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Glue-bond performance of *Dendrocalamus asper* (Schult.) Backer using cold setting and thermosetting adhesives

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Abstract

The study aimed to determine the bonding performance of laminated giant bamboo *Dendrocalamus asper* (Schult.) Backer glued with cold setting (PVAc, PUR) and thermosetting (UF and PF) adhesives at different surface pairings (pith-pith, pith-skin, and skin-skin) and glue spread rates (100 g/m^2, 150 g/m^2, and 200 g/m^2). Kiln-dried giant bamboo poles were ripsawn, planed, and cut-to-length to produce slats for lamination. Slats for surface roughness and wettability tests were sanded with 180 grit sandpaper on both skin and pith surfaces. Surface roughness of the skin and pith was measured using Mitutoyo SJ-210 Surftest unit, while wettability was determined via the sessile drop method. Giant bamboo slats were bonded using specific lamination parameters for each adhesive. Tensile shear tests at dry and wet conditions were performed on the laminates to determine bond strength. The results showed that the bamboo pith had a rougher texture than the skin but with insignificant contact angle differences. Moreover, PVAc-D3 and PUR gave the highest and lowest initial contact angles on both sides, respectively, with PUR maintaining the smallest values throughout the contact duration. Adhesive, surface pairing and some interactions (adhesive x glue spread and adhesive x surface pairing) significantly affected the dry shear strength while adhesive and adhesive x surface pairing influenced wet shear strength. PUR-bonded laminates had the highest dry shear strength, followed by PF, PVAc-D3 and UF. In terms of wet shear strength, only PVAc-D3 did not conform to the minimum glue bond strength requirement of more than 1 MPa and cohesive bamboo failure of at least 40% (PNS 2099:2015). Skin-skin and pith-pith surface pairing yielded the highest and lowest dry shear strengths, respectively. Increasing the amount of glue did not translate to a stronger bond. PUR, UF, and PF are feasible alternatives to PVAc-D3 in engineered bamboo production for various end-uses.

Keywords Engineered bamboo; Pvac-D3, PUR; Phenol formaldehyde; Urea formaldehyde; Lamination; Surface roughness; Wettability

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1. Introduction

The use of bamboo as a sustainable substitute for wood is gaining popularity worldwide (INBAR 2022). Various consumer products such as furniture, housewares, and construction materials, which have been traditionally made from wood are now being produced from bamboo. In the Philippines, diverse promotions to utilize bamboo (PBSAI 2023) are due to its fast growth and strength attributes that are comparable to and even better than some commercial wood species (Verma et al. 2014; Chaowana and Barbu 2017). Apart from these, environmental, economic and social benefits from planting to processing bamboo have been the driving forces in mainstreaming its use (Razal et al. 2012).

In its natural round form, bamboo cannot be a substitute to wood plank. To mimic wood, bamboo has to be converted into forms that can be glued (rectangular slats, flattened round or half-round culm, veneer, fissured strip, broomed strip, chip, fiber, arc-split segments) to create a lumber-like form popularly known as engineered bamboo composites (Bansal and Zoolagud 2002; Biswas et al. 2011; Marinho et al. 2013; Jimenez and Natividad 2019; Nkeuwa et al. 2022, Ramos et al. 2022).

The adhesives used for gluing bamboo are mostly the same ones used in wood. Among the commercial wood adhesives available in the Philippines, polyvinyl acetate (PVAc-D3) is the most common glue used for laminating rectangular slats to produce engineered bamboo (Razal et al. 2012; Alipon and Cabangon 2013). This is due to its low cost, cold-press curing, and wide distribution in most hardware stores. Other cold-setting adhesives such as polyurethane (PUR) are also used but are less common as they are four to six times more expensive than PVAc-D3. Thermosetting adhesives such as urea formaldehyde (UF) and phenol formaldehyde (PF), though cheaper than PVAc-D3 and PUR, are seldom used in engineered bamboo production due to the need for a hot press machine which is too costly for micro and small bamboo processing enterprises.

One of the most suitable species for making engineered bamboo is giant bamboo [*Dendrocalamus asper* (Schult.) Backer]. This species grows practically straight, is very large, has a thick culm wall with a long internode, and can be harvested easily compared to *Bambusa blumeana* (Jimenez et al. 2021). It has been planted in Luzon (Laguna, and the CAR provinces); Visayas (Cebu, Iloilo, Negros Occidental), and Mindanao (Bukidnon, South Cotabato, and Sultan Kudarat) (Razal et al. 2012). In Bukidnon province, giant bamboo grows very well (Alipon et al. 2011) and is the main species used in making engineered bamboo products that are made into furniture, housewares, construction materials (Razal et al. 2012), and musical instruments (Kusumaningtyas et al. 2016).

In bamboo composites production, several factors affect the strength of the glue bond. In Marra's (1992) theory of bond formation as adopted and modified by Nkeuwa et al (2022), nine interconnected links influence bamboo bond formation. These links are composed of the (1) bulk adhesive, (2&3) adhesive interphase, (4&5) bamboo-adhesive interface, (6&7) bamboo interphase, and (8&9) bulk bamboo. Any of these links can be a source of bond failure and thus must be considered in bond strength evaluation.

The present study compared the performance of four commercial adhesives (PVAc-D3, PUR, UF, PF) on giant bamboo laminates and determined the effect of surface pairing, glue spread rate, and their interactions on the laminates' bond strength. Assessing the surface pairing (Chaowana et al. 2015; Uslinawaty et al. 2017; Zhang et al. 2018) and glue spread rate (Lee et al. 1998; Correal 2010; Anokye et al. 2016) is important because they can significantly affect the quality of the adhesive bond. This is due to inherent differences in the anatomical properties of the culm wall from the skin to the pith side, such as density, fiber orientation, and chemical composition (Liese 1998). Further, the interaction between the adhesive and the bamboo substrate can affect the bond's wetting, penetration, and adhesion properties, and therefore affect its overall performance over time. By examining the suitability of alternative glues (OPP EO 879 s. 2010), the study will enable the use of the other adhesives tested in making engineered bamboo products in the Philippines, considering cost and availability of equipment

2. Materials and Methods

2.1. Bamboo Samples

Three-year old giant bamboo poles obtained from San Juan, Batangas, Philippines were used. Harvested poles were transported to Forest Products Research and Development Institute (FPRDI) in College, Laguna. Thirty 2.4-m long mid-sections of the poles were kiln-dried using the FPRDI furnace type dryer. Following the schedule developed by the Institute, the kiln-drying lasted for 138 h from the initial moisture content (MC) of 110% to the final 10%. The MC was monitored using three 60-cm long sample poles that were weighed regularly to compute for the current MC until desired MC was obtained. For the gluing research, only 15 defect-free kiln-dried culms were randomly selected and used. These culms were conditioned for one week at room temperature and relative humidity of 25°C and 65%, respectively.

2.2. Surface Roughness

Conditioned culms were split to 25-mm width using a twin ripsaw, producing 8 to 12 slats per culm depending on the culm diameter. For surface roughness measurement, one slat each from five randomly selected culms was picked as a replicate. The slats were planned to remove the cortex layer on the skin side and the pith layer on the inner side. The portion of removed skin and pith varied depending on their curvature/arc from the slats' width. A thickness planer was used to ensure that uniform 8-mm thick slats were produced. Samples were cut-to-length using a radial arm saw to achieve a uniform length of 152 mm. To remove tiny loose fibers on the surface, the specimens were sanded using 180-grit sandpaper and then dusted off with a rag prior to surface roughness measurements.

Surface roughness of kiln-dried specimens was measured using a stylus-type surface roughness tester (Mitutoyo SJ-210 Surftest unit) with a diamond tip stylus and 60° tip angle. Measurement followed ISO 4287:1997 roughness standard where average roughness (Ra) and average roughness depth (Rz) were taken perpendicular to the grain orientation at 0.5 mm/s measuring speed. Measurements on the skin/outer and pith/inner side of the samples were taken from five equidistant locations along the width. The measurements were taken from five replicates at five lines as shown in Figure 1.

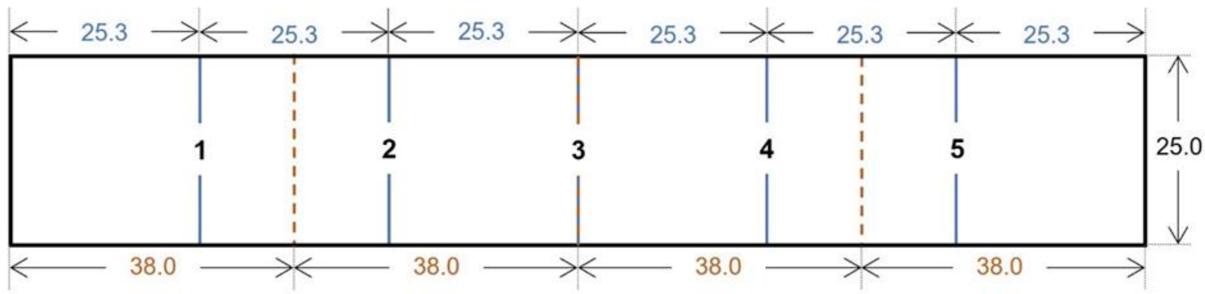


Figure 1. Diagram for measuring the surface roughness and wettability of the sample slat. Surface roughness was measured on lines 1 to 5 (25.3 mm apart). For wettability, the slat was divided into 4 sections (38 mm apart) to designate the areas where specific adhesives will be dropped (1 section = 1 adhesive). For each section, two drops were placed.

2.3. Wettability

Five surface-sanded specimens from the roughness test were used to evaluate the wettability of four adhesives, i.e., polyvinyl acetate (Rakoll Woodworking Adhesive D3, H.B. Fuller, Manila, Philippines), polyurethane resin (PUR 1964, AkzoNobel, Makati, Philippines), urea formaldehyde resin (RI Chemical Corporation, Pasig, Philippines), and phenol formaldehyde resin (RI Chemical Corporation, Pasig, Philippines). These adhesives are commercially used in the Philippines in the manufacture of various bonded wood products such as finger-jointed lumber, particleboard, fiberboard, and interior- and exterior-grade plywood. The initial viscosities of the adhesives were measured using a Krebs Viscometer (TQC VK 2000 DV1300) and listed in Table 1 together with the working properties of the adhesives as described in their technical product information sheet. Liquid urea formaldehyde (UF) resin was added with ammonium chloride catalyst (1% by mass) and then mixed for 5 min at 1000 rpm. The viscosity of the UF adhesive was taken right after mixing. Prior to testing, each surface was equally divided and marked into four sections (Figure 1) to designate areas where each adhesive was dropped.

Using the sessile drop method (Shi and Gardner 2001), a camera was placed on the tabletop at a lens distance of approximately 254 mm from the edge of the bamboo specimen. A syringe with 1.2 x 38 mm needle was used to drop 0.01 mL of adhesive onto the surface of the slat. The distance of the needle tip and the bamboo surface was approximately 20 mm. Each adhesive had a total of 4 drops (2 on the pith surface and 2 on the skin surface) applied to each replicate. For each droplet, photographs were captured at every contact duration of 0.25, 1, 2, 3, 4, and 5 min. Contact angle of each drop image was measured using the ImageJ software version 1.52a used by Marasigan et al (2020).

Table 1. Working properties of the commercial adhesives used in the study.

Working Properties	**Adhesives** **PVAc-D3**	**PUR**	**UF**	**PF**
Appearance	White	Yellow	White	dark red
pH	2.7 - 3.7	NA	6.5 - 6.8	12.0 - 13.0
Catalyst	not indicated	not indicated	NH_4Cl	not indicated
Density	not indicated	1.14 g/cm^3	1.20 g/cm^3	1.25 - 1.28 g/cm^3
Viscosity[1]	1533.33 cP	1520.33 cP	233.00 cP	251.33 cP
Solids content	48-50%	not indicated	44-46%	44-46%
Type	1-component	1-component	catalyzed during mixing	ready to use even without additives
Curing	Coldest	Coldest	thermoset	thermoset
Glue amount	160 - 180 g/m^2	100 - 300 g/m^2	140 - 230 g/m^2	150 - 240 g/m^2
Open assembly time	8 - 10 min	10 - 15 min	30 min	30 min
Pressing pressure[2]	0.1 - 0.8 N/mm^2	0.4 - 0.8 N/mm^2	0.6 - 0.9 N/ mm^2	0.6 - 0.9 N/ mm^2
Pressing time[3]	2 h	1 h	10 min	10 min

Note: 1 actual measurement prior to use

2 pressing pressure can vary and may be established by experience and testing

3 as practiced for laminating bamboo for coldset while for thermoset, it is based on the basic time plus allowance for heat penetration depending on the thickness of the laminate or distance to the deepest glueline

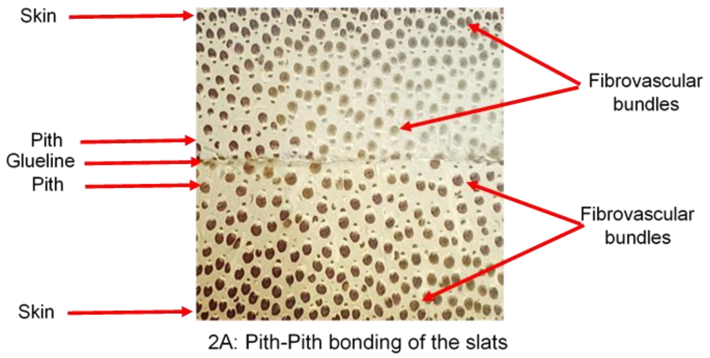
2.4. Lamination

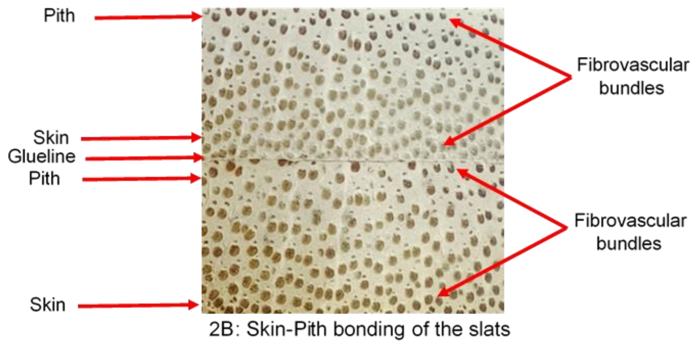
Cortex- and pith-free giant bamboo slats (T: 8 mm x W: 25 mm x L) were selected and cut using a radial arm saw 114 mm long. Specimens were then paired according to the morphological surface of the bamboo (Figure 2) to determine how it affects the bond shear strength. The laminates were bonded using cold-setting (PVAc-D3 and PUR) and thermosetting (PF and UF) adhesives following most of the glue manufacturers' instructions based on the gluing parameters shown in Table 2. The adhesives' initial viscosities were the same as shown in Table 1. Two batches were prepared for dry and wet bond shear tests. A total of 360 laminates were used for the shear test and equally divided into two: 180 laminates for the dry condition and 180 laminates for the wet condition.

Laminated slats bonded using PUR and PVAc-D3 adhesives were consolidated for 60 min and 120 min, respectively, using a fabricated hydraulic press at 0.55 MPa. Laminates bonded with UF and PF were hot-pressed at 105°C and 130°C, respectively, at a pressure of 0.55 MPa applied for 10 min. For each adhesive, 90 laminates were produced.

Table 2. Lamination parameters of the giant bamboo slats for each adhesive.

Surface Pairing	Glue Spread (g/m^2)	Replication Dry Shear	Wet Shear
Inner-inner or Pith-Pith	100	5	5
	150	5	5
	200	5	5
Outer-Outer or Skin-Skin	100	5	5
	150	5	5
	200	5	5
Outer-Inner or Skin-Pith	100	5	5
	150	5	5
	200	5	5





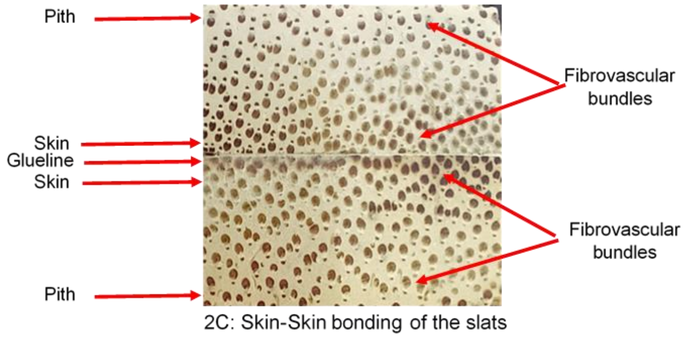


Figure 2. Dinolite digital microscope image of surface pairing viewed at 20x magnification. Pairing of the laminates was according to the morphological surface of the bamboo: pith-pith (2A), skin-pith (2B) and skin-skin (2C).

2.5. Bond (Tensile) Shear Strength

Bond (tensile) shear strength test was carried out according to PNS 2099:2015 with slight modification on the shear area of the samples. The shear area was reduced to 10 mm x 25 mm as the laminates were parallel to the fibers' orientation. From experience, having a bigger area as stated in the standard would mean higher pulling force which frequently resulted in slippage of the sample from the machine's grip.

Laminated shear samples were grooved on both sides of the adherend until reaching the glue line, achieving shear dimensions of 10 mm x 25 mm (Figure 3). Forty-five samples were used for dry shear and another 45 for wet shear. All samples for wet shear test were soaked for 24 h prior to testing. Soaking is a basic pretreatment for all bonding classes in the standard and is necessary to determine which among the adhesives would pass the minimum gluebond strength requirement for engineered bamboo.

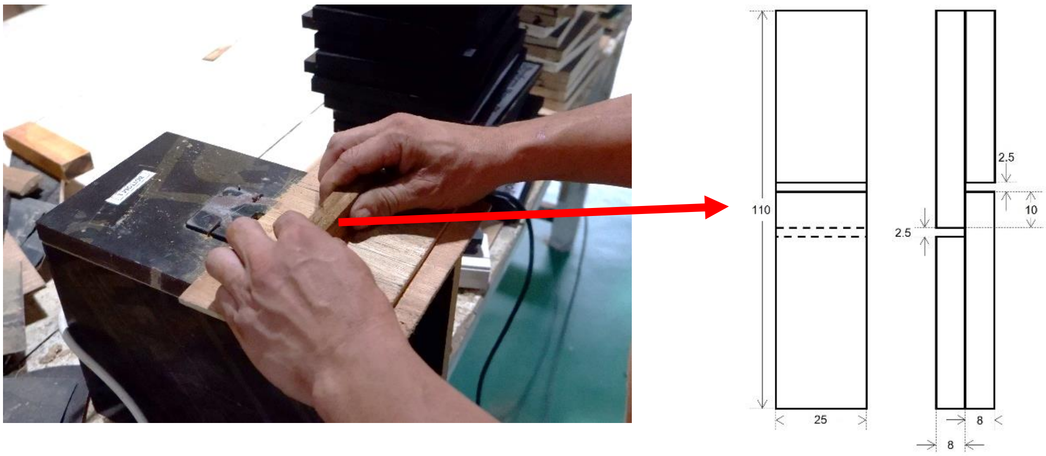


Figure 3. Grooving of 2-layer laminated bamboo slats on both sides to produce a shear area of 10 mm x 25 mm.

The bond shear test was performed using a Shimadzu Universal Testing Machine (UTM), where a grooved sample was gripped by two pneumatic clamps and continuously pulled at 5 mm/min test speed (Figure 4). The sample was loaded until failure as indicated by the graph displayed on the computer monitor. The sample was removed from the machine and cohesive bamboo failure (CBF) was evaluated according to the PNS ISO 12466-1 standard

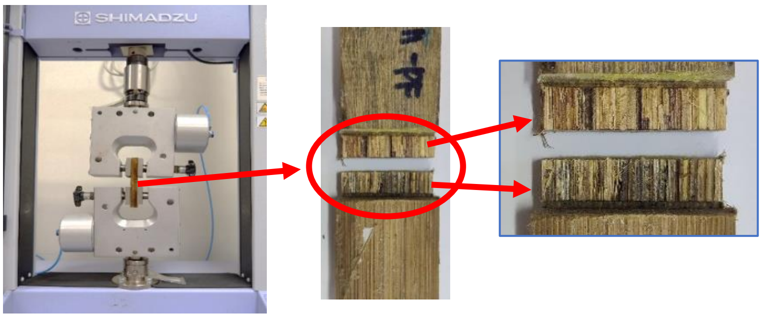


Figure 4. Tensile shear test of bamboo laminate using Shimadzu UTM (left) and PF sheared sample (middle) showing cohesive bamboo failure (right).

2.6. Statistical Analysis

The experimental design for the surface roughness and wettability was a simple CRD and mean comparison was made using unpaired t-test. For the bond strength test, a factorial experiment was employed with adhesive, surface pairing, and glue spread rate as the main factors. Analysis of Variance (ANOVA) at 5% significance level was performed to determine the difference of all parameters. Significant differences between the mean values were separated using Tukey's HSD. All statistical analysis was calculated using SAS 9.4 for Windows.

3. Results and Discussion

3.1. Surface Roughness

There was a significant difference between the average roughness (Ra) and average roughness depth (Rz) of the giant bamboo's pith and skin side of the slats (Table 3.). For the Ra, the difference between the pith and skin was 2.27 µm while for the Rz, it was 9.27 µm. During processing such as planing, the cut cell wall opened up the cell lumen and showed the cavity which might be deep or shallow depending on the size of the cut cells. Anatomically, smaller and denser fibrovascular bundles contributed to the smoother surface of the skin side than the pith side. The pith or inner surface of bamboo is known to have a rougher texture as it has less dense and bigger fibrovascular bundles than the skin or outer surface. In addition, the pith side is composed of numerous large parenchyma cells which contribute to surface roughness when cut open (Liese 1998).

Table 3. Unpaired t-test of average roughness (Ra) and average roughness depth (Rz) of giant bamboo's pith versus skin side

Surface roughness parameter		**Pith**	**Skin**
average roughness **(Ra)**	Mean	10.61 a	8.34 b
	SD	2.66	1.60
	SEM	0.53	0.32
	N	25	25
	Df	48	
	T	3.6508	
	ρ-value	0.0006 **	
average roughness depth **(Rz)**	Mean	54.46 a	45.19 b
	SD	12.89	9.12
	SEM	2.58	1.82
	N	25	25
	Df	48	
	T	2.9335	
	ρ-value	0.0051 **	

Note: Means with different letters are significantly different.

SD = standard deviation; SEM = standard error of the mean; N = total number of measurements

** highly significant at $\alpha = 0.01$

3.2. Wettability

The contact angle at different time intervals between the inner and outer surfaces varied significantly among the adhesives (Figure 5). PVAc-D3 had the highest initial contact angle on the pith at 80°, followed by PF at 67°, UF at 62° and PUR at 54°. On the skin, the same order of the adhesives' contact angle was observed at 79°, 68°, 66°, and 56°, respectively. The contact angle difference of the pith and skin was notably small based on the initial measurement at 15 sec (PVAc-D3 = 1°; PUR = 2°; PF = 1°; UF = 4°) and on the succeeding intervals. T-test showed that these were not statistically significant. In comparison to the results of Marasigan et al. 2020 for PVAC-D3, a higher contact angle of 107.53° (outer) and 101.92°(inner) with a difference of 5.61° was obtained and found statistically significant. The smaller difference in the contact angle of the present study might be attributed to the small difference in the surface roughness of the pith and skin, which could be due to the finer sanding done on the specimens. Wu et at. (2022) and Chen et al (2022) showed that fine sanding could have an effect on the reduction of surface roughness and improved wettability of the bamboo substrate.

Among the four adhesives, PUR surprisingly had the smallest contact angle initially, which was maintained all throughout the measurement period (Figure 6). Despite the higher initial viscosity of PUR at 1,520 cP which was almost the same as that of PVAc-D3 at 1,533 cP, PUR displayed better rate of wetting on the giant bamboo's surface. It is worth mentioning that PVAc-D3 and PUR are both cold setting adhesives. On the other hand, UF and PF, which are both thermosetting, had initial viscosities of 223 cP and 251 cP, six times lower than those of PVAc-D3 and PUR. Final contact angle of UF and PF measured after 300 s was smaller than the contact angle of PVAc-D3 but a little bigger than PUR.

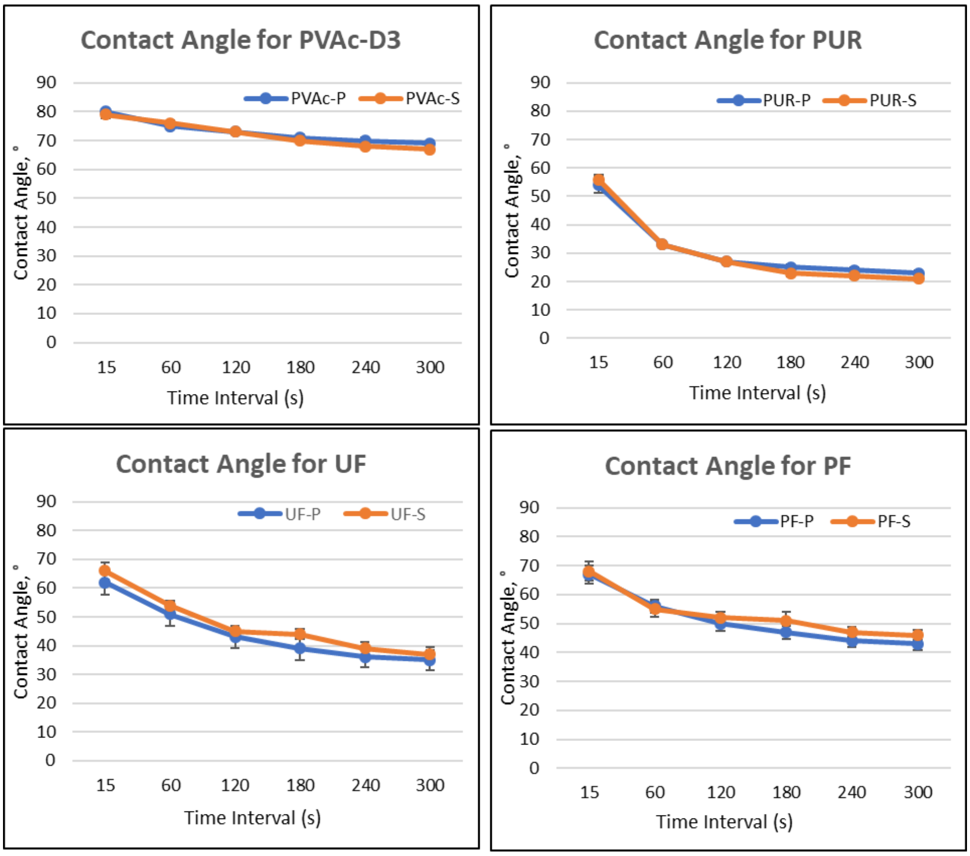


Figure 5. Contact angle of inner and outer surfaces of the bamboo laminates using the four commercial adhesives

Viscosity of adhesive could be a factor in the wettability of the adherend as less viscous fluid flows easily. However, other factors may have influenced the wetting of the giant bamboo's surface. These include the pH and molecular weight of the adhesive as well as the surface roughness of the adherend which could be affected by its anatomical or morphological structure (Ahmad & Kamke 2003; Nkeuwa et al. 2022).

As viscosity is a measure of a fluid's resistance to flow, a liquid with high viscosity means that it is thick and sticky, and it tends to flow slowly. Wettability, on the other hand, is a measure of how well a liquid can spread over a solid surface. A liquid with high wettability will tend to spread out over a solid surface, while a liquid with low wettability will tend to bead up and resist spreading (Frihart 2005; Ulker 2016).

There is a complex interplay between viscosity and wettability that depends on several factors, such as the surface tension of the liquid, the surface energy of the solid, and the contact angle between the liquid and the solid. In general, a liquid with low viscosity will tend to have higher wettability than a liquid with high viscosity, because it can spread more easily over a solid surface (Frihart 2005; Ulker 2016). However, the relationship between viscosity and wettability is not always straightforward, and other factors can come into play. For example, if the solid surface has a high surface energy, it may be able to overcome the resistance of a high-viscosity liquid and promote wetting. Similarly, if the liquid has a low surface tension, it may be able to spread more easily over a solid surface, even if it has high viscosity (Pizzi and Mittal 2018).

In the case of PUR, despite its higher viscosity than other adhesives such as UF and PF, it has a lower surface tension and high surface energy (Lehringer and Gabriel 2014; Shirmohammadli et al. 2023), which probably contribute to its high wettability on bamboo. The one-component PUR used in the experiment was not a water-based adhesive unlike PVAc, UF and PF.

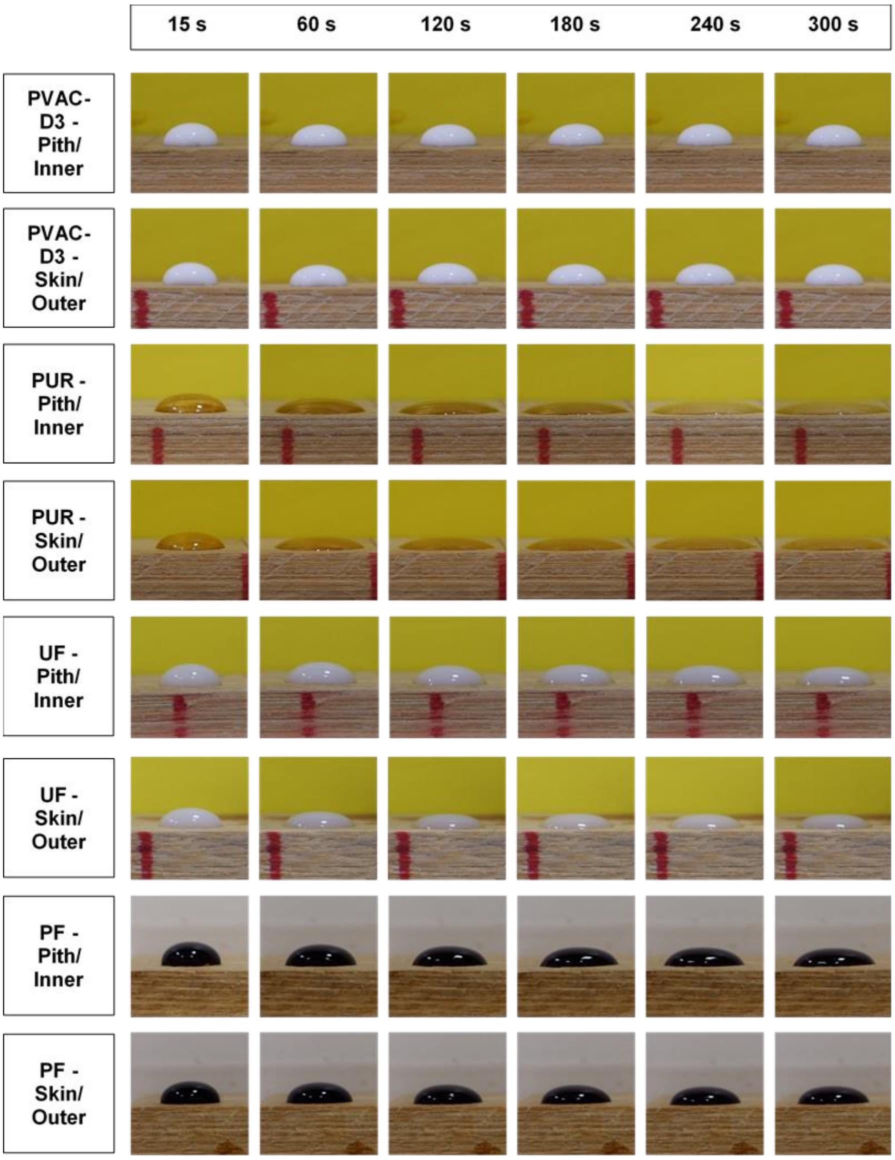


Figure 6. Droplets of the different commercial glues showing contact angles on the surface of the bamboo adherend at different time intervals.

3.3. Bond (Tensile) Shear Strength

ANOVA (Table 4.) showed that for the dry shear strength ($f_{v,d}$), only adhesive and surface pairing were the significant factors while glue spread rate was not. Among the interactions, only adhesive x glue spread and adhesive x surface pairing were significant. For the wet shear strength ($f_{v,w}$), only adhesive and adhesive x surface pairing resulted in notable differences among the specimens.

Table 4. Analysis of Variance (ANOVA) of the dry and wet shear strength of bamboo laminates and their corresponding cohesive bamboo failure.

Property	Condition	Source of Variation	DF	F value	p-value
Tensile Shear Strength	Dry	Adhesive (A)	3	56.96	<.0001**
		Glue Spread (GS)	2	1.04	0.3576 ns
		A x GS	6	2.79	0.0135 *
		Surface Pairing (SP)	2	24.47	<.0001**
		A x SP	6	5.42	<.0001**
		GS X SP	4	0.59	0.6700 ns
		A X GS X SP	12	0.52	0.8990 ns
		Error	144		
		Total	179		
				$R^2 = 0.66$	CV = 25.48
	Wet	Adhesive (A)	3	184.43	<.0001 **
		Glue Spread (GS)	2	0.83	0.4368 ns
		A x GS	6	1.25	0.2836 ns
		Surface Pairing (SP)	2	2.79	0.0646 ns
		A x SP	6	11.81	<.0001 **
		GS X SP	4	1.18	0.3200 ns
		A X GS X SP	12	1.55	0.1127 ns
		Error	144		
		Total	179		
				$R^2 = 0.82$	CV = 25.97
Cohesive Bamboo Failure	Dry	Adhesive (A)	3	49.36	<.0001 **
		Glue Spread (GS)	2	1.65	0.1964 ns
		A x GS	6	5.50	<.0001 **
		Surface Pairing (SP)	2	1.70	0.1862 ns
		A x SP	6	5.19	<.0001 **
		GS X SP	4	1.17	0.3284 ns
		A X GS X SP	12	1.26	0.2515 ns
		Error	144		
		Total	179		
				$R^2 = 0.62$	CV = 36.58
	Wet	Adhesive (A)	3	151.08	<.0001 **
		Glue Spread (GS)	2	0.56	0.5705 ns
		A x GS	6	1.02	0.4162 ns
		Surface Pairing (SP)	2	18.34	<.0001 **
		A x SP	6	6.76	<.0001 **
		GS X SP	4	0.30	0.8748 ns
		A X GS X SP	12	1.13	0.3421 ns
		Error	144		
		Total	179		
				$R^2 = 0.79$	CV = 36.28

3.4. Effect of adhesives

Figure 7 shows the comparison of the shear strength of the four adhesives in the dry and wet tests. PUR got the highest $f_{v,d}$ followed by PF, PVAc-D3 and UF in descending order. The $f_{v,d}$ values might be related to the adhesives' wettability. Among the four, PUR had the smallest contact angle on the adherend surface and produced the stronger bond shear strength, while PVAc-D3 had the biggest contact angle and produced a low bond shear strength. Between PF and UF, although they had less difference in their contact angles, PF produced the stronger bond because it is a structural adhesive while UF is non-structural adhesive (Pizzi and Mittal 2018).

As all adhesives obtained a $f_{v,d}$ of more than 1 MPa, there was no need to consider the dry cohesive bamboo failure (CBF) since they automatically conformed to the standard's gluebond requirement. However, for the $f_{v,w}$, only PVAc-D3 did not conform to the minimum gluebond strength requirement of more than 1 MPa and there was a need to determine the wet CBF. As shown in Figure 7, PVAc-D3 failed because it did not get the required 40% CBF.

Wet shear test showed the $f_{v,w}$ of PF and PUR did not differ significantly. Both PF and PUR are structural adhesives and can be used in products that can get wet, i.e., outdoor furniture and exterior building components. On the other hand, UF and PVAc-D3 are designed for interior product applications that should not get wet. There would be a risk of delamination of the glued components if these are exposed to high humidity, or if these get wet in indoor applications (Hartshorn 2012; Pizzi and Mittal 2018).

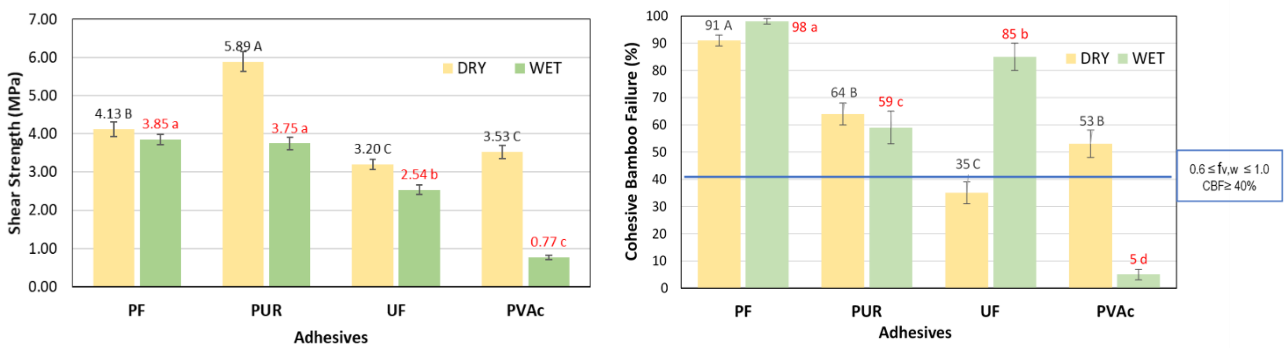


Figure 7. Comparison of the shear strength (left) and the cohesive bamboo failure (right) of the four adhesives in dry and wet tests. (Means followed by the same letter in the same color category of column bar are not significantly different at 95% confidence level.).

3.5. Effect of Glue Spread Rate

Figure 8 shows the comparison of the bond shear strength and the corresponding CBF of the glue spread rate in the dry and wet tests. There appeared to be no trend in the bond shear strength and CBF, even if the amount of glue applied was increased. This suggests that for giant bamboo lamination, there is no need to put more than 100g/m^2 of glue on the adherend as it would not translate to a stronger bond. The results imply lower costs in bamboo lamination for engineered bamboo producers.

In a study by Anokye et al (2014) on the effects of glue type (PF and PVAc) and spread rate (200 and 250 g/m^2) on the shear bond strength of laminated bamboo, the spread rate of 200 g/m^2 for both glues resulted in values higher than 250 g/m^2. In other studies of laminating arc-segments splits from buho (Natividad and Jimenez 2015), bolo and kauyan-tinik (Jimenez and Natividad 2019), a glue spread below 200 g/m^2 was found feasible for PUR and PVAc-D3 without affecting the mechanical properties.

The above studies indicate that a thin glue spread is enough to bond the bamboo adherends. The findings may be explained by the ultrastructure of bamboo cells which has an 8-layer secondary wall, as opposed to wood which has three layers (Liese 1998; Nkeuwa et al. 2022). Bamboo's fine polylamellate cell structure hinders the deep penetration of adhesives to adjoining cell layers which probably resulted in the resting of the liquid adhesive on the bamboo-adhesive interface. In addition, the absence of ray cells in bamboo to transfer liquid to adjoining cells makes bamboo and wood adhesive wetting different.

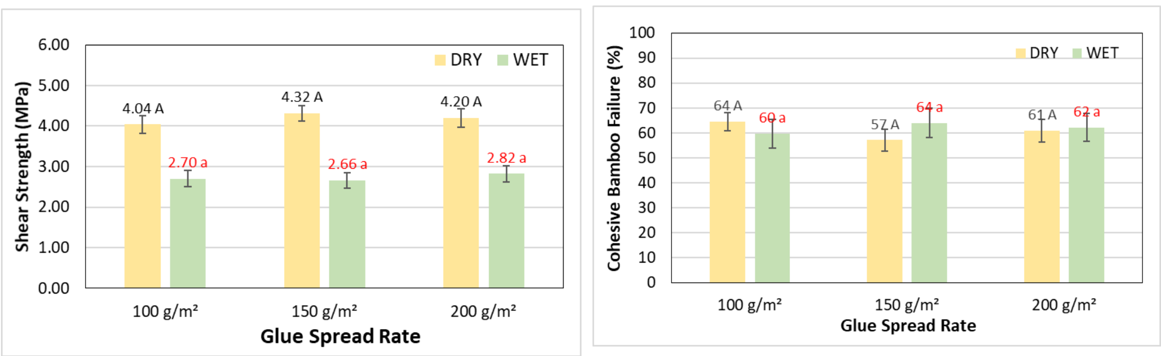


Figure 8. Comparison of the shear strength (left) and the cohesive bamboo failure (right) of the glue spread rate in dry and wet tests. (Means followed by the same letter in the same color category of column bar are not significantly different at 95% confidence level.).

3.6. Effect of Surface Pairing

Figure 9 shows the comparison of the shear strength of the surface pairing in the dry and wet tests. Among the paired surfaces, skin-skin pairing had the highest $f_{v,d}$ at 4.89 MPa, followed by pith-skin at 4.18 MPa, and then by pith-pith at 3.53 MPa. Skin-skin pairing gave the highest $f_{v,d}$ because its surface is composed of higher density small fibrovascular bundles than the pith and middle of the culm wall. On the other hand, pith-pith surface pairing had the lowest $f_{v,d}$ because it is composed of less but bigger fibrovascular bundles with more parenchyma than fiber cells (Liese 1998; Lo et al. 2004). Morphologically, parenchyma cells store the nutrients in bamboo such as starch granules while the fiber cells provide mechanical strength such as stiffness of the culm (Wei et al. 2022).

In the wet shear test, the $f_{v,w}$, was not significantly different among the paired surfaces although the pith-pith pairing was still the lowest. The weakening of bamboo cells due to water absorption is evident in Figure 9, where wet CBF was generally higher than dry CBF, except for the skin-skin pairing which had more tiny fibers that were not easily penetrated by moisture. Bamboo when soaked in water tends to absorb moisture from all surfaces. Hence, the low $f_{v,w}$, could be due to the water saturation of the cell wall be it the fiber or parenchyma cells, whose strength weakened when saturated with water (Wakchaure and Kute 2012; Wei et al. 2022).

The surface pairing results, though significant, might bear little importance in making engineered bamboo. To produce a plank or wide boards, several layers of slats are laminated and might obscure the significance of surface pairing. It might be implied however, that at best, given a piece of engineered bamboo, failure could occur at the weakest link, which is the pith-pith bond.

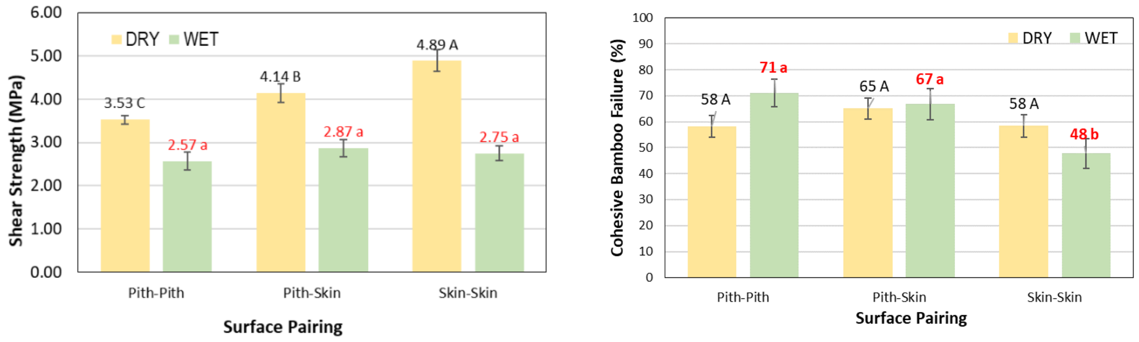


Figure 9. Comparison of the shear strength (left) and the cohesive bamboo failure (right) of the paired surface in dry and wet tests. (Means followed by the same letter in the same color category of column bar are not significantly different at 95% confidence level.)

Conclusions

The gluebond strength performance of the four commercial adhesives used in the study shows that PUR is the strongest in the dry shear test followed by PF, and lastly by PVAc-D3/UF. For the wet shear test, PUR and PF are the top performers, followed by UF. PVAc-D3 is the weakest and does not pass the standard requirement for the gluebond strength for the wet shear test. Regardless of glue type, skin-skin (outer-outer) is the best surface combination, followed by pith-skin (inner-outer). Pith-pith (inner-inner) is the least desirable. It can be inferred that given a piece of engineered bamboo, failure could occur at the weakest link, which is the pith-pith bond. Glue spread rate generally does not influence the bond strength of PUR, PF and UF. Even at 100 g/m^2, these three adhesives can produce a strong gluebond that would pass the minimum standard requirement. PVAc-D3 requires a higher glue spread rate to cover the surface of the adherend due to its poor wettability as evidenced by its higher contact angle.

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Conflict of Interest

The authors declare there is no conflict of interest

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