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Wettability of three Honduran bamboo species

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Abstract—This study was initiated to determine the wettability of three Honduran bamboo species by contact-angle measurements. Static contact angles of urea formaldehyde (UF), phenol formaldehyde (PF), isocyanate (ISO) and distilled water on the bamboo surfaces were measured. The effects of bamboo species, layer (outer, middle and inner) and chemical treatment (hydrochloric acid, sodium hydroxide and distilled water) on the contact angle of bamboo surfaces were examined. The results showed that bamboo species had a significant effect on contact-angle values. Regarding the four adhesives, the contact angle of UF was significantly higher. The adhesives displayed the following mean contact-angle pattern: UF > PF > ISO > distilled water. The effect of the bamboo layer was also significant. The outer layer had the highest contact angle, followed by the inner layer and then the middle layer. With regards to the three chemical treatments, NaOH had the highest total mean contact-angle value.

Key words: Bonding; contact angle; Honduran bamboo; wettability.

1. INTRODUCTION

To obtain proper interfacial bonding and a strong adhesive joint, good adhesive wetting, proper solidification (curing) of the adhesive and sufficient deformability of the cured adhesive (to reduce the stresses that occur in the formation of the joint) are important [1, 2]. Adhesive wettability is the ability of an adhesive to make intimate contact with a surface [3]. Early research in the 1960s and 1970s mainly determined the instantaneous or equilibrium contact angle at the adhesive/adherent interface.

A strong bond can only be achieved by a high level of adhesion forces between adhesive and wood molecules. Wetting is a term to describe what happens when a liquid comes into contact with a solid surface. Wetting also refers to manifestations

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of molecular interaction between liquid and solids in direct contact at the interface between them [4]. For adhesive wetting, these manifestations have been shown to include contact-angle formation, spreading, and penetration. Contact-angle formation is related to the thermodynamics of the liquid/solid interaction. Spreading is due to droplet shape, solid surface structure, and the change of energy states on the solid surface, adsorption and wetting kinetics. A theoretical discussion on the surface dynamic behaviour of polymers can be found in Liu *et al.* [5]. Penetration is primarily related to the surface structure of the adherent [3].

Spreading of the liquid over the surface can occur without limits, or the spreading process might come to an end if an equilibrium state is reached, which is characterized by a contact angle between the liquid–fluid and liquid–solid interfaces. The kinetics of spreading refers to the rate at which the adhesive flows on an adherent. Once surface tension forces have reached equilibrium (i.e. equilibrium of spreading), a contact angle is formed between the adhesive and adhered.

Contact-angle measurements are in most cases the basis for estimations of wetting properties of the material. Contact-angle measurements provide information whether a liquid is wetting or non-wetting a solid surface, which is important for gluing applications [6].

There are three primary methods applied for contact-angle analysis; the sessile-drop method, Wilhelmy plate or dynamic contact-angle method (DCA), and wicking method for powders. In this research, the sessile-drop method was used. For the point of contact of the three phases (i.e. solid, liquid and gaseous), the Young equation states that there is an equilibrium when:

$$\sigma_{SG} = \sigma_{LS} + \sigma_{LG} \cos\theta, \tag{1}$$

where σ_{SG} is the surface tension of the solid/gaseous phase, σ_{LS} is the interfacial tension between liquid and solid, σ_{LG} is the surface tension of the liquid/gaseous phase [7] and θ is the contact angle [6]. It is generally accepted that the lower the contact angle, the better the wettability. Many studies have revealed wettability determined through contact-angle measurement is closely associated with gluability of wood and wood-based composites [8–11].

In early studies of the thermodynamics of the adhesive/adherent interaction, instantaneous of equilibrium contact angles were typically used. These techniques neglected the liquid penetration and spreading process, which are important to evaluation wood adhesion. Recently researchers have realized the importance of measuring contact-angle change as a function of time [7, 12, 13]. Thermodynamic work of adhesion is known to be insufficient for predicting gluability. It is recognized that advanced techniques have yielded new insight and a better understanding of the bonding process. In particular, the development of dynamic contact-angle measurement has been particularly useful. The direct benefit of this technology is a better understanding of how liquids interact with surfaces. However, static contact-angle measurement has provided the basis of our current level of knowledge of gluability and can still provide useful information. In particular, static contact-angle measurement is a simple and quick method of rapidly screening various species and treatments for future follow-up more comprehensive studies.

The objectives of this study were to compare the wetting properties of three Honduran bamboo species (*Dendrocalamus aspera*, *Bambusa arundinacea* and *Guadua angustifolia*) as assessed by four adhesives, urea formaldehyde (UF), phenol formaldehyde (PF), isocyanate (ISO) and distilled water on different radial layers (outer, inner and middle) of each bamboo species. It is acknowledged that distilled water is not technically an adhesive but the term adhesive is used for all compounds for purposes of consistency and simplicity. Another objective was to determine the effect of chemical treatment (hydrochloric acid, sodium hydroxide solution and distilled water) of the specimens on the contact angle.

MATERIALS AND METHODS

Two representative bamboo culms for each of three species were harvested at Lancetilla National Park near Tela, Honduras. The species were *Dendrocalamus aspera*, *Bambusa arundinacea* and *Guadua angustifolia*. The culms were cut radially into 1-m-long sections and then longitudinally cut into four pieces of approximate equal dimension, which were air-dried for 24 h prior to cutting into pieces measuring 2.5 × 7.6 cm. The surfaces of the layers were manually sanded with 100 grain aluminum oxide fine sandpapers for 30 s. Then the bamboo pieces were treated in 60°C 0.1 M hydrochloric acid, 0.1 M sodium hydroxide solution, or distilled water for 30 min. The pieces were then put in an Aminco conditioning chamber at 85% relative humidity and 99°C to obtain an equilibrium moisture content of approximately 12% prior to contact-angle determination. Aminco is a brand of environmental conditioning chambers that allow control of dry bulb and wet bulb temperatures to adjust relative humidity and influence equilibrium moisture content.

The adhesives were three resins (UF, PF and ISO) and distilled water. The concentrations of the adhesive solutions of UF and ISO were 51% and 100%, respectively. The PF resin contained 44% percent concentration, 300 cps viscosity and a mol ratio of 1.95 : 1 : 0.45 of formaldehyde to phenol to sodium hydroxide.

Contact-angle determination was accomplished with a microscope equipped with a goniometer eyepiece. The microscope tube was arranged horizontally. The specimen was placed on the stage and a 0.06-ml droplet of adhesive was applied with a pipette to the surface of the specimen. The contact angle was measured by rotating the goniometer eyepiece so that the hairline passed through the point of contact between the droplet and the bamboo surface and was tangent to the droplet. All measurements were made 5 s after the resin had been dropped. Five seconds was an arbitrary time value that was selected based on logistical constraints to record measurements any sooner and the known change in static contact angles that occur over time based on data by Scheikl *et al.* [13]. It was also selected for consistency. Previous work with several hardwood species has shown that 5 s can yield accurate and useful data [14]. Analysis of variance (ANOVA) was performed to determine the significance of the main effects (bamboo species, layers, chemical treatments, adhesives) and the interaction effect. All statistical analysis was conducted by using SAS software [15]. The significance of the factors and factor interactions were analysed at $\alpha = 0.05$ level and F-tests were constructed using Type 3 Sum of Squares. The presence of higher order interactions prevented the utilization of Duncan's Multiple Comparison of Means. The ANOVA for each dependent variable revealed that cross-products that included types and other higher order interactions were often significant. Therefore, species cannot be addressed singularly and any multiple comparisons are invalid.

RESULTS AND DISCUSSION

Comparison of bamboo species and bamboo layers

Table 1 presents the mechanical and physical properties and statistical analysis of the three bamboo species from our previous study [16]. *Bambusa arundinacea* is significantly lower than the other two species for modulus of rupture and modulus of elasticity and has a lower specific gravity. The mean and standard deviations of the contact angles of three bamboo species at different treatment conditions are shown in Table 2. Table 3 summarizes the ANOVA results of the effects of bamboo species, layer, chemical treatment and adhesive on the contact angle.

As expected, there were significant differences between the three bamboo species (Fig. 1). It is evident that *Dendrocalamus aspera* and *Bambusa arundinacea* yielded similar mean contact-angle values, while *Guadua angustifolia* had the highest total mean contact angle. The total mean contact-angles value of *Dendrocalamus aspera* was 72.3° and *Guadua angustifolia* gave the highest total mean contact angle at 73.8°.

In the present study, the effect of bamboo layer (outer, middle and inner) was observed as significant. The comparatively higher surface hardness of the outer

Table 1.
Mean mechanical and physical properties of three bamboo species from Honduras[a]

Scientific name	SG[b,c]	MC (%)[c,d]	MOR (MPa)[e]	MOE (Gpa)[f]
Dendrocalamus aspera	0.56	12.00	45.8 (A)[g]	5.75 (A)
Bambusa arundinacea	0.51	13.8	30.3 (B)	3.36 (B)
Guadua angustifolia	0.59	11.6	41.6 (A)	6.36 (A)

[a] Data from Shupe *et al.* [16].
[b] Specific gravity based on air dry dimensions and oven dry weight.
[c] Represents the mean of three samples.
[d] Moisture content.
[e] Modulus of rupture.
[f] Modulus of elasticity.
[g] Similar letters denote no significant test at $\alpha = 0.05$ using a two-tailed t-test.

layers had an adverse effect on resin penetration and resulted in a higher mean contact angle for the outer layer. The outside layer of bamboo is typically hydrophobic in nature due to its relatively high silica content, which typically results in higher contact angles and poorer gluability.

The outer layer had the highest total mean contact angle and the middle layer had the smallest mean contact angle. From the results of the ANOVA, the contact angles of three bamboo species showed significant differences in wettability (Table 3). According to several previous studies of Chen *et al.* [17–19], the middle layer of bamboo has better wettability than the inner and the outer layers because of the

Table 2.
Mean contact angle values of three Honduran bamboo species

Liquid	Species	Chemical treatment								
		HCl			NaOH			Distilled water		
		Outside	Inside	Middle	Outside	Inside	Middle	Outside	Inside	Middle
UF	1[a]	80.3 (0.58)	78.2 (0.93)	74.0 (0.94)	82.0 (0.94)	78.4 (0.70)	72.3 (0.82)	82.3 (1.83)	80.2 (0.82)	69.1 (1.92)
	2	75.5 (0.53)	72.6 (0.52)	68.6 (0.97)	82.5 (1.08)	74.6 (0.97)	71.2 (1.14)	83.0 (0.82)	79.9 (0.99)	74.2 (0.63)
	3	83.1 (0.99)	80.0 (0.82)	75.7 (1.06)	84.8 (0.63)	79.8 (1.23)	77.3 (1.06)	82.2 (1.40)	78.9 (0.74)	76.8 (1.42)
PF	1	76.8 (0.79)	67.2 (0.63)	66.9 (1.29)	77.4 (0.52)	76.0 (0.82)	69.4 (1.17)	78.3 (1.25)	77.7 (1.16)	63.9 (3.98)
	2	76.7 (0.67)	72.9 (0.57)	69.2 (1.03)	82.1 (0.74)	73.3 (0.95)	71.1 (1.10)	81.5 (0.85)	75.0 (1.94)	72.4 (1.26)
	3	76.8 (1.03)	76.4 (0.70)	69.4 (0.92)	76.5 (0.53)	74.7 (0.82)	71.6 (0.84)	78.2 (1.03)	76.7 (1.06)	69.5 (0.97)
ISO	1	79.7 (0.68)	78.4 (0.52)	67.8 (1.87)	77.4 (0.52)	73.1 (1.10)	71.5 (1.27)	72.4 (1.26)	69.7 (0.95)	66.0 (0.82)
	2	81.0 (0.61)	80.3 (0.67)	72.1 (0.88)	77.8 (1.23)	73.0 (0.82)	70.9 (0.85)	74.9 (1.37)	70.3 (1.25)	66.3 (1.67)
	3	79.5 (0.71)	75.1 (0.74)	66.3 (1.16)	77.9 (0.56)	75.6 (0.52)	72.8 (0.63)	76.0 (0.82)	74.3 (1.45)	69.3 (1.67)
Distilled water	1	73.7 (1.34)	68.5 (0.83)	61.0 (0.82)	72.8 (0.63)	72.5 (0.53)	65.8 (1.23)	67.7 (0.82)	67.2 (1.14)	63.9 (1.20)
	2	66.4 (0.97)	61.8 (0.63)	54.6 (0.52)	74.2 (0.79)	68.1 (0.74)	59.6 (1.71)	68.8 (1.14)	61.0 (0.82)	59.8 (1.69)
	3	66.2 (0.79)	64.4 (0.52)	55.3 (0.67)	74.4 (1.71)	64.7 (0.67)	62.2 (1.35)	72.6 (0.97)	67.7 (0.67)	60.2 (1.14)

Specimens were subjected to three different chemical treatments, hydrochloric acid, sodium hydroxide, or distilled water, prior to contact-angle measurement with urea formaldehyde (UF), phenol formaldehyde (PF), isocyanate (ISO), and distilled water on three layers (outside, inside and middle). Each value represents 10 observations. Numbers in parentheses are coefficients of variation (%).

[a] 1 = *Dendrocalamus aspera*, 2 = *Bambusa arundinacea*, 3 = *Guadua angustifolia*.

Table 3.
Analysis of variance

Source	DF	F value	Pr > F
Wetting agent	3	4149.98	<0.0001
Layer	2	5703.34	<0.0001
Species	2	104.83	<0.0001
Chemical treatment	2	262.62	<0.0001
Wetting agent* layer	6	39.7	<0.0001
Wetting agent* species	6	236.46	<0.0001
Wetting agent* chemical treatment	6	376.88	<0.0001
Layer* species	4	34.7	<0.0001
Layer* chemical treatment	4	17.75	<0.0001
Species* chemical treatment	4	76.78	<0.0001

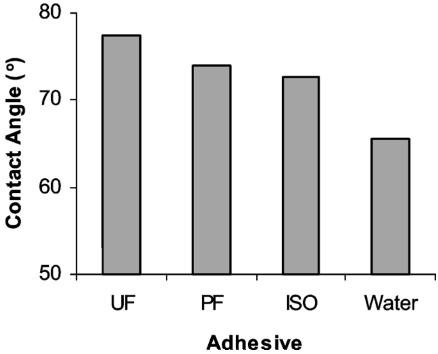

Figure 1. Effects of four adhesives (UF, PF, ISO and distilled water) on the mean contact angle of Honduran bamboo.

existence of hard texture of the bamboo outer layer and the wax-like materials in the inner layer can both impede the penetration of adhesives. It was recommended that when using bamboo to manufacture ply-bamboo, the inner layer and the outer layer should be removed, since they have very low wettability, which is not conducive for strong bond formation. Otherwise, effective treatments should be used to improve the wettability and enhance bonding.

It is known that some of the factors that influence the contact angle of different bamboo layers include specific gravity, chemical composition, species, adhesive, measurement ambient conditions and time elapsed from placing the adhesive droplet on a surface and making the measurement. In this case, the middle layer has a lot more exposed fibres which will increase the surface tension between the adhesive and the bamboo surface.

Effects of chemical treatments and adhesive type

The mean contact angles of the three bamboo species treated with the three chemical treatments are shown in Table 2. The sodium hydroxide treatment has the highest mean contact-angle value on all three layers while hydrochloride and distilled water has approximately the same contact-angle values on each layer. Since bamboo itself is weakly acidic, the base treatment to bamboo could have a minor effect on the wettability of the bamboo species.

Figure 1 shows the effect of the adhesives on the mean contact angles of the three bamboo species. There is a significant difference between the three bamboo species concerning the effect of the adhesives. However, UF and distilled water showed more variability among the bamboo species. UF had the highest contact angles for all three adhesives. It is noted that PF and ISO has the similar mean contact angles, while distilled water has the lowest contact angles. Distilled water has the lowest contact angle since it can more easily penetrate the bamboo surface than the adhesives and, thus, reduce the contact angle.

Interaction between layer and species, layer and chemical treatment, and species and chemical treatment of the contact angle of UF resin

Four adhesives showed a similar interaction trend. The contact angle of UF resin was selected to determine the effect of interaction between layer and species, layer and chemical treatment, and species and chemical treatment.

Figure 2 shows the interaction between layer and species, layer and chemical treatment, and species and chemical treatment. From Fig. 2a, we can see that the contact angle decreases from the outer layer to inner layer and the lowest is the middle layer. In each layer, the mean contact angles of *Guadua angustifolia* is the highest. Figure 2b shows the interaction between layer and chemical treatment. The mean contact angle was nearly similar at a particular layer for all three chemical treatments. Species and chemical treatment of UF resin had an interaction (Fig. 2c). Hydrochloric acid treatment had the highest contact angle on *Dendrocalamus aspera*, while it had the lowest contact angle on *Bambusa arundinacea*. For *Guadua angustifolia*, hydrochloric acid and distilled water had approximately the same contact angle.

CONCLUSIONS

The wettability of three Honduran bamboo species subject to different treatments was determined using the static contact-angle technique. Three bamboo species were investigated and the species effect was a significant source of variation. Four adhesives (actually three adhesives and distilled water) were also investigated, and the adhesive effect was a significant source of variation in the ANOVA. The result showed that UF had the highest mean contact angle and the distilled water had the lowest mean contact angle. Samples were tested on the inner, middle, and outside location of each culm. The test location was a significant source of variation. The outer layer had the highest mean contact angle and the middle layer has the lowest contact angle for each chemical treatment (HCl, NaOH and distilled water) that was used to treat the samples prior to contact-angle determination. The contact-angle

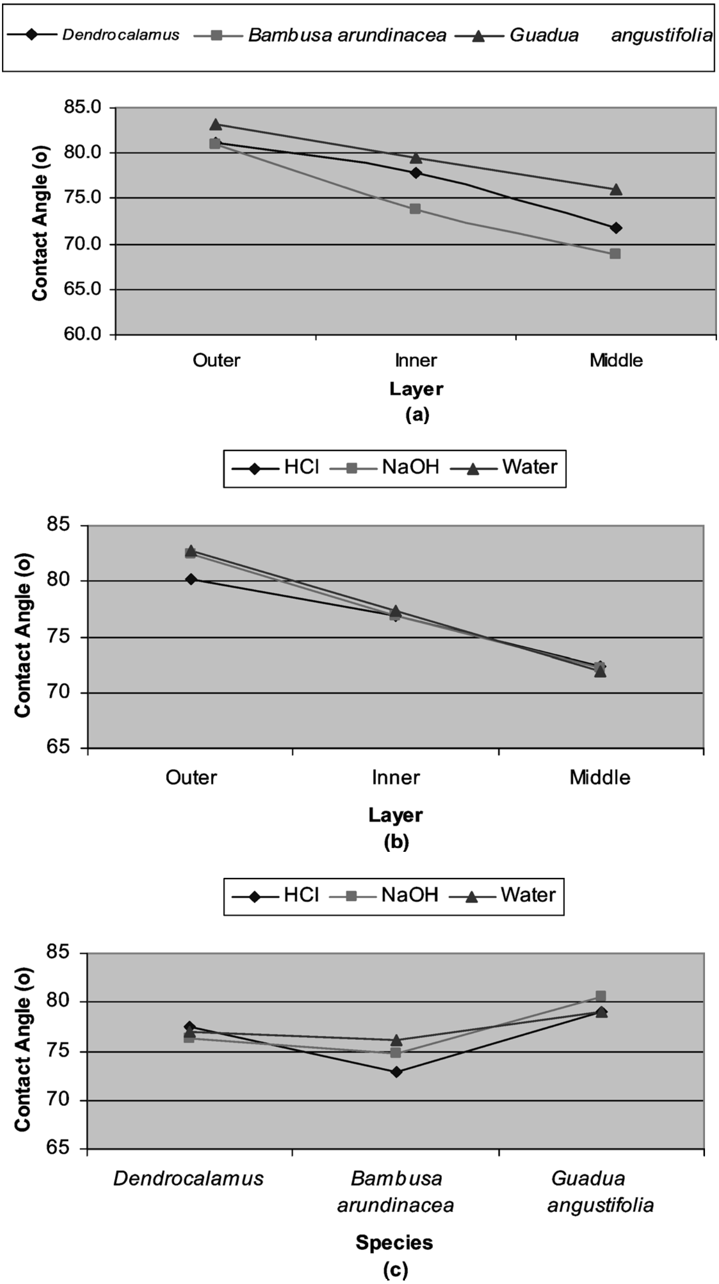

Figure 2. Interaction between layer and species, layer and chemical treatment, and species and chemical treatment of the contact angle of UF resin.

data from this study would seem to indicate that these bamboo species have less favourable wettability as compared with most wood species. To improve gluability, treatment to improve the wettability of these species is needed prior to adhesion.

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