same time would further reduce the BTCA loading level. The spraying method or any other low-cost method need to be investigated further to lower the cost of acid application step.

ACKNOWLEDGMENT

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