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BRIEF ORIGINAL

Effect of wood moisture content and adhesive open time on the adhesion strength of wet bonded *Pinus radiata* wood

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Abstract

Gluing wood in the wet state can reduce warping, splitting, and increase processing volume recovery. Adhesive open time and moisture content may play an important role in bond line strength, but there are no specifications for wet wood bonding. Wood specimens at two different moisture contents were glued with three polyurethane adhesives and tested in shear on the bond line. Open time of 15 min was superior to 4 and 40 min. All adhesives performed better when wood was glued at 30% moisture content than at 101%, but only the 15- and 40-min open time met the minimum shear requirement.

1 Introduction

Gluing wood before it dries has been reported to provide a series of benefits and, at the same time, to provide adhesion with strength that meet the minimum requirements for a series of applications. The adhesive, after cured, restrains the wood movement when it dries below the fiber saturation point, avoiding warping and splitting (Wessels et al. 2020). These facts can help the reduction of waste and increase the recovery of wood used for engineered products. Polyurethane adhesives perform better on wood in the wet state than the alternatives (Sterley and Gustafsson 2012), but not much is known about the influence of the open time of these adhesives on the bond line strength. It is especially important for PUR adhesives at high MC timber since this type of adhesive has a residual isocyanate group that reacts with water (Properzi et al. 2003). Despite adhesive manufacturers not having clear guidelines on using their adhesives on wet wood, this method is currently being used in commercial applications (Crafford and Wessels 2016). The objectives of the present study were to assess the influence of the open time of PUR adhesives on the strength of bond lines, and on wood glued at two different moisture contents, both in the wet state.

2 Material and method

Four green *Pinus radiata* boards (approximately 2500 × 100 × 75 mm) were provided by the Bostap Sawmill in Klapmuts, Western Cape, South Africa. The material was obtained from plantation trees sourced from the Western Cape area of South Africa. Before processing, the boards were soaked in water to standardize their initial MC. The timber was processed to generate around 300 blocks of dimensions 50 × 27 × 40 mm, which were later glued to form bond line shear test specimens. Three polyurethane adhesives were used, their technical data are presented in Table 1.

Just after their processing, all blocks were kept soaked under water until reaching constant mass. Then, 20 blocks were weighed and kept in an acclimatization room (temperature = 20 °C, air relative humidity = 65%) until they reached the equilibrium MC (12%). They were weighed after 30, 48, 78, and 98 h in the acclimatization room, dried to 0% MC, and then weighed again to calculate their MC at every step. With this data, a curve was built to estimate the time necessary to reach the goal MCs. The other 280 blocks

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Table 1 Technical data of the three adhesives used in the experiment

Comercial Name*	Code	Adhesive type	Spread rate ($kg.m^{-2}$)	Clamping pressure (MPa)	Open time (min)	Clamping time (min)	Wood MC (%)
Henkel Purbond HB S049	H4	1 component PUR adhesive	0.140–0.180	0.6–1.0	4	10	8–18
Henkel Purbond HB S159	H15	1 component PUR adhesive	0.140–0.180	0.6–1.0	15	38	8–18
Henkel Purbond HB S409	H40	1 component PUR adhesive	0.140–0.180	0.6–1.0	40	100	8–18

*Technical datasheets available from manufacturer

MC: moisture content; PUR: polyurethane

were then transferred to the acclimatization room. When they completed the estimated time to reach 100% MC, 120 blocks free of defects were selected. Thirty of them were weighed, oven-dried, and weighed to confirm their actual MC, and 90 were processed in a circular blade to produce a freshly exposed surface prior to bonding, and glued in pairs with the same fiber orientation, resulting in 15 samples per adhesive type. When blocks completed the estimated time to reach 35% MC, the exact same procedure was followed with another 120 blocks. The processing variables were maintained at a constant, with an adhesive spread rate of 0.22 $kg.m^{-2}$, time between machining and bonding of less than 1 h, assembly time lower than 4 min, clamping pressure of 1 MPa, and clamping time of 24 h. All other variables were kept within the manufacturer's specifications. None of the adhesive manufacturers had specifications for gluing wet wood. A figure showing the processing steps is available as supplementary material (Favis et al. 2023).

Thus, 15 shear testing specimens were produced for each of the 6 treatments, which were composed of a combination of two different wood MCs and three different adhesive types. They were kept in the same acclimatization room described above until constant mass was reached, indicating they reached the equilibrium moisture content of 12%. The shear specimens were then destructively tested in a Universal Testing Machine (Instron with 50KN load capacity) at the Department of Forest and Wood Science at Stellenbosch University. The shear test on the bond line was conducted with the load applied perpendicularly to the fiber direction to simulate stresses of board shrinking and twisting during drying on edge-glued panels assembled with wet wood. These panels are meant to compose layers of cross-laminated timber, and green-gluing can decrease the processing losses due to drying deformation. The shear strength on the bond line on both initial MCs was compared using a t-test. To compare the averages of shear strength on the bond line by adhesive open time an analysis of variances was adopted with both MCs separately. Both tests were conducted at a level of confidence of 95%.

3 Results and discussion

At the time of bonding, the specimens had 101% and 30% average MC, values in conformity with the objectives of this study (data available at Favis et al. 2023). The results of shear strength on the bond line for the three adhesives and two MCs can be seen in Fig. 1. T-test results showed a significant (p-value = 2.2 10^{-16}) difference between the mean shear strengths of the 30% and 101% MC specimens. Specimens glued at 101% MC had a shear strength (2.38 MPa) 50% lower than those glued at 30% MC (4.15 MPa). Higher MC resulted in a weaker bond independent of the adhesive open time and the results suggest that the closer the MC gets to the fiber saturation point, the stronger the bond. In Fig. 1, the three box plots for each MC clearly show a similar mound-shaped pattern, with H40 showing a slightly higher negative influence of the higher MC. This result is encouraging, as it suggests that the adhesives behaved consistently, and that the MC is the main influencing variable. The high initial MC harmed the adhesion strength to the point that all test specimens were below the minimum requirement of 3.5 MPa for edge bonds indicated by the standard EN 16,351 (2015).

The H15 adhesive was the best performing in this study. For the longest assembly-time adhesive (H40) at 30% MC, the bond strength decreased slightly (8.9%) when compared to H15. These two adhesives were the only ones with all specimens above the requirement when the initial MC was 30% MC. H4 probably had an open time too short, and although it did not differ from H40, it is possible to observe some specimens had shear strength below the minimum requirements - H4 average was 13.3% lower than H15. The presence of excessive liquid water is probably harming the adhesive cure, and higher open times (40 min) seem to be more impacted, with a higher decrease (51.2%) between 30 and 101% MC compared to the other two PURs used (37.8 to 41.0%). The high amounts of liquid water in 101% MC samples may induce the adhesive to start curing with surface contact. The adhesive curing in this situation may have two curing stages, one influenced by the liquid water (faster) and the other one isolated from this influence by the cured layer (slower). The curing time difference of these possible two steps might be the reason for the lower adhesion strength

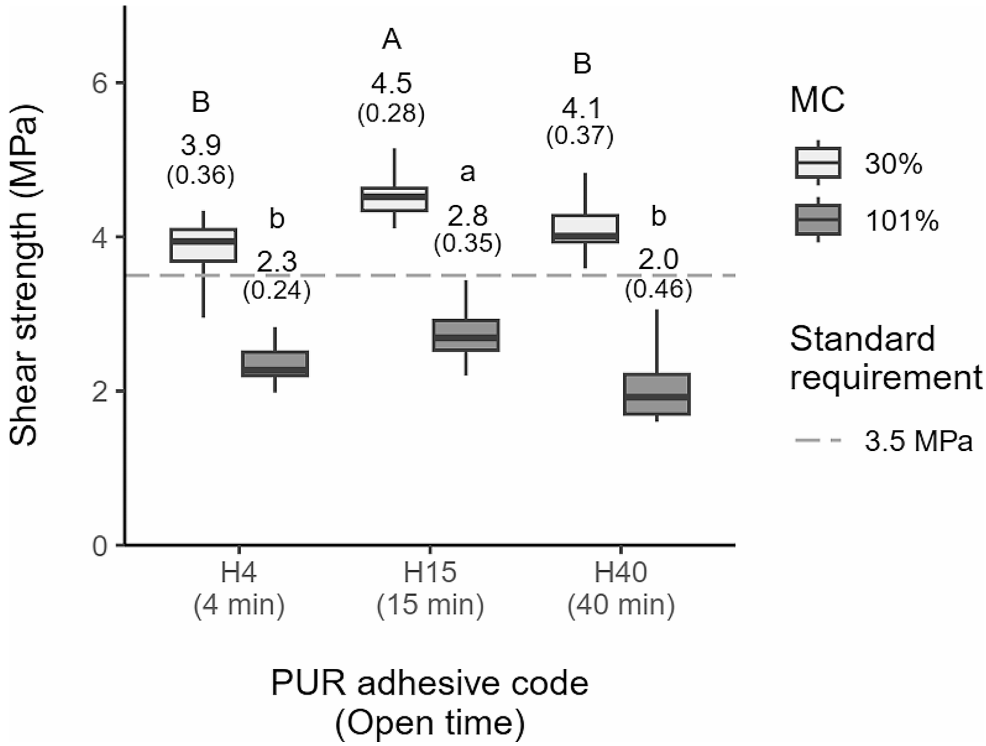

Fig. 1 Perpendicular shear strength on the bond line of wood glued with three different adhesives at two moisture contents (MC). Numbers indicate the average value, numbers between parenthesis represent the standard deviation, capital letters refer to the statistical groups (ANOVA, α = 0.05) of wood glued with 30% MC, non-capital letters refer to the statistical groups (ANOVA, α = 0.05) of wood glued with 101% MC. PUR: polyurethane. Standard requirement EN 16351 (CEN 2015). PUR: polyurethane; H4: Henkel Purbond HB S049; H15: Henkel Purbond HB S159; H40: Henkel Purbond HB S409

of samples with high MC. Samples with 30% MC did not have much liquid water available that possibly avoided the two-step curation hypothesised. Sterley and Gustafsson (2012), found a large difference in bond line shear strength according to the wood moisture content when the clamping time was low (3 h), but the difference was neglectable when a high clamping time was used (48 h). It suggests that, in the present study, the H40 adhesive might need a higher clamping time for the full curation of the adhesive. Because of the interaction between water and the isocyanate group present in the PUR adhesives, a stronger influence of working open time on bond quality was expected, but the differences observed might be relevant to the manufacture of edge glued panels with unseasoned wood.

4 Conclusion

PUR adhesives perform better when gluing wet wood with an open time of around 15 min. The excess of liquid water might be harming the adhesive cure, so wood with moisture contents closer to the fiber saturation point provides a stronger adhesion, mostly above minimum requirements established. The adhesive working open time is very important for the manufacturing process, and 15 min might be limiting. Although 40 min open time still met the minimum requirements, there might be open times between 15 and 40 min which deliver good results for adhesion strength and allow a higher manufacturing time than 15 min. The high amount of liquid water available is possibly making the adhesive cure to happen in two stages, a fast one, with influence of the wood moisture and a second one, slow, which is isolated from the wood moisture by the layer formed in the first stage. For the next step, tests should be conducted varying the MC levels between 15 and 40 min to understand better the influence of liquid water to the bond strength of wood glued in the wet state. Moisture content values between 30 and 100% should also be assessed. Pressing time in these different conditions should also be studied together with a microscopic evaluation of the bond line to assess the possibility of a two stage curing happening.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00107-024-02050-w.

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Data Availability Data available at Favis et al. (2023).

Declarations

Competing interests The authors declare no competing interests.

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