The Effects of Drying Method on the Wood Permeability, Wettability, Treatability, and Gluability of Southern Pine from Australia

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Drying has a major impact on the viability of sawn timber production, particularly through its influence on productivity, energy usage, and product quality. Traditionally, plantation-grown southern pine structural grade timber from Australia has been dried using high temperature (≥ 180 °C) conventional batch kilns. However, the Australian industry is showing increasing interest in continuous drying kilns because of reported cost savings and potential improvements in product quality. This study investigated the differences between continuous drying and conventional drying schedules on the radial permeability, wettability, gluability, and treatability of southern pine timber from Queensland plantations. The high temperature drying resulted in significantly lower liquid permeability compared to low temperature drying; however, there were no significant differences between drying schedules for gas permeability. For combined wood surface and core data, there were no significant differences in liquid permeability between low temperature drying and continuous drying or between continuous drying and high temperature drying schedules. For earlywood after surface machining, continuous drying resulted in the greatest wettability (based on *K*-values), whereas for latewood after surface machining, low temperature drying produced the greatest wettability. Earlywood had greater wettability compared to latewood. Continuous drying resulted in better gluability and treatability compared to conventional drying schedules.

Keywords: Wood drying; Continuous drying; Wood wettability; Wood permeability; Wood gluability; Wood treatability; Pinus elliottii; Pinus caribaea; Southern pine

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INTRODUCTION

Drying is a critical component in sawn timber production and has a major influence on the profitability of sawmills. Wood drying is essential to 1) provide dimensional stability; 2) improve strength; 3) reduce the moisture content to an acceptable level for wood preservation, gluing, finishing, and other manufacturing processes; 4) improve the durability and resistance to biological degradation; and 5) reduce the weight and minimise costs in handling and transport. For the sawn timber production process, converting logs to finished dried wood components, drying can consume up to 70% of the energy and 90% of the time, depending upon species and product type (Kumar and Redman 2019).

Therefore, drying is often considered the bottleneck of the production process (Redman 2017; Kumar and Redman 2019).

In Australia, for more than 25 years, the most common drying method for sawn timber of southern pine (*Pinus elliottii* (PEE), *Pinus caribaea* (PCH), and PEE × PCH: the hybrid between these two species), and other exotic (to Australia) pines such as radiata pine (*Pinus radiata*) has been high temperature conventional batch kiln drying, where temperatures can exceed 180 °C, and drying times can be less than 12 h. However, internationally, the relatively new continuous drying (CD) kiln technology for kiln drying structural softwood sawn timber is increasingly replacing conventional kilns (Oliveira and Lazarescu 2018; Kumar and Redman 2019; Windsor Engineering Group 2020). The CD method results in major reductions in energy usage and drying costs. Timber stacks dried in typical CD kilns pass through the kiln in opposite directions on two tracks, so that heat coming off the dried, exiting timber preheats the timber packs entering the drying process, and moisture coming off the undried timber conditions the dry timber. This energy-efficient process happens at both ends. Significant thermal energy efficiencies of approximately 30% can be achieved with CD kilns, with several other reported benefits for product quality (Friday Offcuts 2011; Kumar and Redman 2019). The Australian softwood processing industry is showing interest in this technology due to anticipated savings in energy and production costs. However, the effects of this drying method on dried wood quality and key wood properties such as permeability, wettability, gluability, and treatability are unknown for plantation-grown southern pine timber in Australia. The wood quality and characteristics of southern pine grown in plantations in Australia are expected to vary from those of southern pine in the USA due to differences in genotypes, silviculture, climate, and other growing conditions. The hybrid pine (PEE × PCH) now dominates exotic softwood plantations and log supply in Queensland, Australia, with approximately 94,100 ha planted and an annual log production soon to exceed 1 million cubic meters per year (Leggate *et al*. 2019).

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; Booker 1990; Milota *et al*. 1995; Hansmann *et al*. 2002; Lee *et al.* 2008; Leggate *et al*. 2019). The permeability of wood influences many of its important processing and utilization properties, including gluing, 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).

Wood permeability is significantly influenced by drying conditions (Bamber 1972; Booker 1990; Booker and Evans 1994; Hansmann *et al*. 2002; Lee *et al.* 2008; Ahmed *et al*. 2012, 2013; Tarmian *et al*. 2020). Many studies have shown that higher temperature drying tends to increase permeability because of effects on the wood microstructure such as the collapse of thin-walled cells resulting in interstitial spaces; rupturing in the pit torus, pit borders, and cell walls; and creation of micro-checks caused by the high temperature drying process that improves liquid penetration (Tiemann 1910; Weiss 1912; Booker and Evans 1994; Zhang and Cai 2008; Lande *et al*. 2010). Drying conditions also influence the movement and modification of natural resin in the wood, which can then influence permeability (Booker and Evans 1994; Winandy *et al*. 2001). However, no studies have reported the effects of continuous drying on the permeability of Queensland-grown southern pine.

Wettability refers to an adherend's ability to attract a liquid, such as an adhesive (Hovanec 2015). Adequate wetting of the surfaces of wood adherends is necessary to achieve a strong adhesive bond (Wellons 1980; River *et al*. 1991; Hovanec 2015). A typical method used to assess wood wettability is liquid droplet contact angle measurement (Leggate *et al*. 2020). Wood surfaces which have been exposed to a high temperature condition can experience surface inactivation or reduced wettability, and higher temperature drying reduces wood wettability (Sernek 2002; Šernek *et al*. 2004; Navickas *et al*. 2015).

The gluing of wood is a mainstream manufacturing process, with large volumes of southern pine timber being glued to produce engineered wood products such as glued laminated timber (glulam). Understanding the impacts of different drying conditions on timber gluability is important for optimising the manufacture of glued wood products and avoiding bond performance problems and product failures.

Wood treatment with chemicals such as preservatives, fire retardants, and water repellents is used to improve the performance of wood. In Australia, the majority of the southern pine sawn timber production is treated with insecticides and/or fungicides to prevent degradation in service. Treatability measures the extent to which a porous material such as wood can be impregnated with liquids such as wood preservatives (Tarmian *et al*. 2020). The treatability of wood is usually measured by the amount of uptake of preservative solution, active ingredient penetration, and retention. Wood treatability is usually closely related to wood permeability, so factors that affect wood permeability can be expected to similarly affect wood treatability (Siau 1984). However, no significant link was found between the method of drying and treatability in studies by Lebow *et al*. (2006) and Jewell *et al*. (1990) on southern pine species from the USA, although a non-significant trend was found by Jewell *et al*. (1990), indicating that higher temperature schedules may increase preservative penetration.

Given the strong interest by the Australian softwood industry to investigate continuous drying methods, attracted by the promoted benefits of potential energy usage reductions and cost savings, this study sought to overcome the scarcity of information on the effects of this drying method on key wood performance criteria. This study directly compared the effects of continuous kiln drying *versus* conventional drying methods on the permeability, wettability, gluability, and treatability of southern pine timber from Queensland, Australia.

EXPERIMENTAL

Sample Preparation from Unseasoned Timber

Fifty-six boards of backsawn, unseasoned (average moisture content (MC) of 84%) southern pine timber with nominal dimensions of 100 mm × 38 mm × 6000 mm (width (W) × thickness (T) × length (L)) were obtained from a major commercial sawmill in Queensland, Australia. Samples of 100 mm × 38 mm × 900 mm (W × T × L) (nominal dimensions) were cut from each board and then randomly allocated to three different drying regimes (Fig. 1). The 900-mm lengths were immediately end-sealed with a polyurethane sealant (Sikaflex, Sika AG, Baar, Switzerland), weighed (for MC monitoring during drying), wrapped in plastic, and then stored in a cold room at 4 °C until the drying experiments commenced.

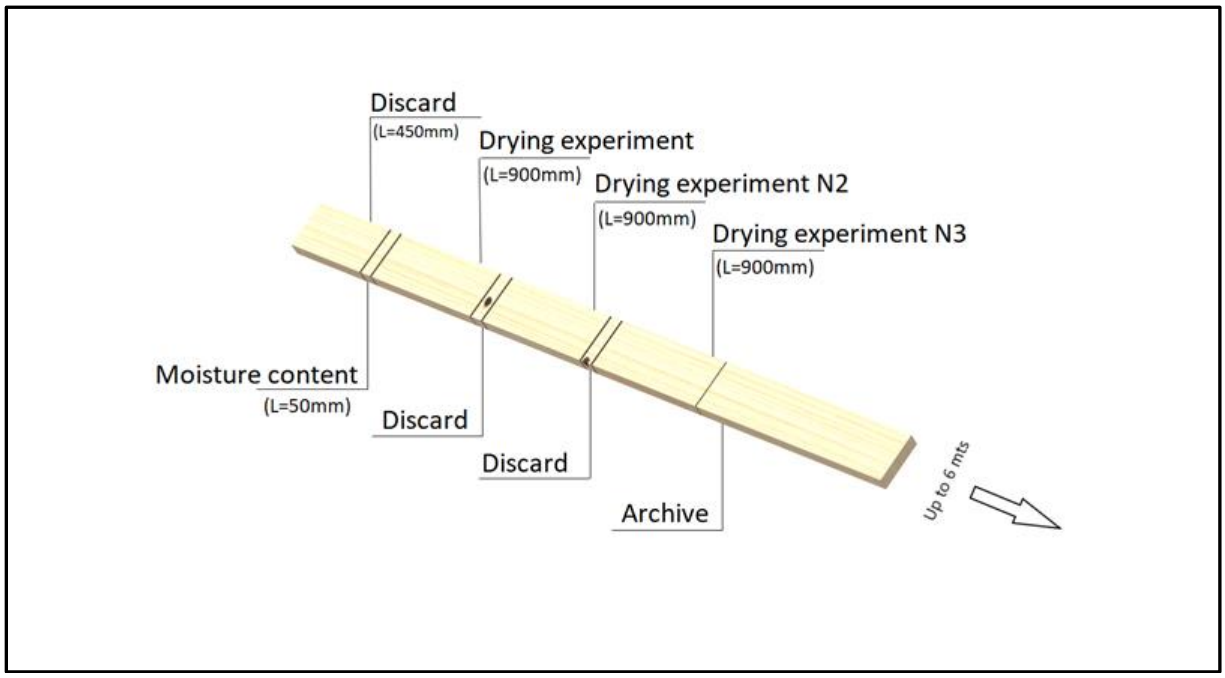

Fig. 1. Sample cutting from green boards for drying experiments

Drying

Table 1 provides details on the three different drying regimes adopted. The low temperature drying was performed initially in a constant environment chamber set at 20 °C and 45% relative humidity (RH) (approximately 8% equilibrium moisture content (EMC)) for 384 h (16 d). The boards were then dried in an experimental kiln at 40 °C dry bulb temperature (DB) and 48% RH (approximately 8% EMC) with an air velocity of 3 m/s for 52 h. The total drying time of the low temperature dried boards was 436 h (approximately 18 d). High temperature drying was undertaken in an experimental kiln with a schedule representative of typical high temperature drying schedules used for drying softwood structural-grade sawn timber in Australia. Set points ranged from 25 °C to 180 °C DB, 7.3% to 82% RH, 0% to 12% EMC, and 3 m/s to 7 m/s air flow depending on the stage of the drying schedule. The total drying time was 477 min (8 h). Continuous drying was undertaken in an experimental kiln with a schedule representative of typical drying conditions targeted with continuous drying kilns for structural-grade softwood timber. Set points ranged from 25 °C to 115 °C DB, 34% to 100% RH, 2.3% to 23% EMC, and 3 m/s to 5.5 m/s air flow depending on the stage of the drying schedule. The total drying time was 36 h.

Table 1. Maximum Temperature and Sample Number for Each Drying Group

Drying Group	Maximum Drying Temperature (°C)	Number of Samples
Low Temperature Drying Schedule	40	35
Continuous Drying Schedule	115	29
High Temperature Drying Schedule	180	33

Moisture content was monitored throughout the drying process using load cells and board weight. After kiln drying, all boards were conditioned to 12% MC in a constant environment chamber set at 20 °C and 65% RH (12% EMC) until board weight stabilised.

Sample Preparation from Dried Timber

After conditioning, a 450-mm-length piece was removed from each 900-mm dried board. Samples were then obtained from the surface and core (mid-board thickness) of the 450-mm piece for the determination of permeability, gluability, and treatability as shown in Fig. 2. An additional sample from the full cross section was also obtained for wettability tests (Fig. 2).

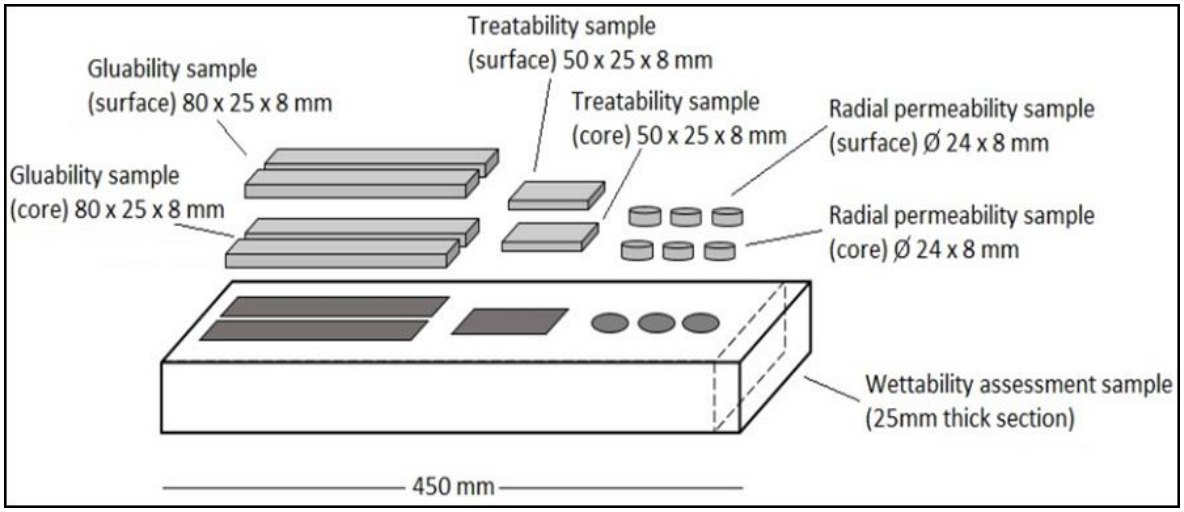

Fig. 2. Sample cutting from dried boards for permeability, treatability, gluability, and wettability tests

Permeability

The methodology adopted for the permeability tests was similar to that adopted by Leggate *et al*. (2020). Samples for the permeability tests were 24 mm in diameter and 8 mm in thickness (flow direction). The edge of each sample was coated with epoxy resin on its lateral surface to direct gas and liquid movement in the radial direction to measure only the wood radial permeability.

Radial permeability measurements were undertaken using a POROLUX 1000 porometer (IB-FT GmbH, Berlin, Germany). Both gas and liquid permeability were measured, with gas permeability tests undertaken before liquid permeability tests. For gas permeability, samples were subjected to pressurized, atmospheric air until the 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. Permeability was calculated in accordance with Darcy's law (Eq. 1),

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

in which Q, K, A, L, η, and ΔP are the liquid or air volume flow rate (m^3/s), the permeability of the wood (m^2), area perpendicular to the liquid flow (m^2), the sample length in the direction of flow (m), the dynamic viscosity of the liquid or air (Pa·s), and the pressure decrease (Pa), respectively (Kucerová 2012).

Wettability

The wettabilities of the samples were determined using the sessile drop method, by measuring the contact angle of a drop of pure water on the timber surface (Fig. 3) (Burch 2015; Leggate *et al*. 2020). Testing followed the methodology developed by Leggate *et al*. (2020). The contact angle is the angle that the liquid forms when in contact with a solid, as shown in Fig. 3 (Burch 2015). Because the tendency of a liquid to spread increases as contact angle decreases, the determination of contact angles is a useful inverse measure of wettability (Zisman 1964; Leggate *et al*. 2020). Contact angles were measured before and immediately after surface machining to a 1.5-mm depth. The surface machining was undertaken using a Ledinek Rotoles 400 D-S (Hoče, Slovenia) face miller with a feed rate of 45 m/min and a cutter speed of 2100 rpm (57 m/s). Contact angles were measured on both earlywood and latewood for each sample.

An electronic pipette (Labco electronic pipettor, Labco Limited, Lampeter, UK) 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, Shenzhen Apexel Technology Co., Ltd, Shenzhen, Guangdong, China) was attached to the camera to provide adequate magnification of the droplet. The macro lens and camera combined provided a total of approximately 50× magnification (21× from the macro lens and approximately 2.5× from the camera). The camera was securely mounted to prevent movement and vibration. A droplet of 1 µL of 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 at least 10 s following were recorded by video.

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. 4a). Then, one image was taken per second for 10 s, providing a total of 11 contact angle images. These images were processed by the open-source image-processing software ImageJ (IJ 1.46r) (U.S. National Institutes of Health, Bethesda, MD, USA) (Schneider *et al*. 2012) with the contact angle plugin (Lamour *et al*. 2010) (Fig. 4b). For each image measurement with the software, two points were manually selected at the intersection of solid-liquid-air interfaces (marked by an arrow in Fig. 4a) to define the baseline, and four points were selected along the drop profile. The software contact angle plugin then fitted the points with the sphere approximation or ellipse approximation and calculated the contact angle.

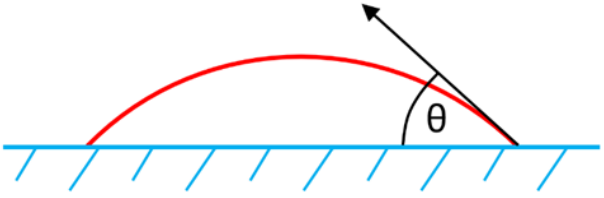

Fig. 3. Contact angle *(θ)* for a liquid droplet on a solid surface (Burch 2015; Leggate *et al*. 2020)

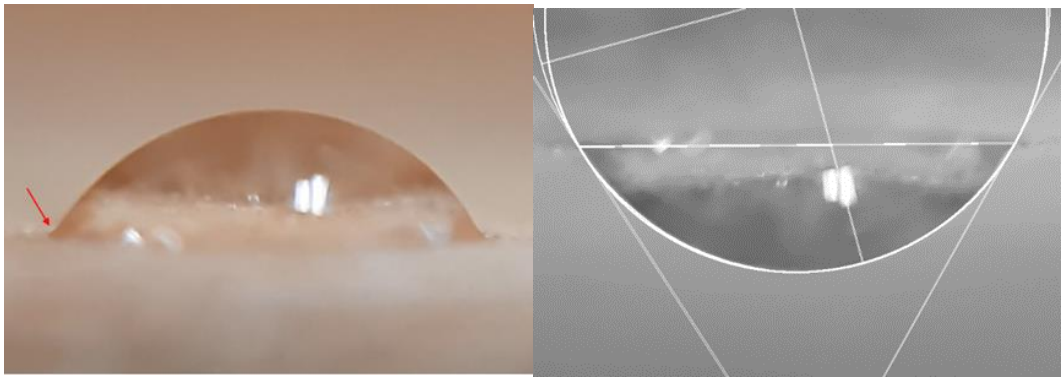

Fig. 4. Water droplet in contact with timber surface: (a) a drop of water on timber surface and (b) the same drop processed with the software (the image is inverted as part of the processing) (Leggate *et al*. 2020).

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 wettabilities of various wood surfaces (Qin *et al*. 2014; Burch 2015; Wang *et al*. 2015; Leggate *et al*. 2020). The model was developed to quantify the change in contact angle over time. The wetting model is shown in Eq. 2,

$$\theta = \frac{\theta_{\mathrm{i}}\theta_{\mathrm{e}}}{\theta_{\mathrm{i}} + (\theta_{\mathrm{e}} - \theta_{\mathrm{i}}) \exp[K\left(\frac{\theta_{\mathrm{e}}}{\theta_{\mathrm{e}} - \theta_{\mathrm{i}}}\right)t]} \quad (2)$$

where θ_{i} is the initial contact angle at time 0 s, θ_{e} is the equilibrium contact angle (for the data of this study, at the test time of 10 s), t is time (s), and K is the constant intrinsic relative contact angle decrease rate (1/s). 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; Leggate *et al*. 2020). 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 slowly penetrates into the wood surface. A K-value of zero represents no change between initial and equilibrium contact angles (Burch 2015). The nonlinear least squares method was used to estimate the K-value of the nonlinear model using RStudio (Studio Version 1.1.453, RStudio, Boston, MA, USA) (Baty *et al*. 2015). The contact angle values at the times 0 s and 10 s were assigned as the initial (θ_{i}) and equilibrium (θ_{e}) contact angles, respectively. For a typical exponential decay of a contact angle *vs.* time curve, the K values were approximately between 0.1 to 1.0 (Burch 2015); therefore the initial value of K was assigned to 0.3.

Gluability

Lap shear specimens were prepared from the surfaces and cores of samples from each drying group (Fig. 2) following the principles of the European Standard BS EN 205 (2016). The lap shear specimens were prepared with samples that had been machined using the face miller with a feed speed of 45 m/min and a cutter speed of 3000 rpm (82 m/s). The depth of face milling was 1.5 mm. The lap shear sample dimensions are shown in Fig. 5. The adhesive-bonded overlap in the lap shear samples was 10 mm (Fig. 5).

The application of adhesive commenced within 20 min of surface machining. A one-component moisture-curing polyurethane (1C-PUR) adhesive (Jowat Jowapur 681.40, Jowat SE, Detmold, Germany) was used. This glue type is representative of a typical glue used commercially in softwood structural glulam production. In accordance with the technical data sheet for this adhesive, the lap shears had 1C-PUR applied at a spread rate of 250 g/m^2 (gsm). Open assembly time was 10 s, and closed assembly time was 5 min to 20 min.

The lap shear samples were then pressed at 0.8 MPa for a minimum of 100 min. After pressing, the lap shear samples were then conditioned in a constant environment chamber set at 20 °C and 65% RH (12% EMC) for a minimum of 7 d before tensile strength testing.

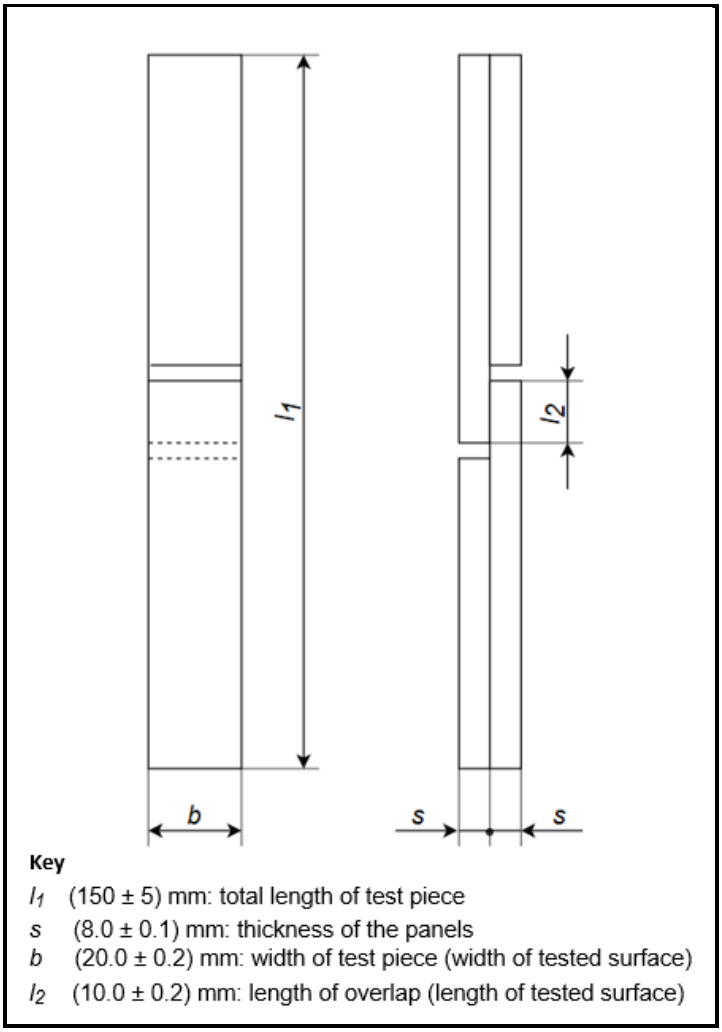

Fig. 5. Lap shear sample dimensions

Lap shear tensile testing was performed using a universal testing machine (AG-100X, Shimadzu Corporation, Kyoto, Japan) testing rig fitted with a 100-kN load cell with a crosshead displacement rate of 1.5 mm/min. The data were processed using Trapezium X single cycle software (Version 1.5.1, Shimadzu Corporation, Kyoto, Japan). The lap shears had a minimum of 40 mm of each end clamped into the jaws of the testing rig before

being loaded in tension until failure. The maximum force applied to reach failure was recorded. The tensile shear strength (τ) (MPa) was then calculated using Eq. 3:

$$\tau = \frac{F_{\max}}{l_2 b} \quad (3)$$

where F_{max} is the applied maximum force (N), l_2 is the length of the bonded test surface (mm), and b is the width of the bonded test surface (mm).

Treatability

The treatability sample dimensions were 25 mm × 8 mm × 50 mm (W × T × L). The samples were weighed before and after being immersed in an alkaline copper quaternary (ACQ) wood preservative solution (0.7% concentration) for 2 h. The 2-h immersion time was deliberately chosen so that the treatment did not result in 100% cross section penetration, which would not have allowed comparisons of copper penetration differences between samples. The change in sample weight was used to determine the ACQ solution uptake in L/m^3. The treated samples were then dried and cut in half, and spot tests were conducted on the end-matched transverse surfaces to determine the preservative penetration (on one surface) and heartwood presence (on the other matching surface). Copper penetration was determined by a spot test according to the Australian and New Zealand standard AS/NZS 1605.2 (2018). The presence of heartwood on the end-matching face of the other half of the sample was determined according to AS/NZS 1605.2 (2018). Heartwood content overall was less than 1% and any heartwood containing pieces were not included in the data analysis. The image-processing software was used to quantify the copper penetration area in each sample.

Statistical Analysis

Statistical analysis was performed using the open-source statistical package RStudio (Studio Version 1.1.453, RStudio, Boston, MA, USA) (Baty *et al*. 2015) Both analysis of variance (ANOVA) and pairwise comparisons using Fisher's protected least significant difference (LSD) test were used. Both liquid and gas permeability data were transformed using natural log to stabilise the variance before conducing pairwise comparisons using Fisher's protected LSD test using GenStat (Version 19, VSN International, Hemel Hempstead, UK).

RESULTS AND DISCUSSION

Permeability

Results of the gas and liquid permeability tests are shown in Tables 2 and 3 and Figs. 6 and 7.

The differences between the drying groups in gas permeability were not significant (Tables 2 and 3). Considering combined surface and core test data, the high temperature drying resulted in a significantly lower liquid permeability compared to low temperature drying (Table 2). For combined data, there were no significant differences in liquid permeability between low temperature and continuous drying or between continuous and high temperature drying (Table 2). In all cases shown in Table 3 and Figs. 6 and 7, mean gas and liquid permeabilities were greatest with surface samples, compared to core samples. This result is most likely a consequence of the greater incidence of checking

observed in surface samples compared to core samples. For gas permeability, there were no significant differences within or between groups for surface permeability compared to core permeability. However, surface liquid permeability was significantly greater compared to core liquid permeability for the continuous and high temperature dried samples (Table 3).

Table 2. Summary of Permeability Results for Each Drying Group (Combined surface and core data)

Drying Group	Mean Gas Permeability (mD)	Mean Liquid Permeability (mD)
Low Temperature Drying Schedule	107[a]	13.04[a]
Continuous Drying Schedule	96[a]	12.98[ab]
High Temperature Drying Schedule	80[a]	5.97[b]

Note: Means followed by the same letter in the same column are not significantly different (0.05). mD = millidarcies.

Table 3. Summary of Permeability Results for Surface and Core Samples of Each Drying Group

Drying Group	Surface or Core	Mean Gas Permeability (mD)	Mean Liquid Permeability (mD)
Low Temperature Drying Schedule	Surface	147[a]	17[abc]
	Core	98[a]	12[a]
Continuous Drying Schedule	Surface	104[a]	16[a]
	Core	88[a]	10[bcd]
High Temperature Drying Schedule	Surface	81[a]	9[ab]
	Core	79[a]	5[c]

Means followed by the same letter in the same column are not significantly different (0.05). mD = millidarcies.

The greater mean permeability of low temperature schedule dried timber compared to high temperature schedule dried timber in this study is contrary to other studies which have shown the opposite result of a greater permeability with greater temperature drying (Booker and Evans 1994; Zhang and Cai 2008; Lande *et al*. 2010), although there are contradictory reports about the effects of drying method on wood permeability and treatability (Tarmian *et al*. 2020). The reasons presented for the reported trend of greater permeability with higher temperature drying include the effects of high temperature drying schedules on the wood microstructure, such as the collapse of thin-walled cells resulting in the creation of interstitial spaces; rupturing in pit torus, pit borders, and cell walls; creation of micro-checks caused by the high temperature drying process, improving liquid penetration; and mobilisation and dispersal of natural wood resin (Tiemann 1910; Weiss 1912; Booker and Evans 1994; Winandy *et al*. 2001; Zhang and Cai 2008; Lande *et al*. 2010).

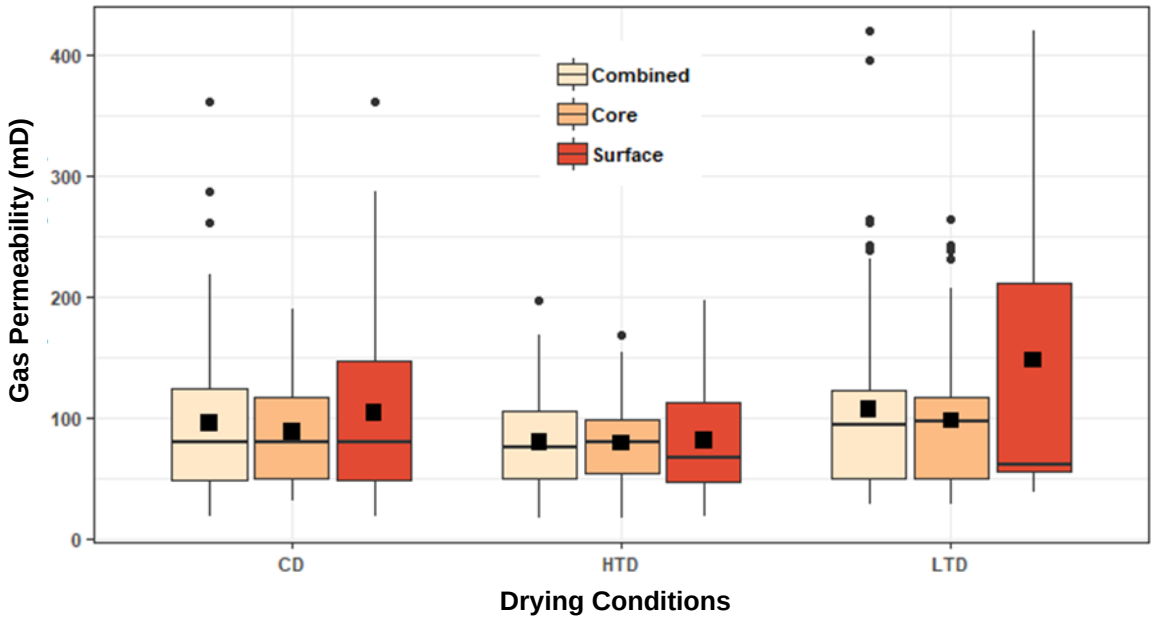

Fig. 6. Gas permeabilities of surface and core samples from each drying group (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

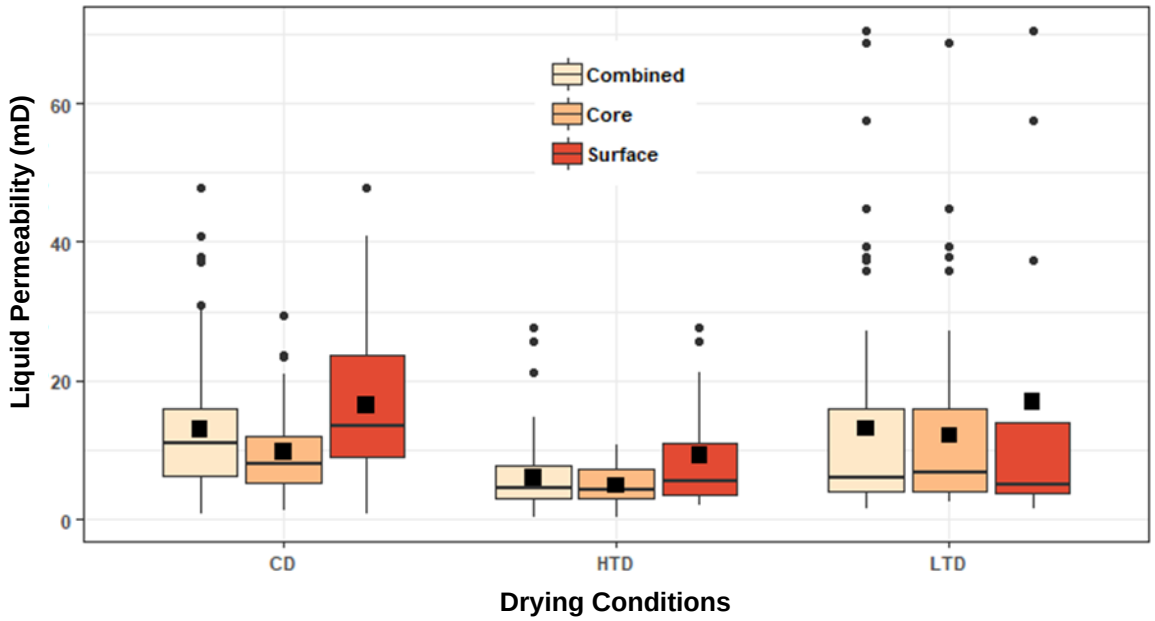

Fig. 7. Liquid permeabilities of surface and core samples from each drying group (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

Even though, in this study, the low temperature drying resulted in the greatest mean gas and liquid permeabilities for the combined data and for the surface and core, it resulted in the lowest median surface gas and liquid permeabilities. Further investigations on the reasons for the differences in permeability between the different drying groups are warranted. These studies should include assessments on changes in wood anatomy and resin distribution caused by drying schedules that might influence permeability.

Gas permeability was much greater than liquid permeability (for overall data, on average, approximately nine times greater). Due to greater viscosity, molecular size, and liquid-wood interactions, liquid permeability is usually much lower than gas permeability (Taghiyari 2012; Rezende *et al*. 2018; Leggate *et al*. 2019, 2020). There was also a significant positive relationship (R^2 = 0.68, $p < 0.001$) between gas and liquid permeabilities, as shown in Fig. 8. This result was consistent with other studies by Leggate *et al*. (2019, 2020), who also reported a significant positive relationship between the gas and liquid permeabilities of plantation grown southern pine from Queensland, Australia.

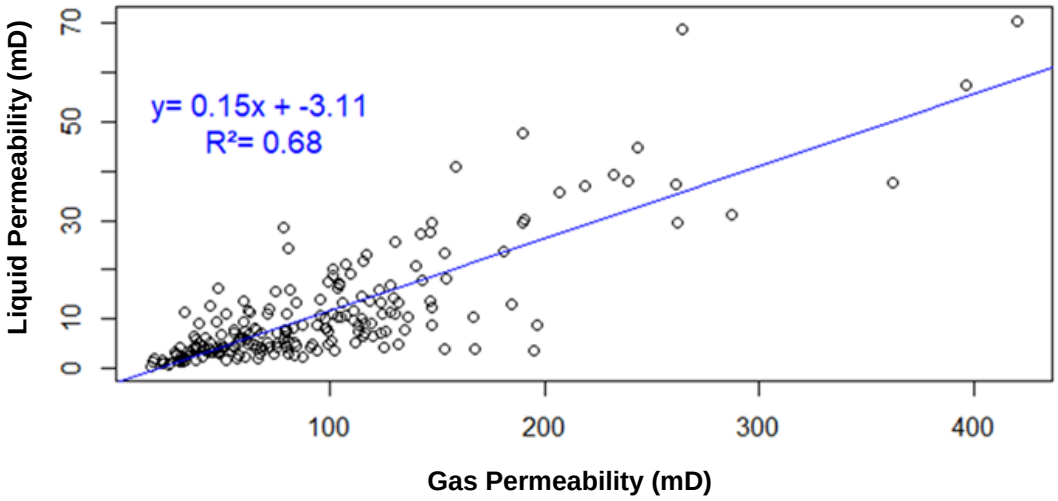

Fig. 8. Relationship between gas and liquid permeabilities

Wettability

Across all drying groups for all data combined, contact angles were significantly reduced, and therefore wettability increased, over the 10-s test time period ($p < 0.001$) (Table 4 and Figs. 9 and 10). This result reflected 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 (Leggate *et al*. 2020). However, different trends were observed for pre-machining *versus* post-machining, with the pre-machining samples having significantly greater contact angles for all data combined ($p < 0.001$) and therefore lower wettabilities compared to the post-machining samples (Table 4). Additionally, pre-machining contact angles throughout the 10-s test time remained much greater, no less than 45°, whereas post machining contact angles decreased much faster, reaching 0° in many cases very quickly (less than 3 s) (Figs. 9 and 10). The increased wettability of the wood surface after machining is the reason that wood usually undergoes a surface machining process such as planing prior to gluing. Surface machining increases the wettability of the wood surface by activating the wood surface through the removal of extractives (which have migrated to the surface) and contaminants (*e.g*., dust and dirt) (Leggate *et al*. 2020).

Table 4. Summary of Wettability Results (at 10 s of test time)

Drying Group	Earlywood/Latewood	Machining Stage	Mean Contact Angle (°) *	Mean *K*-value
Continuous	Earlywood	Pre-machining	47 (9)[b]	0.15
		Post-machining	0 (0)[c]	17.47
	Latewood	Pre-machining	50 (7)[b]	0.15
		Post-machining	8 (14)[c]	0.46
High Temperature	Earlywood	Pre-machining	48 (5)[b]	0.16
		Post-machining	0 (0)[c]	6.66
	Latewood	Pre-machining	62 (11)[a]	0.12
		Post-machining	5 (8)[c]	0.58
Low Temperature	Earlywood	Pre-machining	45 (10)[b]	0.18
		Post-machining	0 (0)[c]	12.43
	Latewood	Pre-machining	66 (16)[a]	0.08
		Post-machining	7 (12)[c]	0.61

Note: Means followed by the same letter in the same column are not significantly different (0.05).
* Standard deviations are presented in parentheses.

The contact angles of earlywood were overall significantly lower than those of latewood for both the pre- and post-machining groups ($p < 0.01$ for pre-machining; $p < 0.05$ for post-machining). This result was in accordance with another recent study on southern pine by Leggate *et al*. (2020) and also other studies showing that pine earlywood has greater wettability and is easier to glue compared to latewood (Herczeg 1965; Hse 1968; Scheikl and Dunky 1998). The greater wettability of earlywood is related to its lower density, greater tracheid lumen diameters, and greater porosity compared to latewood (Scheikl and Dunky 1998; Frihart 2013).

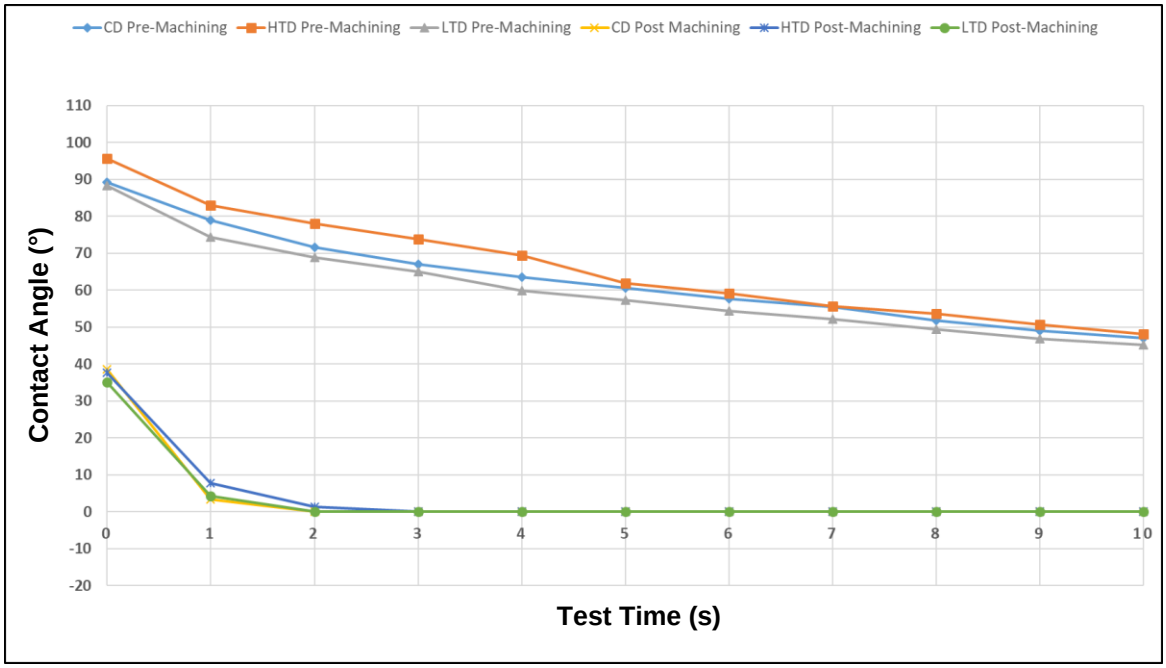

Fig. 9. Change in contact angle with time for earlywood: before and after surface machining (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

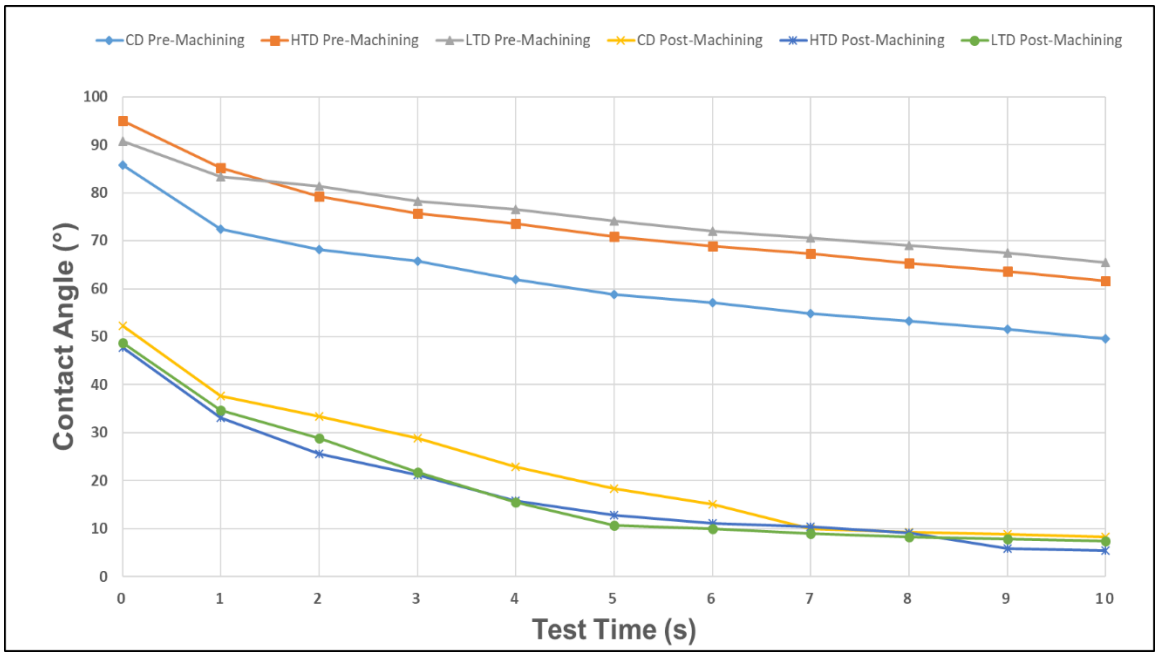

Fig. 10. Change in contact angle with time for latewood: before and after surface machining (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

In terms of drying group differences in wettability based on contact angle data, the trends were different for earlywood and latewood and for pre- and post-machining. For pre-machining earlywood at 10 s of test time, the ranking of wettability results from greatest to lowest was as follows: low temperature drying, continuous drying, and high temperature drying. For post-machining earlywood at 10 s of test time, there were no differences between drying groups, with all drying groups reaching a mean contact angle of 0°. However, across the 10-s test time, the high temperature drying group remained at a greater contact angle for longer, compared to the low temperature and continuous drying groups (Fig. 9). The lower wettability of higher temperature dried wood is consistent with other studies, which have shown that wood surfaces that have been exposed to a high temperature condition (including higher temperature drying) can experience surface inactivation or reduced wettability (Sernek 2002; Šernek *et al*. 2004). The better wettability of continuous dried wood (for earlywood) compared to high temperature schedule dried wood is a positive finding for companies looking to convert from high temperature to continuous drying kilns. Positive relationships have been shown between wettability and improved bond quality (Sernek 2002; Aydin 2004; Hernández and Cool 2008; Kläusler *et al*. 2014). However, different trends for the effect of drying schedules on wettability were observed for latewood. For pre-machining latewood at 10 s of test time, the ranking of wettability results (based on contact angle data) from greatest to lowest was as follows: continuous drying, high temperature drying, and low temperature, with continuous drying resulting in significantly greater wettability compared to low and high temperature drying (Table 4 and Fig. 10). For post-machining latewood at 10 s of test time, the ranking of wettability results (based on contact angle data) from highest to lowest was as follows: high temperature drying, low temperature drying, and continuous drying (Table 4 and Fig.

10). However, the differences between the drying groups for post-machining latewood contact angles were not significant (Table 4).

The *K*-values shown in Table 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; Leggate *et al*. 2020). By knowing the *K*-value, the spreading and penetration for a given liquid-solid system can be quantified and compared (Huang *et al*. 2012; Leggate *et al*. 2020). Greater *K*-values indicate that the contact angle reaches equilibrium more rapidly, and the liquid penetrates and spreads faster (increased wetting) (Huang *et al*. 2012; Leggate *et al*. 2020). The *K*-values were generally consistent with the contact angle data, with greater *K*-values (and therefore increased wettability of the surface) after surface machining. The *K*-values of earlywood were also greater than for latewood (Table 4). The *K*-value rankings for each drying group also matched the contact angle rankings with one exception: For post-machining latewood, low temperature drying produced a greater *K*-value compared to the other two drying groups.

Gluability

Results for tensile shear strength of the lap shear samples are shown in Tables 5 and 6 and Fig. 11.

Table 5. Summary of Tensile Shear Strength Results for Each Drying Group (Combined surface and core data)

Drying Group	Mean Tensile Shear Strength (N/mm^2)
Low Temperature Drying Schedule	11.18^a
Continuous Drying Schedule	11.99^a
High Temperature Drying Schedule	11.49^a

Note: Means followed by the same letter in the same column are not significantly different (0.05).

Table 6. Summary of Tensile Shear Strength Results for Surface and Core of Each Drying Group

Drying Group	Surface or Core	Mean Tensile Shear Strength (N/mm^2)
Low Temperature Drying Schedule	Surface	12.24^a
	Core	10.13^b
Continuous Drying Schedule	Surface	12.11^a
	Core	11.87^a
High Temperature Drying Schedule	Surface	11.23^{ab}
	Core	11.74^{ab}

Note: Means followed by the same letter in the same column are not significantly different (0.05).

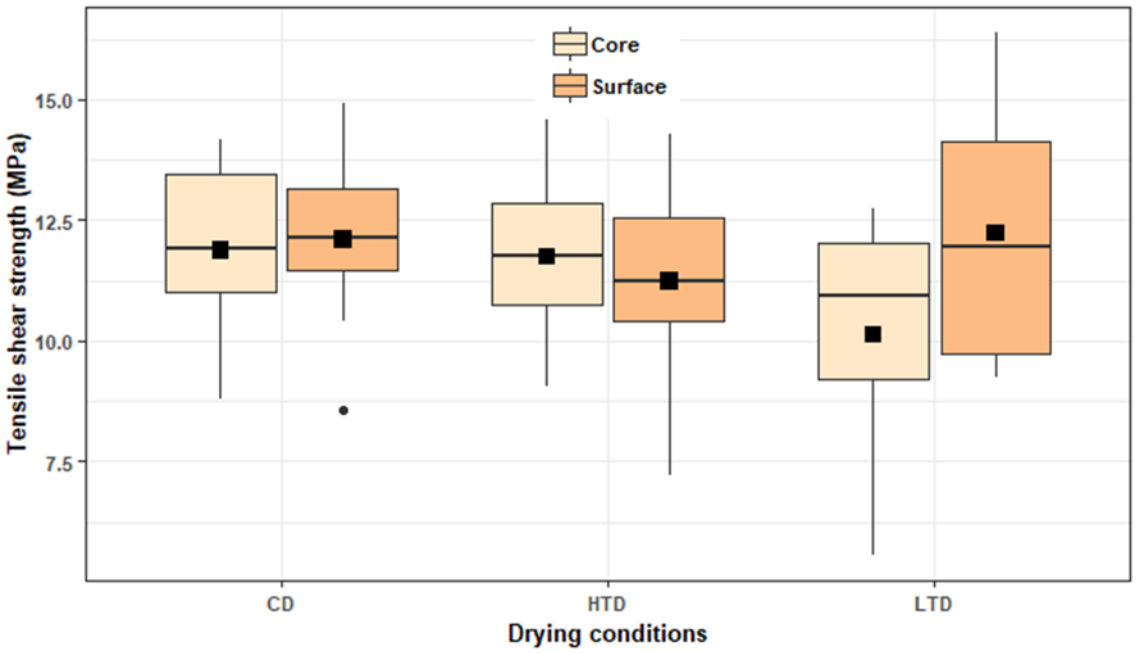

Fig. 11. Tensile shear strength results of lap shear samples from each drying group (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

As shown in Table 5, for combined surface and core data, there was no significant effect of drying type on the tensile shear strength of lap shear samples. However, the continuous drying group had the greatest mean tensile shear strength. Differences between surface and core samples were not significant with the exception of the low temperature drying group, where the surface samples had a significantly greater shear strength than the core samples (Table 6). This result could possibly be caused by greater resin content in the core compared to the surface of low temperature dried wood, where the resins may not have been mobilised towards the surface due to the low temperatures used. However, resin content and distribution were not assessed in this study.

Treatability

Results for copper penetration and preservative uptake are shown in Tables 7 and 8 and in Figs. 12 and 13. As shown in Table 7, for combined surface and core samples, the continuous drying schedule resulted in significantly greater preservative uptake compared to the other two drying groups and significantly greater copper penetration compared to low temperature drying. There was no significant difference between continuous drying and high temperature drying for copper penetration. The lowest mean preservative uptake and copper penetration resulted from low temperature drying. Table 8 shows that within drying groups there were no significant differences between surface and core samples in preservative uptake and copper penetration. However, with the exception of the continuous drying group, surface samples had greater mean preservative uptake and copper penetration compared to core samples. The greater treatability of the surface samples in the low temperature and high temperature dried groups is most likely related to the greater frequency of surface checking observed in these samples, which would increase the number and size of pathways for fluid flow through the samples. The surface samples also had the greatest permeability (discussed above). However, apart from this similarity, the rankings for permeability (mean values) for the three different drying groups did not match the

rankings for mean preservative uptake and copper penetration. For example, low temperature drying resulted in the greatest mean gas and liquid permeabilities but the lowest mean preservative uptake and copper penetration.

Table 7. Summary of Results for Copper Penetration and Preservative Uptake for Each Drying Group for Combined Surface and Core Data

Drying Group	Mean Copper Penetration Area (%)	Mean Preservative Uptake (L/m^3)
Low Temperature Drying Schedule	7.49[b]	155.53[b]
Continuous Drying Schedule	14.8[a]	199.08[a]
High Temperature Drying Schedule	14.47[a]	172.35[b]

Means followed by the same letter in the same column are not significantly different (0.05).

Table 8. Summary of Results for Copper Penetration and Preservative Uptake for Surface and Core Samples for Each Drying Group

Drying Group	Surface or Core	Mean Copper Penetration Area (%)	Mean Preservative Uptake (L/m^3)
Low Temperature Drying Schedule	Surface	7.54[b]	161.8[bc]
	Core	7.43[b]	148.86[c]
Continuous Drying Schedule	Surface	13.4[a]	198.72[a]
	Core	16.31[a]	199.48[a]
High Temperature Drying Schedule	Surface	16[a]	190.89[ab]
	Core	13.09[a]	155.66[bc]

Means followed by the same letter in the same column are not significantly different (0.05).

Usually, permeability is regarded as closely related to treatability; however, some studies have shown that this is not always the case (Prak 1970). Prak (1970) explained that high permeability values indicate that fluid or gas passage through the wood is easy, but they do not necessarily mean that all voids are filled readily with a fluid—some portion of the specimen may be even almost inaccessible, while the whole specimen appears highly permeable. Another reason for the finding of a limited relationship between permeability and treatability in the current study is that only radial permeability was measured, whereas the treatability results reflect liquid movement into the wood in all directions. The results for treatability better matched the expected results based on other studies, compared to the permeability results. As explained above, many studies have reported lower treatability and permeability with wood that has been low temperature dried compared to wood that has been high temperature dried. Differences in treatability and permeability between the drying groups are likely explained by the effects of the different drying conditions on wood

anatomical structure, including the presence of interstitial spaces and micro-checks, 2) pit aspiration and integrity of pit membranes and cell walls, and 3) wood resin distribution. Further studies into the differences between the three different drying types in terms of their effects on wood anatomy and resin distribution would likely help to elucidate the reasons for the differences in permeability and treatability.

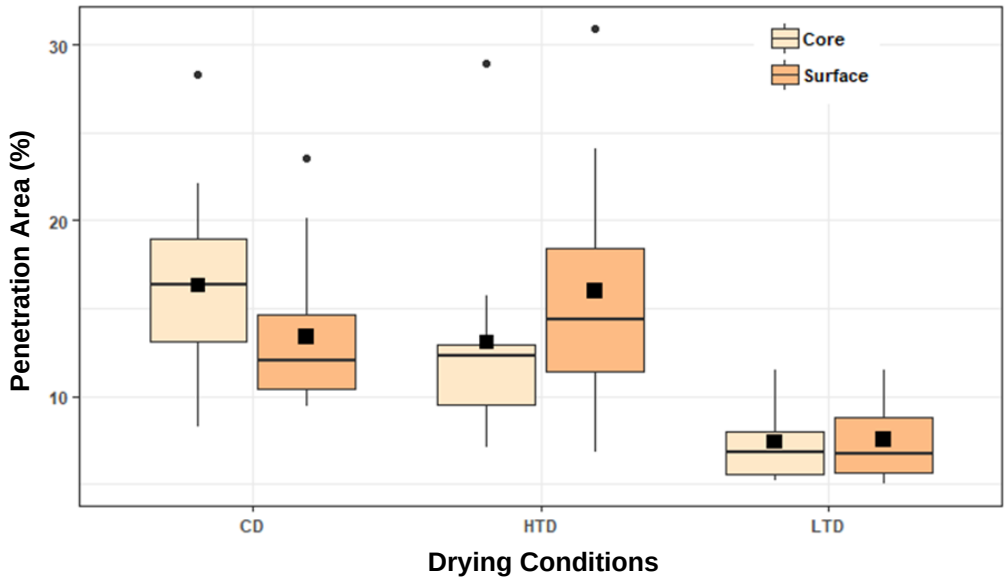

Fig. 12. Copper penetration in surface and core samples of each drying group (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

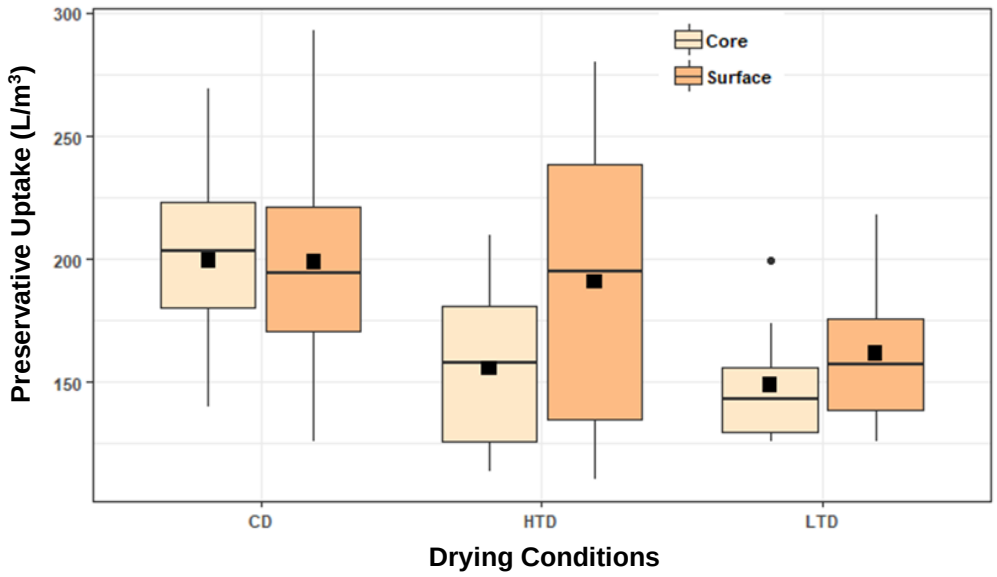

Fig. 13. Preservative uptakes in surface and core samples of each drying group (CD= Continuous Drying; HTD=High Temperature Drying; LTD=Low Temperature Drying)

CONCLUSIONS

1. For combined surface and core assessments, the greatest mean gas and liquid radial permeabilities were exhibited by the low temperature drying group, followed by the continuous drying group, and then the high temperature drying group, which exhibited the lowest mean gas and liquid radial permeabilities. However, the differences between the groups in gas radial permeability were not significant. For combined surface and core assessments, the high temperature drying resulted in significantly lower liquid radial permeability compared to low temperature drying; however, there were no significant differences in liquid radial permeability between low temperature drying and continuous drying or between continuous drying and high temperature drying. In most cases, surface samples had greater gas and liquid radial permeabilities compared to core samples. This result could be attributed to the greater incidence of surface checking in the surface samples. There was a significant positive relationship between gas and liquid radial permeabilities.
2. Surface machining significantly increased the wood wettability, and earlywood had significantly greater wettability than latewood. Rankings in wettability between drying groups varied with pre- and post-machining, as well as for earlywood and latewood. Comparing post-machining *K*-values for earlywood, continuous drying resulted in greater wettability compared to high temperature drying and low temperature drying. However, for post-machining latewood, the low temperature drying schedule resulted in the greatest wettability.
3. The highest tensile shear strength for lap shear samples resulted from the continuous drying schedule; however, differences between drying groups were not significant.
4. For treatability, continuous drying resulted in greater preservative uptake and copper penetration compared to the high temperature and low temperature drying schedules, although there was no significant difference in copper penetration between the continuous and high temperature drying schedules.
5. Overall, the results revealed better outcomes for the continuous drying schedule compared to the high temperature drying schedule for permeability, wettability, gluability, and treatability. This result is encouraging for companies looking to switch from drying with conventional high temperature batch kilns to continuous drying kilns.

ACKNOWLEDGMENTS

The authors are particularly grateful for the technical support of Mrs. Rica Minnett, Mr. Stuart Meldrum, Mr. Andrew Outhwaite, Mr. Chuang Miao, Mr. Jack Dorries, and Dr. Maryam Shirmohammadi with the preparation, processing, and testing of wood samples. Kerri Chandra is thanked for her assistance with statistical analysis. Mr. Tomas Leggate is acknowledged for his assistance with diagram preparation. The support provided by the Queensland Government, Department of Agriculture and Fisheries (DAF), through the provision of the unique facilities located at the Salisbury Research Facility is acknowledged as critical to facilitate studies of this nature. The authors are also grateful to Hyne Timber, in particular Dr. Henri Bailleres, for the supply of the timber for this project. Mr. Rod Vella from Jowat Universal Adhesives Australia Pty Ltd is also thanked for the

provision of the adhesives used in the study. The authors also acknowledge the Australian Research Council and the Centre for Future Timber Structures for the funding support provided for this research.

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Article submitted: September 20, 2020; Peer review completed: October 31, 2020; Revised version received and accepted: November 30, 2020; Published: December 7, 2020.
DOI: 10.15376/biores.16.1.698-720