Bond Ability of Oil Palm Xylem with Isocyanate Adhesive

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Abstract

Oil palm xylem composed of vascular bundles and parenchyma tissue and directly related to its properties. Utilization of oil palm xylem into the wood laminate products requires information on its bond ability to adhesive used. Isocyanate adhesive is a prospective adhesive due to its various advantages compared to other adhesives. This study aimed to obtain information about the bond ability of the oil palm xylem with isocyanate adhesive. The results showed that isocyanate adhesive has good wettability on oil palm xylem indicated by its contact angle of below 90°. Isocyanate adhesive also showed good performance by looking at the value of wood failure and delamination. However, the shear strength of laminated oil palm xylem was low. Wood failure occurred in the parenchymal tissues region.

Key words: bond ability, isocyanates, laminated board, oil palm xylem

Introduction

Anatomically, oil palm stem consists of vascular bundles and parenchyma tissues that determine the properties of its woody component (Tomlinson 1961). Wood density and distribution of vascular bundles decrease from the outer to the center of the trunk. Therefore, the outer part of the trunk is stronger than the central part. One third of the outer part of oil palm stem can be used for the building material of lightweight construction and furniture (Bakar *et al.* 1999). Limited amount of oil palm biomass is also available for laminated wood products production.

Glue laminated timber (Glulam), a laminated wood product, is prepared by boards gluing with parallel structure of the boards to the fiber length. Constructional glulam requires durable and strong binding adhesives, such as isocyanate type adhesives. Schollenberger (1990) and Langenberg *et al*. (2010) have revealed the advantages of isocyanate adhesive. Isocyanate is capable of forming covalent bond with active hydroxyl groups of the bonded materials (Marra 1992, Lay & Cranley 1994).

Bond ability of adhesive to oil palm xylem might be different to that of wood due to characteristics differences between wood and oil palm xylem. Shear strength is indicative to interfacial stress under stress conditions, and thus the most common reference parameter used in adhesives bonding evaluation. It also provides a useful criterion for the estimation of the mechanical compatibility between wood and adhesive (Pizzo *et al.* 2003). Bond ability of oil palm xylem veneer and various formaldehyde-based adhesives have been reported by Sulaiman *et al*. (2009). Bond ability can be understood by examining the wood wettability by contact angle measurements, shear strength and wood failure in bonded areas, delamination of wood, and scanning electron microscopy (SEM) micrograph. These types of evaluation can be used to asses and observe adhesive interactions with bonded materials.

Bond ability of oil palm xylem with isocyanates in laminated wood products has not been discussed to a greater extent. Therefore, the present research was focused on the evaluation of the bond ability between oil palm xylem and isocyanate adhesive. It was expected that the present works would provide basic information on a more proper used of oil palm xylem as the raw material of isocyanate adhesive based wood laminate.

Materials and Methods

Materials

Oil palm trunk from 20 years old tree was obtained from PTPN 7, Lampung Province, Indonesia. The characteristics of isocyanate used in the present works are listed in Table 1.

Lamina preparation

One third of the outer oil palm trunks were cut into board with band saw. Boards cutting was following polygon sawing pattern (Figure 1). The resulting lamina boards were then sawed with a size of 1000 mm (*l*) x 60 mm (*w*) x 20 mm (*t*). All specimens were initially conditioned to equilibrium moisture content of ±12%.

Contact angle measurement

The wettability of wood lamina was evaluated through contact angle measurement, in which 10 ml of distilled water was dropped on the surface of oil palm xylem lamina and then was snapped with a digital camera. Contact angle measurements (photographing) started after 0 to 120 s of water dropping with an interval of 10 s. The contact angle was analyzed with scion image software. Contact angle measurement was carried out in triplicates.

Manufacture of glued laminated oil palm xylem

Isocyanate adhesive bonded of two layers glulam (Figure 2) was prepared with base resin and hardener composition of 100 to 15 and spread rate of 200, 250, 300 g m^{-2}. Adhesive was spread out on both bonding surfaces (double spread) before a cold press with a lateral pressure of 10 kg cm^{-2} for 1, 2, and 3 h was applied. The resulting laminates were conditioned for 7 days.

Shear strength and wood failure measurements

Sample size for shear strength measurement (Figure 3) refers to the Japanese Agricultural Standard for Glued Laminated Timber Notification No. 1152 (JPIC 2007) with an area of 6.25 cm^2 shear field.

Table 1 The characteristics of isocyanate adhesive and cross linker

Parameters	Isocyanate	Cross linker (Hardener)
Appearance	White fluid	Dark brown fluid
Viscosity at 25 ^{o}C (ps)	150±30	1,5±0,2
Solid content (%)	43±3	-
pH	7±1	0,03-0,05

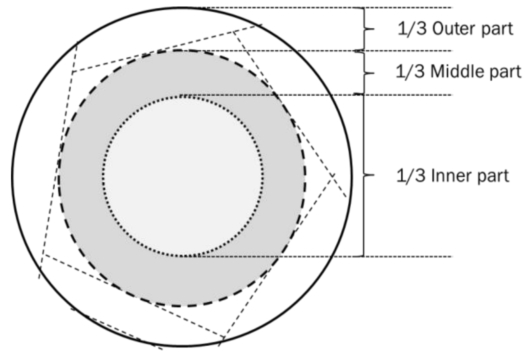

Figure 1 The polygon sawing pattern (Bakar *et al.* 2006).

Figure 2 The structure of the 2 layers laminated wood.

Measurement of shear load was carried out with Universal Testing Machine (UTM) Instron 330 at loading rate of 0.6 mm per minute. Shear strength was determined based on failure at maximum load and was calculated by the following formula:

$$\mathrm{SR}\left(\frac{Kgf}{cm^2}\right) = \frac{A}{\mathrm{B}}$$

SR = Shear strength
A = Maximum load at specimen failure
B = Area of the adhesion portion

Wood failure was estimated at 0-100% of shear area. The bonding performances of the specimens were classified into four categories, i.e. excellent (80-100% retention both for wood strength and wood failure), good (60-79%), bad (40-59%), and worst (0-39%) (Alamsyah *et al.* 2007). Excellent and good bonding performances indicate better adhesive penetration and uncomplicated bonding of the samples.

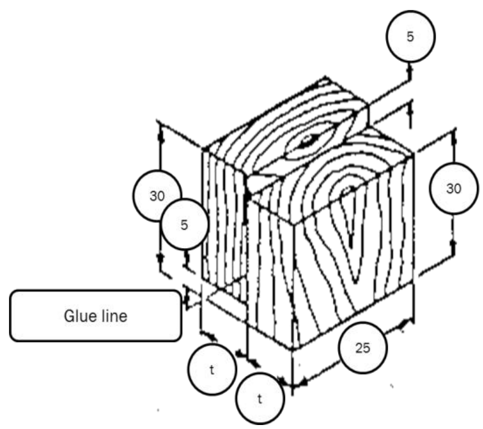

Figure 3 Block shear tests (unit: mm); JPIC (2007).

Delamination test

Immersion delamination test

Japanese Agricultural Standard for Glued Laminated Timber Notification No. 1152 (JPIC 2007) was referred for delamination test. A test specimen of 75 mm length was respectively prepared from both ends of all glulam. Immersion of samples was carried out in water at room temperature (10-25 °C) for 6 h. Proceeding the immersion; samples were dried in a thermostatically controlled dryer at 70±3 °C for not less than 24 h. Allowed maximum delamination is 5% and no more than ¼ length of the sum glue line. Delamination rate shall be calculated by the following equation:

$$DR\ (\%) = \frac{A}{B}\ x\ 100$$

DR = Delamination rate (%)
A = Sum of the length of delamination on both butt ends
B = Sum of the length of glue lines on both butt ends

Boiling water delamination test

The sample size of boiling water delamination test is equal to that of water immersion delamination test. Delamination testing refers to the Japanese Agricultural Standard for Glued Laminated Timber Notification No. 1152 (JPIC 2007). Samples were successively immersed in boiling water for 4 h and in room temperature (10–25 °C) water for 1 h, and then dried in a thermostatically controlled dryer at 70±3 °C for not less than 24 h. Similar testing on control samples were also done.

Scanning electron microscopy (SEM)

SEM micrographs were obtained with a secondary electron detector using an acceleration voltage of the primary electron beam of 10 kV. Before the measurements, all samples were sputtered with gold to enable sufficient electrical conductivity.

Statistical analysis

The resulting data of the present treatment were analyzed with the analysis of variance (ANOVA) at α = 0.05. A completely randomized factorial design of 3x3 with 2 factors and 3 replications was applied. Factor B is spread rate that consists of 3 levels, i.e. 200 g m^{-2} (B2), 250 g m^{-2} (B25) and 300 g m^{-2} (B3), and factor T is the pressing time that consists of 3 levels, i.e. 1 h (T1), 2 h (T1) and 3 h (T3). The linear model of the experimental design is:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk}$$

Where:
i = Spread rate level (1, 2, 3)
j = The level of pressing time (1, 2, 3)
k= Replications (1, 2, 3).

Duncan's multiple range tests were used to determine differences among mean values. Data were processed using SPSS v. 16 software.

Results and Discussion

Wettability

Wettability of a surface indicates the condition that determines the extent to which the fluid will be spread by the surface, affecting the absorption, adsorption, penetration and spread of adhesive (Marra 1992). Wettability of oil palm xylem can be obtained by measuring the contact angle between the liquid adhesion lines and the oil palm xylem surface. Contact angle of below 90° indicates a high wettability where the liquid wets the surface well, and when contact angle is greater than 90°, liquid does not wet the surface well (Yuan & Lee 2013). Contact angle trend of water and isocyanate on oil palm xylem of the present works are shown in Figure 4.

These results indicated that the contact angle decreased with wetting duration of water and isocyanate adhesive on the surface of the oil palm xylem.

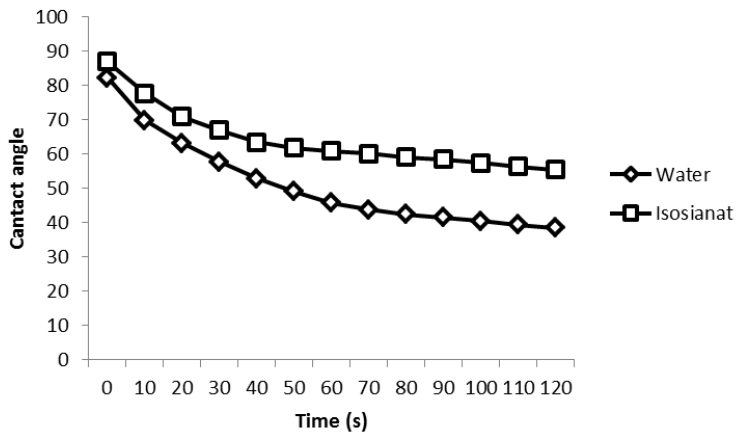

Figure 4 Contact angle of water and isocyanate adhesive on the surface of oil palm xylem.

Initial contact angle (just after 0 s) of water and isocyanate on the surface of oil palm xylem was of 82.184^o and 86.862^o decreased to 38, 417^o and 55.315^o at the end of observation (120 s). Water and isocyanate adhesive have good wettability on oil palm xylem as the values of its contact angle were below 90°. The contact angle of water is lower than that of isocyanate adhesive. Sulaiman *et al.* (2009) reported that the initial contact between the water and veneer palm oil xylem was of 86^o (Tight side) and 82^o (Loose Side).

Shear strength and failure of oil palm xylem

Shear strength is the most common interfacial stress under service conditions, thus it is used for the reference parameter of the evaluation of adhesive bonds. It also provides a useful criterion for the estimation of the mechanical compatibility between wood and adhesive (Pizzo *et al.* 2003). The present results showed that the shear strength of oil palm xylem glulam with isocyanate adhesive was influenced by the spread rate of adhesive. Shear strength increased with increasing amount of spread rate (Table 2). The spreading of adhesive on oil palm xylem surface was less uniform at the spread rate of 200 and 250 g m^{-2}. An uneven distribution of adhesive on laminated panels made from OPT was thought due to the effects of its rough surface (Nordin *et al.* 2013). Machining properties and surface roughness of oil palm xylem has been thoroughly studied by Way *et al.* (2010). A rough wood surface may not be completely wetted by the adhesive, leaving voids at the interface (River 1994). Faust and Rice (1986) reported that smooth veneer surface gave 33% higher bonding strength than that of rough surface veneers. Dundar *et al.* (2008) stated that rough veneers reduce contact between veneer and substrate resulting in a weak glue line and low strength properties. Glulam with spread rate of 200 g cm^{-2} and pressing time of 3 h retained minimum shear strength of 12.81±0.99 kg cm^{-2}. The highest shear strength value was found for glulam with spread rate of 300 g cm^{-2} (14.52±0.57 kg cm^{-2}).

The wood failure of oil palm xylem glulam with spread rate of 250 g cm^{-2} and pressing time of 1 h was the lowest (78.33%) and that with the spread rate of 300 g cm^{-2} was the highest (100%).

Table 2 Shear strength and failure of glulam oil palm xylem

Treatment		Shear strength (kg cm^{-2})	Failure (%)
Spread rate (g cm^{-2})	Pressing time (h)		
200 [a]	1	12.81 (0.99)	78.33 (16.07)
	2	12.84 (0.63)	80.00 (13.23)
	3	12.83 (0.68)	81.67 (7.64)
250 [b]	1	13.60 (0.45)	90.00 (10.00)
	2	13.71 (0.49)	93.33 (5.77)
	3	13.75 (0.36)	95.00 (5.00)
300 [b]	1	14.27 (0.64)	100.00 (0.00)
	2	14.27 (0.56)	100.00 (0.00)
	3	14.52 (0.57)	100.00 (0.00)

Note: Figures in parentheses are standard deviation values. The same letters indicate insignificantly different value according to Duncan's multiple range tests at 5% level.

Wood failure to shear plane occurred on oil palm xylem, indicated that the isocyanate adhesive has a good ability to bind oil palm xylem. Figure 5a shows that the failure to the plane shears occurred on oil palm xylem. Such failure occurred in the parenchyma tissue constituent (Figure 5b) and no failure was occurred in the plane of sliding of the vascular bundles (Figure 5c). This was due to parenchymal tissue has a lower density than that of vascular bundles. In addition, the parenchymal cells have thin walls that susceptible to failure when subjected to a compressive force.

Interaction between isocyanate adhesive and oil palm xylem was observed through SEM micrographs (Figure 5d). Adhesives were well capable of binding both surfaces of oil palm xylem. It can be seen from the micrograph that the adhesive was filled into the cell lumen in bonded xylem surface. From the SEM micrograph is also visible that the vascular bundles and parenchyma cells undergo compaction due to the applied pressure. Apparently the pressure brought about the vascular bundles partially separated from the parenchyma tissue. This contributed to the low shear strength of laminated oil palm xylem.

Statistical analysis showed that the spread rate influenced the shear strength of the laminate and wood failure. Duncan's multiple range tests showed that the glulam oil palm xylem with spread rate of 200 g cm^{-2} produced different shear strength and wood failure to these of other glue spread rates. Pressing time did not show any significant differences, and thus in the manufacture of glulam palm oil xylem, pressing time of 1 h will be adequate.

Delamination

Delamination rate of glulam are shown in Table 3. Glulam with spread rate of 300 g cm^{-2} did not undergo delamination for both soaked in room temperature water and in combined room temperature water with boiling water. This suggests that the adhesive was very good binding agent in the lamina of oil palm xylem. All combinations of treatments was found satisfying the ratio of delamination required by the standard of Japanese Agricultural Standard for Glued Laminated Timber Notification No. 1152 (JPIC 2007), i.e. at least of 5%.

Statistical evaluation showed that all factors (pressing time and spread rate) and its interaction significantly influenced the delamination ratio. Further, Duncan's multiple range tests showed that at spread rate of 300 g m^{-2}, the pressing time did not significantly influence delamination.

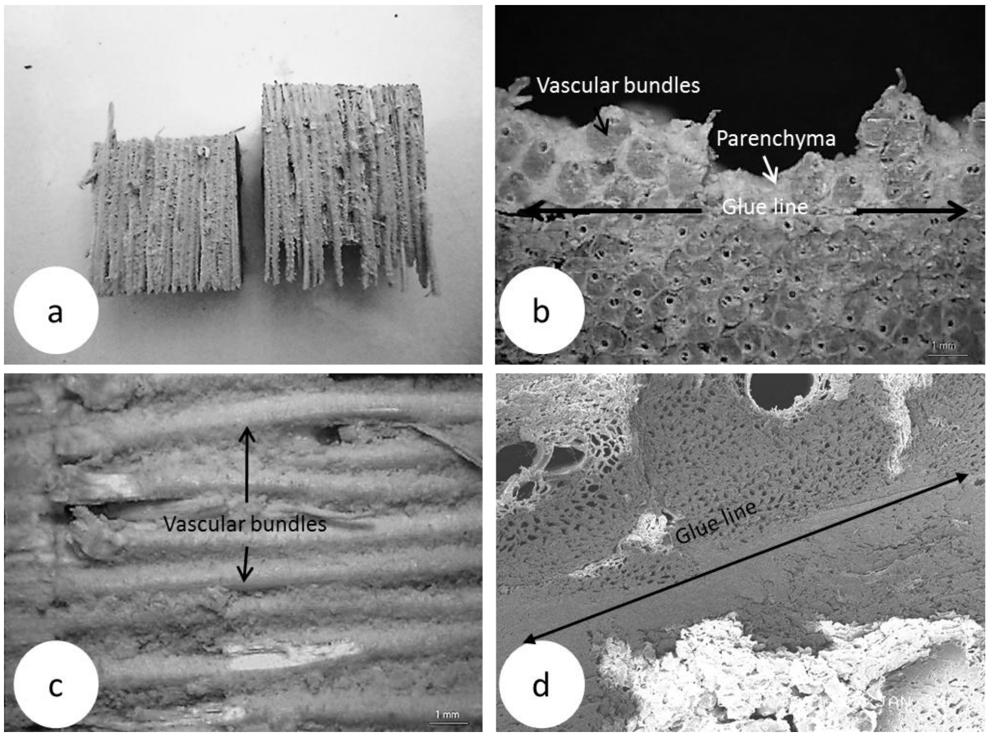

Figure 5 Optical micrographs of longitudinal-section wood failure (a), cross-section view of the parenchymal tissue damage (b) and less damage of vascular bundles in longitudinal-section (c); and a SEM micrograph showed a well bonded cross-section of oil palm xylem by isocyanate adhesive (d).

Table 3 Delamination of glulam oil palm xylem

Treatment		Water soaks delamination treatment (%)	Boiling water soak delamination treatment (%)
Spread rate (g cm^{-2})	Pressing time (h)		
200	1	0.09 (0.01) ^{c}	0.15 (0.01) ^{D}
	2	0.15 (0.02) ^{e}	0.15 (0.02) ^{D}
	3	0.13 90.02) ^{d}	0.13 (0.02) ^{D}
250	1	0.06 (0.02) ^{b}	0.06 (0.01) ^{B}
	2	0.06 (0.02) ^{b}	0.11 (0.01) ^{C}
	3	0.09 (0.01) ^{c}	0.13 (0.01) ^{CD}
300	1	0.00 (0.00) ^{a}	0.00 (0.00) ^{A}
	2	0.00 (0.00) ^{a}	0.00 (0.00) ^{A}
	3	0.00 (0.00) ^{a}	0.00 (0.00) ^{A}

Note: Figures in parentheses are standard deviation values. Figures followed by the same lowercase letters and numbers followed by the same capital letter insignificantly different according to Duncan's multiple range test at the 5% level.

Conclusions

Isocyanate adhesive retained high wettability on oil palm xylem as indicated by the contact angle below of 90°. It was capable of binding both surfaces of the oil palm xylem. High binding quality was indicated by the absence of adhesive failure upon shear strength testing. Wood failure was occurred in the oil palm xylem, instead. Wood failure was thought to occur in the parenchyma tissue due to its lower density compared to that of the vascular bundles, as well as its thin cell walls. The delamination rate of the present works on the lamina board of oil palm xylem with isocyanate adhesive satisfied the requirement of the standard of Japanese Agricultural Standard for Glued Laminated Timber Notification No. 1152-2007. One hour pressing time was adequate to produce satisfying glued laminate oil palm xylem at 300 g m^{-2} spread rate.

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