The Influence of Mechanical Surface Preparation Methods on Southern Pine and Spotted Gum Wood Properties: Wettability and Permeability

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The demand for engineered wood products (EWPs) continues to rise internationally. However, for some important Australian commercial timbers such as plantation grown southern pine and native forest sourced spotted gum, a major impediment to achieving commercially viable EWP production is difficulties experienced in gluing – particularly for sawn laminate based EWPs such as glulam. Wettability and permeability have a major influence on wood adhesion. This study investigated the efficacy of different surface machining preparations on the wettability and permeability of southern pine and spotted gum. For both species, planing resulted in poor wettability, whereas face milling and sanding treatments post-planing improved wettability. Wettability increased in southern pine earlywood compared to latewood; and wettability decreased for both species with increased time post-surface machining. Planing resulted in the highest permeability for southern pine but the lowest permeability for spotted gum. Face milling resulted in higher permeability compared to sanding treatments.

Keywords: Wood surface machining; Wood wettability; Wood permeability; Wood adhesion; Pinus elliottii; Pinus caribaea; Corymbia citriodora

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INTRODUCTION

The softwood and hardwood timber supply for Queensland, Australia, is dominated by plantation grown southern pine (*Pinus elliottii* [PEE], *Pinus caribaea* [PCH], PEE x PCH -the hybrid between these two species), and native forest grown spotted gum (*Corymbia citriodora*) respectively (Queensland Government 2016). Although these species have many commercially attractive and valuable wood properties, they can be difficult to glue, especially when targeting durable and structural quality bonds. The technical challenges encountered in gluing these species have been mainly attributed to their high density and wood extractives chemistry relative to many other commercial timbers that are easier to glue (Widtsen *et al.* 2006; Vella *et al.* 2019).

Given ongoing trends of diminishing log size and quality from forest resources, coupled with shifts in markets towards more sustainable materials, the demand for and use of engineered wood products (EWPs) continues to increase globally (Market Research Future 2020). In response, the Australian industry seeks to increase the production of EWPs to meet the increasing demand. One target product group is glue-laminated timber (glulam) for post and beam type products as a substitute for larger dimension sawn timber. Historically, these would have been sourced mainly from now scarce, large dimensioned and high quality sawn hardwood. A major impediment to greater commercial production of structural glulam from southern pine and spotted gum in Queensland is the difficulty in achieving consistently durable glue-bonds suitable for structural products within commercially acceptable production timeframes and costs. For southern pine, this problem has been shown to be worse for higher density wood such as that typical of higher stiffness grades used in structural glulam (Vella 2020).

Suitable preparation of the wood surface is considered critical in achieving successful wood adhesion. Mechanical surface preparation is a standard international timber industry practice that is used to facilitate wood adhesion. The most typical method used is planing of the wood surface before gluing (Knorz *et al.* 2015). Mechanical preparations have been shown to increase the wettability of the wood surface, enhance adhesive penetration and improve wood adhesion by activating the wood surface through the removal of extractives (which have migrated to the surface) and contaminants (*e.g.*, dust and dirt), by creating microcracks and exposing wood cell lumens (Vick 1999; Sernek 2002; Aydin 2004; Vella 2020). Mechanical surface preparation can also rupture the molecular bonds between wood components, creating open bonds; this increases the number of active sites for the adhesive polar groups to bond to (Vella 2020). Mechanical surface preparations also create a flat surface allowing for a close fit between the two wood adherends, which is necessary for strong glue lines (Vick 1999; Vella 2020). A further benefit of some mechanical surface preparation methods, especially those that increase surface roughness and fibrillation, is to increase the surface area and number of mechanical interlocking sites for the adhesive to bond with the wood.

Previous studies have compared the benefits for wood adhesion of different mechanical surface preparation methods such as planing, sanding post-planing, face milling, and more recently, scarification or incising (Hernández and Cool 2008a,b; Kläusler *et al.* 2014; Knorz *et al.* 2015; Vella *et al.* 2019; Vella 2020). Various studies have generally shown face milling to be more successful in improving the glue-bond quality of timbers compared to either planing or sanding post-planing, although results vary depending on adhesive type and timber species (Kläusler *et al.* 2014; Knorz *et al.* 2015; Vella 2020).

Planing, and to a lesser degree, sanding post-planing, are methods commonly targeted by the Australian timber industry to try and improve the quality of bonds. Face milling has not yet been tested on Australian commercial timbers as a means to improve wood adhesion. Another type of mechanical surface preparation, scarification or incising, has been shown to dramatically improve the bond performance of southern pine timber with isocyanate adhesives (Vella *et al.* 2019), although it is currently limited in its commercial viability due to the much greater adhesive spread rates required and the long production times involved.

In investigating the influence of mechanical surface preparation techniques on the gluability of wood, many studies have focused on the wettability of the wood surface through liquid droplet contact angle measurements. The wettability of wood refers to an adherend's ability to attract a liquid, such as an adhesive (Hovanec 2015). Adequate wetting of the surfaces of adherends is necessary to achieve a strong adhesive bond (Wellons 1980; River *et al.* 1991; Hovanec 2015). Different mechanical surface preparations have been shown to influence the wettability of wood, and positive relationships have been shown between wettability and improved bond quality (Sernek 2002; Aydin 2004; Hernández and Cool 2008; Kläusler *et al.* 2014). Wettability is also an important indicator in many other wood manufacturing areas such as application of wood preservatives, paints, varnishes, and coatings.

Permeability is a measure of the ease with which liquids and gases flow through a porous substance under the influence of a pressure gradient (Comstock 1968; Tesoro 1973; Milota *et al.* 1994; Leggate *et al.* 2019; Leggate *et al.* 2020). The permeability of wood influences many of its important processing and utilization properties including gluing, but also drying, preservation, wood modification systems, pulping, finishing, and even durability (Fogg 1968; Tesoro 1973; Hansmann *et al*. 2002; Zimmer *et al*. 2014; Leggate *et al.* 2019, 2020). Wood permeability is one of the main controlling factors influencing the depth of adhesive penetration (Burch 2015; Hovanec 2015; Kumar and Pizzi 2019). Given its importance, many studies have been conducted to investigate ways to improve the permeability of wood, and these range from chemical pre-treatments and adjuvants, biological techniques such as using microorganisms, microbial enzymes and biological incising, physical or mechanical methods such as steaming, knife-incising, compression, and microwave treatments. However, the information specific to the effect of different mechanical surface preparations such as planing, post-planing sanding, and face milling on permeability is scarce.

This study investigates the effect of various surface machining preparation methods on the wettability and permeability of southern pine and spotted gum wood from Queensland, Australia. Its primary objective is to evaluate the efficacy of the different surface preparation techniques in improving the gluability of these major Australian commercial timbers.

EXPERIMENTAL

Wood Samples

Southern pine from Queensland plantations and native forest grown spotted gum (*Corymbia citriodora*) were included in the study. In Queensland, southern pine timber is produced and sold commercially without any separation of species, and is typically comprised of *Pinus elliottii [PEE], Pinus caribaea [PCH]*, or *PEE x PCH* -the hybrid between these two species. The southern pine was graded as machine-graded pine 15 (MGP15). The difficulties in gluing southern pine have been shown to increase with higher density wood. Therefore, targeting MGP15 ensured that higher density southern pine was used in the study. The spotted gum boards used for the study were defect-free feedstock destined for milled products such as flooring and decking. Seasoned boards were randomly selected from packs obtained from commercial providers of these timbers.

Sample Preparation

For each species, boards were initially machined into pieces with dimensions of 20 mm x 11 mm (for wettability) and 30 mm x 11 mm (for permeability). All pieces were cut free of defects. These pieces were then conditioned in a constant environment chamber set at 20 °C and 65% relative humidity (RH) (12% equilibrium moisture content [EMC]).

Table 1. Mechanical Surface Machining Preparations

Surface Machining Identifier	**Surface Machining Method**	**Machine Details**	**Cutter Specifications**	**Feed, Cutter and Sanding Speeds**
SM1	Face milling (fast feed speed and fast cutter speed).	Ledinek, Rotoles 400 D-S, (Hoče, Slovenia) Face Miller	Type: Tungsten Carbide Pt No: Leucodur – HL 40 Dim: 14 x 14 x 2 mm 48 Cutters @ 520mm Ø	Feed rate = 45 m/min, Cutter speed = 3000 rpm (82 m/sec)
SM2	Face milling (fast feed speed and slow cutter speed).	Ledinek, Rotoles 400 D-S, (Hoče, Slovenia) Face Miller	Type: Tungsten Carbide Pt No: Leucodur – HL 40 Dim: 14 x 14 x 2 mm 48 Cutters @ 520mm Ø	Feed rate = 45 m/min, Cutter speed = 2100 rpm (57 m/sec)
SM3	Face milling (slow feed speed and fast cutter speed).	Ledinek, Rotoles 400 D-S, (Hoče, Slovenia) Face Miller	Type: Tungsten Carbide Pt No: Leucodur – HL 40 Dim: 14 x 14 x 2 mm 48 Cutters @ 520mm Ø	Feed rate = 10 m/min, Cutter speed = 3000 rpm (82 m/sec)
SM4	Face milling (slow feed speed and slow cutter speed).	Ledinek, Rotoles 400 D-S, (Hoče, Slovenia) Face Miller	Type: Tungsten Carbide Pt No: Leucodur – HL 40 Dim: 14 x 14 x 2 mm 48 Cutters @ 520mm Ø	Feed rate = 10 m/min Cutter speed = 2100 rpm (57 m/sec)
SM5	Planing	SCM Group Mini Max, Formula SP1 Planer, (Rimini, Italy)	High Speed Steel Blade 40.5° Blade tip angle 120mm Cutterblock Ø	Feed Rate: 8 m/min Cutter RPM: 4500 (28 m/sec)
SM6	Planing and sanding (40 grit).	SCM Group Mini Max, Formula SP1 Planer, (Rimini, Italy) and SCM Group, SANDYA 16S, Model 16/S M2 135 Belt Sander (Rimini, Italy)	Belt : KLINGSPOR PS 29 F Grit: Aluminium Oxide Backing: Paper	Planed 8 m/min feed rate + Sanding using 40 grit belt removing 0.3mm Belt Speed = 18m/min Feed rate = 3.5m/min
SM7	Planing and sanding (80 grit).	SCM Group Mini Max, Formula SP1 Planer (Rimini, Italy) and SCM Group, SANDYA 16S, Model 16/S M2 135 Belt Sander (Rimini, Italy)	Belt : KLINGSPOR PS 29 F Grit: Aluminium Oxide Backing: Paper	Planed 8 m/min feed rate + Sanding using 80 grit belt removing 0.3mm Belt Speed = 18 m/min Feed rate = 3.5 m/min

Surface Machining

After conditioning, the samples were randomly allocated to seven different mechanical surface machining preparations (Table 1). During each surface machining process described in Table 1, 1.5 mm was removed from the upper and lower timber surface to reduce the thickness from 11 mm to 8 mm. Test samples were then prepared to the final dimension for wettability tests (20 mm [width] x 8 mm [thickness] x 50 mm [length]) and permeability tests (24 mm [diameter] x 8mm [thickness]). Thirteen wettability samples and 20 permeability samples were prepared for each of the seven surface machining types.

Wettability

The wettability was determined by using the sessile drop method: by measuring the contact angle of a drop of pure water on the timber surface (Burch 2015). Contact angle is the angle that the liquid forms with a solid, shown in Fig. 1 (Burch 2015). Since the tendency for a liquid to spread increases as contact angle decreases, the determination of contact angles is a useful inverse measure of wettability (Zisman 1964). Contact angles were measured at three time intervals: <3 min, 15 min and 30 min after surface preparation. For southern pine, whether the contact angle measurement point on the sample was on earlywood or latewood was also recorded for each contact angle test.

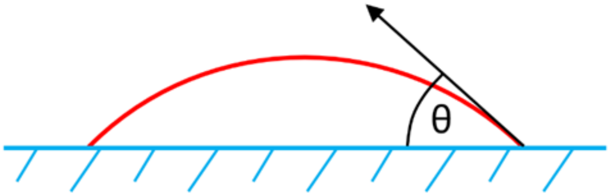

Fig. 1. Contact angle *(θ)* for a liquid droplet on a solid surface (Burch 2015)

Test set up

The wettability test configuration is shown in Fig. 2. An electronic pipette (Labco Electronic Pipettor, Labco Limited, Lampeter, Wales) was mounted on a stand so that the default position of the pipette tip was approximately 20 mm from the sample surface. The pipette could be moved vertically towards the sample surface to place a water droplet onto the sample surface but automatically retracted once manual control was released. A video camera (Samsung Galaxy A20, Samsung, Seoul, South Korea) was positioned approximately 10 mm in front of the sample and level with the timber surface. The camera was used to record the process of the droplet being applied and spreading on the sample surface. A clip-on macro lens (Apexel, APL-24XMH, Shenzen Apexel Technology Co. Ltd, Guangdong, China) was attached to the camera to provide adequate magnification of the droplet. The macro lens and camera combined provided a total of around 50x magnification (21x from the macro lens and about 2.5x from the camera). The camera was securely mounted to prevent movement and vibration.

Test procedure

A droplet of 1 μL water (HPLC-grade) was dispensed from the pipette per test. The pipette was manually repositioned towards the sample surface to aid dispensing and then immediately retracted once the droplet moved onto the sample surface. The process of the droplet dispensing and a minimum of ten seconds following were recorded by video.

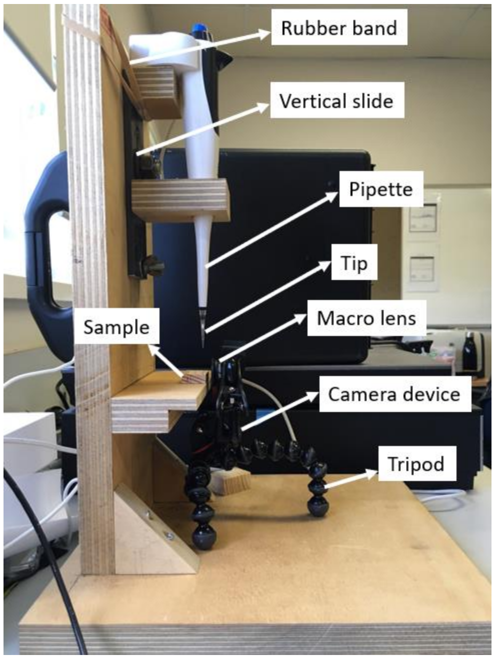

Fig. 2. Contact angle test setup

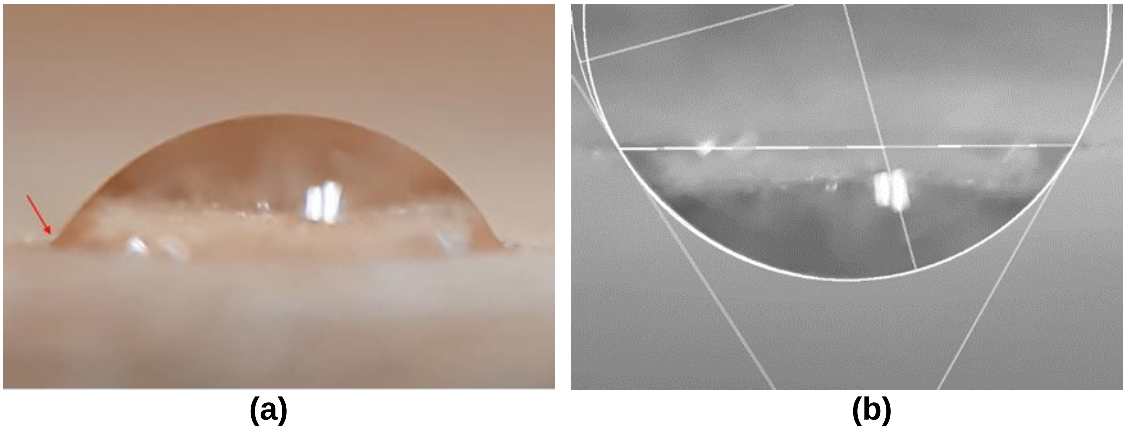

Fig. 3. Water droplet in contact with timber surface. (a) A drop of water on spotted gum surface. (b) Same drop as in (a) processed with the ImageJ software (note the image is inversed as part of the processing).

Contact angle measurement

For each sample, screenshots of the video were saved as images at specific times. The first image was taken once the pipette had applied the droplet on the surface (Fig. 3A) and after that, one image was taken per second until 10 seconds later, providing a total of 11 contact angle images. These images were processed by the open-source software, ImageJ (IJ 1.46r) (U.S. National Institutes of Health, Maryland, USA) (Schneider *et al*. 2012) with the contact angle plugin (Lamour *et al.* 2010) (Fig. 3B). For each ImageJ measurement, two points were manually selected at the intersection of solid-liquid-air interfaces (marked by an arrow in Fig. 3A) to define the baseline and four points along the drop profile. The ImageJ contact angle plugin then fitted the points with the sphere approximation or ellipse approximation and calculated the contact angle.

The change in contact angle over time was assessed using the wettability model developed by Shi and Gardner (2001) for wood. This wettability model has been adopted by many researchers for assessing the wettability of various wood surfaces (Burch 2015, Qin *et al.* 2014; Wang *et al.* 2015), where the model was developed to quantify the change in contact angle over time. The wetting model is shown in Eq. 1,

$$\theta = \frac{\theta_i \theta_e}{\theta_i + (\theta_e - \theta_i) \exp\left[K\left(\frac{\theta_e}{\theta_e - \theta_i}\right) t\right]} \qquad (1)$$

where θ_i is the initial contact angle at time 0 sec, θ_e is the equilibrium contact angle (for our data, at the 10 second test time), t is time (seconds), and K is the constant intrinsic relative contact angle decrease rate (1/sec). The K-value represents the rate at which a liquid spreads and penetrates across or into the wood substrate (Shi and Gardner 2001; Burch 2015). A high K-value represents a liquid that quickly spreads and/or penetrates into the wood surface, while a low K-value represents a liquid that slowly spreads and/or penetrates into the wood surface. A K-value of zero represents no change between initial and equilibrium contact angles (Burch 2015). The nonlinear least square method (nls function in R studio) was used to estimate the K-value of the nonlinear model (Baty *et al.* 2015). The contact angle values at time 0 s and at 10 s were assigned as initial (θ_i) and equilibrium (θ_e) contact angle respectively. The initial value of K was assigned to 0.3 in the nls function.

Permeability

Samples for permeability tests were 24 mm in diameter and 8 mm in thickness (flow direction). Each sample was coated with epoxy resin on its lateral surface in order to direct gas and liquid movement in the radial direction in order to measure only radial permeability.

Radial permeability measurements were undertaken using a Porolux 1000 Porometer (1B-FT GmbH, Berlin, Germany). Both gas and liquid permeability were measured for southern pine, with gas permeability tests undertaken before liquid permeability tests. For spotted gum, only gas permeability was measured because no liquid flow was achieved for liquid permeability measurement. For gas permeability, samples were subjected to pressurized, atmospheric air until pressure reached the target pressure of 4000 millibars. For liquid permeability, samples were subjected to pressurized water (non-distilled) with a constant pressure of 4000 millibars for 5 min. All permeability measurements were recorded in less than 45 min after surface machining. Permeability was calculated in accordance with Darcy's law as follows,

$$Q = K \cdot \frac{A}{L} \cdot \frac{1}{\eta}\, \Delta P \qquad (2)$$

where Q, K, A, L, η, and ΔP are the liquid or air volume flow rate ($m^3.s^{-1}$), specific permeability of wood (m^2), sample length in the direction of flow (m), dynamic viscosity of the liquid or air (Pa.s), and the pressure drop, respectively (Pa) (Kucerová 2012).

Statistical Analysis

Statistical analysis was carried out using GenStat v19 (VSN, Hemel Hempstead, United Kingdom). Both ANOVA and pairwise comparisons using Fishers Protected Least Significant Differences were used. For contact angle data for each species, only values at

0 and 10 second test times were analysed, and these were done separately, because of large differences (and variances) between the two. These analyses had 2 strata. The first was a one-way analysis comparing machine treatments, and the second strata involved delay times and included an interaction between machine treatments and delay. For the pine species, all data were used (earlywood and latewood) in these analyses. A separate analysis of pine species, using earlywood and latewood as a third factor was performed. In this analysis the first strata comprised a machine treatment × wood type factorial with the second strata involving delay as before.

RESULTS AND DISCUSSION

Wettability

Southern pine

Contact angle results are shown for southern pine in Table 2 and Figs. 4 to 6. Across all surface machining treatments and test times, the contact angle for southern pine decreased over the 10 second test period from mean values above 35° to 0° in many cases. Differences between contact angle at different test times (from 0 to 10 seconds) were significant (p<0.001). This reflects the typical wetting process, which includes: the formation of a contact angle between the surface and the droplet, the spreading of the droplet on the surface, and then the penetration of the droplet into the sample. Contact angle also tended to significantly increase and consequently surface wettability decrease with increasing time after surface machining (p=<0.001 for 0 and 10 second contact angle test times) (Fig. 6 and Table 2). This has been observed in other studies and has been attributed to 'ageing' of the wood surface linked to physical and chemical modifications of the wood surface (Gardner *et al*. 1991; Sernek 2002; Gindl *et al*. 2004; Piao *et al. 2010;* Santoni and Pizzo 2011; Qin *et al*. 2015). According to Burch (2015), a material's highest possible surface energy (therefore wettability) is obtained immediately following machining and exposure of a fresh surface. This reinforces the advantage of applying adhesive to the wood surface as soon as possible after surface machining.

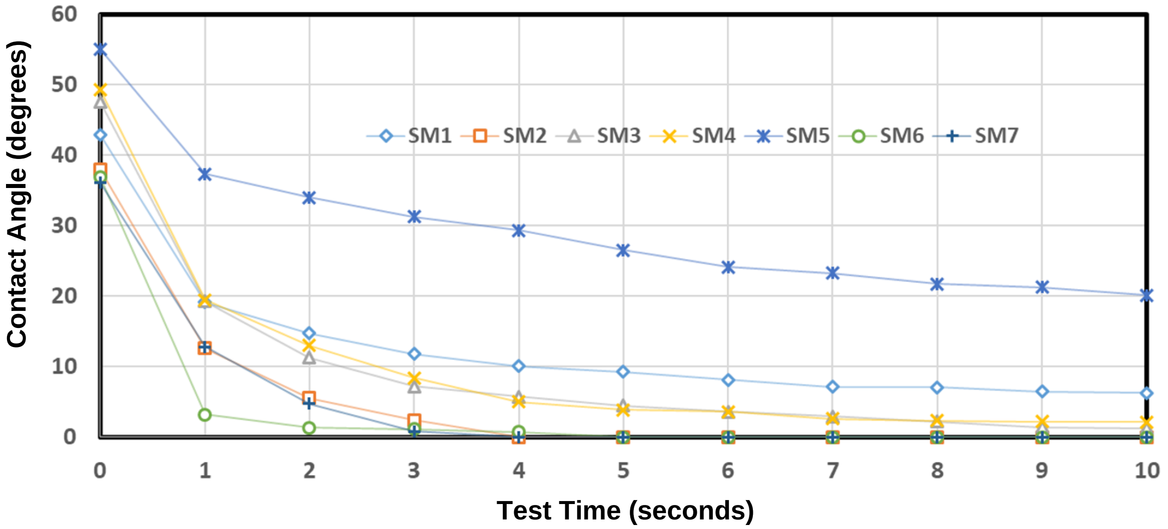

Fig. 4. Change in mean contact angle over a 10 second test time at <3 min after surface machining (southern pine)

Table 2. Summary of Contact Angle Measurements for Southern Pine

Surface Machining Method	Test Time (seconds)	Time after Surface Machining (min)	Mean Contact Angle (degrees)*	Mean K-value**
SM1	0[a]	<3	43 (14)	-
		15	45 (13)	-
		30	48 (13)	-
	10[b]	<3	6 (10)	1.28
		15	7 (10)	1.22
		30	7 (12)	1.13
SM2	0	<3	38 (10)	-
		15	41 (10)	-
		30	48 (8)	-
	10	<3	0 (0)	3.19
		15	0 (0)	3.26
		30	1.8 (5)	1.95
SM3	0	<3	48 (8)	-
		15	48 (13)	-
		30	51 (14)	-
	10	<3	1 (5)	1.83
		15	5 (10)	1.03
		30	3 (8)	1.71
SM4	0	<3	49 (15)	-
		15	45 (14)	-
		30	49 13)	-
	10	<3	2 (8)	1.89
		15	1 (4)	1.57
		30	4 (9)	1.15
SM5	0	<3	55 (7)	-
		15	59 (7)	-
		30	62 (8)	-
	10	<3	20 (10)	0.39
		15	16 (11)	0.52
		30	21 (13)	0.43
SM6	0	<3	37 (8)	-
		15	40 (5)	-
		30	45 (7)	-
	10	<3	0 (0)	12.23
		15	0 (0)	2.23
		30	1 (4)	2.60
SM7	0	<3	36 (4)	-
		15	39 (11)	-
		30	44 (9)	-
	10	<3	0 (0)	3.23
		15	0 (0)	3.40
		30	0.9 (3)	3.03

[a] For 0 second test time, Mean Contact Angle Least Significance Difference (LSD)1(0.05)=5.5; LSD2(0.05)=8.2 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.

[b] For 10 second test time, Mean Contact Angle LSD1(0.05)=4.1; LSD2(0.05)=5.7 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.

**Standard deviations are presented in parentheses*

***K-values are only calculated after 10 seconds, therefore not applicable to test time of 0 seconds*

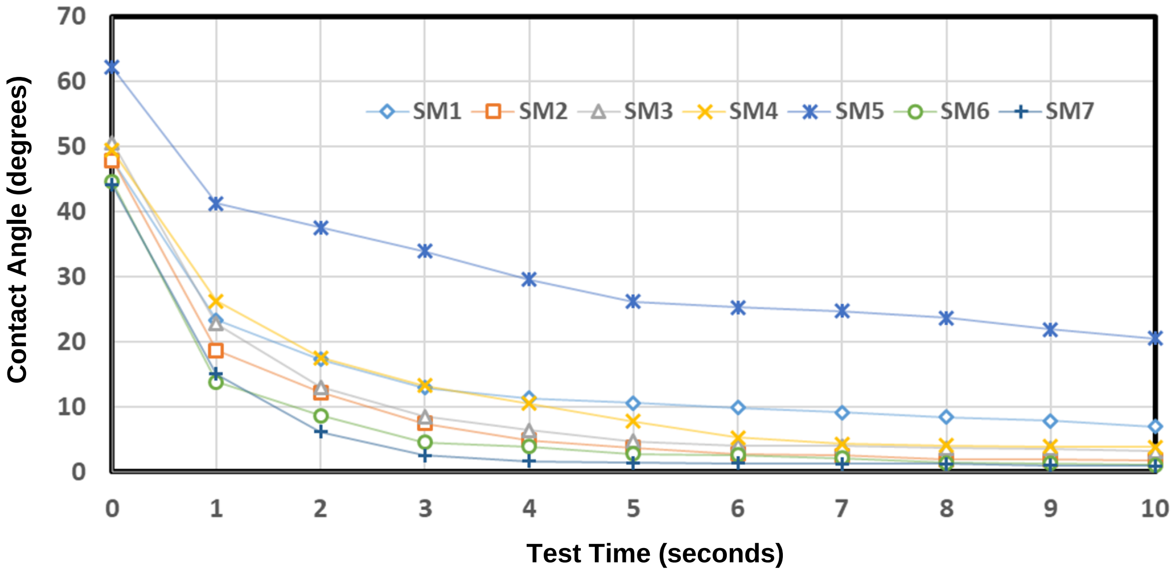

Fig. 5. Change in mean contact angle over a 10 second test time at 30 min after surface machining (southern pine)

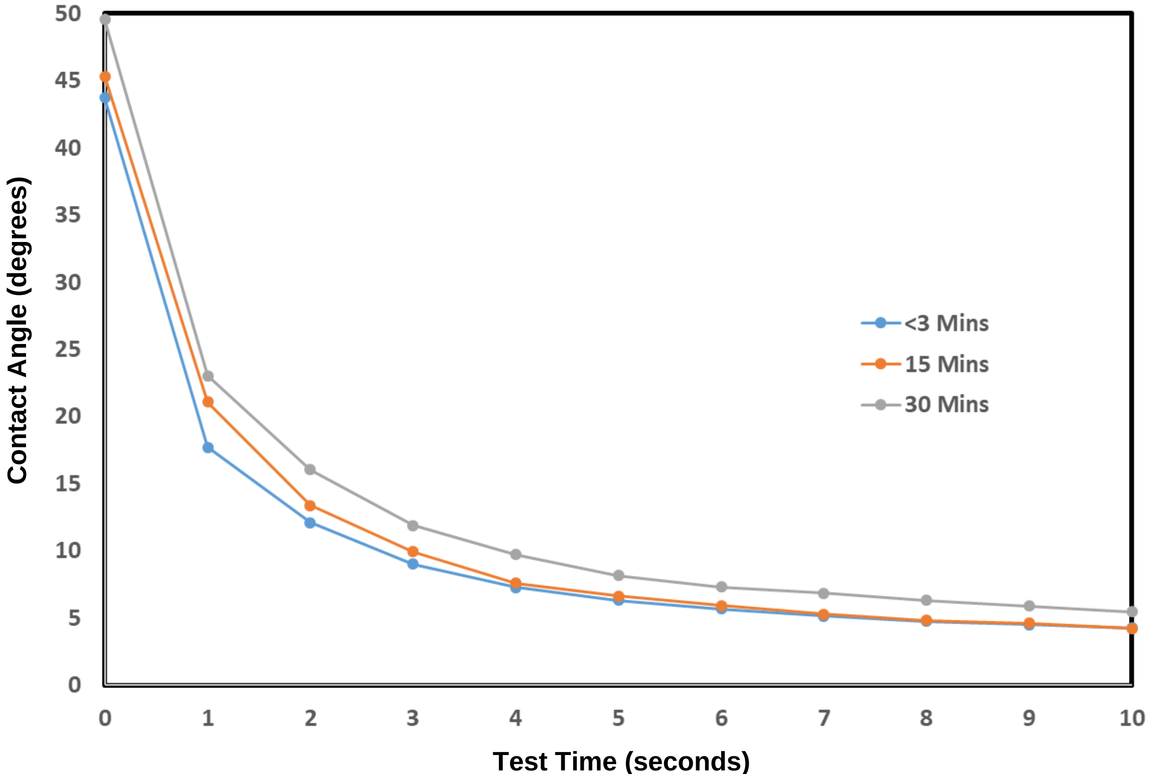

Fig. 6. Mean contact angle for different intervals after surface machining and for each test time (southern pine)

Surface machining method had a significant effect on contact angle ($p<0.001$ for 0 and 10 second contact angle test times). When compared at the 10 second test time period, for all timeframes after surface machining, the highest mean contact angle and therefore the lowest surface wettability was recorded with the planing surface machining method (SM5). The lowest mean contact angle and therefore highest surface wettability varied depending upon time frame after surface machining; however, the surface machining methods- 80 grit sanding post-planing (SM7), 40 grit sanding post-planing (SM6), and face milling with fast feed/slow cutter speed (SM2) performed similarly, producing high wettability compared to other surface machining methods. This result is in line with numerous studies which report that the rougher surface produced by sanding or face milling improves the wettability of wood compared to planing (Stehr *et al.* 2001; Aydin 2004; Hernández and Cool 2008; Arnold 2010; Huang *et al.* 2012; Kläusler *et al.* 2014; Qin *et al.* 2015; Jankowska *et al.* 2018). Stehr *et al.* (2001) attributed the improved wettability of rougher surfaces to the increased surface area, which facilitates the movement and penetration of liquids due to capillary forces. Another explanation for the improved wettability with increased surface roughness is the greater exposure of hydrophilic active groups (hydroxyl groups) on the wood surface (Qin *et al.* 2015; Jankowska *et al.* 2018).

As shown in Table 3, the contact angles for earlywood were overall significantly lower than latewood for all timeframes after surface machining (p<0.001 for 0 and 10 second contact angle test times). This is in accordance with other studies that have shown that pine earlywood has higher wettability and is also easier to glue compared to latewood (Herczeg 1965; Hse 1968; Scheikl and Dunky 1998). The higher wettability of earlywood is related to its lower density, larger tracheid lumen diameters and higher porosity compared to latewood (Scheikl and Dunky 1998; Frihart 2013).

Table 3. Summary of Contact Angle Measurements for Earlywood and Latewood of Southern Pine

Surface Machining Method	**Test Time (seconds)**	**Time after Surface Machining (min)**	**Mean Contact Angle (degrees)***	**Mean K-value****
Earlywood	0[a]	<3	38 (11)	-
		15	37 (9)	-
		30	42 (11)	-
	10[b]	<3	2 (7)	3.28
		15	1 (5)	3.43
		30	3 (7)	3.58
Latewood	0[a]	<3	46 (10)	-
		15	48 (11)	-
		30	53 (10)	-
	10[b]	<3	6 (10)	1.06
		15	7 (11)	0.95
		30	8 (12)	0.83

[a] For 0 second test time, Mean Contact Angle LSD1(0.05)=3.1; LSD2(0.05)=3.6 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.
[b] For 10 second test time, Mean Contact Angle LSD1(0.05)=2.1; LSD2(0.05)=2.3 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.
**Standard deviations are presented in parentheses*
***K-values are only calculated after 10 seconds, therefore not applicable to test time of 0 seconds*

Table 4. Summary of *K* results for Earlywood and Latewood for each Surface Machining Method (Southern Pine)

Earlywood/Latewood	Surface Machining Method	Time after Surface Machining (min)	Mean K-Values
Earlywood	SM1	<3	14.91
		15	7.24
		30	7.04
	SM2	<3	2261.92*
		15	2452.16*
		30	14.45
	SM3	<3	6.35
		15	1.91
		30	9.24
	SM4	<3	13.43
		15	5.96
		30	8.74
	SM5	<3	0.60
		15	0.68
		30	0.52
	SM6	<3	2745.29*
		15	3005.41*
		30	6.76
	SM7	<3	5.39
		15	2562.81*
		30	8.56
Latewood	SM1	<3	0.53
		15	0.50
		30	0.47
	SM2	<3	2.13
		15	2.28
		30	1.09
	SM3	<3	0.94
		15	0.70
		30	9.24
	SM4	<3	1.39
		15	1.58
		30	0.91
	SM5	<3	0.28
		15	0.35
		30	0.31
	SM6	<3	5.27
		15	1.47
		30	1.18
	SM7	<3	2.72
		15	2.45
		30	2.09

**These high K values are due to the droplet being absorbed immediately after release for all samples in this group and where there was only one contact angle value at 0 seconds test time and all other values from 1 to 10 s were zero.*

The *K*-values shown in Tables 2, 3, and 4 represent the rate at which a liquid (in this case water) spreads and penetrates into the porous structure of wood (Huang *et al.* 2012). By knowing the *K*-value, spreading and penetration for a given liquid-solid system can be quantified and compared (Huang *et al.* 2012). Higher K-values indicate that the contact angle reaches equilibrium more rapidly and the liquid penetrates and spreads faster (increased wetting) (Huang *et al.* 2012). *K*-values are generally consistent with the contact angle data, with in most cases lower *K*-values (therefore decreasing wettability of the surface) with increased time after surface machining. Also lower *K*-values resulted with the planing treatment (SM5) compared to the other surface machining methods. The highest *K*-values were produced with the surface machining methods – face milling fast feed/slow cutter speed (SM2), 80 grit sanding post-planing (SM7) and 40 grit sanding post planing (SM6). Surface machining method had a significant effect on *K*-values ($p<0.001$). *K*-values of earlywood were significantly higher than latewood ($p<0.001$).

Spotted Gum

Contact angle results are shown for spotted gum in Table 5 and Figs. 7 to 9. As witnessed during the southern pine tests, contact angle for spotted gum also decreased over the 10 second test period; however, unlike the southern pine, mean contact angles didn’t reach 0° in any samples during the 10 second test period. Differences between mean contact angle at different test times (from 0 to 10 seconds) were significant ($p<0.001$). Overall, the contact angle results for the spotted gum were much higher (*e.g.* spotted gum mean of 38° for <3 min after surface machining and at 10 seconds test time) than the southern pine (average of 4° for <3 min after surface machining and at 10 seconds test time), reflecting the much lower wettability of spotted gum compared to southern pine. The lower wettability of spotted gum compared to southern pine is related to the very different wood anatomy, wood properties and extractives content of the two species. Widsten *et al.* (2006) highlighted the very high phenolic and lipophilic extractives content of spotted gum (*Corymbia maculata*) compared to many other important Australian commercial timbers. Studies by Redman *et al.* (2016) also demonstrated the very low porosity of spotted gum. Contact angle also tended to increase and consequently surface wettability decrease with increasing time after surface machining ($p=<0.001$ and 0.023 for 0 and 10 second contact angle test times) (Table 5 and Fig. 9).

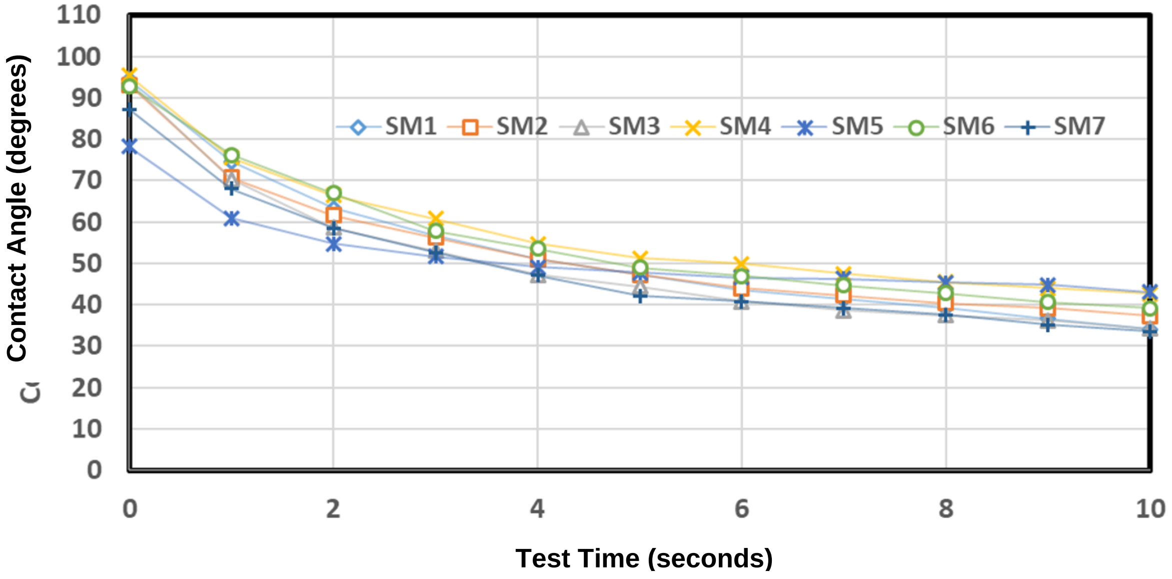

Fig. 7. Change in mean contact angle over a 10 second test time at <3 min after surface machining (spotted gum)

Table 5. Summary of Contact Angle Measurements for Spotted Gum

Surface Machining Method	Test Time (seconds)	Time after Surface Machining (min)	Mean Contact Angle (degrees)*	Mean K Value**
SM1	0[a]	<3	94 (11)	-
		15	104 (7)	-
		30	105 (6)	-
	10[b]	<3	34 (9)	0.31
		15	39 (7)	0.29
		30	40 (8)	0.26
SM2	0 [a]	<3	93 (8)	-
		15	95 (10)	-
		30	93 (12)	-
	10 [b]	<3	37 (12)	0.33
		15	37 (11)	0.35
		30	30 (16)	0.38
SM3	0	<3	94 (14)	-
		15	94 (14)	-
		30	95 (11)	-
	10	<3	34 (8)	0.37
		15	37 (15)	0.37
		30	39 (12)	0.35
SM4	0	<3	95 (5)	-
		15	98 (8)	-
		30	102 (5)	-
	10	<3	43 (7)	0.29
		15	42 (5)	0.29
		30	43 (12)	0.28
SM5	0	<3	78 (8)	-
		15	88 (6)	-
		30	87 (8)	-
	10	<3	43 (7)	0.28
		15	46 (5)	0.28
		30	46 (8)	0.22
SM6	0	<3	93 (12)	-
		15	94 (13)	-
		30	99 (9)	-
	10	<3	39 (8)	0.27
		15	43 (7)	0.24
		30	40 (7)	0.24
SM7	0	<3	87 (12)	-
		15	95 (11)	-
		30	98 (8)	-
	10	<3	34 (11)	0.32
		15	39 (9)	0.28
		30	42 (7)	0.26

[a] *For 0 second test time, Mean Contact Angle LSD1(0.05)=6.2; LSD2(0.05)=7.8 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.*

[b] *For 10 second test time, Mean Contact Angle LSD1(0.05)=5.8; LSD2(0.05)=7.5 where LSD1 is for comparing Delay means in the same Surface Machining Method and LSD2 is for all other pair-wise comparisons.*

**Standard deviations are presented in parentheses*

***K-values are only calculated after 10 seconds, therefore not applicable to test time of 0 seconds*

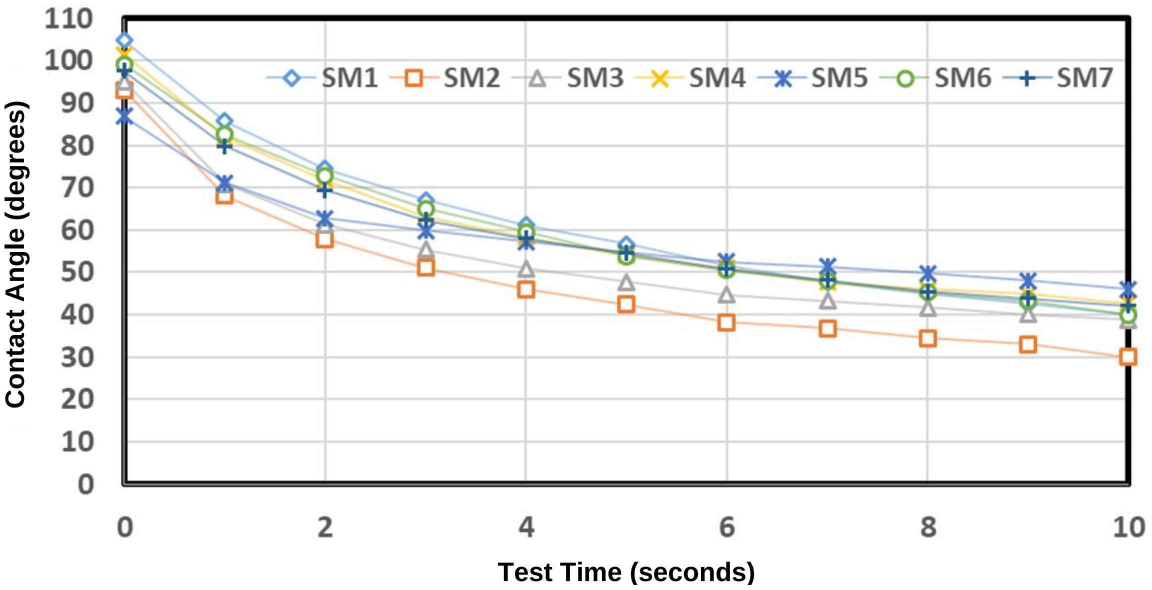

Fig. 8. Change in mean contact angle over a 10 second test time at 30 min after surface machining (spotted gum)

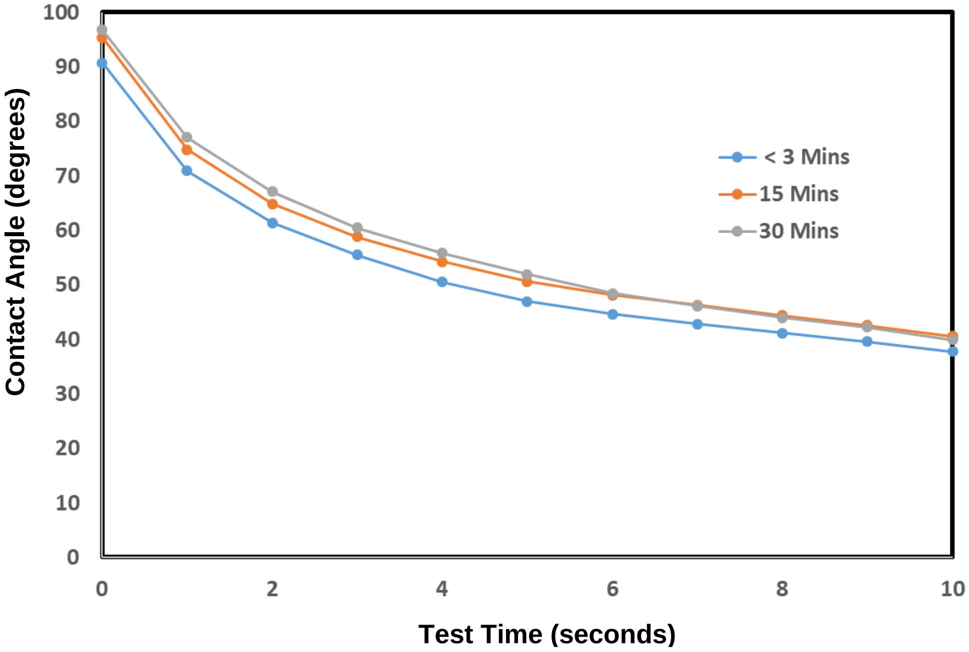

Fig. 9. Mean contact angle for different intervals after surface machining and for each test time (spotted gum)

Surface machining method had a significant effect on contact angle for spotted gum ($p<0.001$). When compared at the 10 second test time period, for all timeframes after surface machining, the highest mean contact angle and therefore the lowest surface wettability was recorded with the planing surface machining method (SM5). Therefore, for both the southern pine and spotted gum, planing produced the worst result for surface wettability.

The lowest mean contact angle and therefore the highest surface wettability for spotted gum varied depending upon time frame after surface machining, with 80 grit sanding post-planing (SM7), face milling with slow feed speed/fast cutter speed (SM3) and face milling with fast feed speed/slow cutter speed (SM2) producing the highest surface wettabilities at <3, 15 and 30 min after surface machining, respectively.

Similar to that observed with the southern pine, the *K*-values for spotted gum were generally consistent with the contact angle data, with lower *K*-values (therefore on average overall decreasing wettability of the surface) with increased time after surface machining. The *K*-values within each surface machining method varied depending on the timeframe after machining, however at the 10 second test time and 30 min after surface machining, the highest *K*-values resulted from the face milling with fast feed/slow cutter speed (SM2). The lowest *K*-value resulted from planing (SM5).

The *K*-values for spotted gum (*e.g.* average 0.31 across all surface machining methods and at < 3 min since surface machining) were much lower than for southern pine (*e.g.* average 3.43 across all surface machining methods and at < 3 min since surface machining), therefore a markedly smaller decrease in contact angle over time, again reflecting major differences in wettability between the two species.

The wettability results discussed above for both spotted gum and southern pine indicate that face milling and sanding post-planing are likely to produce better outcomes for wood adhesion for both species compared to conventional planing treatments.

Permeability

Southern pine

Table 6 and Figs. 10 and 11 show the differences in gas and liquid permeability with each surface machining method for southern pine. Gas permeability was much higher (for overall data, 11-times higher) than liquid permeability. Due to higher viscosity, molecular size and liquid-wood interactions, liquid permeability is usually much lower than gas permeability (Rezende *et al.* 2018; Taghiyara 2012; Leggate *et al*. 2019). There was also a significant positive relationship between gas and liquid permeability ($r=0.84$; $p<0.001$). This is consistent with Leggate *et al.* (2019), who also reported a significant positive relationship between the gas and liquid permeability of plantation grown southern pine from Queensland. Mean gas and liquid permeability for the current study are also close to those reported by Leggate *et al.* (2019), although gas permeability was lower (mean 45 mD versus 52 mD) and liquid permeability higher (mean 4 mD versus 3 mD) than the values reported by Leggate *et al.* (2019). However, the two studies varied in tree age, genotypes, and wood sample position in tree.

Surface machining method had a significant effect on both gas and liquid permeability ($p<0.001$). Planing (SM5) produced the highest permeability, while 80 grit sanding post-planing (SM7) yielded the lowest permeability. In another study on southern pine (*Pinus spp*.), Choong *et al.* (1975) reported that the method of surface preparation had a profound effect on the rate of flow of fluids through wood, highlighting that laser-cut and scalpel cut surfaces resulted in significantly higher permeability than for sawn and sanded surfaces. In the same study, sanded surfaces also resulted in lower permeability than sawn surfaces. Choong *et al.* (1975) stated that the result was due to debris/and or obstructions blocking fluid flow in the sawn and sanded surfaces. Even though planing resulted in a higher gas and liquid permeability compared to face milling treatments SM2, SM3 and SM4, the differences were not statistically significant (Table 6).

Table 6. Summary of Permeability Results for Southern Pine

Surface Machining Identifier	**Mean Gas Permeability* (mD)**	**Mean Liquid Permeability* (mD)**
SM1	37.4 (23.7) **def**	3.3 (3.9) **bc**
SM2	57.4 (24.6) **fg**	5.9 (5.4) **d**
SM3	54.4 (27.3) **fg**	4.2 (5.4) **cd**
SM4	48.2 (18.1) **efg**	4.2 (2.1) **cd**
SM5	62.9 (29.9) **g**	7.3 (6.3) **d**
SM6	31.8 (11.7) **cde**	1.6 (1.2) **ab**
SM7	20.2 (10.4) **bc**	0.9 (0.7) **a**

Note: Means followed by the same letter in the same column are not significantly different

**Standard deviations are presented in parentheses*

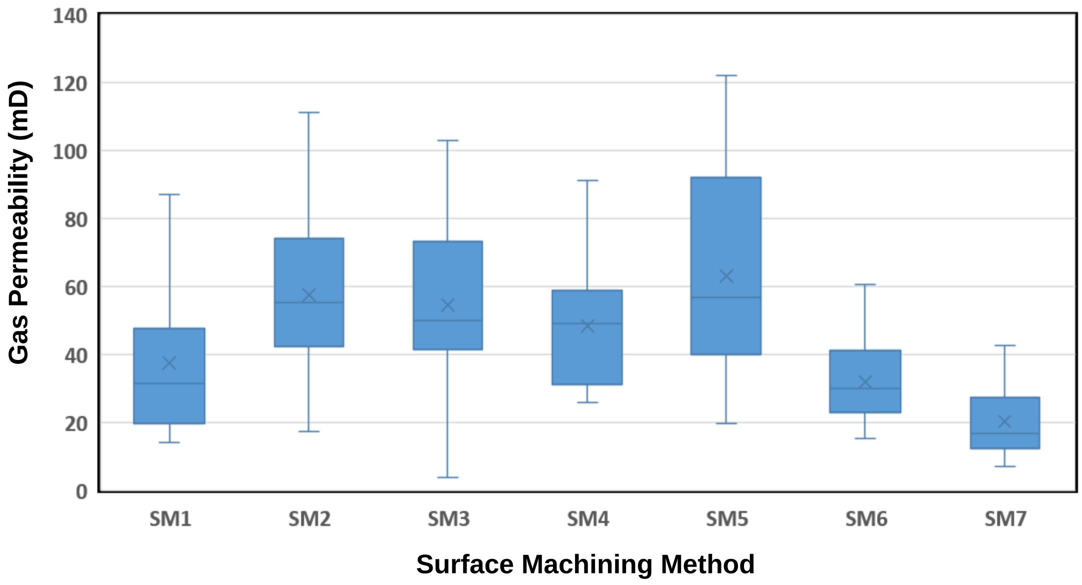

Fig. 10. Gas permeability for each surface machining method (southern pine)

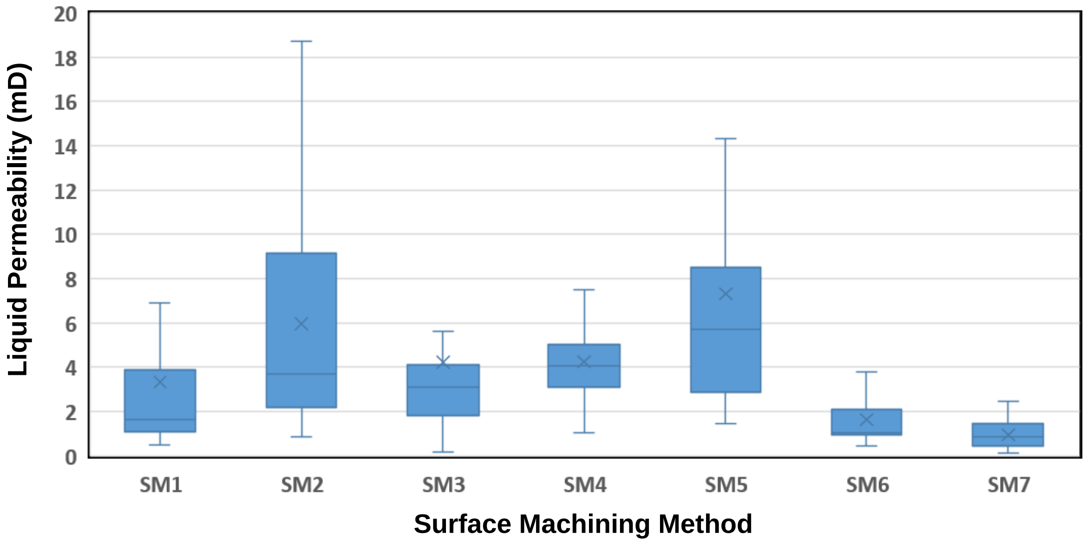

Fig. 11. Liquid permeability for each surface machining method (southern pine)

The results for permeability did not follow the same ranking as observed in the wettability testing for southern pine. For example, planing (SM5) resulted in the lowest wettability, however, achieved the highest permeability, whereas the sanding post-planing although resulting in a high wettability ranking, had low permeability. This most likely reflects that wettability is a wood surface phenomenon measured in this case by the contact angle a liquid droplet makes with the wood surface, whereas permeability is relevant to the measure of the flow of gas and liquid through the full wood cross section and not just the surface.

Spotted gum

Table 7 and Fig. 12 show the differences in gas permeability with each surface machining method for spotted gum. Gas permeability for spotted gum was much lower (for overall data, average 18.7 mD) than for southern pine (for overall data, average 44.7 mD). This is due to major differences in wood anatomy and extractives content between the two species and also due to the spotted gum samples being all heartwood as compared to the sapwood samples used for the southern pine. Surface machining method had a significant effect on gas permeability ($p<0.001$). The highest and lowest permeability results were for surface machining methods face milling with slow feed speed/slow cutter speed (SM4) and planing (SM5) respectively. Planing had an opposite effect on gas permeability in spotted gum compared to southern pine, with planing resulting in the lowest permeability ranking. However, in a similar trend as for southern pine, the surface treatments involving sanding also resulted in low gas permeability. The difference in the effect of planing on the permeability of southern pine and spotted gum is likely due to differences in the nature and magnitude of surface and sub-surface modifications caused by planing in two timbers of very different wood anatomy and properties. These modifications, including surface roughness, fibrillation, and sub-surface cellular damage will be investigated in a later study.

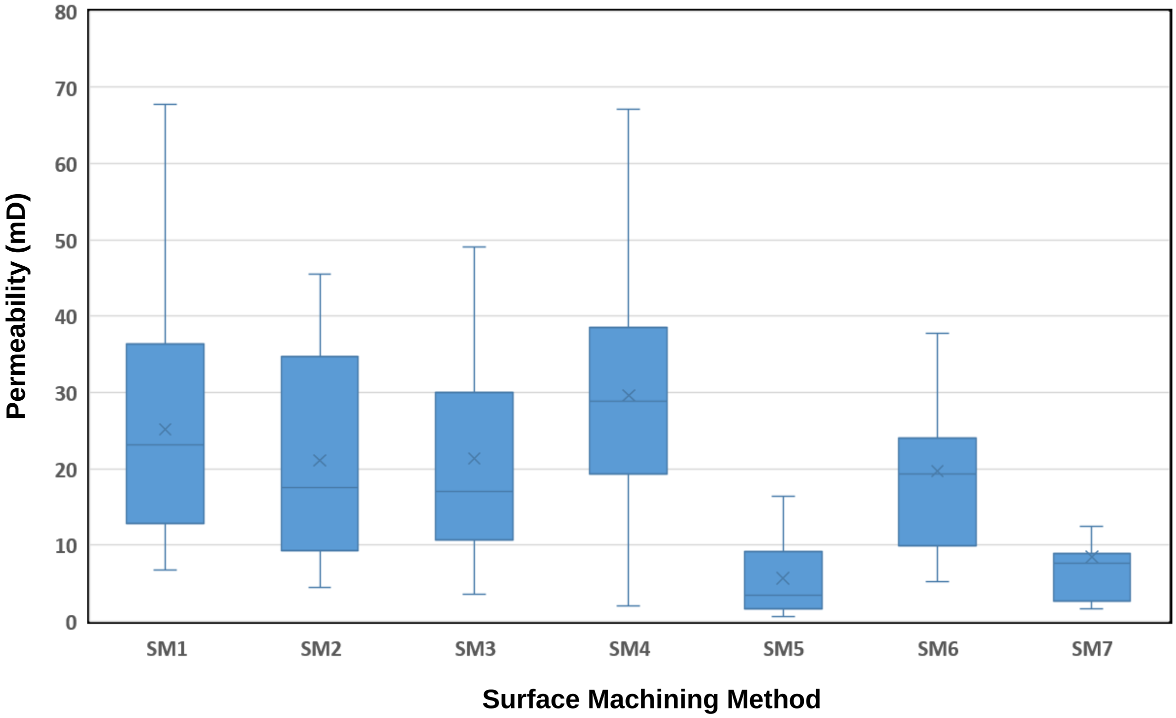

Fig. 12. Gas permeability for each surface machining method (spotted gum)

Table 7. Summary of Permeability Data for Spotted Gum

Surface Machining ID	**Mean Gas Permeability* (mD)**
SM1	25.1 (16.6) **bcd**
SM2	21.1 (13.2) **bc**
SM3	21.3 (14.2) **b**
SM4	29.6 (15.8) **bcd**
SM5	5.7 (5.1) **a**
SM6	19.7 (11.0) **b**
SM7	8.4 (9.6) **a**

Note: Means with the same letter are not significantly different
**Standard deviations are presented in parentheses*

CONCLUSIONS

1. Surface machining methods significantly influenced the wettability and permeability of southern pine and spotted gum timber.
2. For southern pine, the lowest surface wettability was recorded with the planing surface machining method. The highest surface wettability varied depending upon time frame after surface machining; however 80 grit sanding post-planing, 40 grit sanding post-planing, and face milling with fast feed speed/slow cutter speed performed similarly ranking highest for surface wettability. Earlywood had significantly higher surface wettability compared to latewood.
3. For spotted gum, the lowest surface wettability was also recorded with the planing surface machining method. The highest surface wettability for spotted gum varied depending upon time frame after surface machining, with 80 grit sanding post-planing, face milling with slow feed speed/fast cutter speed and face milling with fast feed speed/slow cutter speed ranking highest for surface wettability at <3, 15 and 30 min after surface machining respectively.
4. Overall, for both species, surface wettability generally decreased with increasing time after surface machining. This reinforces the benefit of minimizing the time between surface machining and adhesive application.
5. For southern pine, sanding post-planing resulted in the lowest permeability. Planing resulted in the highest permeability; however there were no significant differences in permeability between planing and most of the face milling treatments trialled. For spotted gum, planing resulted in the lowest gas permeability, whereas face milling with slow feed speed/slow cutter speed resulted in the highest permeability.
6. For both species, based on the wettability and permeability results of this study, face milling is likely to produce a better outcome than conventional planing as a wood mechanical surface preparation prior to gluing. However, future studies would need to confirm this through studies investigating directly the effects of these different surface machining treatments on the glue-bond performance of both species.

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