HOLZ FORSCHUNG

International Journal of the
Biology, Chemistry, Physics and
Technology of Wood

Offprint

Walter de Gruyter · Berlin · New York

ISSN 0018-3830

Holzforschung
55 (2001) 541–548

An Investigation of Selected Factors that Influence Hardwood Wettability

By Todd F. Shupe[1], Chung Y. Hse[2] and Wan H. Wang[3]

[1] School of Forestry, Wildlife, and Fisheries, Louisiana State University Agricultural Center, Baton Rouge, LA, USA
[2] USDA Forest Service, Southern Research Station, Pineville, LA, USA
[3] Nanjing Forestry University, Department of Wood Science and Technology, Nanjing, Peoples Republic of China

Keywords

Contact angle
Drying
Hardwood
Phenol formaldehyde resin
Wettability

Summary

Wettability of sanded and non-sanded transverse and tangential sections of 22 southern hardwoods species was judged by measurement of contact angles using phenol formaldehyde resins. As expected, contact angle values on transverse sections were higher than those on tangential sections for both sanded and non-sanded surfaces. On sanded surfaces, hackberry had the highest mean contact angle (64.7°), and black oak had the lowest mean contact angle (50.1°). On non-sanded surfaces, winged elm had the highest mean contact angle (59.1°), and sweetgum had the lowest mean contact angle (45.9°). In addition, 4 of the 22 species (southern red oak, sweetgum, white oak, and post oak) were selected to investigate the effect of oven-drying, air-drying, and free-drying on wettability. The mean transverse contact was 2.1°–29.0° and 5.1°–31.5° higher than radial and tangential values, respectively. The contact angle pattern typically displayed for a given species and plane was generally oven-dry > air-dry > freeze-dry. The species pattern for most methods and planes was: sweetgum > white oak > post oak > southern red oak. White oak and post oak gave similar contact angle values.

Introduction

The development of adhesive bonding technology has been closely related to surface quality research. Because wood adhesives are applied to the surface of wood, the properties of the wood surface are influential in determining the wettability performance of an adhesive. Contact angle determination is a common method of evaluating the wettability of wood surfaces. Contact angle is the adverse measure of wettability (Zisman 1964; Zisman 1976). It is thermodynamically determined by the balance between adhesive forces, i.e., between liquid (adhesive) and wood (adherend) interfaces, and cohesive forces within the liquid (Johnson and Dettre 1993).

Numerous previous researchers have shown that the wettability of wood as determined through contact angle assessment is intimately associated with glue-line integrity (Freeman 1959; Bodig 1962; Suchsland and Stevens 1968; Hse 1972; Scheikl and Dunky 1998). In North America, most previous studies on wood wettability have been conducted with southern yellow pine (*Pinus* sp.) or Douglas-fir (*Pseudotsuga menziesii*). Hameed and Roffael (1999) established that the wettability of sapwood from pine, Douglas-fir, and larch on cross, radial, and tangential sections with water and various glues is better than that of heartwood. They found that in most cases, the tangential section of sapwood and heartwood was less wettable than radial and cross sections. The literature is sparse with regard to wettability studies of North American hardwoods.

Bonding properties may also vary with regard to the plane (transverse, tangential, or radial) of wood. Due to the anisotrophic nature of wood, we know that it possesses unique hygroscopic properties in its three fundamental directions: longitudinal, radial, and tangential. It is important to understand the bonding properties on these three planes for more efficient utilization.

This project was initiated to 1) investigate the wettability of 22 southern hardwood species, 2) determine the effect of wood plane on wettability, and 3) examine the effect of three drying methods on the wettability of four southern hardwoods.

Materials and Methods

Twenty-two hardwood species were selected for this study. The species' common name, scientific name, pore distribution, and specific gravity range are listed in Table 1. Ten trees with a diameter at breast height near 15.24 cm were selected for each species. The sampling locations were broadly distributed throughout that portion of each species range occurring in the 11-state area extending from Virginia to northern Florida and west to Arkansas and eastern Texas. Only one tree of a particular species was cut at one location.

Our samples were unused samples from a previous study by Choong et al. (1974). Therefore, the sample preparation method is similar. Disks that were 5.08 cm thick were removed at 1.8 m above ground for each tree. Three rectangular-shaped samples were cut from each disk using a fine-toothed bandsaw. The ends of the samples were either perpendicular to the grain (transverse) or to the radial or tangential planes. The wood samples were sawn into

Table 1. Pore distribution and specific gravity range of the 22 southern hardwood species used for wettability determination

Species common name	Scientific name	Specific gravity range[1]	Overall Mean (Darcy)[2]	Fiber radial diameter (μm)[3]
	Ring-porous			
Blackjack oak	*Quercus marilandica* Muenchh.	0.70–0.86	1.688	15.28
White oak	*Quercus alba* L.	0.71–0.91	0.712	14.51
Hackberry	*Celtis occidentalis* L.	0.51–0.70	16.732	12.34
American elm	*Ulmus acericana* L.	0.52–0.64	3.688	14.27
Water oak	*Quercus nigra* L.	0.59–0.78	24.781	15.36
Black oak	*Quercus velutina* Lam.	0.65–0.85	45.536	14.91
Shumard oak	*Quercus shumardii* Buckl.	0.66–0.83	48.261	15.47
Northern red oak	*Quercus rubra* L.	0.65–0.80	59.075	15.00
Post oak	*Quercus stellata* Wangenh.	0.71–0.98	0.110	14.19
Hickory	*Carya* spp.	0.68–0.90	4.873	14.77
Southern red oak	*Quercus falcata* Michx.	0.62–0.88	39.005	14.98
Laurel oak	*Quercus laurifolia* Michx.	0.60–0.74	28.612	15.48
White ash	*Fraxinus americana* L.	0.64–0.76	1.356	17.75
Green ash	*Fraxinus pennsylvanica* Marsh.	0.51–0.71	2.767	17.73
Cherrybark oak	*Quercus falcata* var. *pagodaefolia* Ell.	0.63–0.82	42.914	15.21
Winged elm	*Ulmus alata* Michx.	0.62–0.77	2.601	11.42
Scarlet oak	*Quercus coccinea* Muenchh.	0.64–0.85	44.782	15.45
	Diffuse-porous			
Red maple	*Acer rubrum* L.	0.49–0.60	9.103	18.02
Sweetgum	*Liquidambar styraciflua* L.	0.46–0.57	14.547	22.84
Yellow-poplar	*Liriodendron tulipifera* L.	0.36–0.55	15.968	24.30
Sweetbay	*Magnolia virginia* L.	0.38–0.55	13.311	26.98
Black tupelo	*Nyssa sylvatica* Marsh.	0.45–0.67	8.227	21.66

[1] Specific gravity determined from longitudinal permeability samples, based on oven-dry weight and dimensions (Choong *et al.* 1974).
[2] Overall mean Darcy gas permeability values in the longitudinal direction at 0% moisture content (Choong *et al.* 1974).
[3] Stemwood values from 15.24-cm diameter hardwood species ranging in age from 27–59 years (Manwiller no year given).

thin sections (0.3175 cm thick) from the end for contact angle measurement.

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 phenol formaldehyde (PF) resin 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 droplet and veneer and was tangent to the droplet at that point. All measurements were made 5 seconds after the resin had been dropped. For ring-porous species, all contact angles were determined randomly and regardless of earlywood or latewood.

This study was conducted with a laboratory prepared oriented strand board (OSB) core phenol formaldehyde (PF) resin that contained 44 percent solids, viscosity of 300 cps, and a mole ratio of 1.95:1:0.45 of formaldehyde to phenol to NaOH (sodium hydroxide). Contact angle measurements were recorded on the transverse and tangential sections of 22 species. Measurements were conducted parallel to the grain direction on tangential surfaces. For each specimen, one of the transverse and tangential surfaces was sanded with P320 extra fine sandpaper from 3M™. The corresponding transverse and tangential surfaces on the same specimens were left non-sanded. Therefore, each sample contained sanded and non-sanded transverse and tangential surfaces.

Analysis of variance was performed to determine the potential significance of the main effects: species, surface preparation (sanded and not sanded), and the interaction effect. The Scheffé mean separation test was employed to determine significant differences between the different species. Correlation coefficients between experimental variables were also determined. All statistical analysis was conducted using SAS software (SAS 1989).

Results and Discussion

Species and sanding effect

The mean contact angles and Scheffé grouping for the 22 species on sanded and non-sanded surfaces are presented in Table 2 and Table 3, respectively. Table 4 summarizes the results from the analysis of variance. As expected, there were highly significant differences between the species (Table 4). For the sanded surfaces, white oak and water oak both gave the highest mean contact angle on transverse surfaces (68.3°), and black oak yielded the lowest mean at 51.2° (Table 3). Blackjack oak gave the highest mean contact angle for sanded tangential surfaces (62.3°), and black oak again gave the lowest mean at 49.0°. On the non-sanded surfaces, winged elm (68.6°) and cherrybark oak gave the highest mean contact angles for transverse and tangential planes, respectively. Sweetgum (49.6°) and post oak (38.2°) gave the lowest mean contact angles on non-sanded transverse and tangential planes, respectively (Table 4).

It was expected that species would yield significantly different contact angle values because of inherent differences mostly attributable to differences in wood anatomy and chemistry. For example, in a study of spruce (*Picea abies*

Karsten), pine (*Pinus sylvestris* L.), beech (*Fagus sylvatica* L.), and poplar (*Populus* x *euramericana* Guinier), Scheikl and Dunky (1998) found that penetration was retarded with increasing viscosity of the liquids and the smaller cell diameters in latewood in comparison to earlywood. Data from previous studies on permeability and specific gravity (SG) (Choong *et al.* 1974) and fiber radial diameter (Manwiller no year given) were used to determine correlation between these properties and our contact angle values. The sanded surfaces mean data was negatively correlated with

Table 2. Mean contact angle values and Scheffé groupings for 22 southern hardwood species on the transverse and radial faces. Specimens were tested in the airdry condition, and the surface was sanded

Species	Transverse (X)	Tangential (T)	X–T	Mean
		Ring porous		
Blackjack oak	62.0[1] (ABCD)[2] (8.0)[3]	62.3 (A) (4.4)	–0.3	62.2
White oak	68.3 (A) (5.3)	58.5 (ABCDE) (5.2)	9.8	
Hackberry	67.6 (A) (4.7)	61.7 (AB) (4.3)	–0.1	
American elm	59.3 (CD) (8.4)	55.3 (CDE) (5.7)	4.0	57.3
Water oak	68.3 (A) (3.6)	58.5 (ABCDE) (3.0)	9.8	63.4
Black oak	51.2 (E) (8.9)	49.0 (F) (9.0)	2.2	50.1
Shumard oak	56.5 (DE) (12.0)	53.6 (DEF) (5.9)	2.9	55.1
Northern red oak	63.5 (ABC) (4.4)	57.9 (ABCDE) (6.6)	5.6	60.7
Post oak	62.2 (ABCD) (8.8)	55.3 (CDE) (5.7)	6.9	
Hickory	63.1 (ABCD) (5.4)	61.0 (ABC) (4.7)	2.1	
Southern red oak	62.3 (ABCD) (9.6)	56.3 (BCDE) (6.6)	6.0	
Laurel oak	66.7 (AB) (4.9)	60.9 (ABC) (5.9)	5.8	
White ash	63.5 (ABC) (6.8)	57.5 (ABCDE) (6.1)	6.0	60.5
Green ash	62.3 (ABCD) (5.9)	60.4 (ABC) (3.9)	1.9	61.4
Cherrybark oak	60.3 (BCD) (3.9)	59.5 (ABCD) (3.9)	0.8	59.9
Winged elm	58.9 (CD) (6.4)	59.0 (ABCDE) (6.2)	–0.1	59.0
Scarlet oak	62.2 (ABCD) (3.9)	55.8 (BCDE) (9.7)	6.4	59.0
		Diffuse porous		
Red maple	60.0 (BCD) (5.9)	53.4 (EF) (7.3)	6.6	56.7
Sweetgum	60.1 (BCD) (8.3)	56.6 (ABCDE) (8.9)	3.5	58.4
Yellow-poplar	65.0 (ABC) (4.2)	57.5 (ABCDE) (9.2)	7.5	61.3
Sweetbay	68.0 (A) (4.8)	59.6 (ABCD) (4.5)	8.4	63.8
Black tupelo	62.0 (ABCD) (5.5)	58.0 (ABCDE) (8.3)	4.0	60.0
MEAN	62.4 (6.6)	57.6 (5.4)	4.5	60.0

[1] Each mean value represents 24 observations.
[2] Letters in parentheses represent Scheffé groupings. Species with similar letters are not statistically different at alpha = 0.05. Species comparisons were made within a particular surface (i.e., either transverse or tangential).
[3] Numbers in parentheses are coefficients of variation (%) = (standard deviation/mean) × 100.

the Darcy permeability values (R = −0.33). The non-sanded surfaces mean data was significantly correlated to SG (R = 0.47) and fiber radial diameter (R = −0.57).

The correlation analysis showed that pore type was negatively related to the mean of the non-sanded data (R = −0.52) but not at all related to the mean of the sanded data (R = 0.00). Inferences regarding pore type are somewhat limited because of the larger number of ring porous species than diffuse porous species included in the study. Furthermore, the diffuse porous species selected are all of

Table 3. Mean contact angle values and Scheffé groupings for 22 southern hardwood species on the transverse and radial faces. Specimens were tested in the airdry condition, and the surface was not sanded

Species	Transverse (X)	Tangential (T)	X–T	Mean
		Ring porous		
Blackjack oak	52.6[1] (DEFG)[2] (9.0)[3]	47.4 (ABCDE) (11.4)	5.2	50.0
White oak	59.6 (BCDE) (6.8)	51.5 (AB) (8.9)	8.1	55.6
Hackberry	58.5 (BCDEF) (10.1)	48.0 (ABCD) (11.9)	10.5	53.3
American elm	52.1 (EFG) (7.6)	43.0 (ABCDE) (13.9)	9.1	47.6
Water oak	63.0 (ABC) (5.5)	46.3 (ABCDE) (12.0)	16.7	54.7
Black oak	54.8 (CDEFG) (11.8)	44.7 (ABCDE) (10.9)	9.6	50.0
Shumard oak	61.3 (ABC) (6.9)	43.0 (ABCDE) (17.3)	18.3	52.2
Northern red oak	61.1 (ABCD) (8.9)	44.7 (ABCDE) (11.2)	16.4	52.9
Post oak	58.6 (BCDEF) (9.4)	38.2 (E) (17.4)	20.4	48.4
Hickory	62.0 (ABC) (8.7)	49.8 (AB) (11.9)	12.2	
Southern red oak	57.5 (BCDEFG) (11.6)	49.8 (AB) (11.9)	7.7	53.7
Laurel oak	56.2 (BCDEFG) (10.2)	43.4 (ABCDE) (14.8)	12.8	
White ash	64.5 (AB) (8.5)	44.3 (ABCDE) (10.7)	20.2	
Green ash	61.0 (ABCD) (8.5)	47.2 (ABCDE) (11.3)	13.8	54.1
Cherrybark oak	64.2 (AB) (9.5)	52.3 (A) (10.0)	11.9	58.3
Winged elm	68.6 (A) (5.3)	49.5 (ABC) (5.1)	19.	59.1
Scarlet oak	57.6 (BCDEFG) (8.3)	46.0 (ABCDE) (15.9)	11.6	51.8
		Diffuse porous		
Red maple	62.9 (ABC) (5.7)	39.9 (DE) (12.8)	23.0	51.4
Sweetgum	49.6 (G) (10.1)	42.2 (BCDE) (10.2)	7.4	45.9
Yellow-poplar	54.9 (CDEFG) (9.5)	40.2 (CDE) (13.9)	14.7	47.6
Sweetbay	50.6 (FG) (10.3)	44.7 (ABCDE) (14.2)	5.9	47.7
Black tupelo	55.3 (CDEFG) (9.6)	46.6 (ABCDE) (12.5)	8.7	51.0
MEAN	**58.5 (8.4)**	**45.6 (8.2)**	**12.7**	**52.0**

[1] Each mean value represents 24 observations.
[2] Letters in parentheses represent Scheffé groupings. Species with similar letters are not statistically different at alpha = 0.05. Species comparisons were made within a particular surface (i.e., either transverse or tangential).
[3] Numbers in parentheses are coefficients of variation (%) = (standard deviation/mean) × 100.

Table 4. Summarized analysis of variance for the effect of 22 southern hardwood species and surface preparation technique (sanded and non-sanded) on contact angle. A separate analysis of variance was performed for sanded and non-sanded data. The p-values were similar for all sources of variation for both analyses

SOV[1]	df[2]	p-value
Species	21	0.0001**
Surface preparation (SP)[3]	1	0.0001**
Species x SP	21	0.0001**

** Denotes significance at alpha = 0.01.
[1] Source of variation
[2] Degrees of freedom
[3] Surface preparation was either sanded or non-sanded

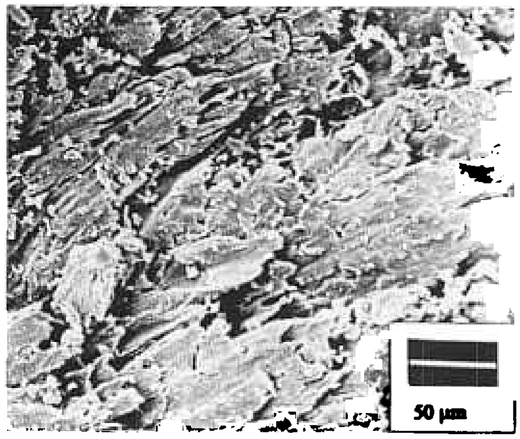

Fig. 1. Scanning electron micrograph of the transverse surface of a sanded yellow-poplar specimen.

low density, and the pore type variable was significantly correlated to SG (R = −0.80) (Table 5). Scheikl and Dunky (1998) found that the penetration behavior of liquids into wood surfaces depends on the different diameters of wood cells and the viscosity and molecule size of the penetrating liquids. However, pore type has been shown to be an important variable in wettability of wood.

The effect of surface preparation (i.e., sanding) was highly significant (Table 4). Contact angles on sanded specimens were greater than not sanded specimens by 3.9° and 12.0° for transverse and tangential surfaces, respectively. In general, sanding of a wood decreases the true surface area and decreases the roughness of the surface. It was expected that the smoother surface of sanded specimens would yield lower contact angles than the non-sanded specimens. However, inexplicably the opposite occurred. The sanded surfaces were visually determined to be smoother than non-sanded surfaces. This difference was confirmed from scanning electron micrographs. The sanded yellow-poplar transverse section (Fig. 1) appears to be smoother than the non-sanded specimen (Fig. 2). Similarly, the radial surface of a sanded southern red oak specimen (Fig. 3) is smoother than a corresponding non-sanded specimen (Fig. 4). It should be noted that surface roughness was not quantitatively measured in this study.

The findings in this study are in agreement with those of previous studies that have shown surface roughness has a minimal impact on wettability (Gray 1961, 1962; Herczeg

Table 5. Correlation coefficients (R) matrix of all experimental variables

	Pore type[1]	Sanded (X)[2]	Sanded (T)[3]	Sanded mean[4]	Not sanded (X)	Not sanded (T)	Not sanded mean	SG[5]	Darcy[6]	Fiber diam.[7]
Pore type		0.08[8]	−0.11	−0.00	−0.43	−0.42	−0.52	−0.80	−0.21	0.86
		(0.72)[9]	(0.64)	(1.00)	(0.04)	(0.05)	(0.01)	(0.00)	(0.34)	(0.00)
Sanded (X)	0.08		0.70	0.94	−0.02	0.16	0.06	−0.17	−0.27	0.19
	(0.72)		(0.00)	(0.00)	(0.94)	(0.49)	(0.78)	(0.46)	(0.22)	(0.39)
Sanded (T	−0.11	0.70		0.900	0.08	0.47	0.29	−0.05	−0.35	−0.00
	(0.64)	(0.00)		(0.00)	(0.73)	(0.03)	(0.18)	(0.81)	(0.11)	(1.00)
Sanded mean	−0.00	0.94	0.900		0.03	0.31	0.18	−0.13	−0.33	0.12
	(1.00)	(0.00)	(0.00)		(0.91)	(0.15)	(0.43)	(0.57)	(0.13)	(0.60)
Not sanded (X)	−0.43	−0.02	0.08	0.03		0.33	0.86	0.40	0.05	−0.53
	(0.04)	(0.94)	(0.73)	(0.91)		(0.14)	(0.00)	(0.06)	(0.84)	(0.01)
Not sanded (T)	−0.42	0.16	0.47	0.31	0.33		0.76	0.36	0.06	−0.37
	(0.05)	(0.49)	(0.03)	(0.15)	(0.14)		(0.00)	(0.10)	(0.78)	(0.09)
Not sanded mean	−0.52	0.06	0.29	0.18	0.86	0.76		0.47	0.07	−0.57
	(0.01)	(0.78)	(0.18)	(0.43)	(0.00)	(0.00)		(0.03)	(0.76)	(0.01)
SG	−0.80	−0.17	−0.05	−0.13	0.40	0.36	0.47		0.19	−0.75
	(0.00)	(0.46)	(0.81)	(0.57)	(0.06)	(0.10)	(0.03)		(0.40)	(0.00)
Darcy	−0.21	−0.27	−0.35	−0.33	0.05	0.06	0.07	0.19		−0.14
	(0.34)	(0.22)	(0.11)	(0.13)	(0.84)	(0.78)	(0.76)	(0.40)		(0.54)
Fiber diam.	0.86	0.19	−0.00	0.12	−0.53	−0.37	−0.57	−0.75	−0.14	
	(0.00)	(0.39)	(1.00)	(0.60)	(0.01)	(0.09)	(0.01)	(0.00)	(0.54)	

[1] Species data entered as 1 = ring porous, 2 = diffuse porous
[2] Transverse.
[3] Tangential.
[4] Mean of transverse and tangential values.
[5] Mean specific gravity (Choong *et al.* 1974).
[6] Longitudinal permeability Darcy values (Choong *et al.* 1974)
[7] Fiber radial diameter (Manwiller no year given).
[8] Pearson correlation coefficient (R).
[9] Probability > |R| under Ho: Rho = 0, N = 22.

1965). However, other studies have found decreasing wetting angles (improved wettability) with increasing roughness (Marian and Stumbo 1962a, b). It is acknowledged that surface roughness affects the contact angle measurement of wood; it is also apparent that other factors in addition to surface roughness have a significant effect and must be considered when considering the relationship between surface properties of the solid and a liquid. These other properties, including the surface tension and viscosity of the liquid, surface molecular packing, critical surface tension of the solid, and the solid-liquid interaction all impact contact angle values.

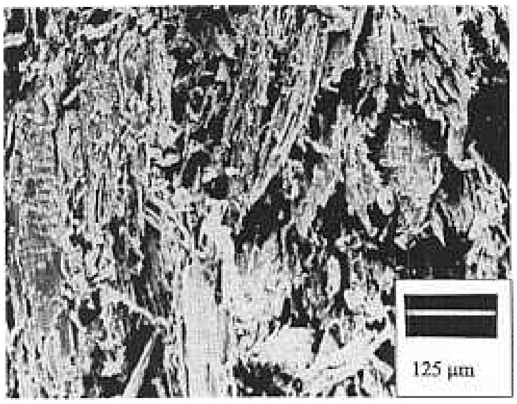

Fig. 2. Scanning electron micrograph of the transverse surface of a non-sanded yellow-poplar specimen.

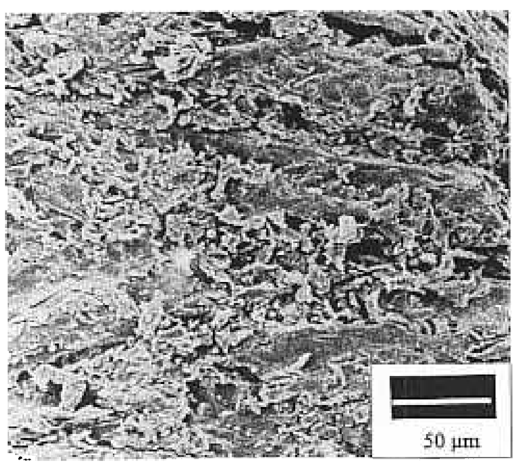

Fig. 3. Scanning electron micrograph of the radial surface of a sanded southern red oak specimen.

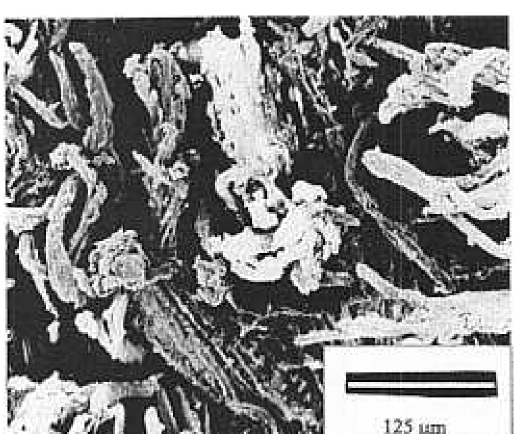

Fig. 4. Scanning electron micrograph of the radial surface of a non-sanded southern red oak

Wood surface (transverse, radial, and tangential) effect

The mean contact angle on the transverse, radial, and tangential surfaces for southern red oak, sweetgum, white oak, and post oak is shown in Table 6. As expected, values on the radial and tangential surfaces were similar because of the relative similar anatomical composition of these longitudinal surfaces compared to the transverse surface. As expected, contact angle values were higher on the transverse surface than the radial and tangential surfaces. This finding contradicts results from Gray (1962) who stated that there is no consistent difference between wettability of some 15 species of wood in different grain directions within the statistical variation encountered with readings in the same direction on the same specimen. The finding by Gray (1962) is peculiar given the inherent variability in wood surface chemistry, permeability, and anatomical structure that exists between species and these properties' influence on contact angle determination and wettability.

Drying method effect

Mean data for the four species included in the drying method effect study are presented in Table 6 and a summarized analysis of variance is shown in Table 7. It was anticipated that oven-dry specimens would give higher contact angles because of the deactivation of the surface that occurs due to the oven-drying process (Gardner *et al.* 1996) and the surface migration of extractives (Hse and Kuo 1988). The oven-dry specimens were dried at 105 °C for 24 hours. Oven-dry specimens yielded the highest mean contact angle of 63.3°, followed in decreasing order by air air-dry specimens (62.9°) and freeze-dry specimens (57.0°). Freeze-dried specimens gave the lowest mean contact angle. The freezing process likely preserves, rather than degrades, the chemical properties of the wood surface. Therefore, surface deactivation is minimal and wetting is more favorable.

This component of the study also investigated contact angles on all three surfaces of each of the four species. Transverse values were consistently higher than radial and tangential values, which were nearly identical. This pattern is largely attributable to the higher surface roughness and open cell lumens on the transverse surface. Compared to the transverse surface, the radial and tangential surfaces are more anatomically similar and would likely have similar surface roughness values.

It is acknowledged that there are other factors that influence contact angle measurements. Chen (1970) reported that wood extractives can influence the contact angle. Jordan and Wellons (1977) found that extraction significantly increased the wetting of dipterocarp veneers. Kajita and Skaar (1992) attributed greater wettability of sapwood compared

Table 6. Mean contact angle values of four southern hardwoods. Specimens were oven-dried, air-dried, or freeze-dried prior to contact angle determination on all three planes of the wood

	Oven-dry				Air-dry				Freeze-dry			
Species	Transverse	Radial	Tangential	Mean	Transverse	Radial	Tangential	Mean	Transverse	Radial	Tangential	Mean
S. red oak	53.3[1] Ca[2] (6.0)[3]	51.2 Ca (7.8)	48.2 Cb (4.9)	51.0	55.2 Da (13.4)	46.4 Bb (6.8)	47.7 Bb (3.0)	49.8	48.3 Ba (9.0)	39.8 Bb (5.9)	41.9 Bb (7.2)	43.3
Sweet-gum	98.0 Aa (8.9)	69.0 Ab (7.8)	66.5 Ab (3.8)	77.8	86.9 Aa (9.3)	63.2 Ab (4.4)	64.3 Ab (6.8)	71.5	73.5 Aa (6.2)	55.6 Ab (13.1)	62.2 Ab (4.6)	63.8
White oak	71.2 Ba (4.7)	57.2 Bb (4.8)	56.4 Bb (9.5)	61.6	78.9 Ba (5.0)	62.3 Ab (4.6)	60.8 Ab (5.5)	67.3	68.3 Aa (6.1)	63.3 Aa (4.2)	55.5 Ab (7.0)	62.4
Post oak	68.9 Ba (4.8)	59.8 Bb (8.7)	59.9 Bb (9.4)	62.9	72.0 Ca (2.6)	58.4 Ab (3.3)	58.2 Ab (5.1)	62.9	63.0 Aa (4.9)	56.3 Ab (6.1)	56.0 Ab (7.8)	58.4
MEAN	72.9	59.3	57.8	63.3	73.3	57.6	57.8	62.9	63.3	53.8	53.9	57.0

[1] Each mean value represents 100 observations. There were ten observations per sample.
[2] Captial letters denote Scheffé comparisons for a particular method of drying and a particular plane of wood. These comparisons were made downward for each column. Lower case letters denote Scheffé comparisons for a particular species and method of drying. These comparisons were made across a row for a particular species and drying method.
[3] Numbers in parenthesis are coefficients of variation (%).

Table 7. Summarized analysis of variance of the effect of species (southern red oak, sweetgum, white oak, and post oak), drying method, and wood plane on contact angle determination

SOV[1]	df[2]	P-value
Species (S)	3	0.0001**
Drying method (D)	2	0.0001**
Plane (P)	2	0.0001**
S*D	6	0.0001**
S*P	6	0.0001**
D*P	4	0.0011**
S*D*P	12	0.0019**

[1] Source of variation.
[2] Degrees of freedom.
** = Denotes significance at alpha = 0.01

to heartwood, to the higher extractive content of heartwood. Although extractives tend to dominate the wood surface, all the chemical components comprising wood contribute to its surface chemistry and thus affect surface activation (Gardner *et al.* 1996). In addition, the surface tension and viscosity of the liquid, surface molecular packing, critical surface tension of the solid, and the solid-liquid interaction all impact contact angle values. Surface roughness also affects contact angle because it creates more than one metastable state at the solid-liquid-vapor interface (Johnson and Dettre 1993).

Conclusions

This study was initiated to determine the contact angle of 22 southern hardwood species on sanded and non-sanded surfaces of transverse and tangential surfaces. Moreover, four species were selected to determine contact angles on transverse, tangential, and radial surfaces with regard to three different drying methods.

Contact angle values differed significantly between species and between the 22 species, sanded and non-sanded surfaces, and transverse and tangential planes. Contact angles on transverse planes were higher than those on tangential planes. Both transverse and tangential planes yielded higher values on sanded surfaces as compared to non-sanded surfaces. Contact angles were found to vary significantly according to drying method and wood surface. Contact angle values observed on transverse surfaces were higher than those observed on radial and tangential surfaces. Air-dried specimens on average had the highest contact angles, and freeze-dried specimens typically gave the lowest contact angles. Many of the differences in contact angle values are largely attributed to surface roughness differences of the different species and different wood surfaces.

Acknowledgement

This paper (No. 00-22-0216) is published with the approval of the Director of the Louisiana Agricultural Experiment Station.

References

Adams, N.K. 1949. The Physics and Chemistry of Surfaces. Third ed. Oxford University Press, London.
Bodig, J. 1962. Wettability related to gluabilities of five Philippine mahoganies. Forest Prod. J. *12*(6), 265–270.
Chen, C.M. 1970. Effect of extractive removal on adhesion and wettability of some tropical woods. Forest Prod. J. *20*(1), 36–40.
Choong, E.T., F.O. Tesoro and F.G. Manwiller. 1974. Permability of twenty-two small diameter hardwoods growing on southern pine sites. Wood Fiber *6*(1), 91–101.
Freeman, H.A. 1959. Relation between physical and chemical properties of wood and adhesion. Forest Prod. J. *9*(12), 451–458.

Gardner, D.J., M.P. Wolcott, L. Wilson, Y. Huang, and M. Carpenter. 1996. Our understanding of wood surface chemistry in 1995. *In*: Wood Adhesives. Eds. A.W. Christiansen and A.H. Conner. 1995. Forest Products Society. Madison, WI. pp. 29–36.

Gray, V.R. 1961. Wetting, adhesion and penetraton of surface coatings on wood. J. Oil and Colour Chemists' Assn. *44*, 756–786.

Gray, V.R. 1962. The wettability of wood. Forest Prod. J. *12*(9), 452–461.

Hameed, M. and E. Roffael. 1999. Über die Benetzbarkeit von Splint- und Kernholz der Kiefer, Douglasie und Lärche. Holz Roh- Werkstoff *57*, 287–293.

Herczeg, A. 1965. Wettability of wood. Forest Prod. J. *15*(11), 499–505.

Hse, C.Y. 1972. Wettability of southern pine veneer by phenol formaldehyde wood adhesives. Forest Prod. J. *22*(1), 51–56.

Hse, C.Y. and M.L. Kuo. 1988. Influence of extractives on wood gluing and finishing – a review. Forest Prod. J. *38*(1), 52–56.

Johnson, R.E. and R.H. Dettre. 1993. Wetting of low-energy surfaces. *In*: Wettability. Ed. J.C. Berg. Marcel Dekker Inc. New York. pp. 1–74.

Jordan, D.L. and J.D. Wellons. 1977. Wettability of dipterocarp veneers. Wood Sci. *10*(1), 22–27.

Kajita, H. and C. Skaar. 1992. Wettability of the surfaces of some American softwoods species. Mokuzai Gakk. *38*, 516–521.

Manwiller, F.G. Stemwood and branchwood fiber dimensions (transverse) in 6-inch-diameter hardwoods of 22 species grown on southern pine sites. Data in files of USDA Forest Serv. Southern Research Station. Study FS-SO-3201-1.42. Pineville, LA.

Marian, J.E. and D.A. Stumbo. 1962a. Adhesion in wood: Part I. Physical factors. Holzforschung *16*(5), 134–148.

Marian, J.E. and D.A. Stumbo. 1962b. Adhesion in wood: Part II. Physico-chemical surface phenomena and the thermodynamic approach to adhesion. Holzforschung *16*(6), 168–180.

SAS Institute, Inc. 1989. SAS/STAT User's guide. Version 6, 4th ed., Vol. 2. Cary, N.C. 846 pp.

Scheikl, M. and M. Dunky. 1998. Measurement of dynamic and static contact angles on wood for the determination of its surface tension and the penetration of liquids into the wood surface. Holzforschung *52*, 89–94.

Suschland, O. and R.R. Stevens. 1968. Gluability of southern pine veneer dried at high temperatures. Forest Prod. J. *18*(1), 38–42.

Wenzel, R.N. 1936. Resistance of solid surfaces to wetting by water. Ind. Eng. Chem. *28*, 988–994.

Zisman, W.A. 1964. Relation of the equilibrium contact angle to liquid and solid constitution. *In*: Contact Angle, Wettability and Adhesion. Advances in Chemistry Series No. 43. American Chemical Society. Washington, DC. pp. 1–51.

Zisman, W.A. 1976. Influence of constitution on adhesion. *In*: Handbook of Adhesives. 2nd ed. Van Nostrand Reinhold Co., New York. pp. 33–71.

Received June 7th 2000

Todd F. Shupe[1]
Assistant Professor
School of Forestry, Wildlife, and Fisheries
Louisiana State University Agricultural Center
Baton Rouge, LA 70803
U.S.A.

Chung Y. Hse[2]
Principal Wood Scientist
USDA Forest Service
Southern Research Station
Pineville, LA 71360
U.S.A.

Wan H. Wang
Associate Professor
Department of Wood Science and Technology
Nanjing Forestry University
Nanjing
Peoples Republic of China

[1] Author to whom correspondence should be directed.
[2] Addresses where the work was performed.