The Effects of the Addition of Surfactants and the Machining Method on the Adhesive Bond Quality of Spotted Gum Glue-laminated Beams

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The effects of adding surfactants to polyurethane and resorcinol formaldehyde adhesives were tested relative to the gluability of spotted gum timber for structural glue-laminated beams (Glulam). While previous attempts to improve the bond performance of this very difficult to glue timber have focused primarily on timber surface preparations, this study concentrated on lowering the adhesive surface tension through added surfactants to improve the adhesive-timber surface wetting. Accordingly, 44 glulam samples were manufactured using polyurethane and resorcinol formaldehyde adhesives, with eight surfactant formulations and two different pre-gluing surface machining methods, *i.e.*, face milling and planing. Although the surfactants were successful in drastically lowering the adhesive surface tension and improving adhesive spreading, none of the surfactant formulations tested were successful in improving the glulam adhesive bond qualities. Overall, the surfactant formulations produced considerably higher delamination, lower shear strength, and lower wood fibre failure compared to the control samples; therefore, they are not a viable solution to improve the gluing of spotted gum. The resorcinol formaldehyde adhesive and face milling produced considerably better results compared to the polyurethane adhesives and conventional planing.

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INTRODUCTION

The gluing of spotted gum (*Corymbia citriodora*) timber is particularly challenging, especially when targeting sawn timber based, structural glue-laminated beam (Glulam) products. Some improvements in spotted gum timber gluability have been achieved using alternative surface preparation approaches, *e.g.*, face milling or sanding post-planing (Leggate *et al.* 2020; Leggate *et al.* 2021a,b,c). However, commercial scale trials with these better performing options still do not consistently produce adhesive bonds that are compliant with the standard for structural glulam in Australia, according to AS/NZS standard 1328.1:1998 (2011).

Previous studies by Leggate *et al.* (2020; 2021a,b,c) have also highlighted the very low permeability and wettability of spotted gum timber, which negatively impacts adhesive

spreading, penetration, and ultimately the adhesive bond quality. Petrie (2021) notes that a critical aspect of successful wood adhesion is optimal surface energy (tension) of the adhesive, so that it can be easily spread onto the wood surface and achieve desirable surface wetting and penetration. Some studies have also shown positive correlations between a lowered surface tension of the adhesive and an improved bond quality (Hse 1971, 1972).

Surface energy can be defined as the sum of all the intermolecular forces that are on the surface of a material – the degree of attraction or repulsion force that a material surface exerts on another material (SpecBond 2018; Colcar 2020). In the case of liquids, this same definition is applied to define the surface tension (Colcar 2020). When the substrate has a high surface energy, and therefore tends to attract, and the adhesive has a low surface tension, a good wetting of the adhesive on the substrate is produced. To achieve optimal bonding, the substrate to be bonded must have a surface energy higher than the surface tension of the adhesive, thus achieving good wettability or wetting. However, adhesives must have a lower surface tension than the surface energy of the substrates to help its wetting (Colcar 2020). Standard approaches to increasing the surface energy of the wood typically include various timber surface preparation processes prior to gluing such as surface machining (especially planing) and chemical treatments. However, limited success has been achieved with these approaches in the gluing of spotted gum for structural glulam. Various types of plasma treatment have also been shown to increase the surface energy of the wood surface; however, despite showing some improvements in spotted gum adhesion, they have not yet been adopted by industry as a viable commercial solution for structural glulam manufacture (Ramos 2001; Acda *et al*. 2012; Kumar and Pizzi 2019).

One of the best methods of reducing the surface tension of a liquid is to add surfactants. Surfactants are compounds that decrease the surface tension (or interfacial tension), and they may also act as soaps, detergents, wetting agents, emulsifiers, foaming agents, or dispersants (Schramm *et al.* 2003; Laurén 2018; Petrie 2021). Surfactants are usually amphiphilic molecules that have both hydrophobic and hydrophilic groups (Schramm *et al.* 2003; Laurén 2018; Petrie 2021). Therefore, a surfactant usually contains both a water-insoluble (or oil-soluble) component and a water-soluble component (Schramm *et al.* 2003; Laurén 2018: Petrie 2021)). However, surfactant formulations vary widely, and classifications can include amphiphilic, anionic, non-ionic, cationic, amphoteric, and zwitterionic (Schramm *et al.* 2003). Surfactants are commonly used in commercial waterborne and solvent-based adhesive formulations for reducing the surface tension, improving the flow, wetting, and dispersion of additives, the stability of pigments, and defoaming (Petrie 2021). However, the effects on wood gluability of adding additional surfactants to pre-prepared commercial adhesive formulations of one component moisture curing (1C-PUR) and resorcinol formaldehyde (RF) adhesives for glulam manufacture has not previously been reported.

In this study, various surfactant types were added to 1C-PUR and RF adhesives to test their efficacy on reducing the surface tension of the adhesives and their influence on the glued performance of spotted gum glulam.

EXPERIMENTAL

Wood Material

The spotted gum boards used for this study were selected from randomly chosen packs obtained from a commercial provider. The packs contained 100 mm x 25 mm

(nominal width and thickness) mixed length, kiln-dried feedstock destined for milled products, *e.g.*, flooring and decking. In preparation for the glulam test sample manufacture, 40 boards averaging approximately 1200 mm in length were ripped to a consistent width of 90 mm and docked to 176 defect free sample boards with a 300 mm length, which were then stored in a constant environment chamber (CEC) set at a temperature of 20 ° C and a relative humidity (RH) of 65% to a target equilibrium moisture content (EMC) of 12%. The boards were randomly allocated to the different test sample manufacturing processes, as described below.

Test Sample Manufacture

Surface machining

The boards were prepared for glulam manufacture using two different surface machining methods, *i.e.*, face milling and planing. Table 1 details the parameters of each surface machining configuration. During each surface machining process (as described in Table 1), 1.5 mm was removed from the upper and lower timber surface to reduce the board thickness to 22 mm.

Table 1. Surface Machining Methods

Surface Machining Type	Cutter Specifications	Machining Parameters
Face Milling	Type: Tungsten Carbide Pt No: Leucodur – HL 40 Dim: 14 x 14 x 2 mm 48 Cutters @ 520 mm diameter (Ø)	Feed rate = 45 m/min Cutter speed = 2100 rpm (57 m/s)
Conventional Planing	High Speed Steel Blade 40.5° Blade tip angle 120 mm Cutterblock Ø	Feed Rate = 8 m/min Cutter speed = 4500 rpm (28 m/s)

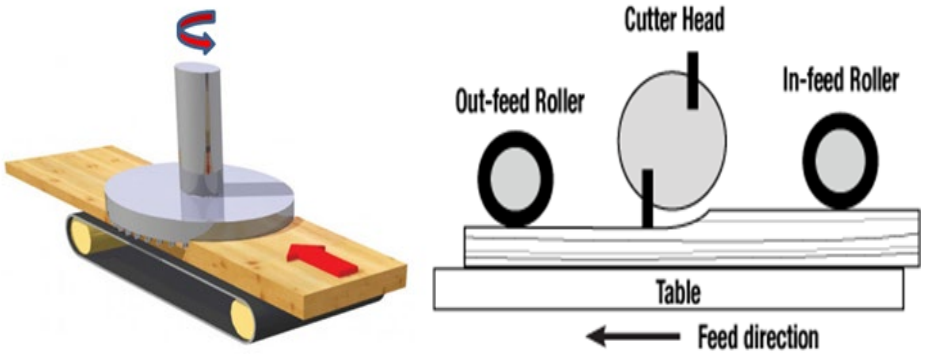

Fig. 1. Machining preparation method comparison between (a) the Rotoles face milling approach (Ledinek 2020; Leggate 2021a); and (b) the conventional planing approach (CCOHS 2020; Leggate 2021a)

Face milling and planing were undertaken using a similar approach to that described in detail in previous studies by Leggate *et al.* (2021a). Face milling was undertaken using a Rotoles 400 D-S single side rotary planer manufactured by Ledinek (Hoče, Slovenia) (Leggate *et al.* 2021a). This face milling approach has the rotary head and cutters positioned parallel to the machining surface with the drive shaft positioned perpendicular to the board surface (Fig. 1) (Leggate *et al.* 2021a). The cutting direction with face milling is primarily perpendicular to the grain (Knorz *et al.* 2015; Leggate *et al.* 2021a). Conventional planing was undertaken using a SCM Group Mini Max Formula SPI thickness planer (Rimini, Italy) (Leggate *et al.* 2021a). The conventional planer has the cutter head drive shaft positioned parallel to the board surface (Fig. 1) (Leggate *et al.* 2021a). The cutting direction with conventional planing is primarily parallel to the grain (Knorz *et al.* 2015; Leggate *et al.* 2021a).

Adhesives

The adhesives used for glulam manufacture in this study were RF and 1C-PUR adhesives. Historically, the most common adhesives used in the manufacture of glulam have been RF and phenol resorcinol formaldehyde (PRF) (Vella *et al.* 2019a; Vella 2020; Leggate *et al.* 2021b). One reason that there has been limited use of PUR adhesives for hardwoods in Australia has been because of concerns over their suitability with higher density timbers. They have been traditionally used with lower density timbers and have not yet been adequately tested with northern-Australian high-density hardwood timbers (Vella *et al.* 2019a; Vella 2020; Leggate *et al.* 2021b). Polyurethane adhesives have many advantages over RF and other adhesive types, including faster curing properties, a lack of formaldehyde emissions, light coloured glue-lines, and a single component system that is supplied ready to use (Lehringer and Gabriel 2014; Vella *et al*. 2019a, Vella 2020; Leggate *et al*. 2021b). RF and PUR adhesives are widely accepted internationally to provide superior bond performance for weather exposed, structural glulam. This study included both RF (55-59% solids content) and 1C-PURs (99 ± 1% solids content) adhesives to determine their relative performance with and without added surfactants.

Surfactant formulations and surface tension measurement

Nine different formulations were trialed, including eight surfactant formulations (referred to as A to H) and one control (no surfactant added). The surfactant formulations included different commercial-in-confidence combinations and compositions of long chain alcohols, amphoteric, non-ionic, cationic, anionic surfactants, and a polar component. These surfactants were added to the adhesive at a concentration of 3% at the recommendation of the supplier.

The surface tension measurements were conducted using the pendant drop method on an Attension Theta Flex (Biolin Scientific, Västra Frölunda, Sweden) optical tensiometer fitted with a manual dispenser holder and manual sample stage. The images and data were processed using One Attension software (Biolin Scientific, Version 4.0.5, Västra Frölunda, Sweden). A 10 s video recording was taken and analyzed using the One Attension software with a surface tension calculation of the droplet being taken every seven hundredth of a second. The One Attension software calculated the mean surface tension from the collected data, which was used to compare the different treatments.

Adhesive application

The adhesive was applied to the timber within one minute of surface machining. The RF adhesive was applied to the faces of each board using a spatula at a spread rate of 450 g/m^2 (gsm). Once the adhesive was spread on the appropriate faces, the boards were closed until a four board (three glue line) glulam sample was produced. The RF adhesive requires a closed assembly time (CAT) to allow for a period of time for adhesive gelation to occur prior to pressure being applied. This allows the viscosity of the adhesive to increase prior to pressing, therefore reducing the amount of adhesive lost from the joint due to squeeze out. The length of the CAT was 20 min, in accordance with the adhesive Technical Data Sheet (TDS).

The PUR adhesive was applied to one adherent surface at a spread rate of 250 gsm, using a spatula. Once the adhesive was spread on the appropriate faces, the boards were closed until a four board (three glue line) glulam sample was produced. The CAT was minimized to no more than 3 min.

Pressing and curing

The curing of the RF and PUR adhesives was carried out under pressure to ensure that the adherent surfaces were held closely together for the duration of the adhesive curing process. At the end of the CAT period, the glulam samples were placed in the platen press and pressure was applied for a minimum of 12 h at 1.4 MPa and 6 h at 1 MPa for the RF and PUR adhesives, respectively.

Test Sample Assessment

The manufactured glulam samples measured 90 mm x 88 mm x 300 mm (W x T x L). A total of 36 glulam samples were manufactured, *i.e.*, 8 glulam samples for each adhesive type. After manufacture, these were stored in a CEC set at a temperature of 20 °C and a relative humidity (RH) of 65% for at least 7 d to ensure full adhesive cure was achieved before the assessment process. After this period, the samples were machined to a width of 84 mm and a 75 mm long section, which represented the full cross section, was removed from the middle of each glulam sample for the assessment of the glue line delamination performance, and two 40 mm x 88 mm x 53 mm (W x T x L) sections for the assessment of glue line shear strength and fibre failure performance (as shown in Fig. 2). Table 2 provides details of the glulam sample numbers allocated across different surface machining, adhesive types, and test methods

Table 2. Glulam Sample (and Glue Line) Numbers Allocation Across the Adhesive Type, Surface Machining Method, Formulation, and Test Methods

Adhesive	Surface Machining	Number of Glulam Samples (Across 9 Formulations)	Number of Glue-lines Assessed (Across 9 Formulations for Delamination, Shear Strength, and Fibre Failure) *
RF	Planing	9	27
	Face Milling	9	27
PUR	Planing	9	27
	Face Milling	9	27
Totals		36	108
*For each configuration of adhesive x surface machining x formulation three glue lines were assessed for delamination, shear strength and fibre failure			

Fig. 2. Post-cure processing of the cured glulam sample: (1) 84 mm x 88 mm x 75 mm (W x T x L) sample for the delamination testing in accordance with AS/NZS standard 1328.1:1998 (2011); (2) 40 mm x 88 mm x 53 mm (W x T x L) sample for block shear testing pre-wet and dry cycling; and (3) 40 mm x 88 mm x 53 mm (W x T x L) sample for fibre failure testing post-wet and dry cycling

The delamination assessment was conducted in accordance with AS/NZS standard 1328.1:1998 (2011), which is used to test structural glulam bond performance in Australia. The glulam samples were tested in accordance with Appendix C, test method A, which allows for qualification for use as a service class 3 (the most stringent class) product. A service class 3 glulam product requires qualification against a delamination test acceptance criteria consisting of a maximum allowable delamination percentage of 40% within any one glueline and a maximum allowable total delamination of 5% within the total cross section after 2 cycles or 10% after 3 cycles.

Prior to commencing the assessment, the length across the end-grain for each glue line within the 75 mm length specimen was measured, with the measurements recorded for later use in calculating the delamination percentages. The samples were then added to a pressure cylinder, submersed in water and a vacuum (70 to 85 kPa) was applied for 5 min followed by a 1 h pressure (500 to 600 kPa) cycle. This vacuum and pressure cycle was conducted twice. The specimen was then dried in an oven at a temperature of 65 °C, a RH of 15%, and an air velocity of 2.4 m/s for 21 h. The wetting and drying process was repeated to provide two full cycles. In accordance with AS/NZS standard 1328.1:1998 (2011), if the total delamination values that resulted after two cycles were greater than 5% but less than 10%, a third saturation and drying cycle was conducted before the final assessment. At the end of the cycles, the length of the adhesive delamination within each glue line was measured. From these measurements, the total delamination and maximum delamination were calculated using Eq. 1 and Eq. 2, respectively,

$$Total\ Delamination\ \% = \ 100\ x\ \frac{l_{tot,delam}}{l_{tot,glueline}} \quad (1)$$

$$Maximum\ Delamination\ \% = \ 100\ x\ \frac{l_{max,delam}}{2l_{glueline}} \quad (2)$$

where $l_{total,delam}$ is the length of the total delamination, $l_{total,glueline}$ is the length of the total glueline, and $l_{max,delam}$ is the length of the maximum delamination.

The block shear assessment of the glue line was conducted in accordance with AS/NZS standard 1328.1:1998 (2011) Appendix D, "shear test of gluelines". Two shear test sample blocks were cut from each glulam sample directly adjacent to the delamination

test sample (as shown in Fig. 2). One of the block shear samples from each glulam was shear tested prior to the wet and dry cycling. The other sample was subjected to the same wet and dry cycles as the delamination test samples described above.

The block shear testing was conducted in a block shear testing apparatus (as shown in Fig. 3) with the shearing force being applied by a Shimadzu AG-X universal testing machine (AG-100X, Shimadzu Corporation, Kyoto, Japan) fitted with a 100 KN load cell, with a cross head displacement of 3.5 mm/min.

Fig. 3. Block shear testing apparatus

Each glue line of the block shear samples was tested consecutively with the maximum load at failure recorded. The shear strength (f_v) was calculated using the load at failure F_{max} and the measured glue line cross-sectional area (A) of the sample as outlined in Eq. 3,

$$f_v = \frac{F_{max}}{A} \quad (3)$$

The block shear samples were also visually inspected after testing to determine the percentage of wood fibre failure. Wood fibre failure is the rupturing of wood fibres adjacent to the glue line, as opposed to an adhesion or cohesion failure within the glue line. Therefore, it shows the quality of the adhesive bond between the timber adherend surfaces. Assessment of the percentage of wood fibre failure provides an indication regarding the strength of the bond relative to the wood (Kuljich *et al.* 2013). Low wood fibre failure indicates that the wood is stronger than the adhesion between the timber and glue or the glue itself. High wood fibre failure indicates that the glue is stronger than the wood. The premise of measuring the percent of wood failure is that structural adhesives are generally assumed to be stronger than the substrate. Therefore, the failure plane in properly fabricated joints should be predominantly located in the wood and not in the glueline (Kuljich *et al.* 2013).

The calculation of the percentage of wood fibre failure was conducted in accordance with ASTM standard D5266-13 (2020). The percentage wood fibre failure was determined by estimating the area of wood fibre that remained adhered at the glue line and expressing this area of fibre as a proportion of the entire glue line area.

Additional Testing at Lower Surfactant Concentrations

To test the effect of using a lower surfactant concentration than the 3% concentration used in the primary study outlined above, the best performing surfactant with each adhesive type was also tested at concentrations of 0.5% and 1%. The methodology for this additional testing was the same as outlined above. However, a smaller number of glulam samples were used, *i.e.*, 2 glulam samples per adhesive type, with the application of face milling only, and assessments were conducted only by delamination in accordance with AS/NZS standard 1328.1:1998 (2011).

Statistical Analysis

Statistical analysis was conducted using GenStat version 19 (VSN, Hemel Hempstead, United Kingdom). The data was analyzed using analysis of variance (ANOVA). Least significance differences testing was completed to compare the means when the ANOVA showed significance in a factor.

RESULTS AND DISCUSSION

Surface Tension and Adhesive Spreading (for 3% Surfactant Concentration Data)

All the surfactant formulations markedly reduced the adhesive surface tension and improved the adhesive wetting and spreading. The resultant surface tensions of the adhesives after mixing with the surfactant at a concentration of 3% are shown in Table 3.

Table 3. The Surface Tensions of the Adhesive/Surfactant Formulations

Formulation	Surfactant + RF Mean Surface Tension (mN/m)	Surfactant + PUR Mean Surface Tension (mN/m)
Control (no surfactant added)	44.64	31.45
A	23.78	24.57
B	22.52	25.61
C	23.20	24.89
D	23.58	26.70
E	22.30	22.80
F	22.91	23.52
G	25.77	24.35
H	29.01	29.59

Figure 4 shows an example of the improved adhesive spreading and wetting on the spotted gum timber, which was observed with all surfactants after being added to the adhesive. The example shown is for the application of the RF adhesive with/without an added surfactant. The addition of a surfactant helped achieve a more uniform adhesive spread with the resultant glued surface having less areas of repelled adhesive.

Fig. 4. Resorcinol formaldehyde adhesive application to spotted gum timber without the added surfactant (left) and with the added surfactant (right)

Assessments of Delamination According to AS/NZS Standard 1328.1:1998 (2011) (for 3% Surfactant Concentrations)

The total delamination and maximum delamination percentage for each of the glulam replicates after application of the assessment criteria in AS/NZS standard 1328.1:1998 (2011) are detailed in Table 4.

All the glulam samples failed to meet the adhesive bond requirements of AS/NZS standard 1328.1:1998 (2011). To pass, the samples have to satisfy both the maximum delamination (less than or equal to 40%) and total delamination (less than or equal to 5% after 2 test cycles) requirements of the standard. All samples failed the total delamination requirements and only three samples passed the maximum delamination requirements of the standard, of which two of these were the control samples (no surfactant added) and one was a face milled sample glued with the surfactant H/RF formulation. Even though all of the surfactants trialed had reduced the surface tension of the adhesive (as shown in Table 3), they were not successful in achieving acceptable adhesive bond performance according to the standard. Figure 5 illustrates the differences between the glulam samples that passed or failed the total delamination requirements of AS/NZS standard 1328.1:1998 (2011).

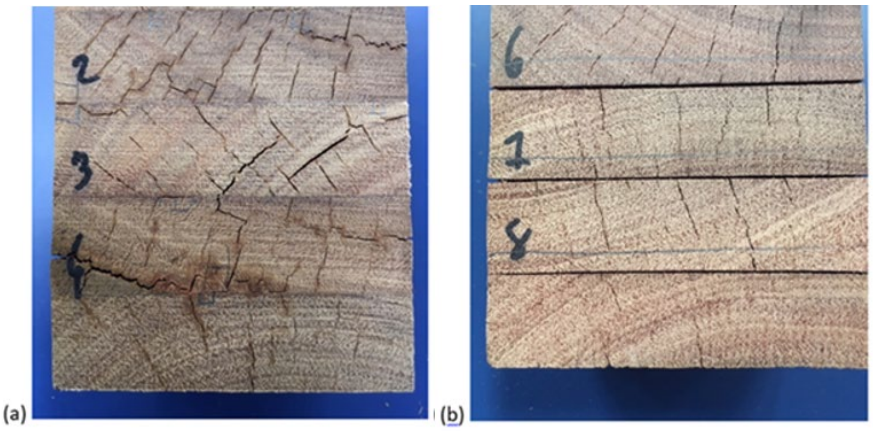

Fig. 5. (a) a glulam sample that has passed the requirements of AS/NZS standard 1328.1:1998 (2011) (b); and a glulam sample that has failed the requirements of AS/NZS standard 1328.1:1998 (2011) as evidenced by the delamination in all the glue lines

Table 4. Delamination Assessments of the Glulam Samples According to AS/NZS Standard 1328.1:1998 (2011)

Adhesive	Surface Machining	Formulation	% Maximum Delamination	% Total Delamination
RF	Planing	Control	30.4	44
	Face milling	Control	29.0	39.6
PUR	Planing	Control	50	100
	Face milling	Control	42.6	66.6
RF	Planing	H	46.0	68.6
	Face milling	H	39.2	65.7
PUR	Planing	H	50.0	99.2
	Face milling	H	50.0	99.2
RF	Planing	A	47.4	76.1
	Face milling	A	45.5	79.6
PUR	Planing	A	50	100
	Face milling	A	50	99.2
RF	Planing	B	48.9	83.4
	Face milling	B	41.5	72.5
PUR	Planing	B	50	100
	Face milling	B	50	75.6
RF	Planing	C	42.1	48.7
	Face milling	C	47.2	72
PUR	Planing	C	50	100
	Face milling	C	50	97
RF	Planing	D	50	94.1
	Face milling	D	50.6	71.6
PUR	Planing	D	50	100
	Face milling	D	50	94.5
RF	Planing	E	48.9	76.6
	Face milling	E	50	96.5
PUR	Planing	E	50	100
	Face milling	E	50	96.2
RF	Planing	F	50	90
	Face milling	F	50	90.2
PUR	Planing	F	50	100
	Face milling	F	50	94.7
RF	Planing	G	47.2	87.1
	Face milling	G	50	86.7
PUR	Planing	G	50	99.7
	Face milling	G	50	78.4

Note: (Pass = green, Fail = red)

Comparison of the Total Delamination, Shear Strength, and Fibre Failure Results between Treatments (for the 3% Surfactant Concentration Data)

Table 5 summarizes the statistically significant relationships between all the experimental factors and response variables.

Delamination (for 3% surfactant concentration data)

As shown in Table 5, the delamination results were significantly influenced by the adhesive type (p-value less than 0.001), formulation (p-value less than 0.001), and surface machining (p-value less than 0.05). There were also significant interactions between the adhesive type and formulation (p-value less than 0.001), adhesive type and surface

machining (p-value less than 0.01), and formulation and surface machining (p-value less than 0.01). These effects and interactions are discussed below. The delamination results for each treatment are shown in Table 6.

Table 5. Significance of the Relationships between the Experimental Factors and Response Variables

	Delamination	Shear Strength (Pre-cycling)	Shear Strength (Post-cycling)	Fibre Failure (Pre-cycling)	Fibre Failure (Post-cycling)
Adhesive Type	***	***	***	***	**
Formulation	***	ns	ns	ns	**
Surface Machining	*	**	***	***	ns
Adhesive + Formulation	***	**	ns	ns	ns
Adhesive + Surface Machining	**	**	***	ns	*
Formulation + Surface Machining	**	ns	*	ns	***
Adhesive + Formulation + Surface Machining	Ns	ns	ns	**	ns
Note: (* = p less than 0.05; ** = p less than 0.01, *** = p less than 0.001; and ns = not significant p greater than 0.05)					

Table 6. Delamination Results for Each Treatment

Formulation	Mean Total Delamination (%) (standard deviation)								
	Planed			Face Milled			Combined Planed & Face Milled Data		All Data
	PUR	RF	Pooled PUR & RF	PUR	RF	Pooled PUR & RF	PUR	RF	
Control	100 (0)	44.0 (10.9)	72.0 (31.4)	66.6 (17.5)	39.6 (14.5)	53.1 (20.6)	83.3 (21.4)	41.8 (11.7)	62.5 (27.2)
A	100 (0)	76.1 (24.7)	88.1 (20.4)	99.2 (1.3)	79.6 (7.7)	89.4 (11.8)	99.6 (0.9)	77.9 (16.5)	88.8 (15.9)
B	100 (0)	83.4 (16.7)	91.7 (13.9)	75.6 (23.4)	72.5 (10.4)	74.1 (16.3)	87.8 (20.0)	78.0 (13.8)	82.9 (17.1)
C	100 (0)	48.7 (11.5)	74.3 (29.0)	97 (1.3)	72.0 (16.5)	84.5 (17.2)	98.5 (1.9)	60.3 (18.0)	79.4 (23.4)
D	100 (0)	94.1 (7.2)	97.1 (5.6)	94.5 (9.5)	71.6 (14.2)	83.0 (16.6)	97.3 (6.7)	82.9 (15.9)	90.1 (13.9)
E	100 (0)	76.6 (23.4)	88.3 (19.6)	96.2 (3.6)	96.5 (3.0)	96.4 (3.0)	98.1 (3.1)	86.6 (18.5)	92.3 (14.0)
F	100 (0)	90.0 (9.4)	95.0 (8.1)	94.7 (4.6)	90.2 (5.6)	92.4 (5.2)	97.3 (4.1)	90.1 (6.9)	93.7 (6.6)
G	99.7 (0.5)	87.1 (5.7)	93.4 (7.8)	78.4 (17.0)	86.7 (7.6)	82.6 (12.6)	89.1 (15.9)	86.9 (6.0)	88.0 (11.5)
H	99.2 (1.3)	68.6 (13.8)	83.9 (19.0)	99.2 (1.3)	65.7 (8.0)	82.5 (19.1)	99.2 (1.2)	67.1 (10.2)	83.2 (18.1)
Combined	99.9 (0.5)	74.3 (21.1)	87.1 (19.6)	89.0 (15.3)	74.9 (18.3)	82.0 (18.2)	94.5 (12.0)	74.6 (19.6)	84.5 (19.0)

The results for the control samples (without a surfactant added) showed that the PUR adhesive resulted in significantly higher delamination compared to the RF samples for both planing and face milling (p-value less than 0.05). In addition, for the control samples, planing resulted in significantly higher delamination compared to face milling (p-value less than 0.05).

There were no significant differences between the control and surfactant formulations for the planed samples glued with PUR; all these samples averaged greater than 99% delamination. Therefore, this study showed that planing in combination with PUR adhesives produced the worst results for delamination out of all the adhesives, formulations, and surface machining combinations that were trialed. For the planed samples glued with RF, the control formulation resulted in lower delamination compared to the surfactant formulations, with the differences in delamination between the controls and other formulations being mostly significant (p-value less than 0.05). For the face milled samples glued with PUR and RF, the control formulation also resulted in the lowest delamination compared to the surfactant formulations, with the differences in delamination between the controls and other formulations being significant with the exception of the B and G surfactants used with the PUR adhesive. Therefore overall, the control formulations produced significantly better delamination results compared to the surfactant formulations (p-value less than 0.05) and face-milling was shown to be advantageous.

It is probable that even though the surfactants lowered the surface tension and improved wettability, they negatively interfered with the other properties of the adhesive, causing the poor delamination results. One drawback that has been reported when using surfactants in adhesive formulations is that they can increase the water sensitivity of the adhesive, which may have negatively impacted the adhesive bonds when subjected to the wet and dry cycling process during the delamination testing process (Bhattacharjee 2017; Petrie 2021). Surfactants can also migrate to the interface, which can lead to a loss in adhesive strength (Bhattacharjee 2017). Surfactants can also solubilize contaminants, *e.g.*, extractives, which can interfere with the adhesion process (ASC 2021). Frihart (2013) also reports that surfactants can create a chemically weak boundary layer on the wood surface that can impede adhesion. Another factor that may explain the high delamination experienced using the surfactant formulations is that the recommended concentration used in the study (3%) may not have been optimal. Lower concentrations of a few selected surfactants were also tested in this study on a smaller number of samples. These results are discussed below.

There was no significant relationship between the surface tension of the surfactant/ adhesive formulation (as shown in Table 3) and the delamination results. Rankings in the delamination results for each surfactant treatment (not including the controls) varied with surface machining and adhesive type. Across all treatments, the best performing surfactant was surfactant C; however, it still produced high delamination results with an average delamination across all treatments of 79.4%, and the difference with the other surfactants was only significant compared to the A, D, E, and F surfactants.

Across all treatments, the RF adhesive resulted in significantly lower delamination (p-value less than 0.05) compared to the PUR adhesive (mean RF 74.6% *vs.* PUR 94.5%) and face milling resulted in significantly (p-value less than 0.05) lower delamination compared to planing (mean face milling 82% *vs.* planing 87.1%). When comparing glulam samples prepared with surfactants only (therefore not including the controls), in most cases the RF adhesive and face milling resulted in lower delamination compared to PUR and planing; however, there were some exceptions as shown in Table 6.

The better results achieved with face milling compared to planing in this study align with other studies that demonstrated the better adhesive bond performance when the surfaces were prepared *via* face milling compared to conventional planing (Leggate *et al.* 2020, 2021a,b,c). It was hypothesized during these studies that the performance differences between face milling and planing were likely attributable to differences in the resulting board surface roughness, fibrillation, and sub-surface cellular damage that resulted from the different machining approaches. This resulting influence affected the adhesive penetration, glue line thickness, *etc.*, and ultimately the bond integrity and performance (Leggate *et al.* 2020, 2021a,b,c). It has been shown that a better foundation for adhesion with spotted gum is provided when a rougher surface finish is achieved (Leggate *et al.* 2020, 2021a,b,c). This may be explained by the rougher surface, allowing for increased wood wettability and bonding strength through the facilitation of adhesive spreading *via* improved capillarity and a greater surface area for mechanical adhesion and an increase in the exposed hydrophilic sites for the adhesive to bond (Hernandez and Cool 2008; Santoni and Pizzo 2011; Kläusler *et al.* 2014; Knorz *et al.* 2015; Qin *et al.* 2015; Jankowska *et al.* 2018; Leggate *et al.* 2020, 2021a,b,c). Another reason that face milling is reported to produce better results for wood adhesion compared to conventional planing is that the face milling cutting action (perpendicular to the grain) generates lower cutting forces and consequently lower sub-surface compaction of the wood structure compared to conventional planing (cutting direction parallel to the grain), which has been reported to crush and damage sub-surface cells (Santoni and Pizzo 2011; Kläusler *et al.* 2014; Knorz *et al.* 2015; Leggate *et al.* 2020, 2021a,b,c).

Shear strength (for 3% surfactant concentration data)

As shown in Table 5, the shear strength results (pre-and post-cycling) were significantly influenced by the adhesive type (p-value less than 0.001 for pre-and post-cycling) and surface machining (p-value less than 0.01 for pre-cycling and p-value less than 0.001 for post-cycling). However, there was no significant effect of the formulation on either the pre- or post-cycling shear strength results. There were also significant interactions between the adhesive type and formulation for pre-cycling (p-value less than 0.01), adhesive type and surface machining (p-value less than 0.01 for pre-cycling and p-value less than 0.001 for post-cycling) and formulation and surface machining for post cycling (p-value less than 0.05). These effects and interactions are discussed below. The shear strength results for before and after cycling are shown in Tables 7 and 8, respectively.

As evident in Tables 7 and 8, there was a significant reduction in shear strength for all treatments after wet and dry cycling (p-value less than 0.001), with an average shear strength reduction of 60%; however, the shear strength reduction for the PUR samples (65%) was greater than for the RF samples (55%). The post-cycling shear strength results are the most relevant because the test methodology detailed in AS/NZS standard 1328.1:1998 (2011) involves assessment post wet and dry cycling. This wet and dry cycling is designed to stress the bond integrity of the glued element *via* the introduction of a moisture gradient within the element (Vella *et al.* 2019b). This induces an associated stress gradient with high tensile stresses perpendicular to the glue line, which will either result in the fracture of the timber lamella or a delamination of the glue lines if the bond strength is inadequate (Vella *et al*. 2019b). For post-cycling results, the shear strength results matched the trends in the delamination results, with the control samples producing the highest overall shear strength compared to the surfactant formulations. Therefore, for the post-cycling data, the control formulations resulted in significantly lower delamination and

higher shear strength (p-value less than 0.05) compared to the surfactant formulations. Possible explanations for the poorer performance of the surfactant formulations have been previously discussed above.

Table 7. Shear Strength Results for Each Treatment (Before Cycling)

Formulation	Mean Shear Strength (MPa) (Standard Deviation)								
	Planed			Face Milled			Combined Planed & Face Milled Data		All Data
	PUR	RF	Pooled PUR & RF	PUR	RF	Pooled PUR & RF	PUR	RF	
Control	14.5 (2.2)	14.8 (0.4)	14.6 (1.4)	15.8 (3.0)	14.7 (5.1)	15.3 (3.8)	15.1 (2.5)	14.8 (3.2)	14.9 (2.7)
A	13.9 (0.7)	19.7 (1.8)	16.8 (3.4)	15.8 (1.6)	17.0 (1.9)	16.4 (1.7)	14.9 (1.5)	18.3 (2.2)	16.6 (2.5)
B	12.1 (3.5)	17.2 (0.8)	14.7 (3.6)	17.7 (1.9)	16.1 (1.5)	16.9 (1.8)	14.9 (4.0)	16.7 (1.2)	15.8 (2.9)
C	14.4 (0.9)	14.8 (1.1)	14.6 (0.9)	15.7 (2.1)	19.2 (0.8)	17.4 (2.4)	15.0 (1.6)	17.0 (2.5)	16.0 (2.3)
D	13.8 (0.4)	16.4 (0.3)	15.1 (1.5)	16.4 (2.4)	18.8 (1.8)	17.6 (2.3)	15.1 (2.1)	17.6 (1.8)	16.3 (2.2)
E	12.2 (0.3)	19.4 (2.3)	15.8 (4.2)	14.2 (1.1)	15.7 (1.7)	15.0 (1.5)	13.2 (1.3)	17.5 (2.7)	15.4 (3.0)
F	14.0 (0.9)	15.2 (1.9)	14.6 (1.5)	18.3 (1.2)	17.5 (0.8)	17.9 (1.0)	16.1 (2.5)	16.4 (1.8)	16.3 (2.1)
G	14.5 (1.5)	13.4 (2.1)	13.9 (1.7)	16.3 (1.6)	16.8 (6.9)	16.5 (4.5)	15.4 (1.7)	15.1 (4.9)	15.2 (3.5)
H	12.8 (1.5)	21.2 (1.8)	17.0 (4.8)	13.9 (2.3)	17.6 (0.8)	15.7 (2.5)	13.3 (1.8)	19.4 (2.3)	16.4 (3.8)
Combined	13.6 (1.6)	16.9 (2.9)	15.2 (2.8)	16.0 (2.1)	17.0 (2.9)	16.5 (2.6)	14.8 (2.2)	17.0 (2.9)	15.9 (2.8)

Assessment of the before and after cycling results for the planed controls (without surfactant added) samples shows that the RF adhesive resulted in greater shear strength compared to the PUR samples, although the difference was only significant for post-cycling data (p-value less than 0.05). However, an opposite trend was seen for the face milled control samples, where the PUR adhesive produced higher shear strength results compared to the RF adhesive samples for both the pre- and post-cycling assessments, however the difference was not significant. Overall, for the control samples, face milling tended to result in greater shear strength compared to planing for both PUR and RF, however, the differences were only significant for the post-cycling data (p-value less than 0.05).

There was no significant relationship between the surface tension of the surfactant/adhesive formulation (as shown in Table 3) and the shear strength results. Rankings in the shear strength results for each surfactant treatment varied according to the surface machining, adhesive type, and pre- and post-cycling. Overall, across all treatments, the best performing surfactants in terms of the shear strength pre-cycling and post-cycling results were A and C, respectively.

Table 8. Shear Strength Results for Each Treatment (After Cycling)

Formulation	Mean Shear Strength (MPa) (standard deviation)								
	Planed			Face Milled			Combined Planed & Face Milled Data		All Data
	PUR	RF	Pooled PUR & RF	PUR	RF	Pooled PUR & RF	PUR	RF	
Control	0.3 (0.2)	5.5 (2.4)	2.9 (3.2)	13.7 (3.0)	11.6 (2.2)	12.7 (2.6)	7.0 (7.6)	8.5 (4.0)	7.8 (5.8)
A	2.8 (1.0)	3.3 (1.1)	3.1 (1.0)	6.9 (5.4)	9.0 (3.2)	7.9 (4.1)	4.8 (4.1)	6.1 (3.8)	5.5 (3.8)
B	2.8 (1.8)	6.4 (2.8)	4.6 (2.9)	10.2 (2.4)	7.1 (3.2)	8.7 (3.0)	6.5 (4.5)	6.8 (2.7)	6.7 (3.5)
C	3.0 (1.0)	9.3 (1.7)	6.2 (3.7)	9.0 (1.7)	8.3 (1.9)	8.6 (1.7)	6.0 (3.5)	8.8 (1.7)	7.4 (3.0)
D	0.3 (0.2)	3.2 (0.5)	1.8 (1.6)	6.3 (2.9)	9.8 (0.6)	8.1 (2.7)	3.3 (3.8)	6.5 (3.6)	4.9 (3.9)
E	0.5 (0.8)	6.3 (5.5)	3.4 (4.7)	10.8 (2.0)	8.1 (1.8)	9.5 (2.3)	5.7 (5.8)	7.2 (3.8)	6.4 (4.7)
F	1.9 (1.1)	4.7 (2.1)	3.3 (2.1)	10.5 (1.4)	10.2 (2.4)	10.3 (1.8)	6.2 (4.8)	7.4 (3.6)	6.8 (4.1)
G	0.4 (0.3)	5.7 (0.4)	3.1 (2.9)	5.8 (0.3)	10.4 (1.2)	8.1 (2.6)	3.1 (3.0)	8.0 (2.7)	5.6 (3.7)
H	0.6 (0.5)	8.2 (2.5)	4.4 (4.5)	8.1 (0.9)	10.2 (4.9)	9.1 (3.3)	4.3 (4.2)	9.2 (3.6)	6.7 (4.5)
Combined	1.4 (1.4)	5.8 (2.9)	3.6 (3.2)	9.0 (3.3)	9.4 (2.6)	9.2 (2.9)	5.2 (4.6)	7.6 (3.3)	6.4 (4.1)

Across all treatments, and for pre- and post-cycling, the RF adhesive resulted in significantly (p-value less than 0.05) higher shear strength (a pre-cycling mean of 17.0 MPa and a post cycling mean of 7.6 MPa) compared to the PUR adhesive (a pre-cycling mean of 14.8 MPa and a post cycling mean of 5.2 MPa), while face milling resulted in significantly (p-value less than 0.05) higher shear strength compared to planing (a pre-cycling mean of 16.5 MPa face milling *versus* 15.2 MPa for planing and a post-cycling mean of 9.2 MPa face milling *versus* 3.6 MPa for planing). When comparing surfactant formulations only (therefore not including the controls), in most cases the RF adhesive and face milling resulted in higher shear strength compared to PUR and planing (as shown in Tables 7 and 8).

For glulam qualification testing, Australian standard AS/NZS 1328.1:1998 (2011) does not specify requirements in terms of the shear strength for glulam used in any service class. Instead, as mentioned earlier, acceptable adhesive bond performance for glulam qualification testing is based only on the delamination performance using the test method outlined in the methodology section. However, in Australia, for routine glulam testing and for some service classes (service class 1 and 2), block shear testing (without wet and dry cycling) can be used as an assessment method. The acceptance criteria for block shear tests specifies that every glue line must reach a minimum shear strength of 6.0 MPa in addition to the other requirements for wood fibre failure.

For conifers and poplar, a shear strength of 4.0 MPa is regarded as acceptable if the wood fibre failure percentage is 100%. In Europe, the standard for glued laminated timber – performance requirements and minimum production requirements, according to EN standard 386 (2001), also specifies that every glue line must reach a minimum shear strength of 6.0 MPa, as well as the glulam meeting the other performance requirements. Even though a number of glulam samples in this study exceeded these minimum shear strength requirements, they did not pass the requirements of the Australian standard for qualification testing because of excessive delamination after wet and dry cycling.

Table 9. Wood Fibre Failure Results for Each Treatment (Before Cycling)

Formulation	Mean Fibre Failure (%) (Standard Deviation)								
	Planed			Face Milled			Combined Planed & Face Milled Data		All Data
	PUR	RF	Pooled PUR & RF	PUR	RF	Pooled PUR & RF	PUR	RF	
Control	5.0 (5.0)	53.3 (45.1)	29.2 (39.0)	56.7 (23.6)	18.3 (16.1)	37.5 (27.7)	30.8 (32.2)	35.8 (35.8)	33.3 (32.6)
A	5.3 (4.0)	41.7 (10.4)	23.5 (21.1)	18.3 (23.6)	13.3 (14.4)	15.8 (17.7)	11.8 (16.8)	27.5 (19.2)	19.7 (19.0)
B	21.0 (15.6)	22.3 (24.2)	21.7 (18.2)	31.7 (17.6)	43.3 (11.5)	37.5 (14.7)	26.3 (16.0)	32.8 (20.5)	29.6 (17.8)
C	16.7 (24.7)	25.0 (15.0)	20.8 (18.8)	5.0 (0)	76.0 (35.5)	40.5 (44.9)	10.8 (16.9)	50.5 (37.1)	30.7 (34.4)
D	5.7 (8.1)	26.7 (27.5)	16.2 (21.5)	11.0 (19.1)	75.0 (30.4)	43.0 (41.8)	8.3 (13.4)	50.8 (37.1)	29.6 (34.6)
E	1.7 (2.9)	9.0 (9.6)	5.3 (7.5)	15.7 (12.1)	41.7 (22.5)	28.7 (21.6)	8.7 (11.0)	25.3 (23.7)	17.0 (19.6)
F	11.7 (20.2)	11.7 (12.6)	11.7 (15.1)	15.0 (26.0)	81.7 (20.2)	48.3 (42.0)	13.3 (20.9)	46.7 (41.2)	30.0 (35.7)
G	5.3 (3.1)	53.3 (35.1)	29.3 (34.5)	17.0 (13.9)	75.0 (35.0)	46.0 (39.7)	11.2 (11.0)	64.2 (33.5)	37.7 (36.5)
H	11.3 (9.1)	66.0 (46.5)	38.7 (42.4)	9.0 (9.6)	53.3 (42.5)	31.2 (36.7)	10.2 (8.5)	59.7 (40.5)	34.9 (38.0)
Combined	9.3 (12.3)	34.3 (30.6)	21.8 (26.3)	19.9 (21.2)	53.1 (33.6)	36.5 (32.5)	14.6 (18.0)	43.7 (33.2)	29.2 (30.3)

Wood fibre failure (for 3% surfactant concentration data)

The wood fibre failure results for both before and after cycling are shown in Tables 9 and 10 respectively. There was a significant reduction in wood fibre failure for the glulam samples in all cases after being subjected to the wet and dry cycling (p-value less than 0.001). The wood fibre failure results post-cycling were the most relevant given AS/NZS standard 1328.1:1998 (2011) targets assessments post wet and dry cycling. For the post-cycling results, the fibre failure results followed the trends in the delamination and shear strength results, with the control samples producing the highest overall fibre failure compared to the surfactant formulations. Therefore, for post cycling, the control samples resulted in significantly lower delamination, higher shear strength, and higher wood fibre failure compared to the surfactant formulations (p-value less than 0.05).

Table 10. Wood Fibre Failure Results for Each Treatment (After Cycling)

Formulation	Mean Fibre Failure (%) (Standard Deviation)								
	Planed			Face Milled			Combined Planed & Face Milled Data		All Data
	PUR	RF	Pooled PUR & RF	PUR	RF	Pooled PUR & RF	PUR	RF	
Control	0 (0)	4.0 (5.3)	2.0 (4.0)	43.3 (18.9)	20.0 (26.5)	31.7 (24.2)	21.7 (26.6)	12.0 (19.2)	16.8 (22.7)
A	0 (0)	5.7 (8.1)	2.8 (6.0)	6.0 (9.5)	7.3 (6.8)	6.7 (7.4)	3.0 (6.9)	6.5 (6.7)	4.8 (6.7)
B	0 (0)	17.0 (14.7)	8.5 (13.2)	4.0 (6.9)	9.3 (3.8)	6.7 (5.8)	2.0 (4.9)	13.2 (10.5)	7.6 (9.7)
C	0 (0)	21.7 (17.6)	10.8 (16.3)	1.3 (1.2)	1.7 (1.2)	1.5 (1.0)	0.7 (1.0)	11.7 (15.6)	6.2 (12.0)
D	0 (0)	0 (0)	0 (0)	0.3 (0.6)	9.0 (9.6)	4.7 (7.7)	0.2 (0.4)	4.5 (7.8)	2.3 (5.8)
E	0 (0)	14.0 (22.5)	7.0 (16.2)	0.0 (0.0)	2.3 (2.5)	1.2 (2.0)	0.0 (0.0)	8.2 (15.7)	4.1 (11.4)
F	0 (0)	1.0 (1.0)	0.5 (0.8)	5.0 (8.7)	3.0 (1.7)	4.0 (5.7)	2.5 (6.1)	2.0 (1.7)	2.3 (4.3)
G	0 (0)	2.7 (2.1)	1.3 (2.0)	1.0 (1.7)	11.7 (7.6)	6.3 (7.7)	0.5 (1.2)	7.2 (7.0)	3.8 (5.9)
H	0 (0)	9.0 (3.6)	4.5 (5.4)	0.0 (0.0)	7.3 (6.8)	3.7 (5.9)	0.0 (0.0)	8.2 (5.0)	4.1 (5.4)
Combined	0 (0)	8.3 (11.9)	4.2 (9.3)	6.8 (14.9)	8.0 (10.2)	7.4 (12.7)	3.4 (11.0)	8.1 (11.0)	5.8 (11.2)

Assessments of the before and after cycling results for the planed control samples (without surfactant added) showed that the RF adhesive resulted in greater fibre failure compared to the PUR samples, although the difference was only significant for pre-cycling (p-value less than 0.05). However, an opposite trend was seen for the face milled control samples where the PUR adhesive produced significantly higher fibre failure results compared to the RF adhesive for both the pre- and post-cycling assessments (p-value less than 0.05). However, this improved wood fibre failure result with the PUR adhesive and face milling did not correspond to an improved delamination result (refer to the discussion above). In addition, for the control samples overall, face milling resulted in significantly (p-value less than 0.05) greater fibre failure compared to planing for both the PUR and RF adhesives, with one exception being the pre-cycling results for the RF adhesive, where there was no significant difference between face milling and planing.

There was no significant relationship between the surface tension of the surfactant/adhesive formulation (as shown in Table 3) and the fibre failure results. Rankings in fibre failure results for each surfactant treatment varied with respects to the surface machining, adhesive type, and pre- and post-cycling. Across all treatments and for pre- and post-cycling, the RF adhesive resulted in significantly (p-value less than 0.05) higher wood fibre failure compared to the PUR adhesive (a pre-cycling mean of 43.7% RF *versus* 14.6% for PUR; and a post cycling mean of 8.1% RF *versus* 3.4% for PUR) and face milling resulted in higher fibre failure compared to planing (a pre-cycling mean of 36.5% face milling *versus* 21.8% for planing and a post-cycling mean face milling of 7.4% *versus* 4.2% for planing); however, the difference was only significant for pre-cycling (p-value less than 0.05). When comparing surfactant formulations only (therefore not

including the controls), in most cases the RF adhesive and face milling resulted in higher fibre failure compared to PUR and planing; however, there were some exceptions as shown in Tables 9 and 10.

As discussed above, for qualification testing of glulam in Australia, only the delamination performance is assessed. However, for the routine testing of glulam, block shear testing (without wet and dry cycling) with shear strength and wood fibre failure assessments can be used in some situations. The required minimum wood fibre failure percentage depends on the shear strength. The majority of the glulam samples did not pass the wood fibre failure requirements of the standard for routine testing.

Reduced Surfactant Concentrations

Surface tension

Table 11 shows that decreasing concentrations of the surfactants tended to result in lower adhesive surface tension reduction, with the exception of the slight difference in surface tensions between surfactant B used with PUR adhesive at concentrations of 1% and 3%.

Table 11. The Surface Tensions of the Adhesive/Surfactant Formulations

Formulation	Surfactant + RF Mean Surface Tension (mN/m)	Surfactant + PUR Mean Surface Tension (mN/m)
Control (no surfactant added)	44.64	31.45
H @0.5%	41.29	-
H @1%	38.28	-
H @3%	29.01	29.59
B @0.5%	-	30.97
B @1%	-	24.52
B @3%	22.52	25.61

Assessments of delamination according to AS/NZS standard 1328.1: 1998 (2011) for reduced surfactant concentrations

The use of surfactant concentrations lower than 3% had minimal impact on delamination results with all glulam samples failing to meet the adhesive bond requirements of AS/NZS standard 1328.1:1998 (2011), as shown in Table 12.

Table 12. Delamination Assessments on the Glulam Samples for Reduced Surfactant Concentrations0

Adhesive	Formulation	0.5% Surfactant Concentration		1% Surfactant Concentration	
		% Maximum Delamination	% Total Delamination	% Maximum Delamination	% Total Delamination
RF	H	48.3	89.2	39.2	63.4
	H	48.3	83.6	46.9	64.0
PUR	B	48.3	80.6	50.0	96.8
	B	50.0	94.0	50.0	93.8
(Pass = Green, Fail = Red)					

All samples failed the total delamination requirements and only one sample passed the maximum delamination requirements of the standard, which was a sample glued with a 1% surfactant H/RF formulation. The poor adhesive bond performance resulting from the use of surfactants in this study suggests that they are not a viable solution to improve the gluing of spotted gum for structural glulam. Future research should investigate the use of alternative adhesion promoting approaches such as trialing different adhesives, alternative mechanical, physical and chemical timber surface preparation processes, varying gluing protocols (*e.g.*, adhesive spread rates, press conditions), optimization of adhesive penetration and wood dimensional stabilization.

CONCLUSIONS

1. All the surfactant treatments reduced the surface tension of the adhesives; however, none of them were successful in improving the gluability and achieving compliant adhesive bonds for spotted gum glulam. This may have been because the concentration of the surfactants was not optimal and/or due to adverse effects on the adhesive properties through various factors, *e.g.*, increased water sensitivity of the adhesive, weaker adhesion caused by surfactant migration to the interfacial region, and solubilisation of extractives.
2. Overall, the control samples featured lower delamination, higher shear strength, and higher wood fibre failure compared to the samples where surfactant was added to the adhesive.
3. There was a significant effect of the adhesive type on the results, where overall, after wet and dry cycling, the RF adhesive produced lower delamination, higher shear strength, and higher wood fibre failure compared to the PUR adhesive.
4. Face milling was shown to be advantageous in improving the bond quality compared to conventional planing, where overall, after wet and dry cycling, face milling produced lower delamination, higher shear strength, and higher wood fibre failure compared to planing.

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