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Effects of Compression Ratio and Phenolic Resin Concentration on The Properties of Laminated Compreg Inner Oil Palm and Sesenduk Wood Composites

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Abstract: Due to its inferior properties, oil palm wood (OPW) extracted from the inner layer of the oil palm (*Elaeis guineensis*) trunk, referred as inner OPW in this study, is frequently regarded as a waste. Phenolic resin treatment and lamination of inner OPW with other hardwoods may be an excellent way to improve the properties of the inner OPW. In this study, inner OPW were treated with two different concentrations (15% and 20%) of low molecular weight phenol formaldehyde resin (LmwPF) and compressed at different compression ratios (10%, 20%, and 30%). The physical and mechanical properties of the modified inner OPW's were evaluated according to British Standards (BS) 373: 1957. The results revealed that inner OPW treated with the highest compression ratio (30%) and resin concentration (20%) exhibited the highest weight percent gain, polymer retention and density. In the following phase of the research, the treated inner OPW was used as the core layer in the fabrication of a three-layer laminated compreg hybrid composites, with untreated and treated sesenduk (*Endospermum diadenum*) wood serving as the face and back layers. The compression ratios of 10% and 20% and resin concentrations of 10% and 20% were used in this phase of study as laminated boards made with 30% compression ratio failed. The findings showed that resin concentration had a significant impact on both the inner OPW and the laminated compreg hybrid panels. Markedly, higher resin concentrations (20%) resulted in improved physical properties, i.e., thickness swelling and water absorption, as well as enhanced mechanical properties (modulus of rupture and modulus of elasticity). Although compression ratios had no significant effect on the properties of the laminated products, those compressed at higher compression ratios (20%) performed slightly better than the panels compressed at lower compression ratios (10%).

Keywords: oil palm trunk; *Endospermum diadenum*; phenolic resin; compregnation; compression ratio; resin concentration

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1. Introduction

As the world's second-largest producer, palm oil production is vital for the national economy of Malaysia. The agriculture sector contributed 7.1% to the country's Gross Domestic Product (GDP) in 2019. Oil palm was the major contributor which accounted for 35.2% of the gross value added of the national agriculture sector in 2021 [1]. In 2021, there are a total of 5.73 million hectares of oil palm-planted areas in Malaysia [2]. Markedly, the palm oil industry generates substantial amounts of waste and by-products in the form of lignocellulosic biomass, including oil palm trunks, oil palm fronds, and empty fruit bunches, estimated to approximately 40 million tonnes per year [3]. It is estimated that 12.8 million tonnes of oil palm trunks could be generated every year during replanting activities [4]. This huge amount of oil palm trunk biomass could serve as an alternative lignocellulosic feedstock for the wood-based industries that are facing constantly increasing demand for natural wood resources. This cascading use of wood waste and by-products, together with the optimization of the manufacturing processes, represent key bioeconomy principles [5–8].

Oil palm trunk is frequently used as a raw material in the manufacture of composite materials such as laminated veneer lumber (LVL); plywood, flooring, furniture, and other composites [9–15]. However, it was reported that oil palm wood extracted from the trunk has four major drawbacks, i.e., low mechanical strength, inferior dimensional instability, poor durability, and poor machining characteristics [16,17]. As a result, Haslett [18] concluded that the oil palm trunk is unsuitable for use as sawn timber. Instead, it can be used to make reconstituted value-added wood-based products such as particleboard, fiberboard, and laminated board. Markedly, treatment is still required in the fabrication of laminated boards. According to a recent study, chemical treatments may improve the outer and inner surfaces of oil palm wood (OPW). Hill [19] discovered that increasing the bulk of low-density wood improves its quality.

Impregnation treatment with phenolic resin and other aminoplastic resins has been reported to be an effective modification method to enhance the properties of low-density wood and oil palm trunks. For instance, numerous studies have been conducted to improve the properties of low-density tropical hardwoods such as sesenduk (*Endospermum diadenum*), jelutong (*Dyera costulata*), and mahang (*Macaranga* sp.), as well as oil palm wood, by bulking them with low molecular weight phenol formaldehyde (LmwPF) resin [20–23]. As shown in another study, oil palm trunks modified by melamine formaldehyde exhibited better dynamic-mechanical and acoustic properties [24]. Generally, there are two different processes involving resin impregnation treatment. One of the processes is called impregnation, when the resins are forced into the wood samples by applying pressure and then polymerized by curing under heat. Meanwhile, compregnation involves the application of compression after the impregnation process. The impregnated wood samples are often compressed under heat for the polymerization of resin to take place [25].

According to Lee and Ashaari [21], impregnation increases the strength and dimensional stability of sesenduk and jelutong wood. Bao et al. [26] produced a hybrid poplar compreg with phenolic resins and discovered that the product's dimensional stability was greatly improved. Ashaari et al. [22] created a compreg laminated bamboo/wood hybrid with sesenduk wood as the core layer. The experiment's main goal was to compensate for the inferior properties of sesenduk wood, which is softer and weaker than bamboo. The softer and more compressible sesenduk wood, on the other hand, may help the compreg laminated bamboo/wood hybrid to achieve better compression and consolidation. The study's findings revealed that the combined application of sesenduk wood and bamboo was capable of producing compreg laminated hybrid products with comparable strength properties to compreg laminated bamboo.

The outer portion of the oil palm trunk, which accounted for nearly 30% of the trunk radius, could be used to extract lumber. Due to its inferior strength properties and dimensional instability, the remaining 70% of the inner part is generally regarded as waste [16]. However, inspired by the previous research, inner OPW can be used as the core in the manufacture of laminated compreg composite products. In this work, three-layer laminated compreg hybrid products were fabricated in laboratory conditions with treated inner OPW serving as the core layer. Face and back layers were made of untreated and phenolic resin-treated sesenduk wood. The effects of compression ratio and phenol formaldehyde resin concentration on the physical and mechanical properties of the laminated compreg composites were evaluated.

2. Materials and Methods

2.1. Materials Preparation

Oil palm trees were felled in a private plantation near Taman Saujana Putra, Puchong, Selangor, Malaysia, for the extraction of OPW. Oil palm trunks were sawed to produce OPW with a thickness of 5 cm. Only the woody part of the trunk's inner part (called inner wood) was used in this study. The inner part of the oil palm trunk was extracted using polygon sawing method as mentioned in Hamzah et al. [16].

The density of the inner wood was approximately 300 kg/m^3. The OPW samples were cut from the trunk and air dried to roughly 50%–60% moisture content (MC). Low molecular weight phenol formaldehyde (LmwPF) supplied by Malaysian Adhesive Chemical (MAC), Shah Alam, with a solid content of 44.6% was used as a treating solution. The properties of the LmwPF resin used are shown in Table 1. Distilled water was used to dilute the LmwPF resin to 15% and 20% (*w*/*w*) concentrations.

Table 1. Properties of low molecular weight phenol formaldehyde (LmwPF) resin used for impregnation treatment.

Characteristic	Liquid
Specific gravity	1.24
pH	9
Boiling point (°C)	~100
Solid content (%)	45
Molecular weight (Mw)	600
Viscosity (poise)	0.213

2.2. Treatability and Dimensional Stability of Compreg Treated Oil Palm Inner Wood

Prior to impregnation treatment, the air dried OPW samples were further dried in an oven to achieve MC of around 15%–20%. A vacuum-pressure technique using custom made impregnation equipment was used to optimize the treatability of the material with PF resin. After 15 min of vacuum treatment, the setup was filled with LmwPF solution. The samples were immersed for 30 min at 689 kPa. The OPW was entirely soaked in the PF resin to ensure total penetration. After impregnation, the samples were partially cured for 7 h at 70 °C. The pre-cured samples were then pressed for 45 min at 150 °C with a stopper bar to achieve a compression ratio (CR) of 10, 20, and 30%, as calculated using the formula below:

$$\text{Compression ratio (\%)} = (T_i - T_f)/T_i \times 100 \quad (1)$$

where CR = compression ratio (%), T_f = final thickness of compressed (mm), T_i = initial thickness before compressed (mm).

2.3. Weight Percent Gain (WPG) and Density Evaluation

All compreg samples were conditioned to a constant weight. The WPG and density of the samples after impregnation treatment were determined.

2.4. Dimensional Stability Evaluation

The samples were cut from the compreg OPW at nominal dimensions of 20 mm × 20 mm × 10–20 mm, then immersed in distilled water for 24 h, and the wet weight and volume were calculated. These data were used to determine the anti-swelling efficiency (ASE), water absorption (WA), and thickness swelling (TS). Untreated samples were utilized as a control. Equations (2)–(5) were used to determine these properties.

$$S (\%) = [(V_1 - V_2)/V_1]\ 100\% \quad (2)$$

where S = volumetric swelling coefficient (%), V_1 = volume of oven-dried material before water immersion (mm^3), and V_2 = volume of material after water immersion (mm^3).

$$ASE (\%) = [(S_1 - S_2)/S_1]\ 100\% \quad (3)$$

where ASE = anti-swelling efficiency (%), S_1 = volumetric swelling coefficient of treated material (mm^3), and S_2 = volumetric swelling coefficient of untreated material (mm^3).

$$TS (\%) = [(T_2 - T_1)/T_1]\ 100\% \quad (4)$$

where TS = thickness swelling (%), T_1 = thickness of material before water immersion (mm), and T_2 = thickness of material after water immersion (mm).

$$WA (\%) = [(W_2 - W_1)/W_1]\ 100\% \quad (5)$$

where WA = water absorption (%), W_1 = weight of material before water immersion (g), and W_2 = weight of material after water immersion (g).

2.5. Production of Laminated Compreg Composite Products

OPW with the highest weight percent gain (WPG) and dimensional stability obtained from the treatment in the first phase was used to fabricate composite laminated products. After pre-curing, the compreg OPW was laminated parallel with untreated or treated sesenduk wood to form three-layer laminae (Figure 1). The description of the laboratory-fabricated laminated compreg composites is given in Table 2.

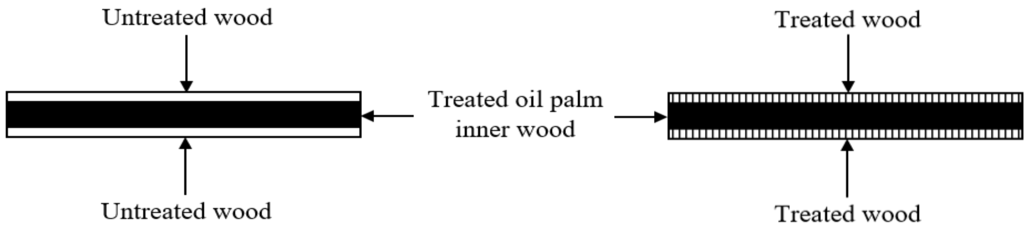

Figure 1. Product description for laminated *compreg* composite products.

Table 2. Description of the product of laminated compreg composites produced in this work.

Label	Compression Ratio (%)	Face Layer	Core Layer	Back Layer
P1	20	Untreated wood	15% PF treated OPT	Untreated wood
P2	20	15% PF-treated wood	15% PF treated OPT	15% PF-treated wood
P3	20	Untreated wood	20% PF-treated OPT	Untreated wood
P4	20	20% PF-treated wood	20% PF-treated OPT	20% PF-treated wood
P5	10	Untreated wood	15% PF-treated OPT	Untreated wood
P6	10	15% PF-treated wood	15% PF-treated OPT	15% PF-treated wood
P7	10	Untreated wood	20% PF-treated OPT	Untreated wood
P8	10	20% PF-treated wood	20% PF-treated OPT	20% PF-treated wood

Using a hydraulic hot press machine (Carver CMG 100H-15, Ontario, NY, USA), the laminae were hot pressed at 150 °C for 60 min at 10% and 20% compression ratio (CR).

The hot-pressing regime was selected on the basis of previous experimental work performed by the authors [21]. A 20 mm stopper bar was used to control the final thickness of the laminated compreg hybrid during compression.

2.6. Mechanical Properties Evaluation

The modulus of rupture (MOR) and modulus of elasticity (MOE) of laminated compreg treated and untreated composites were measured with three-point static bending using a Universal Testing Machine (100 kN, INSTRON, Norwood, MA, USA). The static bending test was carried out using a modified specimen size in line with British Standard BS 373: 1957 [27]. The center loading method was used to test the 350 mm × 20 mm × 20 mm specimens with a span of 300 mm and a constant crosshead speed of 6.64 mm/min.

2.7. Statistical Analysis

The material treated with different treatment combinations was compared to the untreated material using statistical analysis. An ANOVA with a one-way factorial design was utilized to analyze the treatment variables' efficacy, and Tukey's test was utilized to separate the means at $p \leq 0.05$. The study used the Statistical Package for the Social Sciences (SPSS) version 25 (The International Business Machines Corporation (IBM), New York, NY, USA).

3. Results

3.1. Treatability of Compreg OPW

A summary of the results obtained for the polymer retention and polymer loading as measured by WPG is presented in Table 3. Table 3 also depicts the density of the compreg OPW treated at different resin concentrations and CR.

Table 3. Polymer retention, weight percent gain and density of inner oil palm wood treated at different compression ratios and resin concentrations.

Compression Ratio (%)	Resin Concentration (%)	Polymer Retention (%)	Weight Percent Gain (%)	Density (kg/m³)
10	15	61.56 ± 18.80 [b]	64.48 ± 3.53 [d]	612 ± 29.58 [c]
20	15	64.56 ± 13.59 [b]	78.56 ± 2.52 [c]	655 ± 53.38 [c]
30	15	79.20 ± 14.37 [ab]	94.54 ± 4.61 [b]	710 ± 41.95 [b]
10	20	68.53 ± 9.28 [b]	93.09 ± 1.75 [b]	641 ± 45.16 [c]
20	20	81.51 ± 14.68 [ab]	97.87 ± 2.55 [b]	728 ± 27.83 [b]
30	20	92.12 ± 19.18 [a]	140.73 ± 5.26 [a]	809 ± 25.82 [a]
Untreated	Untreated	-	-	308 ± 25.28 [d]

Note: Means followed by the same letter a, b, c, d is not significantly different at $p \leq 0.05$, value after ± sign is standard deviation.

The polymer retention of compreg OPW was determined to be 61.56%, 64.56%, and 79.20% for the samples treated with 15% resin concentration, and 68.53%, 81.51%, and 92.12% for the samples modified with 20% resin concentration with CR ranging from 10 to 30%, respectively. As the resin concentration increased, the polymer retention of the compreg OPW increased. CR exerted a tremendous influence on polymer retention. The greatest polymer retention of 92.12% was recorded for the compreg OPW samples treated with 20% resin concentration and 30% CR. Similarly, WPG increased significantly along with increasing resin concentration and CR. The highest WPG of 140.73% was recorded in the samples treated with 20% resin concentration and pressed with 30% CR. Such phenomena are common because increasing resin concentration usually results in a higher polymer content in the resin, as shown by the higher polymer retention in samples with 20% resin concentration (Table 3). Therefore, the deposition of these polymers in the wood becomes greater and thus increased its bulking coefficient. According to Wang et al. [28], impregnation pressure caused PF resin to penetrate deeply into the wood, as it was found trapped in the lumens of many tracheids. The penetration rate increased as the resin concentration increased. However, the authors stated that a concentration of 20% resin is the threshold because concentrations greater than 20% reduce the permeability of the wood and the WPG resin.

Table 3 shows that the density of the samples treated with different resin concentrations and CR ranged from 612 kg/m^3 to 809 kg/m^3. The trend is similar to that of polymer retention and WPG. The increment in density was more than two times compared to that of untreated OPW (308 kg/m^3) as the increment in density is directly proportionate with the WPG increment [21].

3.2. Dimensional Stability of Compreg OPW

Figure 2 shows that the TS value of untreated OPW was 8.43%. The TS of compreg OPW ranged from 1.79% to 3.81%. When compared to samples with a 15% resin concentration, samples with a 20% resin concentration had lower TS values. Meanwhile, CR had a significant impact on the TS of the samples, i.e., the higher the CR (30%), the lower the TS values.

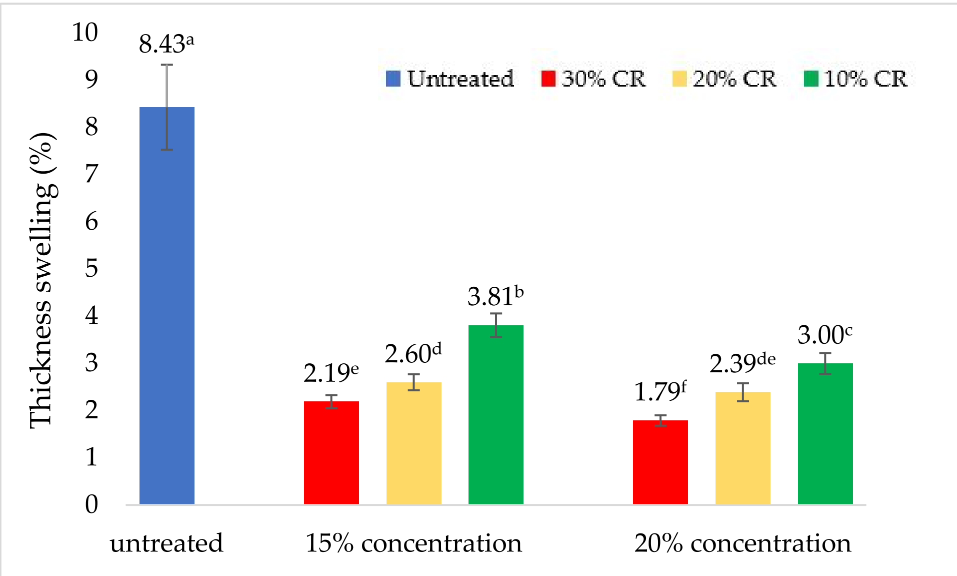

Figure 2. Thickness swelling of compreg oil palm inner wood.
Note: Means followed by the same letter a, b, c, d, e is not significantly different at $p \leq 0.05$

As seen in Figure 3, the increased PF resin concentrations from 15% to 20%, and compression ratios resulted in reduced WA values of the treated OPW. The untreated OPW exhibited an extremely high WA value of 114.19%, due to the high-water absorption capacity of parenchyma tissue. After compregnation, the WA of the OPW reduced from 21.90% to 41.08%. Although OPW is known to be an unstable material due to its anatomical features, which allows for excessive moisture absorption, compreg treatment significantly reduced its WA. The samples treated with 20% PF resin concentration and 30% CR had the lowest WA of 21.90%.

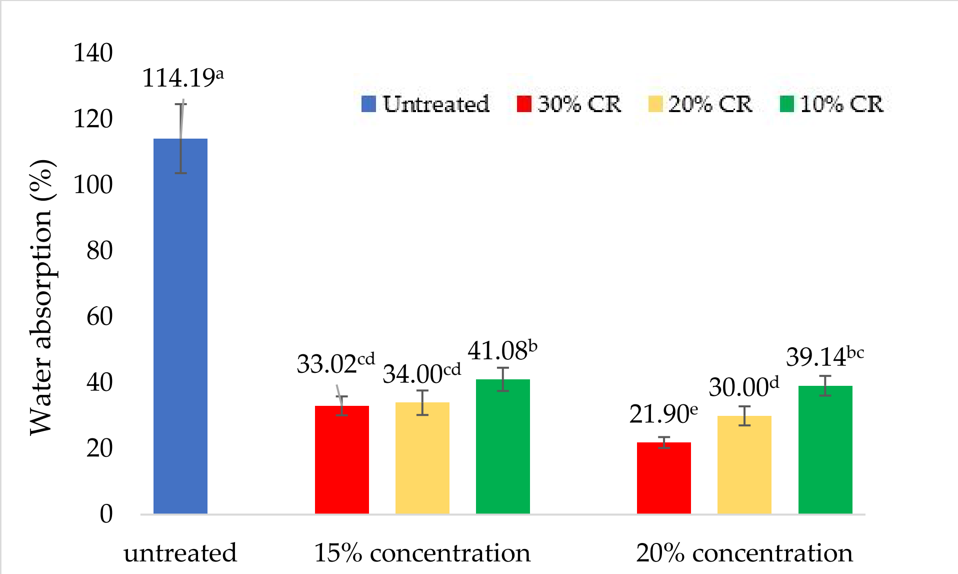

Figure 3. Water absorption of compreg oil palm inner wood. Note: Means followed by the same letter a, b, c, d, e is not significantly different at $p \leq 0.05$

This finding is consistent with the findings of Aizat et al. [29], who reported that compreg treatment was able to reduce the WA of outer oil palm by 23.97%. In general, compreg OPW had lower WA values compared to other compreg wood such as jelutong and sesenduk. Since the PF resin was adequately filled and cured, water could not penetrate the inner wood of the oil palm. Collins [30] reported that during the hot pressing of PF resin, the methyl groups in the phenolic rings were converted to methylene bridges. The conversion resulted in the formation of a very highly cross-linked thermoset polymer, which became hard, infusible, and insoluble, eventually preventing the wood from absorbing water [31].

In this study, the ASE values of the compreg OPW varied from 75.94% to 57.69% for the samples treated with 15% PF resin concentration, and from 76.21% to 59.45% for the samples treated with 20% resin concentration, respectively (Figure 4). In terms of CR, it is demonstrated that ASE increased in tandem with CR, i.e., the higher the CR ratio, the higher the ASE values. The highest ASE value of 76.21% was recorded in the samples treated with 20% PF resin concentration and 30% CR.

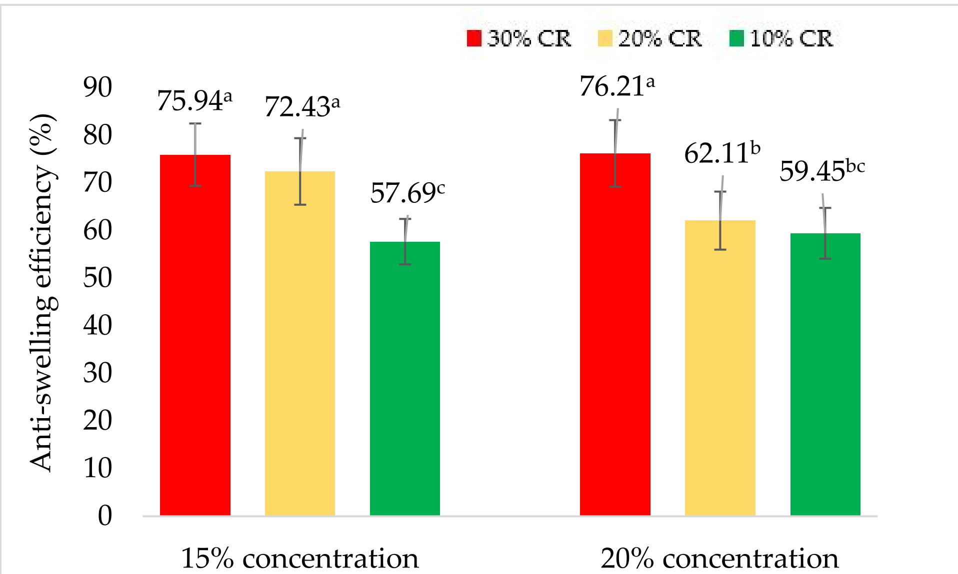

Figure 4. Anti-swelling efficiency of compreg oil palm inner wood. Note: Means followed by the same letter a, b, c is not significantly different at $p \leq 0.05$

WPG improves dimensional stability by increasing density while decreasing porosity. Fadhlia et al. [32] reported that the bulking effect of the PF resin reduces open areas, reduces WA, and increases the dimensional stability of treated wood samples. According to Bhat et al. [33] cell wall polymerization results in improved dimensional stability of OPW. The ASE increased over time, indicating that higher levels of phenolic resin and CR improve the dimensional stability of compreg OPW.

3.3. Performance of Compreg Composites Laminated with Sesenduk

In this phase of the study, 3-layer laminated compreg composites were fabricated by using inner OPW as the core and sesenduk wood (treated and untreated) as the face and back. 10% and 20% CR were employed for the second phase of the study as the laminated compreg composite products, pressed at 30% CR, were split and failed during compression as shown in Figure 5.

Figure 5. Failure of laminated compreg composites pressed with 30% CR.

The high initial moisture level of the compreg inner OPW samples resulted in compression failure. After impregnation treatment, the assembled samples had a moisture content of 60%, which might have been relatively high when the samples were being subjected to compression in a hot press. In the case of compreg inner OPW in phase 1, moisture on wood surfaces, according to Haque [34], can either vaporize or penetrate into the wood during heating. During compression, the moisture was heated, causing it to evaporate. Water vapor from the inner OPW can easily escape through any direction of wood to the sample surface during compression (Figure 6).

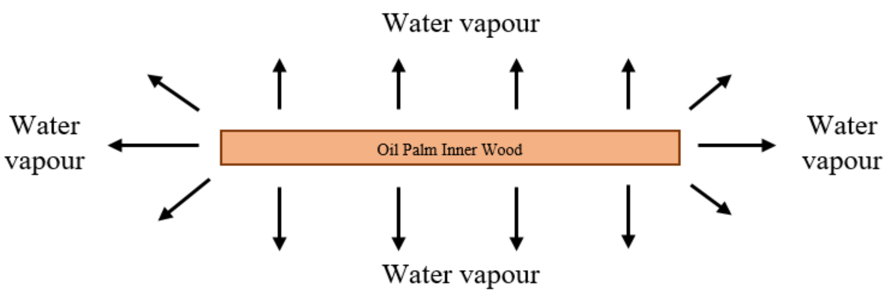

Figure 6. Water vapor is released from a sample of compreg oil palm inner wood during compression.

However, when the inner OPW samples were laminated with sesenduk, the moisture content could only vaporize longitudinally during compression (Figure 7). As a result, the vapor pressure was building in the core layer of the samples and eventually caused the rupture, especially when higher CR was employed.

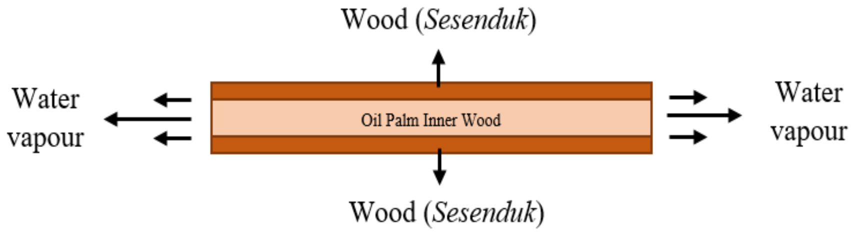

Figure 7. Water vapor release from a sample of laminated compreg OPW composite laminated with sesenduk during compression progress.

3.4. Properties of Laminated Compreg Composites

The results obtained for the WPG and density for laminated compreg composites are shown in Table 4. Generally, the composites laminated with sesenduk wood as face and back (P2, P4, P6, and P8) displayed higher WPG and density. The laminated composites made at 20% CR and 20% PF resin concentration demonstrated the highest WPG value of 105.52% (P4). WPG improved significantly as compression ratio and PF resin concentration were increased.

Table 4. Mean values of WPG and density of laminated compreg composites.

CR (%)	Hybrid	Description	WPG (%)	Density (kg/m^3)
20	P1	U, 15%, U	63.21 ± 3.26 ^{d}	587 ± 5.09 ^{d}
	P2	15%, 15%, 15%	99.53 ± 0.95 ^{ab}	704 ± 20.47 ^{b}
	P3	U, 20%, U	63.09 ± 5.13 ^{d}	660 ± 14.80 ^{c}
	P4	20%, 20%, 20%	105.52 ± 5.16 ^{a}	749 ± 2.93 ^{a}
10	P5	U, 15%, U	65.37 ± 4.20 ^{d}	583 ± 24.72 ^{d}
	P6	15%, 15%, 15%	82.43 ± 2.67 ^{c}	663 ± 8.45 ^{c}
	P7	U, 20%, U	66.17 ± 1.53 ^{d}	649 ± 6.24 ^{c}
	P8	20%, 20%, 20%	95.02 ± 5.28 ^{b}	742 ± 35.20 ^{a}
20	Untreated Wood			412 ± 32.07
	Untreated inner OPW			308 ± 26.82

Note: Means followed by the same letter a, b, c, d is not significantly different at $p \leq 0.05$, value after ± sign is standard deviation.

In the laminated compreg composite samples, the increased CR was responsible for the increased WPG. According to this study, the WPG of 20% CR laminated compreg composites treated with 20% PF resin concentration was higher than that of 10% CR laminated compreg panels. When resin concentration was increased from 15% to 20%, WPG was also increased from 99.53 to 105.52% for the composites manufactured at 20% CR. Meanwhile, WPG rose from 82.43 to 95.02% for the panels compressed at 10% CR. When 20% resin concentration treated OPW was laminated with untreated sesenduk, the WPG value was 63.09% (P3) and 66.17% (P7), respectively. The density values for samples compressed at 20% CR were found to be between 587 to 704 kg/m^3 and 660 to 749 kg/m^3 (P1, P2, P3, and P4). Density values for the samples compressed at 10% CR ranged from 583 to 663 kg/m^3 and from 649 to 742 kg/m^3 (P5, P6, P7, and P8). Overall, density of laminated compreg composites increased with compression ratio and resin concentration.

3.5. Physical and Mechanical Properties of Laminated Compreg Composites

Analysis of variance (ANOVA) was performed, and the summarized results are presented in Table 5. It can be observed that the resin concentration exerted a significant influence on the density, WA, MOR, and MOE values of the laboratory-made laminated compreg composites. Meanwhile, WPG, TS, and ASE were not significantly affected by the PF resin concentration used in this study. On the other hand, CR did not have any significant influence on the properties of the compreg composites. The findings suggested that resin concentration is a more influential factor compared to CR.

Table 5. Summary of analysis of variance (ANOVA) at $p \leq 0.05$ of the interaction between processing parameters and properties of laminated compreg composites.

Source of Variant	WPG	Density	TS	WA	ASE	MOR	MOE
Resin concentration (RC)	0.342^{ns}	0.000**	0.078^{ns}	0.004**	0.114^{ns}	0.000**	0.000**
Compression ratio (CR)	0.271^{ns}	0.317^{ns}	0.297^{ns}	0.115^{ns}	0.303^{ns}	0.536^{ns}	0.797^{ns}
RC*CR	0.710^{ns}	0.654^{ns}	0.439^{ns}	0.786^{ns}	0.715^{ns}	0.921^{ns}	0.832^{ns}

Note: ** significant at $p \leq 0.05$; ^{ns} not significant.

Table 6 depicts the physical and mechanical properties of laminated compreg hybrid products. The TS values of the laminated compreg composites manufactured at 20% CR and 15% PF resin concentration varied from 2.90 to 1.58% (P1 and P2), while those made of 20% resin concentration ranged from 2.28 to 1.23% (P3 and P4). The TS values of the laminated OPW panels fabricated at 10% CR with 15% resin concentration varied from 1.69 to 2.90% (P5 and P6) while those made of 20% resin concentration varied from 1.41 to 2.80% (P7 and P8). All laminated compreg composites, fabricated in this work, had significantly lower TS values compared to the values of OPW (8.43%). The TS values of the samples laminated with untreated sesenduk wood as the face layer (P1, P3, P5, and P7), were higher compared to the TS of the panels fabricated from treated sesenduk as the face layer (P2, P4, P6, and P8). Resin concentration also had a significant effect on the TS values as the samples treated with 20% PF resin concentration had lower TS compared to those modified with 15% resin. However, the effects of CR were not obvious. Untreated OPW had a WA value of 114.19%. Regarding the laminated compreg composites, the lowest WA value of 23.02% was observed in the samples treated with 20% PF resin concentration and compressed with 20% CR (P4). Meanwhile, the samples treated with 15% resin concentration and compressed with 10% CR (P5) had the highest WA value. Although PF resin did not penetrate the vascular bundle of the cell wall, it did penetrate the parenchyma cell as a bulking agent, according to Bakar et al. [35]. This resin penetration may obstruct the space and water absorbed. The resin's swelling-blocking activity was responsible for the significant reduction in swelling in the treated OPW.

Table 6. Thickness swelling (TS), water absorption (WA), anti-swelling efficiency (ASE), modulus of rupture (MOR), and modulus of elasticity (MOE) of laminated compreg composites.

Sample	TS (%)	WA (%)	ASE (%)	MOR (MPa)	MOE (MPa)
Untreated iOPW	8.43 ± 1.01	114.19 ± 11.94	-	15.58 ± 1.34	1034 ± 15
P1	2.09 ± 0.67	32.66 ± 0.50	55.05 ± 0.02	33.91 ± 1.38	673 ± 28
P2	1.58 ± 0.01	24.50 ± 0.63	71.61 ± 5.31	35.05 ± 2.11	1115 ± 78
P3	2.28 ± 0.02	27.81± 0.67	59.12 ± 0.61	39.24 ± 3.95	854 ± 100
P4	1.23 ± 0.04	23.02 ± 0.40	74.00 ± 6.00	40.67 ± 2.68	2534 ± 322
P5	2.90 ± 0.07	36.38 ± 0.45	51.03 ± 0.21	32.82 ± 0.84	656 ± 27
P6	1.69 ± 0.02	25.15 ± 1.20	68.31 ± 0.90	35.06 ± 2.11	1115 ± 78
P7	2.80 ± 0.03	28.89 ± 0.62	58.16 ± 4.05	39.61 ± 3.44	796 ± 100
P8	1.41 ± 0.06	25.03 ± 0.40	71.47 ± 6.95	39.51 ± 2.93	2414 ± 286

The laminated compreg composites had ASE values ranging from 55.05 to 71.61% (P1 and P2) and from 59.12 to 74.00% (P3 and P4) for the samples fabricated at 20% CR with 15% and 20% PF resin loading. The high and positive ASE values indicate the efficacy of the phenolic resin compregnation treatment. The highest ASE value was 74% for the laminated compreg composites with 20% CR and 20% resin concentration, while the lowest

ASE value of 51.03% was determined for products with 10% CR and 15% resin concentration. According to reports, the phenolic resin can effectively bulk up the cell wall and lumen while also inhibiting moisture uptake by the wood. Aizat et al. [29] obtained ASE values of 44 to 73% using LmwPF laminated compreg OPW (outer), whereas Rabi'atol et al., [36] reported ASE values of 30 to 50% on vacuum-treated compreg sesenduk and jelutong strips.

In terms of mechanical properties, the MOR value of the untreated inner OPW was 15.58 N/mm^2. After being compressed into laminated compreg composites, the MOR values were found to almost double compared to that of untreated OPW. The MOR of the laminated compreg panels produced with 20% CR ranged from 33.91 N/mm^2 to 35.05 N/mm^2 and 39.24 N/mm^2 to 40.67 N/mm^2 for 15 and 20% PF concentrations, respectively. Meanwhile, the MOR values of the laminated panels manufactured with 10% CR ranged from 32.82 N/mm^2 to 35.06 N/mm^2 and 39.61 N/mm^2 to 39.51 N/mm^2 for 15 and 20% PF concentration, respectively. It can be observed that laminated compreg composites compressed at a higher CR of 20% and treated with a higher PF resin concentration of 20% exhibited higher MOR. According to Ang et al. [37], higher compression increases the density of the samples while also increasing their rigidity and hardness. According to Nemli et al. [38], higher product density due to high compression during pressing may result in increased MOR. Researchers discovered that polymerizing phenolic resins inside cell walls improved cell reinforcement while improving mechanical properties in another study [31,39]. Similarly, the highest MOE value of 2534 N/mm^2 was found in the laminated compreg composite manufactured with 20% CR and 20% PF resin concentration, while the lowest MOE (656 N/mm^2) was found in the laminated compreg composites produced with 10% CR and 15% resin concentration (P5).

According to Kultikova [40], the phenolic resin in cell wood transforms treated wood into a plastic-like material. Higher resin concentration and compression ratios, according to that explanation, were expected to be the primary causes of improved static bending of the laminated compreg composites. However, it should be noted that the three-layer laminated compreg panels laminated with untreated sesenduk wood as face and back layers (P1, P3, P5, and P7) displayed significantly inferior mechanical properties compared to the treated counterparts (P2, P4, P6, and P8). This finding demonstrated the significance of phenolic resin treatment. The properties of the laminated compreg composites were not solely determined by the bond line formed between layers. The face and back layer surfaces are equally important. Treatment on the surface and back layer may confer increased rigidity as well as exceptional water resistance to these layers, resulting in improved performance of the composites produced.

4. Conclusions

In this work, the inner OPW was treated with PF resin and compressed at different compression ratios. The treatment was found to be effective in lowering the TS and WA values of the inner OPW. The dimensional stability of the treated OPW was higher compared to that of untreated samples. PF resin-treated OPW was used as the core layer for manufacturing three-layer laminated compreg composites, laminated with untreated and treated sesenduk wood serving as the face and back layer. It was determined that PF resin concentration was a significant factor influencing the physical and mechanical properties of the laminated composite products. The higher resin concentration of 20% resulted in enhanced properties of the panels produced. The compression ratio had no significant effect on the performance of the laminated composites. On the other hand, the higher compression ratios applied resulted in slightly better physical and mechanical properties of the panels. It was also concluded that the use of untreated sesenduk wood as the face and back layer of the composites is not suitable since the laminated composites exhibited significantly lower TS, WA, MOR, and MOE values. Future research on the topic should be aimed at studying the penetration mechanism of low molecular weight PF resin in

OPW at the microcellular level, optimizing the modification parameters, and investigating the chemical interaction between PF resin and OPW to achieve an optimal performance.

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