Chapter

The Physical and Mechanical Properties of Compreg Laminated Bamboo Strips Lumber (LBSL) of *G. scortechinii*

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Abstract

The chapter explores the effect of resin concentration and pre-drying time on the physical and mechanical properties of compreg-laminated bamboo strips lumber (LBSL) from G. scortechinii species. The compreg LBSL panels were manufactured using two concentrations of low-molecular-weight phenol formaldehyde (LMwPF) resin, that is, 100 and 70% at three different pre-drying times (12, 18, and 24 h). Based on the findings, the panel with 70% of LMwPF required a longer time and higher temperature to cure than the panel with 100% LMwPF. The weight percent gain (WPG) and moisture content of the panels increased in line with increasing resin concentration but decreased with increasing pre-drying time. The opposite trend is indicated by density. As for the mechanical properties, the strength of the panel increases along with the increase in resin concentration and pre-drying time. However, for high-concentration resins, prolonging the pre-drying time reduces the strength of the sample. The highest flexural strength and tensile strength were observed in the 100/18 sample with values of 260 and 27 MPa, respectively. The results for formaldehyde emissions show panels with lower resin concentrations: 70% LMwPF and prolonged pre-drying time reduce formaldehyde emission levels.

Keywords: compreg, bamboo, mechanical, formaldehyde emission, physical

1. Introduction

Bamboo is limited and less practiced due to heterogeneity in shapes, properties, and lack of standards [1]. Its hollow tubes with high silica content on the surface are difficult to join and adhered [2]. The thin and uneven culm wall thickness with defects caused by fungal and insects attacks worsen the condition. The emergence of new technologies has sparked the transformation of bamboo to engineered bamboo for further extended uses. A combination of bamboo in the form of veneer strands or strips with an adhesive undergo hot pressing or densification could overcome the shortcomings inherited by raw bamboo and possibly provide high performance for its end use [1, 2]. Despite having mechanical properties that are comparable to modern structure materials, their properties are greatly influenced by the species and manufacturing method used [3].

A lot of studies have been conducted to determine the appropriate methods for producing high-performance engineered bamboo. Compreg is one of the effective technique to improve lignocellulosic materials by an impregnated synthetic resin, such as low molecular weight phenol formaldehyde (LMwPF) resin, followed by hot-pressing densification [4]. The blockage of the hydroxyl groups with resin, and increment of the panel density parallel with its compressibility had enhanced their dimensional stability, durability, and strength properties of the panel produced [5, 6]. Studies show that compreg can increase up to two- to three-fold of wood's original strength due to the increase in density [4–7]. However, a major concern of this compreg wood is the emission of formaldehyde.

Formaldehyde emission (FE) is free formaldehyde released by methylol groups in the oligomeric chain when the resin is incompletely cured [7]. It has a negative impact on human health. Previous studies had shown that LMwPF resin released significantly higher free formaldehyde than commercial PF resin [8]. Various methods are taken to derive the FE value of the final panel that was made up of low-concentration resins [9]. However, the presence of high-water molecules in diluted LMwPF resin had decreased its solid content and thus lowered its FE [8].

Consisting of small molecules and short-chained, LMwPF resin requires a longer time to cure than commercial PF. In the case of LMwPF, heat is applied to remove water molecules to form a polymer crosslink in order to cure the resin. However, LMwPF resin takes a longer time to cure compared with other resins because it needs to be transformed to oligomer before end-up with complete polymer linkage [10]. The addition of water molecules in the resin solution increases its curing time. The curing process is vital to produce high-quality panels. A proper rate of time is needed to create a high bonding strength between the substrates. This is because panel failure can occur prematurely when the stress value at that location goes beyond the glue bonding strength sooner than its bottom fiber reaches its tensile strength [11].

Regarding these facts, the objective of this study was to investigate the effect of resin concentration and pre-drying time on the physical and mechanical properties as well as formaldehyde emission of compreg LBSL of *G. scortechinii*.

2. Materials and methods

2.1 Materials preparation

The matured culms of *G. scortechinii*, aged 3 years old with a height of 2.4 m were purchased from the bamboo biocomposite (M) Sdn. Bhd. in Gerik, Perak. The culms are divided into three parts of equal length, namely bottom, middle, and top and cross-cut. Each portion was split into eight parts and peeled off the outer and inner layers using a planner into a strip with a minimum thickness of 0.5 cm. Thereafter, the strips were dried in a kiln dryer to a relative MC of 5–10% at an ideal temperature set at 70°C.

2.2 Resin formulations

The low molecular weight of phenol formaldehyde (LMwPF) resin was obtained from Malaysian adhesive chemicals (M) Sdn. Bhd. in Shah Alam, Selangor. The resin was divided into two types, Type I and Type II. Type I resin was an original formulation resin, while Type II resin was a modified resin of Type I. Type II was prepared by diluting Type I resin with distilled water with a ratio of 30:70 based on Hoong et al. [8]. The solid content and resin curing properties were determined and carried out based on the previous studies [12, 13].

2.3 Manufacturing process

The manufacturing process of compreg laminated bamboo strips lumber (LBSL) of *G. scortechinii* was modified from previous studies [14, 15]. The dried strips of *G. scortechinii* were cut into 25 cm in length and vacuumed for 2 h before being immersed overnight in the resin solution (Type I and Type II). Thereafter, the impregnated strips were removed and pre-dried in the oven at 60°C for three different duration times (12, 18, and 24 h). The strips were arranged in parallel and hot-pressing up to half of their original thickness for 20 min at 150°C and 20 MPa and followed by cold-pressing. The conditions of compreg LBSL panel manufacturing process were presented in **Table 1**. The panel was conditioned in a conditioning room at 25°C and 65% (±2%) prior to properties evaluation.

2.4 Evaluation of physical properties of compreg LBSL of *G. scortechinii*

The density and moisture content (MC) of the sample with dimension of 5×5×1 cm was determined according to BS EN 323 and BS EN 322 based on Eq. (1) [16, 17].

$$\text{Density} = m/v \quad (1)$$

where m is mass of the sample and v is the volume of the sample, while the MC of the sample is calculated using Eq. (2):

$$MC,\% = (Wa - Wb/Wb) \text{ x } 100 \quad (2)$$

where Wa represents the initial weight of the sample and Wb represents the oven-dried weight of the sample.

Sample	Type of resin	Pre-drying time (h)
100/ 12	Type I	12
100/ 18	Type I	18
100/ 14	Type I	24
70/ 12	Type II	12
70/ 18	Type II	18
70/ 24	Type II	24

Table 1.
Manufacturing conditions of compreg LBSL panel made from G. Scortechinii.

2.5 Evaluation of mechanical properties of compreg LBSL of *G. scortechinii*

The modulus of rupture (MOR), modulus of elasticity (MOE), and compression parallel to the grain of the panel were determined according to ASTM 5456 with slight modifications on the sample size [18]. The sample was prepared in size of 20.0×2.5 cm for bending and 10×2.5 cm for compression parallel to the grain and tested by employing Instron machine model UTM-5582. The tensile shear strength was carried out based on EN 302–1-2004 [19]. A total of six samples per condition were prepared for each test.

2.6 Analysis of formaldehyde emissions of compreg LBSL of *G. scortechinii*

The formaldehyde emission test was carried out using the desiccator's method as specified in the Malaysia Standards (MS 2005) of wood-based panels [20]. Samples with a total area of approximately 1800 cm^2 were hung in a container containing 300 ml of distilled water at a height of 4 cm from the water level for 24 h at room temperature. The formaldehyde absorbance was measured photometrically at 412 nm wavelength after 24 h. The formaldehyde emission was determined by Eq. (3) as below:

$$G = f\ (Ad–Ab)\ X\ 1800/S \tag{3}$$

where G is a concentration of formaldehyde due to the test piece (mg/L), Ad is the absorbance of the solution from the desiccator containing test sample, Ab is the absorbance of the background formaldehyde solution, f is the slope of calibration curve for the standard formaldehyde solution, (ppm), and S is the surface area of the test pieces (cm^2).

3. Results and discussions

3.1 Curing characteristics of LMwPF resin

Based on **Figure 1**, both types of resins showed a single exothermic peak, which refers to complete thermal curing without post-curing resulting from homopolymerization [21]. Both resins undergo thermal healing reactions at 28°C with the highest exothermic peaks for Type I and Type II occurring at 89.46 and

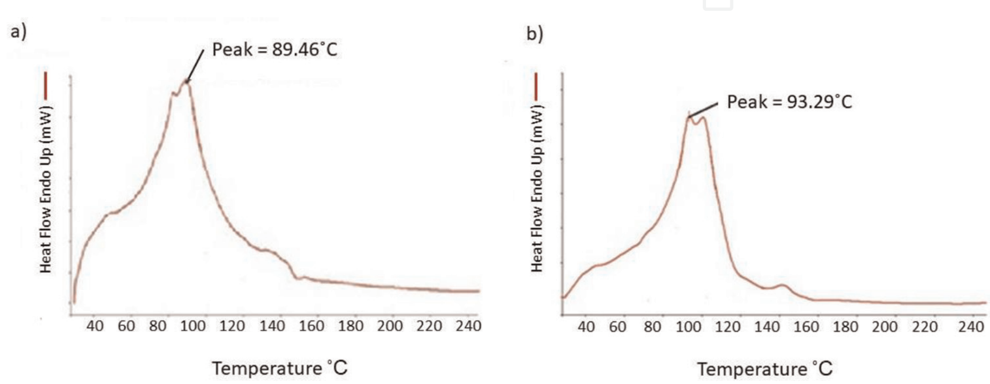

Figure 1.
The DSC analyses of LMwPF resin at different formulations (a) Type I resin and (b) Type II resin.

93.29°C, respectively. The highest exothermic peak indicated the beginning of the curing process where the water molecules are released. Then, the resin undergoes gelation due to the rigid crosslink network and subsequently turns to glass and decomposed as the temperature increases [12, 13]. The curing time for Type I and Type II resin were approximately 15 and 16 min (10°C/min) as both undergo thermal curing reactions up to 148 and 158°C, respectively. Type II resin required higher temperatures and longer time for polymer condensation to form a cross-linked network than Type I due to its less solid content, which is 32%. Moreover, Type II resin contained more water, which acted as an energy barrier for curing process [10, 22].

3.2 Weight percent gain (WPG) of compreg LBSL of *G. scortechinii*

The mean WPG of the panel is shown in **Table 2**. The highest WPG of the panel was detected by sample 100/12, while the lowest was by sample 70/24, with mean values of 26.14 and 15.08%, respectively. The higher solid content of the resin had increased the weight of the sample made from Type I resin. The highly concentrated resin is capable of retaining more polymers in the treated sample compared to low-concentration resin. However, this low-concentration resin known as thin resin, can simply penetrate the cell wall and pass the entire layers of wood cells easily but is difficult to retain in it due to its lower viscosity [9, 23]. Besides that, the pre-drying time also affects the weight of the sample. Based on the results, the mean WPG of compreg sample was inversely proportional to the pre-drying time. Both types of resins showed similar trends. This might be related to the properties of the resin. As a waterborne resin, LMwPF resin releases water during the curing process and prolonged pre-drying time. Thus, more water to be removed and more cross-linked polymers will form. This caused reduction in sample weight [7, 24].

Sample	WPG (%)	MC (%)	Density (g/cm^3)
100/12	26.14	8.67	0.924
	(−4.57)	(−0.14)	(−0.004)
100/18	24.65	8.62	0.876
	(−4.59)	(−0.14)	(−0.008)
100/24	18.91	8.17	0.874
	(−2.75)	(−0.15)	(−0.004)
70/12	16.84	8.82	0.789
	(−2.24)	(−0.23)	(−0.004)
70/18	16.57	8.65	0.799
	(−2.95)	(−0.13)	(−0.005)
70/24	15.08	8.29	0.734
	(−4.56)	(−0.22)	(−0.009)

Note: Values in parentheses are standard deviation.

Table 2.
The physical properties of the compreg LBSL of G. Scortechinii.

Sample	MOR (MPa)	MOE (MPa)	Compression (MPa)	Tensile (MPa)
100/12	260.18 ± 3.22	24097.53 ± 375.50	129.57 ± 1.40	25.62 ± 0.48
100/18	268.33 ± 10.16	25805.50 ± 805.67	130.87 ± 1.41	26.64 ± 0.56
100/24	257.55 ± 10.64	28397.23 ± 676.16	134.18 ± 1.69	25.58 ± 0.57
70/12	217.55 ± 2.35	21361.73 ± 596.00	120.77 ± 1.02	23.82 ± 1.11
70/18	235.70 ± 1.86	23611.95 ± 1319.06	125.65 ± 1.69	24.21 ± 0.58
70/24	237.63 ± 5.36	24299.65 ± 926.32	126.87 ± 2.12	24.27 ± 1.02
Data expressed as an average ± standard deviation.				

Table 3.
The mechanical properties of compreg LBSL of G. Scortechinii.

3.3 Moisture content (MC) and density of compreg LBSL of *G. scortechinii*

The MC of the panel was inversely proportional to the resin concentration and pre-drying time, but the density was the opposite. The density of the panel increased with the increase in resin concentration but decreased with the increase in pre-drying time. Based on **Table 3**, the sample of 70/12 had highest MC value, 8.82%. Meanwhile, the highest value of density was detected in a sample of 100/12, 0.924 g/cm^3. According to Purba et al., density and WPG are interrelated in which the increase in WPG will increase the sample density since the resin will soften the cell wall and thus facilitates its compaction [9]. It is contradicted with samples made from low-concentration resins, where the resin tends to outflow the sample during hot-pressing densification, as it is highly saturated with water, resulting in reduced density [25]. However, the MC of the panel made from LMwPF showed an increment due to its high-water content. Meanwhile, prolonging the pre-drying time decreased the MC and density of the sample because more water evaporated and accelerated the curing process, which minimized the compression rate [7, 9].

3.4 Mechanical properties of compreg LBSL of *G. scortechinii*

Mechanical test results were presented in **Table 3**. Based on the results, the highest MOR was observed in sample 100/ 18 with a value of 260 MPa, while the lowest MOR was observed in sample 70/12 with a value of 218 MPa. Sample 100/24 had highest elasticity (MOE) followed by sample 100/18 with values of 28,397 and 25,806 MPa, respectively. The MOR and MOE of the samples increased in line with the increase in resin concentration and pre-drying time. However, prolonging the drying time, reduced the MOR of the sample, especially for highly concentrated resins. This is because the presence of the resin in the strips had caused the transformation of the strips into a plastic-like material [26]. The retention of resin in bamboo strips as a result of cross-linked formation between it and the substrate during the pre-drying process and hot-pressing densification as well enhanced the MOR and MOE of the sample [8, 27]. However, prolonged pre-drying time causes the resin to excessively cure and become fragile. This was due to high crosslinking in the strips themselves, which weakens the bonding between the layers, and consequently weakens the sample due to poor glue line [5].

The compression parallel to the grain of the sample showed a similar trend with bending strength, which increased with increasing resin concentration and pre-drying time. The samples with high resin content in the lumen and cell walls had higher compressive strength [28]. Higher polymer loading will form a stronger cross-linked thermoset polymer, which is strong, insoluble, and hard to melt and soften [9, 28]. Sample with resin concentration of 100% (Type 1) and pre-drying time of 24 h showed the highest values of compression, 134 MPa followed by sample 100/18 with a value of 131 MPa.

The tensile strength showed the highest reading for sample 100/18 with the value of 27 MPa due to its higher resin concentration. Meanwhile, the lowest was recorded in sample 70/12 with a value of 24 MPa. The lower concentration resins contain high water molecules and these result in starved glue line. Thus, causes a weak bonding between substrates due to the lack of resin retained on the surface other than the limited linkage formation between the substrate [8]. Since the resin compreg relies heavily on the resin emitted by the impregnated strips during hot-pressing densification, it is important to ensure that is sufficient for strong bonding. The pre-drying time increases the tensile strength of the sample but lengthening the pre-drying time will weaken the sample bonding since the resin polymerization process is fully formed in the lumen and this minimizes the formation of cross-linking polymer between the strips [7].

3.5 Formaldehyde emission of compreg LBSL of *G. scortechinii*

The formaldehyde emission (FE) of the panel is shown in **Figure 2**. The highest FE was observed on sample 100/12 with a value of 15.62 mg/L. The sample was made from Type I resin and had undergone 12 h pre-drying times. The highest value of FE might be due to the high solid content of the resin in the sample [7–9]. During polymerization process, formaldehyde formed a linkage with the substrate. The incomplete curing leads to the increase of FE since free formaldehyde released from methylol groups had increased [8]. Prolongs pre-drying time will increase the resin polymerization, especially in a low molecular weight resin, which contains more short-chain oligomers in the system, resulting in decreased FE from the sample [26].

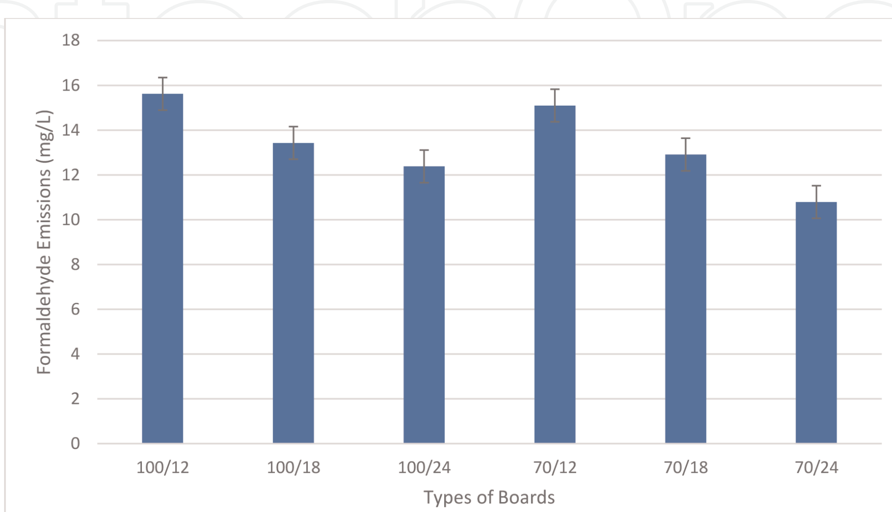

Figure 2.
Formaldehyde emission of compreg LBSL of G. scortechinii sample.

4. Conclusions

The resin concentration and pre-drying time have a significant effect on the strength, density, and formaldehyde emission of compreg LBSL of *G. scortechinii* sample. The increase of resin concentration, increased the weight and density of the panel. Thus, increased strength as well as density is directly proportional to the strength of the panel. The pre-drying time showed a positive effect on the properties of compreg LBSL of *G. scortechinii* panel. Type I resin with a high concentration of resin and 18 h of pre-drying time gave optimum results. However, in terms of formaldehyde released, Type II resin with pre-drying time of 24 h showed some reduction of FE from compreg LBSL of *G. scortechinii* panel.

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