

# EFFECTS OF PROCESSING FACTORS AND POLYMER RETENTION ON THE PERFORMANCE OF PHENOLIC-TREATED WOOD

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**PURBA TP, ZAIDON A, BAKAR ES & PARIDAH MT. 2014. Effects of processing factors and polymer retention on the performance of phenolic-treated wood.** Effects of initial moisture content, soaking time and addition of urea on the performance of sesenduk (*Endospermum diadenum*) wood impregnated with low molecular weight phenol formaldehyde (LmwPF) were investigated. Wood samples with nominal dimensions of 150 mm × 50 mm × 10 mm and initial moisture contents of 15, 25 and 40% were impregnated with either 15% (w/v) LmwPF or mixed separately with urea (10, 20 and 30% based on solid PF) using a vacuum-pressure process. After impregnation, the treated samples were partially cured in an oven at 65 °C for 6 hours and subsequently compressed to a ratio of 50% in a hot press at 150 ± 2 °C for 60 min. Results showed that the initial moisture content and soaking time significantly affected polymer retention and weight per cent gain of the treated wood. Statistical analyses showed that density and reduction in water absorption of the treated wood were positively correlated with weight per cent gain, but thickness swelling was inversely correlated with it. The emission of formaldehyde was highly dependent on weight per cent gain and could be successfully reduced when urea was incorporated into the phenolic resin. The degree of reduction increased with urea concentration. *Compreg* products produced with or without urea had superior mechanical properties and reduction in water absorption compared with untreated wood.

Keywords: *Impreg*, *compreg*, formaldehyde emission, swelling coefficient, *Endospermum diadenum*

## INTRODUCTION

A series of work has been conducted to enhance the properties of low-density tropical hardwood through bulking treatment with phenol formaldehyde (PF) resin. Impregnation with low molecular weight phenol formaldehyde (LmwPF, molecular weight 600) followed by curing under heat has increased the mechanical strength, dimensional stability and durability of sesenduk (*Endospermum diadenum*), jelutong (*Dyera costulata*) and mahang (*Macaranga* sp.) wood against decay and termite (Ang 2010, Nur Izreen et al. 2011). This product is known as *impreg* (Rowell 2005). Impregnation with 30% LmwPF followed by compressing at high temperature has enhanced the bending strength, dimensional stability and durability against fungal attack (Zaidon et al. 2010, Rabiatal Adawiah et al. 2012). This product, known as *compreg* (Rowell

2005), normally has modulus of rupture (MOR), modulus of elasticity (MOE) and hardness greater than untreated wood due to the increase in density.

There are several factors that need to be considered for efficient bulking treatment. These factors include molecular weight of PF resin, concentration of PF resin, as well as thickness of the material and compression ratio (ratio of final thickness to initial thickness of wood) (Zaidon et al. 2010). PF resin with molecular weight of 290–480 is able to penetrate into the cell wall and significantly reduce swelling (Rowell 2005). However, PF resin with molecular weight 820 remains in the cell lumen without resulting in any significant stability (Furuno et al. 2004). There are a couple of drawbacks when using LmwPF resins in bulking treatment of wood such as low

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curing rate of the resin (He & Riedl 2003) and high formaldehyde emission from the treated product. Formaldehyde emission is generated from free, unreacted formaldehyde during curing (Hoong et al. 2010). Formaldehyde emission increases when higher concentration of PF is used as the treating solution. It has been reported that formaldehyde emission of 64 ppm was recorded for *compreg* sesenduk treated with 20% w/v PF, and the emission increased to 110 ppm when treated with 40% PF (Rabiatal Adawiah et al. 2012). Higher formaldehyde emission was also recorded from *impreg* jelutong when treated with higher concentration of PF (Nur Izreen et al. 2011). The authors also revealed that formaldehyde emission could be significantly reduced by mixing urea (formaldehyde scavenger) into the resin. The introduced urea reacts with free formaldehyde and forms a rigid cross-linked polymer of urea formaldehyde. However, the emission is still high compared with standard threshold limit. It is also anticipated that the use of low concentration resin can further reduce formaldehyde emission but the reduction in some properties is inevitable.

Based on these facts, a study was conducted to investigate the effects of processing factors and polymer retention on the performance of *impreg* and *compreg* woods of sesenduk. This paper reports the effects of initial moisture content, soaking time and urea addition on properties and formaldehyde emission of *impreg* and *compreg* sesenduk treated with low concentration of LmwPF. Correlation analyses between the dependent variable (weight per cent gain) and the independent performance of the material are also discussed in this paper.

## MATERIALS AND METHODS

### Preparation of materials

Fresh and defect-free sesenduk (*E. diadenum*) wood was used in this study. End-matched samples with nominal dimensions of 150 mm long × 50 mm wide × 10 mm thick and 150 mm long × 50 mm wide × 20 mm thick were assigned into one of three treatment groups based on initial moisture contents of 15, 25 and 40%. Two moisture content sections were taken adjacent to the matched samples. Initial moisture content was determined on these sections using the oven drying technique. Mean moisture content of the two sections was used to estimate the oven dry weight of each sample. The calculated sample weight was used to determine when each sample had reached the desired moisture contents. Treating solution used was LmwPF with molecular weight of 600 which was specially synthesised at the Malayan Adhesives and Chemical Sdn. Bhd., Shah Alam. Fifteen per cent (w/v) of LmwPF, admixed with 10, 20 and 30% urea (based on solid PF) were prepared and used as the treating solutions. Urea was incorporated into the resin to act as formaldehyde scavenger (Nur Izreen et al. 2011, Rabiatal Adawiah et al. 2012). The experimental design of the study is shown in Table 1.

### Impregnation and compregnation processes

Prior to treatment, samples were weighed and measured. They were impregnated with the treating solution separately using the vacuum pressure process. An initial vacuum of 85 kPa was

**Table 1** Experimental design of the study

Treatment	Treatment process	Sample moisture content (%)	Sample size
T1	Impregnation with LmwPF, followed by curing in oven at 150 °C ( <i>impreg</i> )	15, 25 and 40	150 mm × 50 mm × 10 mm
T2	Impregnation with LmwPF, followed by compressing in hot press at 150 °C ( <i>compreg</i> )	15, 25, and 40	150 mm × 50 mm × 20 mm
T3	Impregnation with LmwPF admixed with urea, followed by compressing in a hot press at 150 °C ( <i>compreg</i> )	15	150 mm × 50 mm × 20 mm

LmwPF = Low molecular weight phenol formaldehyde

applied for 30 min, after which the apparatus was filled with resin solution. An external pressure of 690 kPa was applied and the samples were left soaked in the apparatus for 30, 60 and 120 min. After the impregnation process was completed, the samples were taken out and then wiped with a piece of cloth to remove excessive resin before the final weight was taken. For the *compreg*, after the impregnation process, samples were partially dried in an oven at 65 °C for 6 hours (Zaidon 2009), followed by compressing (force on the wide surface of samples) in a hot press at 150 ± 2 °C for 60 min to compression ratio of 50%. All treated products were left in a conditioning room at 25 ± 2 °C and relative humidity of 65 ± 2% until constant weight was achieved prior to evaluation of properties.

### Treatability of wood

Treatability of the wood was analysed based on polymer retention and weight per cent gain as follows:

$$\text{Polymer retention (\%)} = [(W_t - W_i) / W_i] \times C \quad (1)$$

$$\text{Weight per cent gain (\%)} = [(W_{ot} - W_o) / W_o] \times 100 \quad (2)$$

where  $W_t$  = sample weight after impregnation (g),  $W_i$  = sample weight before impregnation (g),  $C$  = concentration of resin (%),  $W_{ot}$  = oven dry weight of treated wood (g) and  $W_o$  = the oven dry weight of the wood before treatment (g).

### Dimensional stability evaluation

Dimensional stabilisation was quantified by comparing samples of treated and untreated specimens. Dimensional stability of treated samples was determined in terms of swelling coefficient and reduction in water absorption. Swelling coefficient and water absorption of treated samples were determined by vacuum soaking in distilled water. Six test blocks, with 20 mm × 20 mm in cross-sections and 10 mm thick, were cut from the untreated and treated samples and dried in an oven at 103 ± 2 °C to constant weight. The oven dry weight and volume were determined before the samples were immersed in a beaker containing distilled water. The beaker was then placed in a cylinder and a vacuum pressure of 85 kPa was applied into the cylinder for 15 min at ambient temperature. Subsequently, the vacuum pressure

was discharged and the beaker was left in the cylinder at atmospheric pressure for 24 hours (Ashaari et al. 1990). Test blocks were then removed from the beaker and wiped with a tissue paper to remove excessive water. The weight and volume were again measured. Data for initial and final weights were used to calculate swelling coefficient, reduction in water absorption and thickness swelling as shown in the following equations:

$$S (\%) = [(V_f - V_o) / V_o] \times 100 \quad (3)$$

where  $S$  = swelling coefficient,  $V_f$  = volume after soaking in water (%) and  $V_o$  = volume of oven dried wood (%).

$$R (\%) = [(W_t - W_c) / W_c] \times 100 \quad (4)$$

where  $R$  = water absorption,  $W_t$  = weight gain in the treated wood due to water pick-up after 24 hours (%) and  $W_c$  = weight gain in the untreated wood under the same condition (%).

$$TS (\%) = [(T_f - T_o) / T_o] \times 100 \quad (5)$$

where  $TS$  = thickness swelling,  $T_f$  = thickness of wood after soaking in water (mm) and  $T_o$  = thickness of the oven dried-treated wood (mm).

### Evaluation of mechanical properties

Mechanical properties of the treated wood tested included MOE, MOR in static bending, compression parallel to the grain (CS), and hardness. All tests were performed according to the procedure specified in the British Standards BS 373:1957 (BSI 1957), with modification of the specimen size. Smaller test blocks were used in this study due to the limitation size of samples. Static bending test was made on the specimens with dimensions of 10 mm × 20 mm × 150 mm using centre loading method at a span length of 120 mm. The load was applied continuously throughout the test at a cross-head speed of 6.35 mm min<sup>-1</sup>. Load deflection was recorded. Compression strength test parallel to the grain was carried out on sample with dimensions of 10 mm × 20 mm × 60 mm. Load was applied through a metal bearing plate measuring 50 mm in width, which was placed across the upper surface of the specimen at equal distances from the ends and right angles to the length. It was applied continuously

throughout the test at a cross-head speed rate of 0.50 mm min<sup>-1</sup>. The MOE, MOR, and CS were calculated as follows:

$$\text{MOE (N mm}^{-2}\text{)} = P_1 L^3 / 4Dwh^3 \quad (6)$$

$$\text{MOR (N mm}^{-2}\text{)} = 3P_m L^3 / 2wh^2 \quad (7)$$

$$\text{CS (N mm}^{-2}\text{)} = P_{mc} / A \quad (8)$$

where  $P_1$  = load at proportional limit (N),  $P_m$  = maximum breaking load (N),  $L$  = span of the test specimens (mm),  $D$  = deflection at mid-span resulting from  $P_1$  (mm),  $w$  and  $h$  = width and height of the test specimens respectively (mm),  $P_{mc}$  = load at proportional limit under compression (N) and  $A$  = area of cross-section normal to the direction of load (mm<sup>2</sup>).

Hardness test was carried out on samples measuring 10 mm × 20 mm × 60 mm. The test required determination of the load necessary to force into the test piece, to a depth of 5.6 mm and the hemispherical end of a steel ball of 11.3 ± 0.05 mm in diameter. The load was recorded when the ball penetrated to one half of its diameter. The cross-head speed was 6.35 mm min<sup>-1</sup>.

### Formaldehyde emission test

Formaldehyde emission was analysed in accordance with the Malaysian Standards (MS 2005). Pre-conditioned samples from treatment 3 (see Table 1 for details) were tested for formaldehyde emission. A calibration curve was first produced from a standard formaldehyde solution by iodometric titration. A total of 8–10 test pieces with approximately 1800 cm<sup>2</sup> total surface area were put in a desiccator having 300 mL of distilled water and kept for 24 hours at 20 ± 2 °C and 65 ± 5% relative humidity. The background formaldehyde was prepared using a desiccator containing no test piece. Formaldehyde absorbance in water was measured photometrically at 412 nm wavelength. The concentration of formaldehyde was determined using the following equation:

$$G = f \times (A_d - A_b) \times 1800 / S \quad (9)$$

where  $G$  = concentration of formaldehyde due to test pieces (mg L<sup>-1</sup>),  $A_d$  = absorbance of the solution from the desiccator containing the test pieces,  $A_b$  = absorbance of the background

formaldehyde solution,  $f$  = slope of the calibration curve for the standard formaldehyde solution and  $S$  = surface area of the test pieces (cm<sup>2</sup>).

### Statistical analyses

Two-way factorial tests with three levels of moisture contents and three levels of soaking times were conducted on treatability properties to determine if any significant difference existed between the treatment combinations. Analysis of variance was also performed on physical and mechanical properties of *compreg* produced from different treatments. Treatment means were separated using Tukey's test at  $p < 0.05$  level. Pearson's correlation coefficient tests were also employed to determine effects of weight per cent gain on the performance of treated products.

## RESULTS AND DISCUSSION

### Treatability of the *impreg* and *compreg*

The analysis of variance on effects of initial moisture content and soaking time on polymer retention and weight per cent gain of the *impreg* and *compreg* wood is summarised in Table 2. Results showed that polymer retention and weight per cent gain of the *impreg* were significantly affected by moisture content and soaking time, while weight per cent gain for the *compreg* was only affected by moisture content. There was interaction between moisture content and soaking time for polymer retention in *impreg*. The polymer retention for *impreg* with initial moisture content values of 15, 25, and 40% ranged between 27.44 and 31.66, 25.46 and 34.57, and 16.98 and 31.60% respectively. The weight per cent gain values were in between 68.12 and 68.92, 73.65 and 100.91, and 52.98 and 96.13% respectively (Table 3). The higher polymer retention and weight per cent gain values in the 15% moisture content samples were attributed to higher void volume, which was able to absorb as quickly as possible and retain higher resin solution at the early stage of soaking. Figure 1 shows the trend of polymer retention against moisture content for *impreg*. At 15% moisture content, polymer retention decreased (but not significant) when soaking time increased. Nevertheless, for the 25 and 40% moisture content samples, the trend slightly increased up to 60 min and later increased drastically with maximum polymer

**Table 2** Summary of the analysis of variance ( $p \leq 0.05$ ) of polymer retention and weight per cent gain for *impreg* and *compreg*

Treatment	Df	<i>Impreg</i>		<i>Compreg</i>
		Polymer retention (%)	Weight per cent gain (%)	Weight per cent gain (%)
Moisture content	2	0.016	0.124	0.000
Soaking time	2	0.015	0.006	0.505
Moisture content × soaking time	4	0.027	0.187	0.115

**Table 3** Polymer retention and weight per cent gain of *impreg* and *compreg* at different processing factors

Moisture content (%)	Soaking time (min)	Polymer retention (%)	Weight per cent gain (%)	Weight per cent gain (%)
		<i>Impreg</i>	<i>Compreg</i>	<i>Compreg</i>
15	30	31.66 a ± 8.43	68.12 bc ± 21.56	32.68 a ± 3.52
	60	28.46 a ± 7.01	68.52 bc ± 14.41	28.06 ab ± 5.28
	120	27.44 a ± 2.60	68.92 bc ± 3.37	28.92 ab ± 1.48
25	30	25.46 ab ± 4.38	74.4 abc ± 14.79	23.46 bc ± 4.82
	60	25.86 ab ± 5.80	73.65 abc ± 19.73	24.72 bc ± 4.13
	120	34.57 a ± 6.88	100.9 a ± 17.35	24.48 bc ± 2.55
40	30	18.27 b ± 5.13	64.94 c ± 15.37	15.45 d ± 3.79
	60	16.98 b ± 4.74	52.98 c ± 24.10	16.19 d ± 1.84
	120	31.60 a ± 11.41	96.13 ab ± 34.32	18.59 cd ± 5.39

Mean values within column followed by the same letter are not significantly different at  $p \leq 0.05$ ; ± standard deviation

retention values of 34.57 and 31.60% respectively. The same trend was observed for weight per cent gain (Figure 2). However, results showed that weight per cent gain at 30 min soaking was similar regardless of the moisture content of samples. This might be attributed to the high moisture content that facilitated diffusion of resin into the wood. Diffusion is a natural process in which ions or molecules of certain compounds penetrate the wood through liquid pathways. To ensure occurrence of full cell wall penetration, sufficient time should be allowed for impregnant molecules to diffuse into intracellular spaces (Hill 2006). Results of this study reflected this phenomenon. The relationship between weight per cent gain and polymer retention was also evaluated in this study and the result is illustrated in Figure 3. There was strong positive correlation between these two variables, with  $r = 0.8$  and linear equation of  $y = 2.355x + 11.65$ .

For the *compreg*, the highest weight per cent gain was achieved by the 15% moisture content samples (28.06–32.68%) whereas the lowest, 40% moisture content samples (15.45–20.59%). Regardless of soaking time, weight per cent gain in *compreg* showed that the values decreased with the increase in moisture content (Figure 4). This was probably due to two reasons. Firstly, it could be due to low void volume of the wood structure which limited resin penetration. Secondly, the partially curing time of resin used in this study (i.e. 6 hours) was not sufficient to partially cure the whole resin which was highly saturated with water, and as a result, resin might squeeze out during the hot press. At a given moisture content, solution absorption reached maximum at the first 30 min of soaking and prolonging the time did not affect the solution absorption thus maintaining the weight gain (Figure 4).

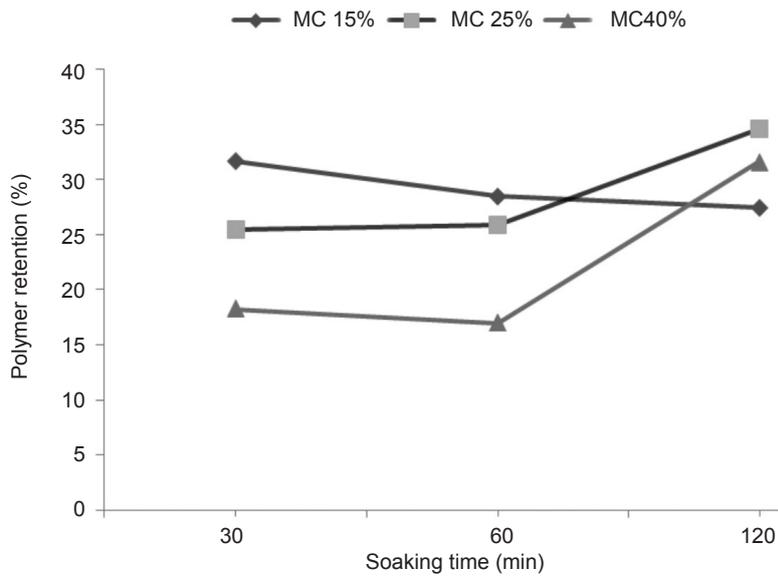


Figure 1 Polymer retention of *impreg* at different soaking times; MC = moisture content

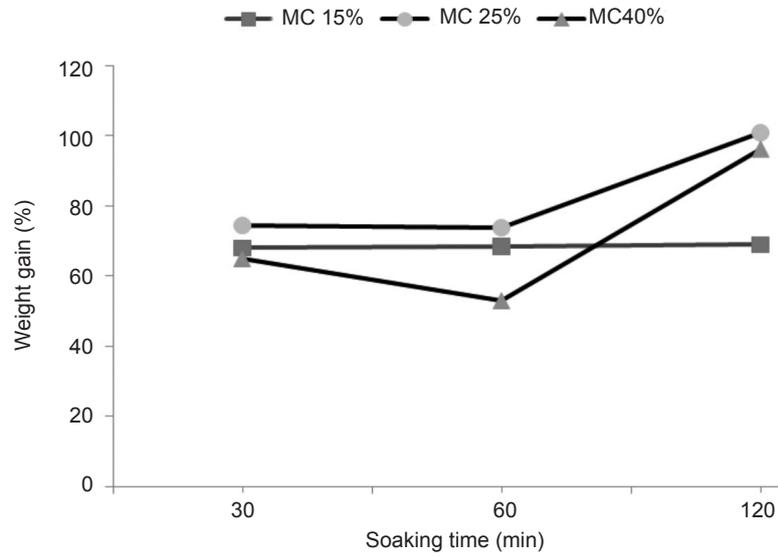


Figure 2 Weight gain of *impreg* at different soaking times; MC = moisture content

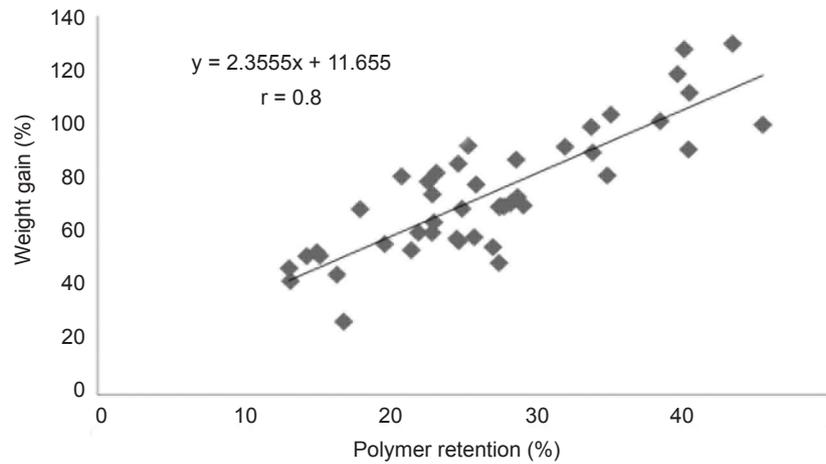
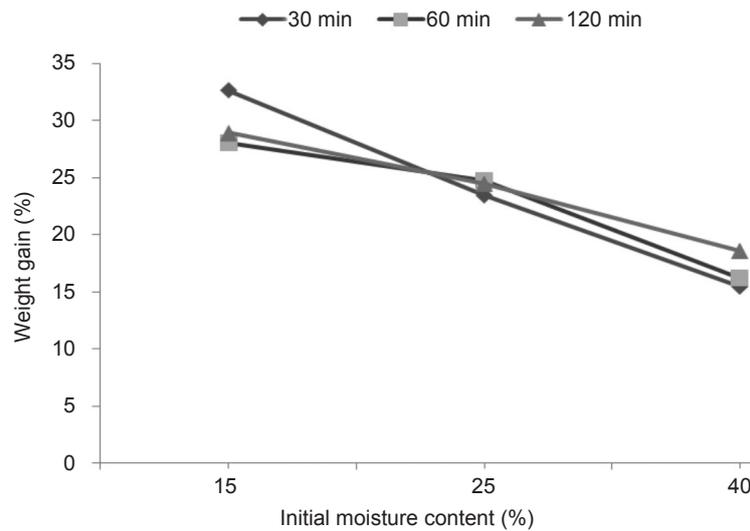


Figure 3 Relationship between polymer retention and weight per cent gain in *impreg*; MC = moisture content



**Figure 4** Weight gain of *compreg* in correlation with initial moisture content and soaking time

### Effect of weight per cent gain on physical properties of *compreg*

Table 4 summarises the correlation between the dependent (weight per cent gain) and independent (density and dimensional stability) variables of the *compreg*. Positive and significant correlations were found between the dependent variables and density ( $r = 0.5$ ) and reduction in water absorption ( $r = 0.7$ ). On the contrary, results showed that there was low negative correlation between the dependent variable and thickness swelling. Low correlation on density reflected that there were other processing factors that might affect the property due to the compression process. Weight per cent gain together with hot-pressing densification determines the final density of the *compreg* (Rowell 2005). It has also been proven that the density of *compreg* increases with the degree of compression in a hot press (Rabiatol Adawiah et al. 2012). Higher correlation calculated for reduction in water absorption could be due to higher amount of polymer retained in the wood structure. This acted as barrier that limited water penetrating into the wood.

A significant negative correlation ( $r = -0.4$ ) was found for thickness swelling, indicating that the polymer retained in the wood had successfully reduced thickness swelling of the *compreg*. Swelling coefficient had low correlation with weight gain ( $r = -0.2$ ). The low correlation of thickness swelling and swelling coefficient reflected that effect of polymer retention was offset by the

spring back of the compressed sample upon exposure to high humidity. Spring back occurred even though thinner wood was treated with higher concentration of phenol formaldehyde (Zaidon et al. 2010, Rabiatol Adawiah et al. 2012). They also revealed that the degree of compression significantly affected the spring back. On the contrary, earlier research showed that *impreg* products (without compression) had significantly lower thickness swelling than the untreated wood (Nur Izreen et al. 2011).

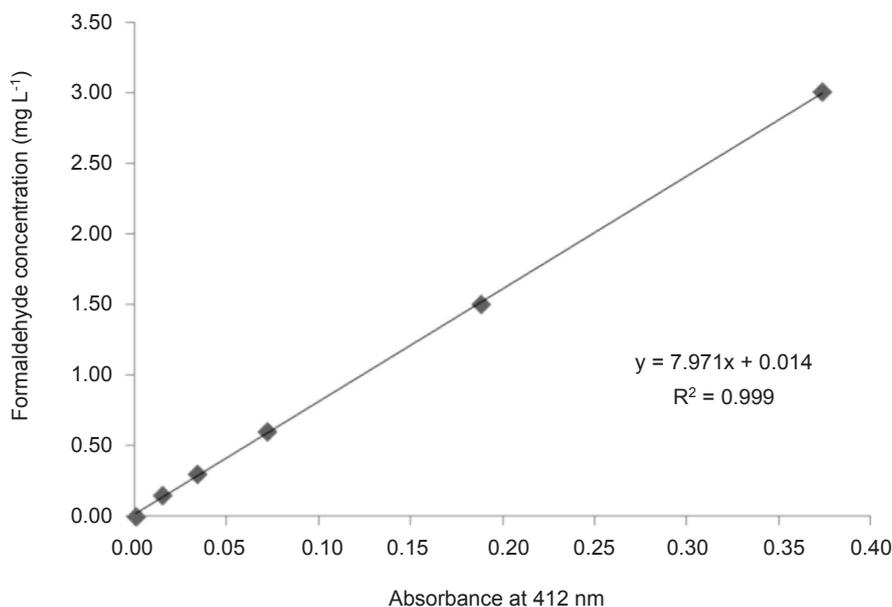
### Effect of urea addition on formaldehyde emission of *compreg*

The calibration curve produced from idometric titration is presented in Figure 5. The graph was plotted to estimate the slope which was then used to determine formaldehyde emission. The slope obtained was  $7.971x$  with  $r^2 = 0.9998$ . Results showed that the admixture of urea in the resin imparted significant reduction of formaldehyde emission levels (Figure 6). Formaldehyde emission level for *compreg* without urea was  $15.91 \text{ mg L}^{-1}$  and the values greatly reduced to  $6.97$  and  $0.61 \text{ mg L}^{-1}$  when 20 to 30% urea was added into the resin. The global threshold limit of formaldehyde emission is  $0.16\text{--}2 \text{ mg L}^{-1}$  (Markessini et al. 2010). Reactive urea bonded with the formaldehyde released by some of the methylol groups from the resin and formed urea formaldehyde cross-linked polymer (Nur Izreen et al. 2012). The excess free formaldehyde was still available in the treated wood as indicated

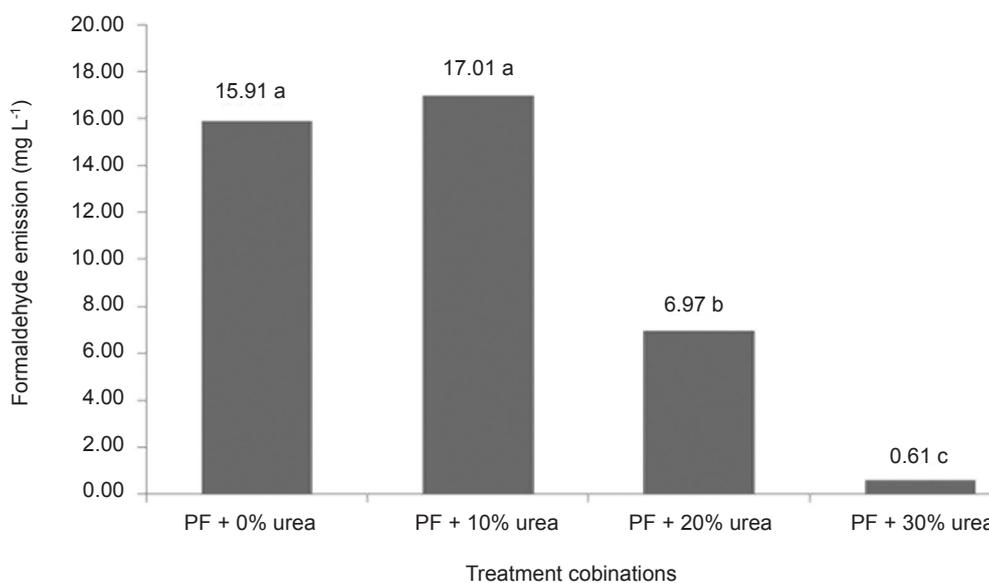
**Table 4** Correlation of weight per cent gain and density and dimensional stability of *compreg* sesenduk

WPG vs	Mean	r (p-value)	Regression equation
WPG	23.37%	-	-
Density	754 kg m <sup>-3</sup>	0.5 (0.00)	7.5654WPG + 577.43
R	52.53%	0.7 (0.00)	1.8441WPG + 9.428
TS	8.60%	-0.4 (0.03)	-0.0805WPG + 10.482
S	11.08%	-0.2 (0.32)	-0.0411WPG + 12.038

WPG = weight per cent gain, R= reduction in water absorption, TS = thickness swelling and S = swelling coefficient



**Figure 5** Calibration curve of standard formaldehyde concentration vs absorbance using spectrophotometer



**Figure 6** Formaldehyde emission of *compreg* following treatment with phenol formaldehyde (PF) with or without addition of urea

by the formaldehyde emission value. It has also been reported that formaldehyde emission can be further decreased by increasing the concentration of the scavenger. However, other properties might adversely be affected.

### Properties of *compreg* with formaldehyde scavenger

Table 5 summarises the descriptive statistics of the *compreg* properties. Untreated wood and the *compreg* without urea were used for comparison purposes. Results showed that properties of *compreg* with or without urea were superior compared with untreated wood, indicating that the treatments had enhanced wood properties. It is believed that resin filled in the lumen and wall of the cell and formed a rigid cross-linked polymer resulting in increase in strength and stiffness. The density of *compreg* increased significantly by 121 to 148% from the original density of 385 kg m<sup>-3</sup>. However, density values among the *compreg* (930–953 kg m<sup>-3</sup>) did not differ significantly. Even though no difference was noted for MOR (114–136 N mm<sup>-2</sup>), MOE (6923–8676 N mm<sup>-2</sup>) and compression strength (65–72 Nmm<sup>-2</sup>) values of the *compreg*, results showed that there was a decreasing trend in the properties as higher amount of urea was added. Similar results were also reported for *compreg* treated with 30% PF + 30% urea (based on solid PF) (Zaidon et al. 2010, Rabiatal Adawiah et al. 2012). This implied that the presence of urea had somehow lowered the properties of *compreg* wood. Significant decrement of hardness was recorded on the treated wood as the amount of urea added increased. The hardness of *compreg* without urea was 4.69 kN whereas for those with urea, the values ranged from 3.12 to 3.63 kN. However, hardness values of *compreg* were significantly higher than the untreated wood, which was 1.78kN.

Swelling coefficient was higher in the *compreg* (12.0–28.1%) compared with untreated wood (10.4%) and the degree of swelling increased with the amount of urea. The same was observed for thickness swelling, i.e. 8.54–23.56% versus 5.38% for *compreg* and untreated wood respectively. On the contrary, reduction in water absorption showed positive results (37.06–64.01%), where *compreg* without urea had the highest value. Results indicated that the spring back of the

compressed wood might have influenced the thickness swelling, resulting in higher swelling coefficient. The amount of urea in the treated wood might also have an impact on the swelling coefficient (Rowell 2005, Nur Izreen et al. 2011). The presence of urea had increased the molecular weight of the resin system, thus, limited the penetration of resin into the cell wall of treated wood.

### CONCLUSIONS

Initial moisture content of the sesenduk wood and soaking time of the impregnation process in low concentration (15%) LmwPF gave significant effect on polymer retention and weight gain of *impreg* product. Meanwhile, for *compreg*, weight gain was affected only by moisture content. Samples with initial moisture content of 15% attained maximum retention after 30 min of soaking, whereas for samples with higher moisture content, maximum retention was attained only after soaking beyond 60 min. It was also found that polymer retention in the treated wood was positively correlated with weight gain. Results also showed that density and reduction of water absorption of *compreg* were positively correlated with weight gain, while thickness swelling was negatively correlated with the dependent variable. However, there was no correlation between dependent variable and swelling coefficient. The presence of urea during the making of *compreg* sesenduk was able to reduce formaldehyde emission from the treated product; the degree of reduction increased with urea concentration. *Compreg* sesenduk produced with or without urea had mechanical properties and reduction of water absorption superior to untreated wood. The treatment did not impart dimensional stability of *compreg* and this was due to the spring back effect caused by residual stress after the compression process.

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**Table 5** Mean properties of *compreg* sesenduk treated with and without urea compared with untreated wood

Moisture content (%)	Density (kg m <sup>-3</sup> )	TS (%)	S (%)	R (%)	MOR (Nmm <sup>-2</sup> )	MOE (Nmm <sup>-2</sup> )	Compression strength (Nmm <sup>-2</sup> )	Hardness (kN)
U <sub>t</sub>	385.0 c ± 36.90	5.38 c ± 1.45	10.41 b ± 0.94	-	84.27 b ± 14.49	5027 b ± 401	41.83 b ± 9.00	1.78 c ± 0.54
0	943.0 a ± 41.93	8.54 bc ± 2.40	12.00 b ± 3.53	64.01 a ± 7.53	135.5 a ± 3.92	8676 a ± 452	71.86 a ± 6.80	4.69 a ± 1.11
10	940.0 a ± 44.32	12.57 b ± 3.06	16.50 b ± 3.62	53.59 a ± 9.45	122.7 a ± 23.99	7434 a ± 2176	68.18 a ± 15.91	3.63 b ± 0.63
20	953.0 a ± 41.79	11.83 b ± 2.91	16.09 b ± 3.74	55.29 a ± 7.3	117.90 a ± 8.22	7637 a ± 865	64.66 ab ± 16.32	3.50 b ± 0.64
30	930.0 b ± 52.63	23.46 a ± 11.80	28.05 a ± 13.63	37.06 b ± 21.95	113.70 a ± 22.57	6923 ab ± 1848	68.79 a ± 3.64	3.12 b ± 0.79

Means within columns followed by the same letter are not significantly different at  $p > 0.05$ , ± standard deviation; U<sub>t</sub> = untreated sample; TS = thickness swelling, S = swelling coefficient, R = reduction in water absorption, MOR = modulus of rupture, MOE = modulus of elasticity

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