

# ADDITION OF UREA AS FORMALDEHYDE SCAVENGER FOR LOW MOLECULAR WEIGHT PHENOL FORMALDEHYDE-TREATED *COMPREG* WOOD

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**RABI'ATOL ADAWIAH MA, ZAIDON A, NUR IZREEN FA, BAKAR ES, MOHD HAMAMI S & PARIDAH MT. 2012. Addition of urea as formaldehyde scavenger for low molecular weight phenol formaldehyde-treated *compreg* wood.** Phenol formaldehyde (PF) resin impregnation followed by compression at considerable high hot pressing pressure can improve strength properties, dimensional stability and durability of wood against decay. Formaldehyde emission from treated materials is, however, very high especially when low molecular weight resin is used. Reduction in formaldehyde emission was attempted by introducing urea in the treating solution. The experiment included impregnation of jelutong (*Dyera costulata*) and sesenduk (*Endospermum diadenum*) strips with 20, 30 and 40% low molecular weight phenol formaldehyde (LMwPF) mixed separately with urea (30% based on solid PF), pre-cured at 65 °C for 7, 8 and 9 hours and subsequently compressed to compression ratio of 80% at 150 °C for 20 min. The formaldehyde emission and properties of the *compreg* wood were analysed. The optimum treatment combination was then applied to produce laminated *compreg* wood. Three-layered laminated *compreg* jelutong and sesenduk were fabricated by assembling the impregnated strips either perpendicular (cross) or parallel to each other, followed by compressing under hot press. The presence of urea in the LMwPF solution was able to reduce formaldehyde emission of laminated *compreg* wood besides generating higher modulus of rupture, modulus of elasticity and dimensional stability. The optimum treatment combination was 30% PF concentration mixed with 30% urea (based on solid PF), 8 hours pre-curing at 65 °C followed by compressing to 80% compression ratio at 150 °C for 20 min. Compared with untreated solid wood of the same size, both parallel and cross-laminated *compreg* wood had superior properties. Shear strength at the bonding line was higher for parallel than for cross-laminated *compreg* wood. The parallel laminated *compreg* wood had bonding shear strength comparable with that of solid wood. The treatment also rendered high resistance against white rot fungus.

Keywords: *Endospermum diadenum*, *Dyera costulata*, anti-swelling efficiency, white rot

**RABI'ATOL ADAWIAH MA, ZAIDON A, NUR IZREEN FA, BAKAR ES, MOHD HAMAMI S & PARIDAH MT. 2012. Penambahan urea sebagai pengutip formaldehid dalam kayu *compreg* yang dirawat dengan fenol formaldehid berat molekul rendah.** Pengisitepuan resin fenol formaldehid (PF) diikuti oleh mampatan tinggi menggunakan tekanan panas dapat memperbaiki ciri-ciri kekuatan, kestabilan dimensi dan ketahanan kayu terhadap pereputan. Bagaimanapun, pelepasan formaldehid daripada bahan yang dirawat sangat tinggi, terutamanya apabila resin berat molekul rendah digunakan. Pengurangan pelepasan formaldehid dijalankan dengan memperkenalkan urea ke dalam larutan rawatan. Kajian melibatkan pengisitepuan bilah kayu jelutong (*Dyera costulata*) dan sesenduk (*Endospermum diadenum*) dengan 20%, 30% dan 40% fenol formaldehid berat molekul rendah (LMwPF) yang dicampurkan secara berasingan dengan urea (30% berdasarkan pepejal PF), pra-pematangan pada 65 °C selama 7 jam, 8 jam dan 9 jam dan diikuti dengan mampatan pada nisbah mampatan 80% pada 150 °C selama 20 min. Pelepasan formaldehid dan ciri kayu *compreg* dianalisis. Gabungan rawatan yang optimum digunakan untuk menghasilkan kayu *compreg* berlaminasi. *Compreg* jelutong dan sesenduk tiga lapisan dihasilkan dengan mengatur bilah kayu yang telah dirawat sama ada secara seranjang atau selari antara satu sama lain dan kemudiannya dimampatkan di bawah tekanan panas. Kehadiran urea dalam larutan LMwPF mampu mengurangkan pelepasan formaldehid daripada kayu *compreg* berlaminasi di samping memberi modulus kepecahan, modulus kekenyalan serta kestabilan dimensi yang lebih tinggi. Gabungan rawatan yang optimum ialah campuran 30% PF dengan 30% urea (berdasarkan PF pepejal), 8 jam pra-pematangan pada 65 °C diikuti dengan mampatan kepada 80% nisbah mampatan pada 150 °C selama 20 min. Berbanding dengan kayu padu bersaiz sama yang tidak dirawat, kayu *compreg* berlaminasi susunan selari dan seranjang mempunyai ciri unggul. Kekuatan rekatan ricih untuk kayu *compreg* berlaminasi selari adalah lebih tinggi daripada kayu *compreg* berlaminasi seranjang. Kayu *compreg* berlaminasi selari mempunyai kekuatan rekatan ricih yang setanding dengan nilai kayu padu. Rawatan ini juga memberi kayu *compreg* berlaminasi rintangan tinggi terhadap kulat reput putih.

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## INTRODUCTION

The increasing global demand for timber products has resulted in depleting supply of high quality traditionally known timbers from tropical forests. Interests have, nowadays, shifted to using lower density timbers that have good appearance and acceptable machining properties comparable with those of commercial hardwood. Sesenduk (*Endospermum diadenum*), jelutong (*Dyera constulata*) and mahang (*Macaranga* spp.) are some of the species which have not been fully utilised due to their poor strength properties. Nonetheless, once properly treated, these timbers can be converted into high value-added products.

Several chemical modification techniques such as bulking, internal coating and cross-linking have shown satisfactory results in enhancing the quality of low density timbers (Hill 2006). Phenol formaldehyde (PF) resin impregnation at considerably high hot pressing pressure is one of the cost effective ways to improve strength properties, dimensional stability and durability of wood against decay (Zaidon et al. 2010). PF resins have been widely used as wood adhesives for many years. One of the main drawbacks of PF resins in the manufacture of wood panels is their lower curing rate compared with amino-type resins (He & Riedl 2003). This problem is augmented when a low molecular weight PF resin is used as greater amounts of short chain oligomers are present in the system which require a longer time to cure. PF resin with molecular weight (Mw) of 290–480 is able to penetrate into the cell wall and increase stability. Upon heating, this low molecular weight PF (LMwPF) resin has softening effect which plasticises the cell wall. Once compressed (under hot pressing), the pressure deforms the cell walls easily without rupturing them. When the resin is cured, the compressed wood remains intact, stronger and dimensionally stable (Yano et al. 1997). However, if higher molecular weight PF resin is used, e.g. 820, the resin tends to be immobilised upon compressing and the bigger portion will remain in the cell lumen. As a result, there will be an apparent lack of compaction even though the weight per cent gain may be about the same. Most of the cured resin will stay in the cell lumen and this does not provide significant stability to the wood (Furuno et al. 2004).

A complete penetration of resin into the wood is vital for an efficient treatment. This can be achieved by treating thin pieces of wood with

LMwPF. Zaidon et al. (2010) treated wood strips (5 mm thick) of sesenduk, jelutong and mahang with LMwPF (Mw 600), followed by laminating and compressing them in a hot press to form three-layered *compreg* laminates. They found that the density of the 12 mm thick *compreg* laminates increased by two to three times compared with the control. The shear stress at the bonding line was slightly lower or comparable, while hardness was significantly higher than those of untreated control samples. The anti-swelling efficiency of the samples was 60–70%. Mechanical properties of such specimens were increased to some extent as a result of the treatment. The *compreg* laminates have potential application in parquet flooring, panelling and furniture components.

One of the drawbacks of using LMwPF is the high amounts of formaldehyde emission during soaking and hot pressing process. Since LMwPF resin contains substantial amounts of methylol groups in the oligomeric chains, some of these methylol groups are released as free formaldehyde upon exposure to high temperature and humidity (Hoong et al. 2010). One way to capture this free formaldehyde is to mix the treating solution with formaldehyde scavenger (Roffael 1993). There are several potential scavengers which can be introduced into the treatment system to catch free formaldehyde. These include urea, ammonium phosphate, potassium sulphite and sodium thiosulphate. Urea is, however, preferred due to its low cost (Zaidon 2009). In another study of the effect of urea addition to PF resin resins, Kim et al. (1996) found that urea additions lowered the free formaldehyde content and increased the degree of polymerisation but decreased the curing rate of PF resin. It is expected that urea would easily bond with the free formaldehyde released by some of methylol groups from the PF resin chains and at the same time the PF chains can be extended by reacting with a small amount of urea. Such reaction would be expected to be similar to that of phenol-urea-formaldehyde (PUF) resin preparation. PUF co-condensed resin is a typical example of an improved PF with faster curing and lower formaldehyde emission (Pizzi et al. 1993, He & Riedl 2003). Upon addition of urea, the gel time became shorter and the viscosity increased with increasing amounts of urea (He & Riedl 2003). Thus, urea can become a good scavenger for the free formaldehyde in the LMwPF resins.

This paper reports the formaldehyde emission, properties and durability of *compreg* strips and *compreg* laminates made from sesenduk and jelutong which have been treated with LMwPF resin in the presence of urea.

## MATERIALS AND METHODS

### Samples

The sesenduk and jelutong wood used were free from defects and the air-dried lumber (moisture content 15%) was flat sawn into samples (the width is on the tangential surface) of nominal dimensions of 150 mm long, 50 mm wide and 5 mm thick. LMwPF was used as treating solution and urea (in the form of granules) as formaldehyde scavenger. Untreated samples served as control.

### Determination of optimum treatment combination

Pre-weighed samples were impregnated separately with 20, 30 and 40% (w/w) LMwPF in a vacuum pressure apparatus. In an exploratory study, it was found that urea concentration in the range of 10–30% (based on formaldehyde solid PF) was able to reduce substantial amount of emission from wood treated with LMwPF (Zaidon 2009). In this study, 30% urea (based on solid contents of PF) was used as formaldehyde scavenger. The urea was mixed in the LMwPF resin solution just before treatment. Initial vacuum was applied for 15 min followed by filling the set up with LMwPF–urea solution. The samples were left soaked under pressure of 689 kPa for 30 min. Preliminary work had shown that the gelation of PF took place within 7–9 hours when the samples were heated at 60 °C (Zaidon 2009). Hence the samples were pre-cured in a forced-circulation oven maintained at 60 °C for either 7, 8 or 9 hours. Subsequently, the treated samples were compressed by hot pressing at 150 °C for 20 min to compression ratio (CR) of 80%. The CR was calculated using equation 1.

$$\text{CR (\%)} = 100 (T_f / T_i) \quad (1)$$

where  $T_i$  = initial thickness (mm),  $T_f$  = final thickness (mm). The *compreg* samples were then left in a conditioning room at 25 °C and relative

humidity (RH) of 65% ± 2 until they reached constant weight. Weight per cent gain (WPG) was determined based on equation 2.

$$\text{WPG (\%)} = 100 [(W_f - W_i) / W_i] \quad (2)$$

where  $W_f$  = constant weight in conditioning room after treatment (g) and  $W_i$  = constant weight in conditioning room before treatment (g).

### Formaldehyde emission test

Formaldehyde emission from the *compreg* samples was analysed in accordance with MS 1787 (MS 2005). The samples were tested after conditioning at 25 °C and 65% RH for two weeks. A calibration curve was first produced from a standard formaldehyde solution by iodometric titration. A total of 8–10 test pieces of wood with approximately 180 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% RH. The background formaldehyde was prepared using a desiccator containing no test piece. The formaldehyde absorbance in water was measured photometrically at 412 nm wavelength. Concentration of formaldehyde due to test pieces was calculated using equation 3.

$$G = f \times (A_d - A_b) \times 1800 / S \quad (3)$$

where  $G$  = concentration of formaldehyde due to test pieces (ppm),  $A_d$  = 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 (mg/L) and  $S$  = surface area of the pieces (cm<sup>2</sup>).

### Determination of dimensional stability

The dimensional stability of the specimens was measured in terms of anti-swelling efficiency (ASE), thickness swelling (TS) and water absorption (WA). Test pieces of size 20 mm × 20 mm were cut from both the *compreg* and untreated wood strips, and dried in an oven at 103 ± 2 °C overnight. The oven-dry weight and dimension of the test pieces were recorded. The test pieces were then placed in a beaker containing water and put under vacuum for 15 min to ensure full penetration of water. The test

pieces were left soaked for 24 hours before final weight and dimension were taken (Ashaari et al. 1990a). Swelling coefficient (S), ASE, WA and TS were determined using equations 4, 5, 6 and 7 respectively.

$$S (\%) = 100 [(V_f - V_i) / V_i] \quad (4)$$

$$ASE (\%) = 100 [(S_c - S_t) / S_c] \quad (5)$$

$$WA (\%) = 100 [(W_f - W_i) / W_i] \quad (6)$$

$$TS (\%) = 100 [(T_f - T_i) / T_i] \quad (7)$$

where  $V_f$  = volume after water test ( $\text{mm}^3$ ),  $V_i$  = volume of oven-dry sample ( $\text{mm}^3$ ),  $S_c$  = untreated volumetric swelling coefficient ( $\text{mm}^3$ ),  $S_t$  = treated volumetric swelling coefficient ( $\text{mm}^3$ ),  $W_f$  = weight after water test (g),  $W_i$  = weight before water test (g),  $T_f$  = thickness after water test (mm) and  $T_i$  = thickness before water test (mm).

### Mechanical properties of *compreg* samples

The specimens were tested for static bending according to the method specified in BS 373 (BSI 1957). Both *compreg* and untreated samples (150 mm × 20 mm × 5 mm in size but the thickness for the former was about 4 mm) were tested using centre loading method at a span of 23 times the thickness with a constant (load speed) crosshead speed of 6.64 mm min<sup>-1</sup>. Load deflection curves were recorded and the values were used to determine modulus of rupture (MOR) and modulus of elasticity (MOE).

### Production of three-layered laminated *compreg* wood

Based on the optimum treatment conditions studied earlier, sesenduk and jelutong wood strips were treated with 30% LMwPF + 30% urea based on the PF solids. After pre-curing, the treated strips were aligned either parallel or perpendicular to each other to form three-layered laminated *compreg* wood. The assembled strips were then compressed at 150 °C for 20 min to obtain CR of 80%. After conditioning at 25 ± 2 °C and 65 ± 2% RH, the laminated *compreg* was tested for dry shear at the joint line, MOR and MOE and fungal decay. For shear test, specimens of 20 mm × 20 mm × 12 mm were used and for bending, specimens were 200 mm × 20 mm × 12 mm. A decay test was conducted according to

ASTM (1999) using white rot fungus (*Pycnoporus sanguineus*) as the decaying agent. Sample blocks were exposed to the white rot for 12 weeks and weight loss (WL) was determined using equation 8. Untreated solid wood was used as control.

$$WL (\%) = 100 [(W_o - W_c) / W_o] \quad (8)$$

where  $W_o$  = weight of conditioned blocks before test (g) and  $W_c$  = weight of conditioned blocks after test (g).

### Statistical analyses

Statistical analyses were performed on physical and mechanical properties to determine if any significant difference existed between values of treated and untreated groups. Two way factorial tests with three levels of concentration (C) and three levels of pre-curing time (PCT) were conducted where treatment means were separated using Tukey's test at  $p < 0.05$  level. Comparison was made with the controls.

## RESULTS AND DISCUSSION

### Formaldehyde emission

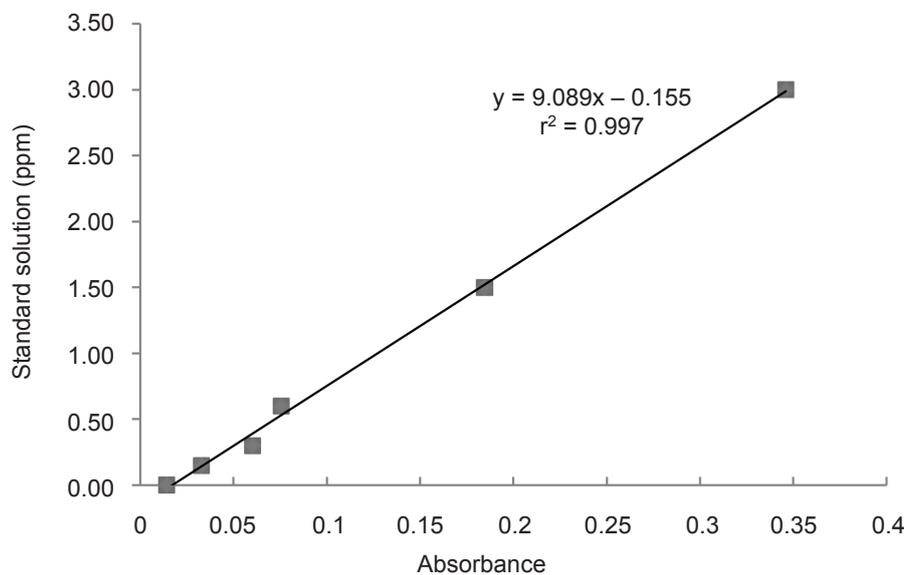
Figure 1 illustrates the calibration curve from iodometric titration. This graph has estimated slope which is used in determination of formaldehyde emission of the samples. The regression line was  $Y = 9.089x - 0.155$  with  $r^2$  value of 0.997. The formaldehyde emission values of the *compreg* products treated with or without the presence of scavenger are shown in Figure 2. For those treated without scavenger, formaldehyde emission increased with the concentration of PF. Regardless of PF concentration, *compreg* jelutong had higher formaldehyde emission values ranging from 215 to 358 ppm as compared with those of sesenduk, from 64 to 110 ppm. With the presence of urea in the treating solution, the formaldehyde emission reduced markedly to 6–17 ppm for jelutong and 3–24 ppm for sesenduk, indicating that urea had successfully absorbed some of the free formaldehyde in the resin system and formed cross-linked polymer of urea formaldehyde. However, the formaldehyde emission was still far beyond the global threshold limit of 0.16–2 ppm (Markessini et al. 2010). It is expected that formaldehyde emission can be further reduced by lengthening the curing time of the resin which in turn helps to increase the rate of polymerisation (Amarullah et al. 2010,

Hoong et al. 2010). However, this process may adversely affect the mechanical properties of the treated wood (Ashaari et al. 1990b).

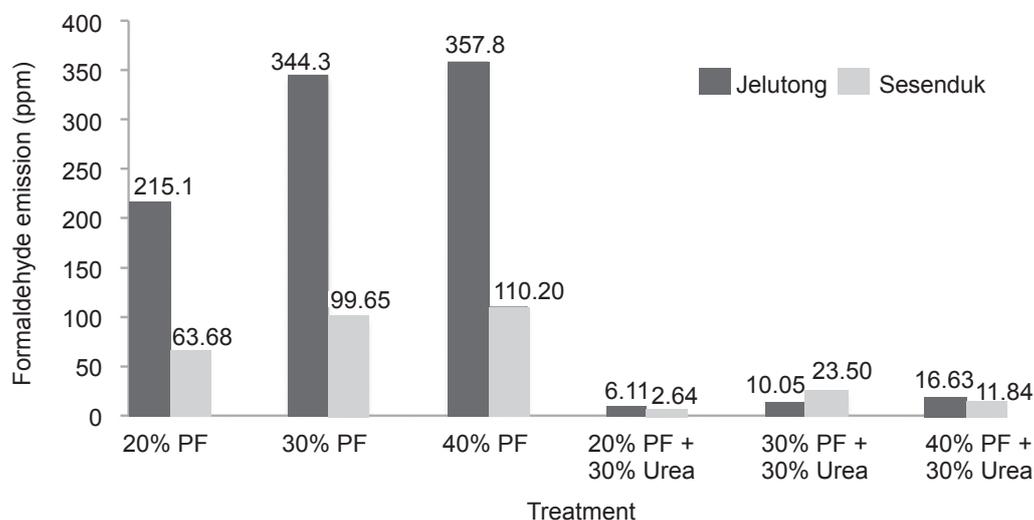
**Properties of *compreg* wood**

Table 1 summarises the analysis of variance (ANOVA) of the effects of resin concentration and pre-curing time on properties of *compreg* wood. Generally, jelutong was more affected by the treatment variables than sesenduk as indicated by the significance level. The ANOVA revealed that the concentration of treating solution significantly affected density, WPG and dimensional stability of jelutong samples as well as density, WPG and MOE of sesenduk. Pre-curing time only affected MOE and ASE of jelutong.

The descriptive statistics of the properties are shown in Table 2. The results clearly showed that the treatment had successfully enhanced the properties of the wood as indicated by the higher values obtained by urea-added *compreg* wood as compared with those of untreated wood. The density of *compreg* jelutong and sesenduk increased by 75–100% and 57–100% respectively. The increment was parallel to the increment in PF concentration. The initial densities of both wood were 404 and 412 kg m<sup>-3</sup> respectively. The WPG also increased with increasing PF concentration where sesenduk (43–86%) exhibited higher weight gain compared with jelutong (36–78%). MOR of the *compreg* wood at different treatment combinations did not differ significantly between wood species. The MOR values ranged from



**Figure 1** Calibration curve of standard formaldehyde concentration vs. absorbance using spectrophotometer



**Figure 2** Formaldehyde emission of *compreg* with or without urea; PF = phenol formaldehyde

**Table 1** Summary of analysis of variance ( $p \leq 0.05$ ) of *compreg* at different treatment combinations

Treatment	Df	Density ( $\text{kg m}^{-3}$ )	WPG (%)	MOR ( $\text{N mm}^{-2}$ )	MOE ( $\text{N mm}^{-2}$ )	WA (%)	TS (%)	ASE (%)
<i>Dyera costulata</i> (jelutong)								
C	2	0.020	0.000	0.219	0.051	0.005	0.000	0.000
PCT	2	0.110	0.517	0.200	0.017	0.108	0.115	0.023
C × PCT	4	0.132	0.384	0.386	0.006	0.198	0.084	0.012
<i>Endospermum diadenum</i> (sesenduk)								
C	2	0.000	0.000	0.102	0.037	0.188	0.265	0.758
PCT	2	0.692	0.464	0.626	0.437	0.445	0.685	0.940
C × PCT	4	0.055	0.856	0.149	0.136	0.572	0.997	0.929

C = resin concentration, PCT = pre-curing time; WPG = weight percent gain, MOR = modulus of rupture, MOE = modulus of elasticity, WA = water absorption, TS = thickness swelling, ASE = anti-swelling efficiency

73–100  $\text{N mm}^{-2}$  for jelutong and 74–125  $\text{N mm}^{-2}$  for sesenduk. Nevertheless, when compared with solid wood, the MOR values of the *compreg* wood were consistently higher. The MOR for solid jelutong and sesenduk were 71.62 and 71.77  $\text{N mm}^{-2}$  respectively. The same was also found for stiffness (MOE); *compreg* wood of jelutong between 8358 and 11,783  $\text{N mm}^{-2}$  and sesenduk, from 8247–15,258  $\text{N mm}^{-2}$  as compared with only 5825 and 7555  $\text{N mm}^{-2}$  respectively for solid jelutong and sesenduk wood.

The results obtained in this study were similar to those reported for sesenduk strips which were treated with only 30% PF (Zaidon et al. 2010). Density, WPG, MOR, MOE and dimensional stability obtained in the present study were relatively lower which implied that the presence of urea had somehow reduced the performance of the *compreg* wood. The MOR for *compreg* wood without added urea was 94  $\text{N mm}^{-2}$  and MOE, 16,277  $\text{N mm}^{-2}$  as opposed to those obtained for 30% PF + urea, 89 and 9696  $\text{N mm}^{-2}$  respectively. Similar results were reported where an increase in urea concentration decreased the properties of particleboard (Kim et al. 1996). Schmidt et al. (2006) attributed this reduction to lower hydrolytic stability and higher formaldehyde emission. At a much lower amount, i.e. < 10% by weight, this addition would result in better strength, and lower viscosity and formaldehyde emission (Schmidt et al. 2006). The addition of urea to the LMwPF prior to resin impregnation can induce reaction between

urea and free formaldehyde in the system to methylolated urea which does not react further under alkaline condition. Thus, the presence of methylolated urea may have increased the viscosity of the resin solution, thereby, limiting the penetration into the cell wall and lumen of the wood. The lower WPG and density values found in the current study reflected this phenomenon. The density and WPG found in an earlier study were 999  $\text{kg m}^{-3}$  and 93.4% respectively.

It is also interesting to note that the increase in density of *compreg* wood yields only a slight increase in MOR and MOE. This is shown by the specific strength (i.e. ratio of mechanical value to density) values of *compreg* wood treated with or without urea and control (Table 3). The specific MOR and MOE values for *compreg* treated without urea were 0.125 and 15.05  $\text{N m}^3/\text{kg mm}^{-2}$  respectively, while for those treated with the presence of urea were 0.105 and 16.29  $\text{N m}^3/\text{kg mm}^{-2}$  respectively. These values were lower compared with untreated wood, i.e. specific MOR, 0.174  $\text{N m}^3/\text{kg mm}^{-2}$  and specific MOE, 18.33  $\text{N m}^3/\text{kg mm}^{-2}$ . Apparently the presence of PF polymer in the wood had changed the characteristics of the wood into plastic-like material.

Dimensional stability in terms of WA, TS and ASE of the *compreg* wood improved significantly. WA for *compreg* jelutong ranged from 21.92–46.93% and 26.37–47.31% for *compreg* sesenduk (Table 2). Untreated wood had WA values of 135 and 179% for jelutong and sesenduk respectively. TS for *compreg* jelutong which was treated with higher PF concentration was significantly lower

**Table 2** Properties of *compreg* strips treated with urea (30% based on solid PF) at each treatment condition

LMwPF conc. (%)	Partial curing time (hours)	Density (kg m <sup>-3</sup> )	WPG (%)	MOR (N mm <sup>-2</sup> )	MOE (N mm <sup>-2</sup> )	WA (%)	TS (%)	ASE (%)
<i>Dyera costulata</i> (jelutong)								
20	7	706.4 a ± 33.53	36.15 d ± 3.93	100.3 a ± 18.13	11,783 a ± 1363	46.63 b1 ± 12.66	5.32 a ± 0.46	17.53 cd ± 11.18
20	8	731.2 a ± 25.76	38.36 d ± 3.69	93.05 a ± 12.21	9549 a ± 1491	34.02 bc ± 8.38	5.44 a ± 0.71	10.77 d ± 5.31
20	9	731.7 a ± 36.44	38.94 d ± 3.31	94.3 a ± 6.14	11,431 a ± 426.2	46.93 b ± 13.81	5.17 ab ± 1.30	18.24 cd ± 12.31
30	7	803.2 a ± 41.47	58.49 c ± 3.59	92.65 a ± 14.21	11,643 a ± 959.6	27.75 bc ± 9.57	2.14 c ± 1.04	51.87 a ± 9.17
30	8	774.3 a ± 65.05	63.71 bc ± 8.38	88.41 a ± 19.17	10,429 a ± 1780	38.18 bc ± 9.88	2.78 bc ± 2.01	34.04 abcd ± 16.09
30	9	723.8 a ± 85.74	66.76 abc ± 10.70	92.93 a ± 9.33	11,582 a ± 575.5	37.75 bc ± 2.43	4.58 ab ± 1.33	19.82 bcd ± 15.01
40	7	808.0 a ± 60.91	76.47 ab ± 8.15	96.91 a ± 22.09	11,121 a ± 835.5	27.79 bc ± 3.29	1.96 c ± 1.42	46.64 ab ± 20.28
40	8	758.1 a ± 36.34	78.14 a ± 9.03	88.85 a ± 10.39	10,783 a ± 1219	21.92 c ± 3.70	1.30 c ± 0.54	59.90 a ± 7.84
40	9	753.3 a ± 30.52	73.34 ab ± 2.34	73.76 a ± 26.19	8358 a ± 1824	35.78 bc ± 6.23	2.10 c ± 0.80	39.40 abc ± 13.53
<i>Endospermum diadenum</i> (sesenduk)								
Solid wood								
20	7	644.7 b ± 49.78	44.51 a ± 3.58	89.83 a ± 16.63	11,272 a ± 3580	47.31 b ± 16.09	5.21 a ± 1.51	27.25 a ± 14.52
20	8	685.5 ab ± 39.82	43.33 a ± 4.21	99.86 a ± 31.49	11,531 a ± 3220	42.67 b ± 16.01	4.97 a ± 1.68	21.16 a ± 17.16
20	9	711.9 ab ± 12.82	44.54 a ± 2.93	125.2 a ± 11.19	15,258 a ± 1181	39.98 b ± 9.624	4.69 a ± 1.78	19.50 a ± 17.98
30	7	787.0 ab ± 68.39	64.35 ab ± 16.97	95.45 a ± 30.04	9285 a ± 5887	30.57 b ± 14.88	4.57 a ± 1.59	20.30 a ± 12.17
30	8	792.0 a ± 41.37	68.61 ab ± 14.66	97.29 a ± 20.83	11,538 a ± 2565	26.37 b ± 10.50	3.87 a ± 1.53	28.74 a ± 20.40
30	9	689.5 ab ± 91.91	62.49 ab ± 8.72	74.38 a ± 37.73	8247 ab ± 4372	46.84 b ± 24.90	4.19 a ± 1.83	25.80 a ± 26.56
40	7	773.8 ab ± 101.94	82.60 c ± 23.51	80.04 a ± 22.35	9718 a ± 3739	29.23 b ± 9.323	4.28 a ± 2.67	27.64 a ± 29.99
40	8	792.5 a ± 102.14	85.52 c ± 25.47	80.31 a ± 35.16	9765 a ± 4839	28.75 b ± 13.91	3.75 a ± 1.08	29.60 a ± 13.33
40	9	823.3 a ± 70.98	84.85 c ± 25.34	93.39 a ± 28.86	11,198 a ± 3610	36.05 b ± 10.27	3.82 a ± 1.08	26.66 a ± 11.68
Solid wood								
		411.9 c ± 32.07		71.77 a ± 10.34	7555 b ± 1535	179.2 a ± 34.30	5.21 a ± 1.51	

Means followed by the same letter in the same column are not significantly different at  $p \leq 0.05$ ; ± is standard deviation; LMwPF = low molecular weight phenol formaldehyde, WPG = weight per cent gain, MOR = modulus of rupture, MOE = modulus of elasticity, WA = water absorption, TS = thickness swelling, ASE = anti-swelling efficiency

than untreated wood. As for sesenduk samples, the TS of *compreg* and untreated samples were comparable with each other. The positive ASE values found in the *compreg* products, i.e. 11–60% for jelutong and 20–30% for sesenduk indicated that the resin had bulked the cell wall. Hill (2006) and Ohmae et al. (2002) revealed that PF resin was able to bulk in the cell lumen and to some extent in the wood cell wall. During hot pressing of PF resin, the methyl groups in the phenolic rings are converted to methylene bridges resulting in the formation of a very highly cross-linked thermoset polymer (Collins 1996). The cross-linked polymer becomes hard, infusible, insoluble and cannot be softened or melted (Hon 2003). However, the ASE found in *compreg* sesenduk was lower compared with those *compreg* without scavenger (ASE 60–70%) found in an earlier study (Zaidon et al. 2010). This could probably be due to only a small amount of resin being bulked into the cell wall while the rest filled the lumen.

In general, regardless of PCT, wood treated at 30% PF with the presence of urea as formaldehyde scavenger had properties similar to those treated

with higher PF, i.e. 40%. Thus, a combination of 30% PF and 8 hours pre-curing time was selected to fabricate three-layered laminated *compreg* wood from jelutong and sesenduk.

### Properties of laminated *compreg*

A summary of laminated *compreg* properties is exhibited in Table 4. The densities of the laminated *compreg* jelutong and sesenduk respectively were about 100 and 80% higher compared with those of the respective untreated solid wood. Parallel laminated *compreg* of jelutong had higher MOR (73.17 N mm<sup>-2</sup>) than perpendicular laminates (66.35 N mm<sup>-2</sup>) and untreated wood (58.93 N mm<sup>-2</sup>). For sesenduk, the MOR values did not differ significantly. In parallel direction, the contact surface area of fibres was larger than in the cross-direction which gave high resistance towards shear. The MOR ranged from 52.72 to 67.37 N mm<sup>-2</sup>. There was no significant difference in MOE between the laminated *compreg* and untreated wood. The values were from 5510–5624 N mm<sup>-2</sup> for jelutong and 4592–6122 N mm<sup>-2</sup> for sesenduk. Majority of the failure found in the

**Table 3** Specific strength of *compreg* (*Endospermum diadenum*) wood compared with untreated solid wood

Treatment	Density (kg m <sup>-3</sup> )	Specific MOE (N m <sup>3</sup> /kg mm <sup>-2</sup> )	Specific MOR
Untreated solid wood	412	0.174	18.33
PF alone (30%)	744	0.125	15.05
PF (30%) + urea (30% based on solid PF)	918	0.105	16.29

MOE = modulus of elasticity, MOR = modulus of rupture, PF = phenol formaldehyde

**Table 4** Properties of *compreg* laminates treated with urea compared with untreated solid wood

Type of laminate	Density (kg m <sup>-3</sup> )	Increment over solid wood (%)	MOR (N mm <sup>-2</sup> )	Increment over solid wood (%)	MOE (N mm <sup>-2</sup> )	Increment over solid wood (%)	Shear (N mm <sup>-2</sup> )	Increment over solid wood (%)
<i>Dyera costulata</i> (jelutong)								
Parallel	840.5 a	116	73.17 a	24.2	5510 a	10.89	9.43 a	25.2
Cross	805.8 a	107	66.35 ab	12.6	5624 a	13.18	4.66 c	-38.1
Solid wood	388.5 b		58.93 b		4969 a		7.53 b	
<i>Endospermum diadenum</i> (sesenduk)								
Parallel	780.8 a	78.1	52.72 a	-18.2	4592 a	-7.40	8.89 a	1.02
Cross	792.9 a	80.9	67.37 a	4.50	6122 a	23.45	4.21 c	-52.2
Solid wood	438.4 b		64.47 a		4959 a		8.80 a	

Means followed by the same letter are not significantly different at  $p \leq 0.05$ ; MOR = modulus of rupture, MOE = modulus of elasticity

laminated *compreg* was in shear at the bonding line indicating the weakest part of the products when subjected to bending. The shear strength tested at the bonding line was higher in parallel laminates of jelutong ( $9.43 \text{ N mm}^{-2}$ ) compared with solid wood ( $7.53 \text{ N mm}^{-2}$ ). However, the shear values for parallel laminates of sesenduk did not show any significant difference from those of solid wood samples. Shear values for cross laminates of jelutong ( $4.66 \text{ N mm}^{-2}$ ) and sesenduk ( $4.21 \text{ N mm}^{-2}$ ) were 38 and 52% lower than those of solid wood.

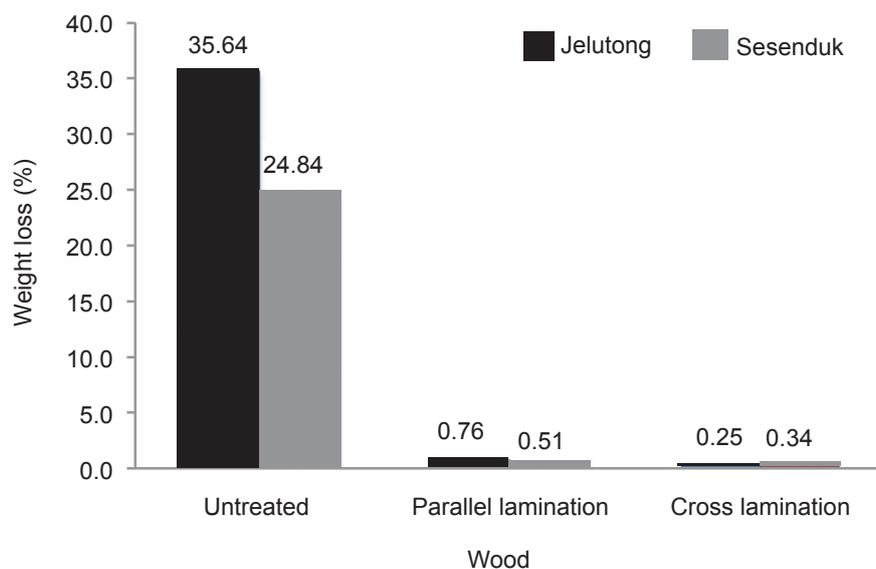
### Resistance of laminated *compreg* towards fungal decay

The weight loss of laminated *compreg* untreated solid wood after 12 weeks exposure to *P. sanguineus* is shown in Figure 3. Weight loss for laminated *compreg* jelutong were 0.76% for parallel and 0.25% for cross laminates compared with 35.64% for untreated solid wood. For laminated *compreg* sesenduk, the weight loss were 0.51 and 0.34% for parallel and cross laminates respectively. The results showed that phenolic *compreg* technique had successfully increased the resistance of sesenduk and jelutong to fungal decay by 98–99%. Ang (2010) found that WPG of 30% for *compreg* *Macaranga* sp. was enough to protect the

product from decay fungus. In another study, it was reported that resin weight gain of 10–20% was sufficient to suppress the growth of decay fungi (Furuno et al. 2004).

### CONCLUSIONS

The presence of urea in LMwPF (urea 30% based on solid PF resin) during the making of *compreg* jelutong and sesenduk was able to reduce formaldehyde emission from the products but the emission was still high compared with the standard threshold limit. The addition of urea, however, gave lower strength compared with *compreg* wood without urea but higher than those of untreated solid wood. The optimum treatment combination found in this study was 30% PF concentration mixed with 30% urea, 8 hours pre-curing at  $65^\circ\text{C}$ , followed by compressing to 80% CR at  $150^\circ\text{C}$  for 20 min. Laminated *compreg* aligned either parallel or perpendicular to each other had properties superior or comparable with those of untreated solid wood. The shear strength at the joint line was higher in the parallel laminates than in the cross laminates and the shear for parallel laminates were comparable with that of solid wood. The treatment rendered *compreg* laminates with a 99% increase in resistance to white rot fungus.



**Figure 3** Weight loss of *compreg* laminates after exposure to *Pycnopores sanguineus* for 12 weeks

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