ENHANCING MECHANICAL PROPERTIES AND DIMENSIONAL STABILITY OF PHENOLIC RESIN-TREATED PLYBAMBOO

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This study evaluated the mechanical properties and dimensional stability of 3-ply phenolic-treated plybamboo influenced by treatment methods, namely, impregnation and soaking for 30, 60 and 90 min. Medium molecular weight phenol formaldehyde (MMwPF) resin with 1500 g mol^{-1} was applied to bamboo (*Gigantochloa scortechinii*) slivers of 2-mm thickness following resin treatments. The phenolic-treated bamboo slivers were precured at 60 °C for 6 hours, followed by hot pressing at 140 °C for 15 min to produce a 3-ply phenolic-treated plybamboo. Untreated boards were prepared using commercial phenol formaldehyde resin as binder. Use of MMwPF resin increased the density of boards. Modulus of rupture and impact resistance of the samples were significantly affected ($p \leq 0.01$) by treatment methods but treatment duration did not show any significant effect. Reduced water absorption, thickness swelling and linear expansion suggested improved dimensional stability of the phenolic-treated sample. Treatment with phenolic resin markedly increased anti-shrinkage efficiency at $p \leq 0.05$. Impregnation was more effective compared with soaking method.

Keywords: Impregnation, soaking, medium molecular weight phenol formaldehyde, *Gigantochloa scortechinii*, anti-shrinkage efficiency

INTRODUCTION

Phenolic resin enhances the mechanical, physical and durability properties of most wood and non-wood materials (Ryu et al. 1991). It improves the surface smoothness, density distribution and adhesive penetration of oil palm trunk veneers which gives rise to much improved physical, mechanical and dimensional stability properties of the resulting plywood (Paridah & Anis 2008, Loh et al. 2011). This resin also improves dimensional stability of multi-layered strand (Paridah et al. 2006).

Two common methods used to induce phenolic resin into wood cells are vacuum impregnation and soaking. Impregnation modification is defined as any method that results in the filling of the wood/lignocellulosics substance with an inert material (impregnant) in order to bring about a desired performance (Hill 2006). Impregnation using low molecular weight phenol formaldehyde resin offers a simple and effective way to improve dimensional stability as well as strength properties of lignocelluloses material (Anwar et al. 2009). Meanwhile, the simplest, inexpensive and rapid method to induce resin into the wood is by merely soaking the samples in the resin solution. The main reason for introducing resin into the wood through soaking is to bind parenchyma tissues to become harder and stronger upon curing through physical and chemical bonding formation (Loh et al. 2011). Compressed sugi wood specimens soaked in different concentration of phenolic resin and melamine formaldehyde resin exhibited resisted swelling and high anti-shrink efficiency as well as improved hardness, modulus of elasticity (MOE) and modulus of rupture (MOR) (Norimoto 2001).

Medium molecular weight phenol formaldehyde (MMwPF) has the ability to ease penetration of resin into cell walls, whereas resin with higher molecular weight is attached to the inner surfaces of cell lumen in the form of minute resin granules, giving slight improvement in dimensional stability (Kajita &

Imamura 1991). Oil palm trunk plywood treated with MMwPF resin has greater thermal stability than the low molecular weight and commercial phenolic resins (Nor-Hafizah et al. 2012). Oil palm trunk plywood made from prepreg veneers using low and medium molecular weight phenol formaldehyde resins had greater strength, stiffness and bonding shear values compared with commercial phenolic resin for plywood. This method can be applied to any wood and non-wood material which require additional improvement.

Bamboo is a high potential future construction material because of its strength properties and high resistance-to-weight ratio (Falk 2009). *Gigantochloa scortechinii* has a MOR value of 176 MPa which is equivalent to some Malaysian heavy hardwood such as resak (*Vatica* sp., 91–133 MPa), balau (*Shorea* sp., 142 MPa) and merbau (*Intsia palembanica*, 116 MPa). Excessive moisture reduce strength and rigidity of bamboo (Okhio et al. 2011). In this study, bamboo slivers (2-mm thick) were treated using impregnation and soaking treatments for 30, 60 and 90 min. The weight percentage gain, moisture content, density, MOE, MOR, impact resistance, thickness swelling, water absorption, linear expansion parallel and perpendicular to the grain and anti-shrinkage efficiency were evaluated to get better understanding on how the treatment methods and duration influenced the properties of 3-ply phenolic-treated plybamboo.

MATERIALS AND METHODS

Material preparation and resin treatment

Four-year old bamboo (*Gigantochloa scortechinii*) culms were obtained from a natural forest stand in Hulu Sungai, Pahang. The epidermis at the outer and inner layers of the bamboo strips were removed and then trimmed to 2 mm thickness using a sliver machine. Final dimensions of the bamboo slivers were 250 mm × 25 mm × 2 mm. The bamboo slivers were dried in a kiln dryer at 40 °C and relative humidity of 60% to reach 12% moisture content.

Samples were treated with MMwPF resin by applying two different treatment methods, namely, vacuum impregnation and soaking. Duration for each treatment was maintained at 30, 60 or 90 min. The MMwPF resin having 1500 g mol^{-1} with 50% solid content was supplied by the Malayan Adhesive Chemicals in Shah Alam.

Vacuum impregnation procedure was carried out according to that described by Anwar et al. (2004). Bamboo slivers were submerged into the MMwPF resin in a container and were impregnated using vacuum chamber set at initial pressure 42 cm Hg^{-1}. Initial vacuum pressure was maintained for 15 min. External pressure was applied at 2.5 kg cm^{-2} in 30, 60 or 90 min. Air in the vacuum chamber was slowly released within 1 hour. In the soaking method, bamboo slivers were immersed in MMwPF resin for 30, 60 or 90 min at ambient temperature. Each of the treatment combination had three replications of plybamboo boards.

Weight gain of the samples

Bamboo slivers (30 mm × 25 mm × 2 mm) were weighed before treatment. The samples were treated either using vacuum impregnation or soaking and placed in an oven at a 103 °C for 24 hours. The oven-dried phenolic bamboo slivers were weighed and weight gain of the samples was calculated using Equation 1:

$$\text{Weight gain } (\%) = \frac{W_1 - W_0}{W_0} \times 100 \qquad (1)$$

where W_1 = final oven-dry weight of treated bamboo sliver and W_0 = initial oven-dry weight of untreated bamboo sliver.

Manufacture of plybamboo

Phenolic-treated bamboo slivers from both treatment methods were precured by placing them in an oven maintained at 60 °C for 6 hours. Using the remaining MMwPF resin as binder, the precured phenolic-treated bamboo slivers were assembled perpendicular to the grain into a 3-ply panel. The bamboo boards (250 mm × 250 mm × 6 mm) were hot pressed at 140 °C for 15 min by applying a pressure of 14 kg cm^{-2} (Anwar et al. 2012).

Final moisture content of untreated bamboo sliver was approximately 12%. The untreated bamboo slivers were clamped edge-to-edge for 4 hours using phenol resorcinol formaldehyde to fabricate a single layer bamboo panel. The bamboo panels were then glued together perpendicular to the grain using commercial

phenol formaldehyde resin to produce a 3-ply laminated plybamboo board. The glue was spread at a rate of 225 g m^{-2} single glue line (BSI 1985). The plybamboo boards were pressed under hot press at a temperature of 140 °C for 6 min and pressure of 14 kg cm^{-2}.

Evaluation of plybamboo samples

Plybamboo boards were conditioned for 1 week at 23 ± 3 °C and 65 ± 3% relative humidity prior to testing and then cut into test specimens with dimensions 170 mm × 20 mm × 6 mm (support span at 120 mm) for MOR and MOE, 80 mm × 10 mm × 6 mm (support span at 64 mm) for impact, and 50 mm × 50 mm × 6 mm for physical and dimensional stability tests. MOR and MOE were determined using universal testing machine with some modifications (BSI 1957). The Charpy impact testing for notched specimens was performed by a CEAST impact tester in accordance with EN ISO 179 (DIN 2001). Physical properties (moisture content and density) and dimensional stability (thickness swelling, water absorption, linear expansion parallel and perpendicular to the grain and anti-shrinkage efficiency) were measured following BSI (1993).

Data obtained were statistically analysed using Statistical Analysis System (SAS) software, version 9.0. An analysis of variance (ANOVA) and mean separation were carried out using the least significant difference (LSD) method at $p \leq 0.05$ to further evaluate effects of treatment methods and duration on the 3-ply phenolic-treated plybamboo and interaction between both variables.

Evaluation of resin penetration

Scanning electron micrograph (SEM) was used to analyse the morphological images of phenolic-treated plybamboo to observe the resin penetration. A thin section of the sample containing a glue line between the plybamboo was prepared using a sharp razor blade. The samples were mounted onto stubs with an adhesive carbon tape and then coated with gold particles in a vacuum evaporator. The coated samples were observed with a variable pressure scanning electron micrograph.

RESULTS AND DISCUSSIONS

Weight percentage gain of bamboo slivers

ANOVA showed that weight percentage gain was significantly affected by treatment methods and duration ($p \leq 0.05$, Table 1). However, there was no significant interaction between treatment method and duration on the weight percentage gain. There was significant difference ($p \leq 0.05$) between impregnation and soaking treatment methods on the weight percentage gain (Table 2). Impregnated samples had substantially higher weight percentage gain than samples soaked in resin, i.e. 20.17–25.81% compared with 7.19–12.23% respectively. The higher weight percentage gain value obtained in impregnated samples could be attributed to the impact of resin penetration. Phenol formaldehyde resin occupied the parenchyma cell of bamboo because pressure during impregnation forced the resin to fill the cell wall and lumen of the bamboo (Furuno et al. 2004, Anwar et al. 2012).

In both impregnation and soaking methods, weight percentage gain values increased as treatment durations increased. Thus, prolonging treatment duration resulted in substantially high weight percentage gain. The highest percentage in weight gain was 25.81% which was recorded after the bamboo slivers were impregnated in MMwPF resin for 90 min. This is the maximum capacity of the bamboo slivers for impregnation. The amount of phenol formaldehyde resin

Table 1 Summary of ANOVA on the effects of treatment methods and treatment duration on weight percentage gain

Source	df	Mean square	F-value	p-value
Treatment method	1	5026.155	99.560	0.0001***
Treatment duration	2	299.936	5.941	0.0400**
Treatments method × duration	2	3.779	0.075	0.9280 ns

ns = not significant, ** = significantly different at $p \leq 0.05$, *** = significantly different at $p \leq 0.01$, df = degrees of freedom

Table 2 Weight percentage gain of phenolic-treated bamboo slivers at different treatment methods and duration

Treatment duration (min)	Weight percentage gain (%)	
	Impregnation	Soaking
30	20.17 b (5.19)	7.19 d (5.44)
60	23.50 b (3.53)	11.19 c (10.62)
90	25.81 a (4.95)	12.23 c (9.83)

Values in parentheses are standard deviations; means followed by the same letter within the same column are not significantly different at $p \leq 0.05$ according to least significant difference method

embedded in the porous parts of impregnated oil palm trunk sample was more when treatment duration was at 90 min compared with 60 min (Abdul-Khalil et. al 2012). Prolonging the bulking process could significantly increase weight percentage gain. Soaking treatment did not significantly increase weight percentage gain after 60 and 90 min. It appears that the rate of resin penetration influences weight percentage gain (Deka & Saikia 2000).

Evaluation of physical and mechanical properties of untreated and 3-ply phenolic-treated plybamboo

The summary of ANOVA on the physical and mechanical properties of 3-ply phenolic-treated plybamboo is given in Table 3. There was no significant interaction between treatment methods and duration on the examined properties. Moisture content, density, MOR and impact resistance of the phenolic-treated plybamboo were influenced ($p \leq 0.05$) by treatment methods but they were not affected by duration of treatment, except for density.

Average values of the moisture content, density, MOE, MOR and impact resistance of the phenolic-treated and untreated plybamboo samples are tabulated in Table 4. Moisture contents of treated samples were relatively lower than that of control. This shows that high amount of resin that enclosed the bamboo slivers increased their resistance to moisture uptake. Chemical treatments using alkaline solution decrease moisture absorption and enhance absorption resistance of bamboo strips (Chen et al. 2011). This effect of chemical treatment was not significant in impregnation and soaking treatment methods.

Phenolic-treated plybamboo was approximately 20% denser than untreated board. Density increased as MMwPF resin increased and cured in the cell voids and made the bamboo more densified. Impregnation was more effective in increasing density than soaking irrespective of the duration applied. Phenolic-treated plybamboo with 90-min impregnation achieved the highest density (860 kg m^{-3}) compared with the rest of the plybamboo. Vacuum pressure applied to facilitate penetration of phenol formaldehyde resin into the cell wall during impregnation also contributed to increased density (Sulastiningsih & Nurwati 2009). MMwPF resin was forced to penetrate the cell voids

Table 3 Summary of ANOVA on the physical and mechanical properties of 3-ply phenolic-treated plybamboo

Source	df	Moisture content	Density	Modulus of elasticity	Modulus of rupture	Impact resistance
Treatment method	1	0.0283**	0.0031***	0.1097 ns	0.0002***	0.0001***
Treatment duration	2	0.1700 ns	0.0006***	0.4834 ns	0.8889 ns	0.0768 ns
Treatments method × duration	2	0.8031 ns	1.0000 ns	0.8869 ns	1.0000 ns	0.8820 ns

ns = not significant, ** = significantly different at $p \leq 0.05$, *** = significantly different at $p \leq 0.01$, df = degrees of freedom

Table 4 Physical and mechanical properties of 3-ply phenolic-treated and untreated plybamboo

Treatment method	Treatment duration (min)	Moisture content (%)	Density (kg m^{-3})	Modulus of elasticity (MPa)	Increment (%)	Modulus of rupture (MPa)	Increment (%)	Impact resistance (kJ mm^{-2})	Increment (%)
Impregnation	30	6.19 b (0.87)	791.82 b (28.87)	17328 a (3088)	18.86	163.47 a (12.71)	29.76	54.34 a (7.13)	121.80
	60	6.14 b (0.67)	820.00 b (57.30)	19888 a (4405)	36.42	165.96 a (25.53)	31.74	58.99 b (11.79)	140.78
	90	6.33 b (1.05)	860.00 a (74.15)	20093 a (4628)	37.82	166.67 a (27.50)	33.09	60.97 b (6.86)	148.86
Soaking	30	6.33 b (0.42)	732.86 d (57.39)	15626 b (4172)	7.18	129.70 b (11.76)	2.95	30.48 c (5.65)	24.41
	60	6.40 b (0.45)	770.00 c (15.94)	17075 b (4912)	17.12	130.82 b (8.13)	3.84	33.48 c (12.44)	36.65
	90	6.65 b (0.27)	832.00 a (18.09)	17232 b (4605)	18.19	134.86 b (31.54)	7.05	39.67 d (13.32)	61.91
Untreated	-	8.30 a (1.17)	645.20 e (68.05)	14579 b (2058)	-	125.98 b (13.36)	-	24.50 e (11.83)	-

Values in parentheses are standard deviations, means followed by the same letter within the same column are not significantly different at $p \leq 0.05$, per cent increment is based on value of untreated samples

resulting in almost all parts of bamboo samples being bulked by the resin.

The same pattern of weight percentage gain intake was observed for MMwPF-soaked samples but at a much lesser extent. Soaking in MMwPF resin solution without applying external forces resulted in very little absorption of resin. The amount of resin that penetrated into the cells relies mainly on the ability of the phenol formaldehyde resin to be absorbed by the hydroxyl functional group on the cellulose chain. This is caused by polarity attraction and, to some extent, a diffusion action. Higher concentration of phenol formaldehyde resin would move to the lesser concentration woody cells . Forces are limited during soaking, therefore, the penetration of the resin is only up to a few voids.

There were substantial differences between impregnation and soaking treatment methods on MOE, MOR and impact resistance values. There were no significant differences between MOE and MOR values of soaking and untreated plybamboo. Soaking resulted in little increment of the MOE, MOR and impact resistance of the phenolic-treated plybamboo, i.e. 7.18–18.19, 2.95–7.05 and 24.41–61.91% respectively (Table 4). MOE and MOR values increased following impregnation and increased treatment duration. MOR values for phenolic-treated plybamboo impregnated for 30, 60 and 90 min were 29.76, 31.74 and 33.09% compared with 2.95, 3.84 and 7.05% respectively for soaking. Polymerisation of phenol formaldehyde resins between cell walls increases cell reinforcement and improves MOE and MOR (Gindl 2010). Weight percentage gain also contributes to the high strength of phenolic-treated plybamboo. In this study, impregnated plybamboo has > 50% increment of weight percentage gain compared with soaked plybamboo. Phenol formaldehyde resin improves MOR and MOE values due to increased weight percentage gain (Kajita & Imamura 1991).

Impact resistance of impregnated plybamboo exceeded that of soaking (Table 4). Impact resistance plays an important role on plybamboo which are designed to withstand dents and punctures when directly struck with hard or heavy objects (Marcon et al. 1999). Similar to MOE and MOR, improvements observed in impact resistance of the plybamboo are associated with resin loading/uptake and panel density. Impregnation for 90 min contributed to highest density and impact resistance (860 kg m^{-3} and 60.97 kJ mm^{-2} respectively). Phenol formaldehyde resin acts as a stress transferring medium resulting in improved impact resistance (Bhat et al. 2010). Upon curing, these phenolic-treated plybamboo behave similarly to phenol formaldehyde resin, i.e. they become hardened when heated due to curing of the phenol formaldehyde and are heat and water resistant.

Dimensional stability of plybamboo samples

Treatment method had significant effect ($p \leq 0.05$) on all dimensional stability properties of the phenolic-treated plybamboo (Table 5). Treatment duration had significant differences in thickness swelling, water absorption and anti-shrinkage efficiency of the samples. There was significant interaction ($p \leq 0.01$) between treatment method and duration in the water absorption only.

Mean values of thickness swelling, water absorption, linear expansion parallel to the grain and linear expansion perpendicular to the grain of the phenolic-treated and untreated plybamboo are given in Figures 1–4. Phenolic-treated plybamboo at 90 min impregnation resulted in the lowest thickness swelling value (2.56%, Figure 1). This was due to the presence of MMwPF resin in the bamboo cell walls which restricted water uptake. During hot pressing of phenol formaldehyde resin, methyl groups in the phenolic rings are converted to methylene bridges resulting in the formation of very highly cross-linked thermoset polymer (Collins 1996). Once the cell wall of the treated samples is bulked fully with no further expansion or contraction when in contact with moisture, it will strengthen and impart excellent dimensional stability (Rowell & Banks 1985).

Water absorption exhibited a similar trend to that of thickness swelling (Figure 2). This could be related to the replacement of free hydroxyl groups of cellulose and lignin in the wood by carbon atoms of the phenol formaldehyde resin. Hence, the decrement in moisture uptake of the fibres is due to the cross-linking reaction between phenol formaldehyde resin polymer and the cell (Abdul-Khalil et al. 2009). Water absorption values decreased significantly when treatment duration was prolonged. High resin content

Table 5 Summary of ANOVA on the dimensional stability of 3-ply phenolic-treated plybamboo

Source	df	TS	WA	LE∥	LE⊾	ASE
Treatment method	1	0.0257**	0.0230**	0.0001***	0.0054***	0.0055**
Treatment duration	2	0.0006***	0.0112**	0.6531 ns	0.0768 ns	0.0003***
Treatment method × treatment duration	2	1.0000 ns	0.0001***	0.3830 ns	0.3474 ns	0.8516 ns

ns = not significant, ** = significantly different at $p \leq 0.05$, *** = significantly different at $p \leq 0.01$, df = degress of fredom; TS = thickness swelling, WA = water absorption, LE∥ = linear expansion parallel to the grain, LE⊾ = linear expansion perpendicular to grain and ASE = anti-shrinkage efficiency

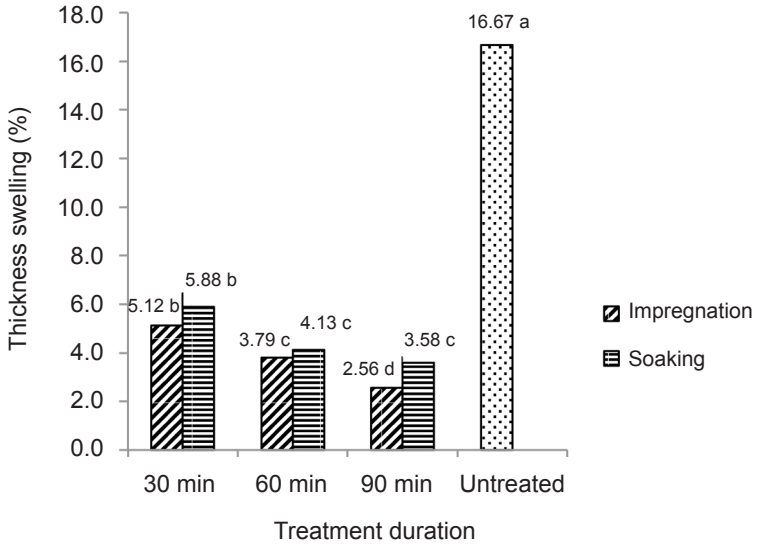


Figure 1 Thickness swelling of the samples manufactured using different treatment conditions; means followed by the same letter are not significantly different at $p \leq 0.05$

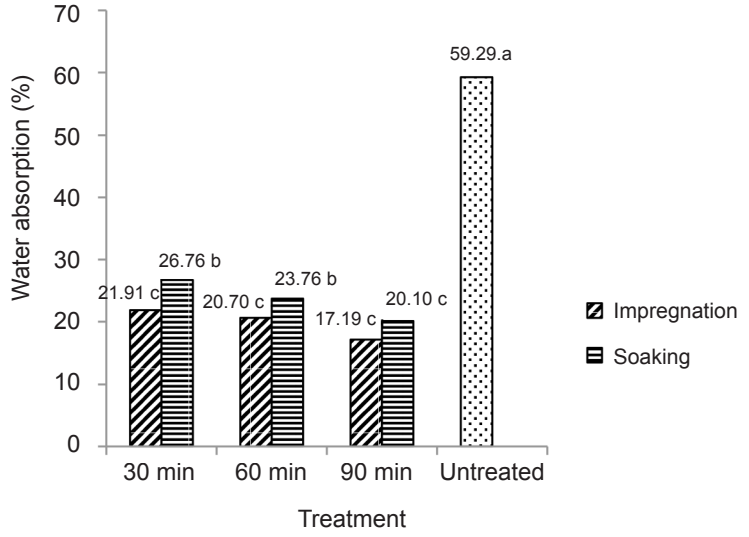


Figure 2 Water absorption of the samples manufactured under different treatment conditions; means followed by the same letter are not significantly different at $p \leq 0.05$

of treated plybamboo cover the parenchyma tissues and reduce their ability to absorb water (Abdullah et al. 2012).

Significant differences in linear expansion parallel to the grain between the phenolic-treated and untreated plybamboos were observed except for the 30-min soaked sample (Figure 3). Linear expansion perpendicular to the grain of phenolic-treated plybamboo was significantly lower than untreated sample (Figure 4). Average values of parallel and perpendicular linear expansions for phenolic-treated and untreated plybamboo ranged from 0.15–1.45%.

The highest anti-shrinkage efficiency value (83.01%) was achieved after 90 min impregnation (Figure 5). This high value showed that impregnation treatment was succeeding to achieve a high stability value

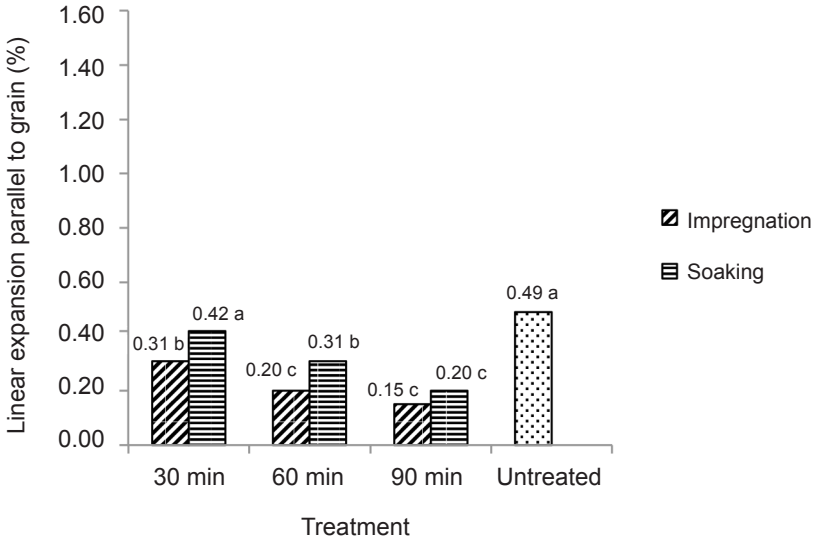


Figure 3 Linear expansion parallel to grain of the samples manufactured using different treatment conditions; means followed by the same letter are not significantly different at $p \leq 0.05$

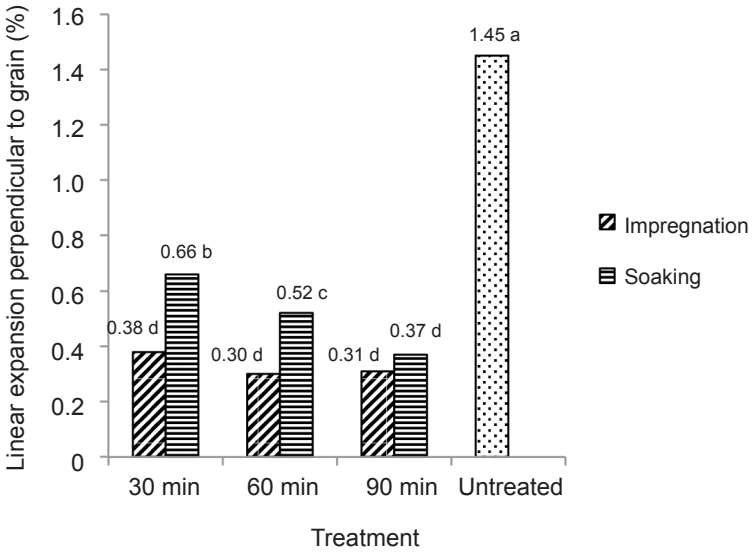


Figure 4 Linear expansion perpendicular to grain of the samples manufactured using different treatment conditions; means followed with the same letter were not significantly different at $p \leq 0.05$

of anti-shrinkage efficiency. Application of pressure during impregnation proved to be efficient in getting the MMwPF resin into the cells and interlocking with the bamboo cell wall. The plybamboo bulked fully with no further expansion or contraction when in contact with moisture. Cell wall is strengthened and gives excellent dimensional stability (Rowell & Banks 1985).

Anti-shrinkage efficiency can be improved by phenolic resin impregnation (Wan-Tarmeze et al. 1993). Formation of wall polymers inside the cell wall of wood enhances dimensional stability of strand board (Paridah et al. 2006). Scanning electron microscope micrographs of impregnated and untreated bamboo slivers clearly showed that the parenchyma cells of the former were covered quite homogeneously with the MMwPF resin, which prohibited the absorption of water molecules into cells (Figures 6a and b). It has been reported that High anti-shrinkage efficiency values were recorded for both low and high molecular weight resins, thus implying that these modifications were effective in reducing volumetric shrinkage which occurred in untreated sample (Gabrielli & Kamke 2010).

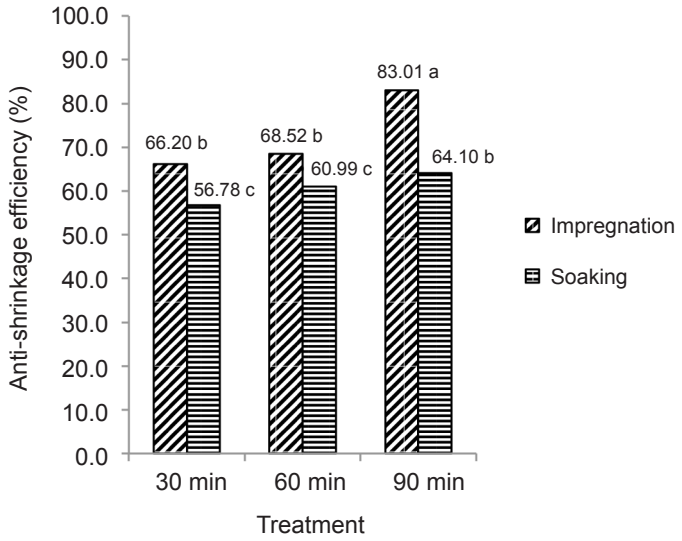
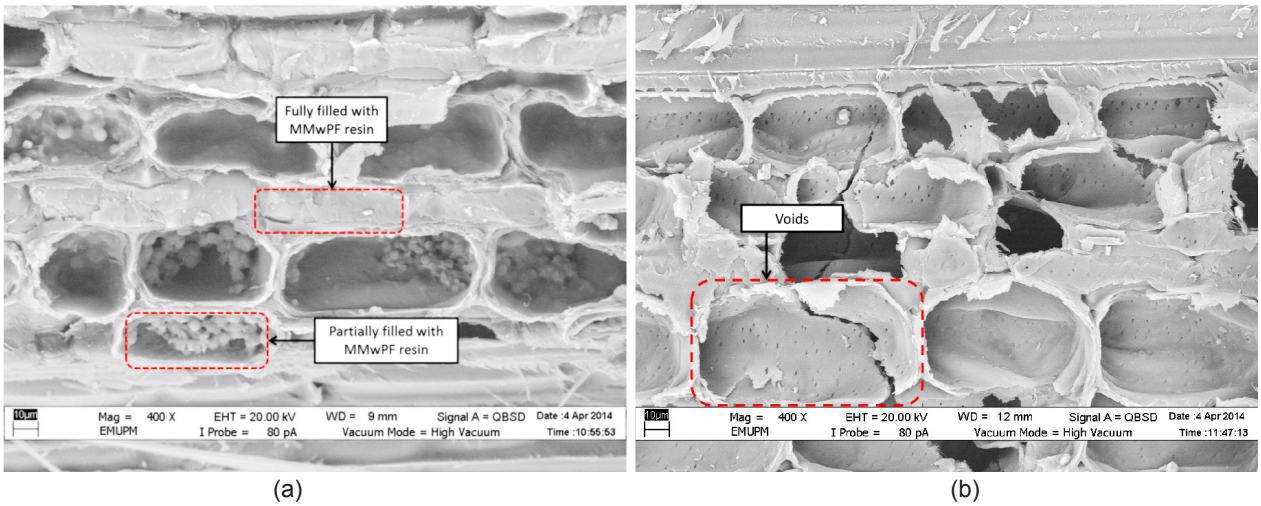


Figure 5 Anti-shrinkage efficiency of the samples manufactured under different treatment methods and durations; means followed by the same letter are not significantly different at $p \leq 0.05$



(a) (b)

Figure 6 Scanning electron microscope micrograph of (a) impregnated and (b) untreated bamboo sliver (400× magnification); MMwPF = medium molecular weight phenol formaldehyde

CONCLUSIONS

Based on findings in this work, treatment methods had more pronounced effect in improving mechanical properties and dimensional stability of 3-ply phenolic-treated plybamboo compared with treatment duration. The impregnation treatment method for 90 min resulted in improved physical properties, bending strength and impact resistance of the samples. On the other hand, soaking treatment at 30, 60 and 90 min showed lower physical and mechanical properties, but had comparable value in anti-shrinkage efficiency. High dimensional stability was achieved by soaking and impregnation treatments, thus implying that these treatments were effective in reducing volumetric shrinkage which occurred in untreated sample.

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