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Gluing characteristics of Papua New Guinea timber species for various non-structural applications

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Abstract:
Papua New Guinea (PNG) has abundant natural forest resources but there are many constraints which need to be addressed to support the development of competitive value-added wood industries. There is a need to develop knowledge and capacity in wood science and processing technologies which support successful domestic value-adding wood processing enterprises. A comprehensive testing program has been developed to assess the glue-bond strength and performance of selected commercial PNG timber species in various climatic conditions to simulate service conditions in potential market destinations. Two criteria namely shear strength and wood failure have been used to determine if a species can meet the minimum requirements for either dry use or wet use applications. The performance of 24 different PNG commercial timber species has been assessed using a one-component cross-linking polyvinyl acetate emulsion adhesive. The bondability of the selected species has been carefully estimated considering the wood density and wood moisture content for the strength and durability in dry- and wet-use conditions. The testing results show that as the wood density as a wood property factor and moisture content as a service condition factor increase, high shear strength with high wood failure become more difficult to achieve consistently. The highest shear strength and wood failure results were achieved by softwood plantation species and low-density hardwood species. Based on the testing results, the selected species have been classified into bondability classes (bond very well, bond well, bond with difficulty, very difficult to bond).

Keywords: Bondability, Papua New Guinea, plantations, shear strength, wood failure, glue bond strength, timber.

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Introduction

Gluing is considered one of the most important technologies in the production of value-added wood products. In the majority of wood products, both appearance (e.g. furniture, flooring) and structural (e.g. glue-laminated beams, plywood, LVL) timber elements are joined together into larger components through edge and surface laminating, finger jointing and other types of joints. In order to meet requirements and criteria for strength and performance of glued components and products a sound knowledge of gluing characteristics of Papua New Guinea (PNG) timbers is required together with the selection of adhesives.

The concept of adhesion is defined as the state in which two surfaces are held together by interphase forces where the general term adhesive includes any substance capable of holding materials together by surface attachment ASTM D907 (2012). Technically, the standard for excellent bonds is that the wood breaks away from the adhesive joint and that the bond strength is equal to the strength of the solid wood according to Frihart and Hunt (2010).

The selection of an adhesive depends on whether or not the product is for structural application and water resistance requirements. Factors such as the wood properties, timber preparation, and adhesive application need to be carefully considered since the joint can be significantly improved through the implementation of optimal parameters and methods used in machining, joining and finishing (Marra 1992). Many standards cover the specifications and testing methods for strength properties of adhesives based on the type of product. A perusal of the international standards reveals a multitude of shear test geometries, each with the objective of producing a state of pure uniform shear in bulk adhesive or within an adhesive layer (AS/NZS

2010, ASTM D5751 (2012b), ISO 6238 (2018)). Performance requirements are very different for different climatic conditions in service use and types of applications (Figure 1).

There are many parameters influencing the performance of wood adhesives joints like wood property factors, glued product performance, wood preparation factors, adhesive application factors, product service factors, among others. (Marra 1992). ASTM D5751 (2012b) covers performance levels for all types of adhesive to be used in laminate joints in non-structural lumber products. It may be used to evaluate the adhesive bonds in a laminate joint that is the industrial end product of a manufacturing process. This specification is the only one listed that provides a method to determine the requirements for a specific wood species based on the species' mechanical properties and a bondability grouping, as defined in the Wood Handbook (Frihart and Hunt 2010), where the other standards provide a single set of test requirements not influenced by the tested species.

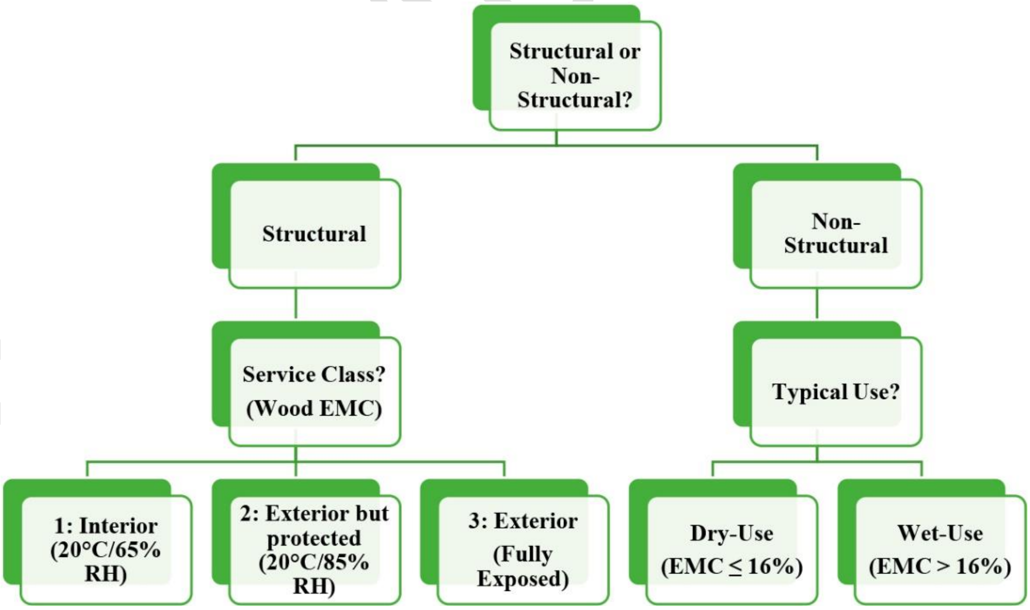
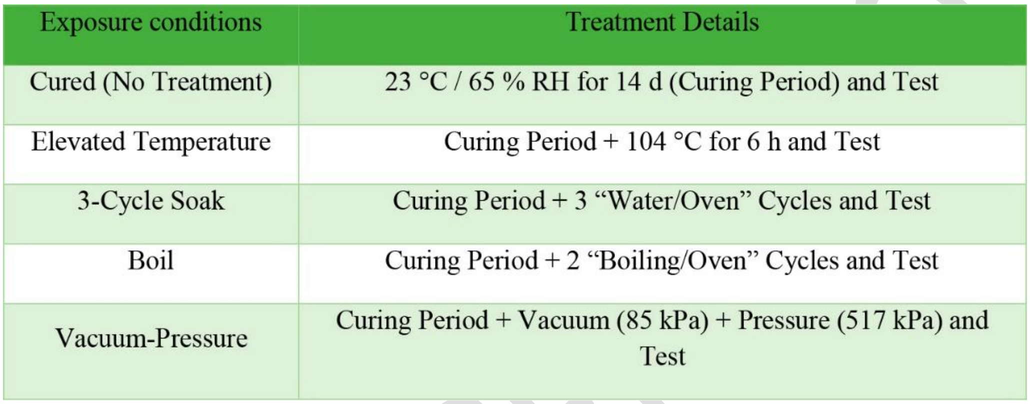


Figure 1: Performance requirements for adhesives according to suitability for specific use in defined environmental conditions.

Two categories of adhesive are identified based on their end use: 1) Dry-use non-structural adhesive capable of producing sufficient strength and durability to make the bonded lumber product serviceable in non-structural use, under conditions in which the equilibrium moisture content (EMC) of the wood does not exceed 16 %; 2) Wet-use non-structural adhesive capable of producing sufficient strength and durability to make the bonded lumber product serviceable in non-structural use, under conditions in which the EMC of the wood may be 16 % or greater. Two criteria, namely shear strength and wood failure, are used to determine if an adhesive meets the minimum requirements for either category. The common measures used to estimate the potential performance of bonded wood joints are strength, wood failure, and delamination. A procedure to determine shear strength and wood failure is detailed in ASTM D905 (2008) and ASTM D5266 (1999).

The percentage of wood failure represents the amount of wood that fails as a percentage of the area of the bonded joint. It is usually expressed as the percentage of ruptured wood fibers on the total area of a bonded specimen following visual assessment. The strength requirements can be based on more than 5 different exposure conditions (Table 1). Dry-use (no treatment) specimens are placed in a conditioning chamber at 20 °C and 65 % relative humidity (RH) for 14 d (curing period) and tested. Specimens exposed to elevated temperature are placed in an oven at 103 °C for 6 h and then tested. Three-cycle soak specimens are placed in a water bath at room temperature, separated by wire screens in such a manner that all surfaces are freely exposed to the water. The specimens are immersed for a period of 4 h, followed by drying at a temperature of 41 °C for 19 h. This procedure is repeated twice more for a total of 3 cycles before testing. Boiling specimens are placed in a tank of boiling water, separated by wire screens so that all surfaces are freely exposed to the water. Samples are boiled for 4 h, followed by drying for 20 h at 63 °C. Following a second 4-h boil cycle, samples are removed and cooled in running water at 20 °C for 1 h before shear testing. Finally, specimens exposed to a vacuum-pressure treatment are placed in a vessel where a vacuum of 85 kPa is drawn for 30 min and then followed by pressurization at 517 kPa for another 30 min prior to mechanical testing. The minimum wood shear strength and wood failure requirements for laminated joints are determined using ASTM D5751 (2012b).

Table 1: Exposure conditions and treatment details as per ASTM D5751 (2012b).



Exposure conditions	Treatment Details
Cured (No Treatment)	23 °C / 65 % RH for 14 d (Curing Period) and Test
Elevated Temperature	Curing Period + 104 °C for 6 h and Test
3-Cycle Soak	Curing Period + 3 “Water/Oven” Cycles and Test
Boil	Curing Period + 2 “Boiling/Oven” Cycles and Test
Vacuum-Pressure	Curing Period + Vacuum (85 kPa) + Pressure (517 kPa) and Test

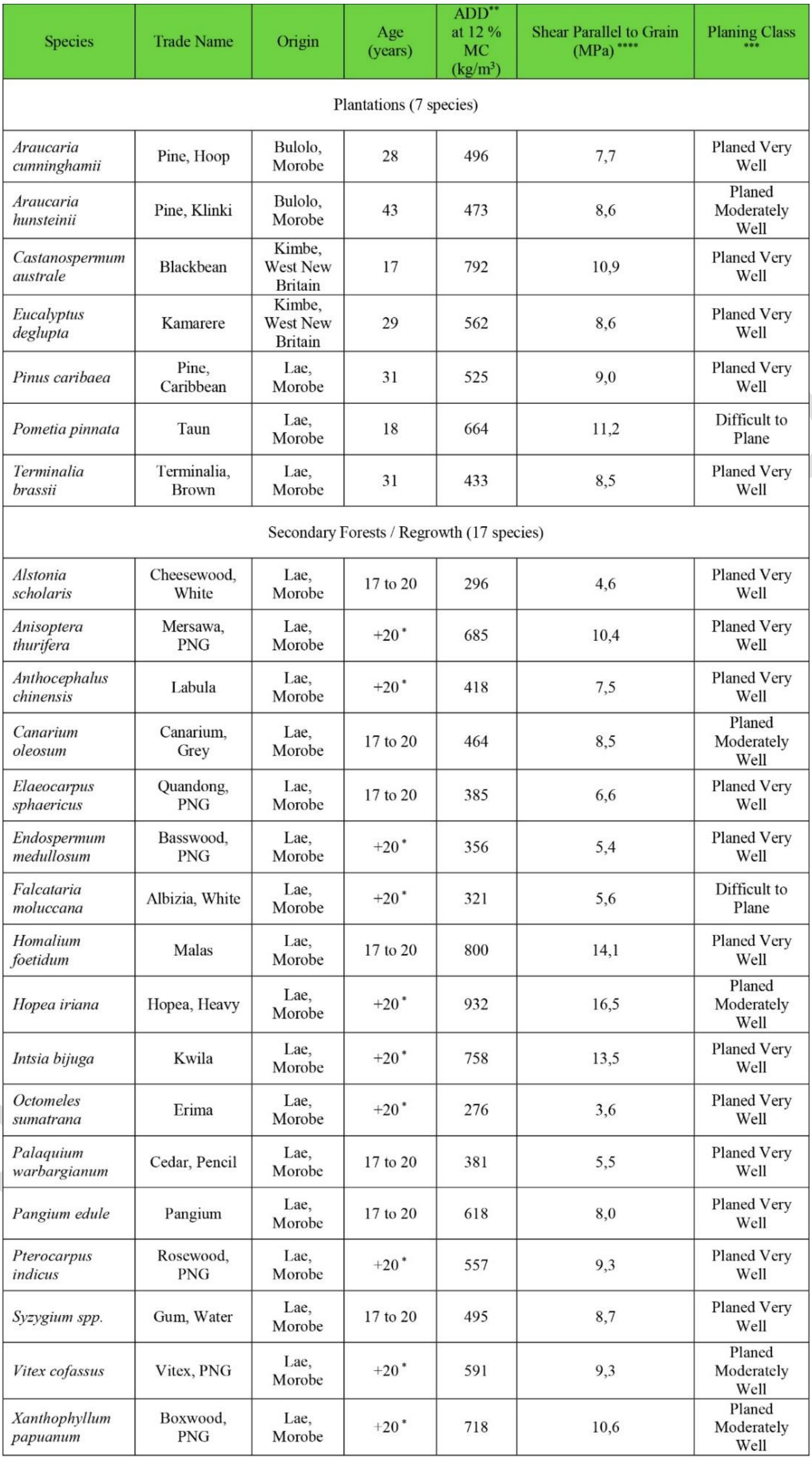
Although many data have been published on the basic physical and mechanical properties and processing methods for PNG timber from primary and plantation forests by Belleville *et al.* (2020a), Belleville *et al.* (2020b), there is limited information available on wood gluing properties and characteristics, and technologies applicable to the utilization of these timbers for various products. The PNG Government has announced a ban in round log export and an increase in downstream processing but there is limited information available on gluing characteristics of PNG timbers and technologies applicable to the utilization for various products. The lack of this information creates a barrier for using these timbers for value-added wood products. The aim of the present study was to increase the contribution that utilization of forest resources makes to national and local economies, including landowners and processors, through the development of domestic value-added wood processing methods. The specific objectives were to 1) Enhancing the knowledge of wood properties and processing characteristics of PNG timbers; 2) Conduct laboratory testing of glue-bond strength for selected commercial PNG Timber species and assessment of their performance in various climatic conditions which simulated service conditions in potential market destinations. Therefore, a testing program has been developed and conducted according to relevant international standards so that the data can be published and used for promoting PNG timbers.

Materials and methods

Harvesting and milling

An exhaustive testing program including 24 selected PNG timber species has been divided into two batches to facilitate harvesting and specimens' preparation logistic. Each batch included 12 species from plantations and secondary forests (also known as regrowth forests) located in the Morobe and West New Britain provinces, Papua New Guinea (PNG). Seven species have been harvested from plantations and 17 from secondary forests. The group included 3 softwoods and 22 hardwoods (Table 2).

Table 2: PNG studied timber species information.



Species	Trade Name	Origin	Age (years)	ADD** at 12 % MC (kg/m^3)	Shear Parallel to Grain (MPa) ****	Planing Class ***
Plantations (7 species)						
Araucaria cunninghamii	Pine, Hoop	Bulolo, Morobe	28	496	7,7	Planed Very Well
Araucaria hunsteinii	Pine, Klinki	Bulolo, Morobe	43	473	8,6	Planed Moderately Well
Castanospermum australe	Blackbean	Kimbe, West New Britain	17	792	10,9	Planed Very Well
Eucalyptus deglupta	Kamarere	Kimbe, West New Britain	29	562	8,6	Planed Very Well
Pinus caribaea	Pine, Caribbean	Lae, Morobe	31	525	9,0	Planed Very Well
Pometia pinnata	Taun	Lae, Morobe	18	664	11,2	Difficult to Plane
Terminalia brassii	Terminalia, Brown	Lae, Morobe	31	433	8,5	Planed Very Well
Secondary Forests / Regrowth (17 species)						
Alstonia scholaris	Cheesewood, White	Lae, Morobe	17 to 20	296	4,6	Planed Very Well
Anisoptera thurifera	Mersawa, PNG	Lae, Morobe	+20 *	685	10,4	Planed Very Well
Anthocephalus chinensis	Labula	Lae, Morobe	+20 *	418	7,5	Planed Very Well
Canarium oleosum	Canarium, Grey	Lae, Morobe	17 to 20	464	8,5	Planed Moderately Well
Elaeocarpus sphaericus	Quandong, PNG	Lae, Morobe	17 to 20	385	6,6	Planed Very Well
Endospermum medullosum	Basswood, PNG	Lae, Morobe	+20 *	356	5,4	Planed Very Well
Falcataria moluccana	Albizia, White	Lae, Morobe	+20 *	321	5,6	Difficult to Plane
Homalium foetidum	Malas	Lae, Morobe	17 to 20	800	14,1	Planed Very Well
Hopea iriana	Hopea, Heavy	Lae, Morobe	+20 *	932	16,5	Planed Moderately Well
Intsia bijuga	Kwila	Lae, Morobe	+20 *	758	13,5	Planed Very Well
Octomeles sumatrana	Erima	Lae, Morobe	+20 *	276	3,6	Planed Very Well
Palaquium warbargianum	Cedar, Pencil	Lae, Morobe	17 to 20	381	5,5	Planed Very Well
Pangium edule	Pangium	Lae, Morobe	17 to 20	618	8,0	Planed Very Well
Pterocarpus indicus	Rosewood, PNG	Lae, Morobe	+20 *	557	9,3	Planed Very Well
Syzygium spp.	Gum, Water	Lae, Morobe	17 to 20	495	8,7	Planed Very Well
Vitex cofassus	Vitex, PNG	Lae, Morobe	+20 *	591	9,3	Planed Moderately Well
Xanthophyllum papuanum	Boxwood, PNG	Lae, Morobe	+20 *	718	10,6	Planed Moderately Well

* No exact records of age are available in the harvested area. Species estimated age is +20 years old.
** ADD: Air-dry density. *** Belleville *et al.* 2020a. **** Belleville *et al.* 2020b.

A total of 130 trees, i.e. 5 trees per species, have been selected and harvested in accordance with ASTM D5536 (2010). The trees have been selected based on the following selection criteria: 1) the tree had to be more than 15 years old after regrowth or planting; 2) all trees for a specific species had to be from the same forest area; 3) the selected trees had to be representative of the population, with good form and merchantable height. Following harvesting, the total merchantable height of each tree has been further cut into 3 to 4 m-long logs and milled. The milled sawn boards were then kiln-dried to 12 % moisture content (MC).

Samples preparation and testing

In this study, a one-component cross-linking polyvinyl acetate (PVAc) emulsion adhesive was used (Jowat 2018a). Polyvinyl acetate emulsion adhesive has been widely used due to its good bonding performance and environmentally friendly properties. Among the several kinds of wood adhesives used currently, polyvinyl acetate (PVAc) emulsion is one of the non-structural types that are used most commonly in furniture and other wood product manufacture.

The wood material was first conditioned to 23 °C and 65 % RH until a constant mass was achieved. Plainsawn boards measuring 20 mm x 65 mm x 305 mm were selected to conform to ASTM D5751 (2012b) and dressed in a planer 1h prior to adhesive application. One-component cross-linking polyvinyl acetate (PVAc) emulsion adhesive (Jowat Jowacoll® 107.20 D4) was manually applied on one side at a rate of 200 g/m^2 for an open time of 10 min as per manufacturer recommendations (Jowat 2018a, Jowat 2018b). The assembled laminates were then pressed using a laboratory press. The pressing pressures considered were 0,7 MPa, 1,0 MPa, and 1,3 MPa. The pressing pressure for each species was determined based on the species density (e.g., 0,7 MPa for an air-dry density (ADD) < 500 kg/m^3, 1,3 MPa for an ADD > 800 kg/m^3) and results from preliminary trials.

Twenty-one laminate joint assemblies have been prepared for each species. Following a 30-min pressing time, the laminate assemblies were returned to 23 °C and 65 % RH for 1 week prior to further machining. From each laminate assembly, 25 mm has been discarded from each end. Five block shear specimens were prepared from the remaining section of each laminate joint assembly (Figure 2). Following another week at 23 °C and 65 % RH, the specimens have been tested in accordance with ASTM D5751 (2012b) using a 50 kN universal testing machine (Instron 5569, MA, USA). A control group (C), composed of 21 block shear specimens, has been tested without any post-lamination treatment i.e. tested once cured or dried. The remaining specimens have been divided into 4 groups and tested after exposure to different conditions i.e., 3-cycle soak (W), boil (B), elevated temperature (T); vacuum pressure (V).

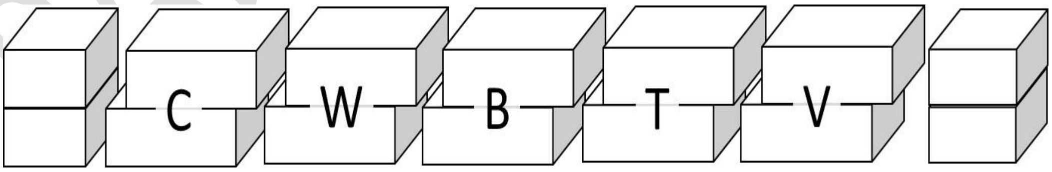


Figure 2: Block shear specimens sampling methodology and exposure condition allocation per assembly.

C: Cured specimen; W: 3-cycle soak; B: Boil; T: Elevated temperature; V: Vacuum pressure.

Statistical analysis

Data were analyzed using the statistical software RStudio (Version 1.4.1106) to evaluate the effect of MC and wood density on the PVAc glue-bond shear strength and wood failure of the selected PNG timber species across different service conditions for dry-use and wet-use application. A factorial analysis of covariance (ANCOVA) was conducted using a 5 % level of significance. Two separate models were used to test for shear strength and wood failure separately as response variable, both, containing the treatments (5 different exposure conditions), MC (%) and timber species as independent variables and ADD as a covariate.

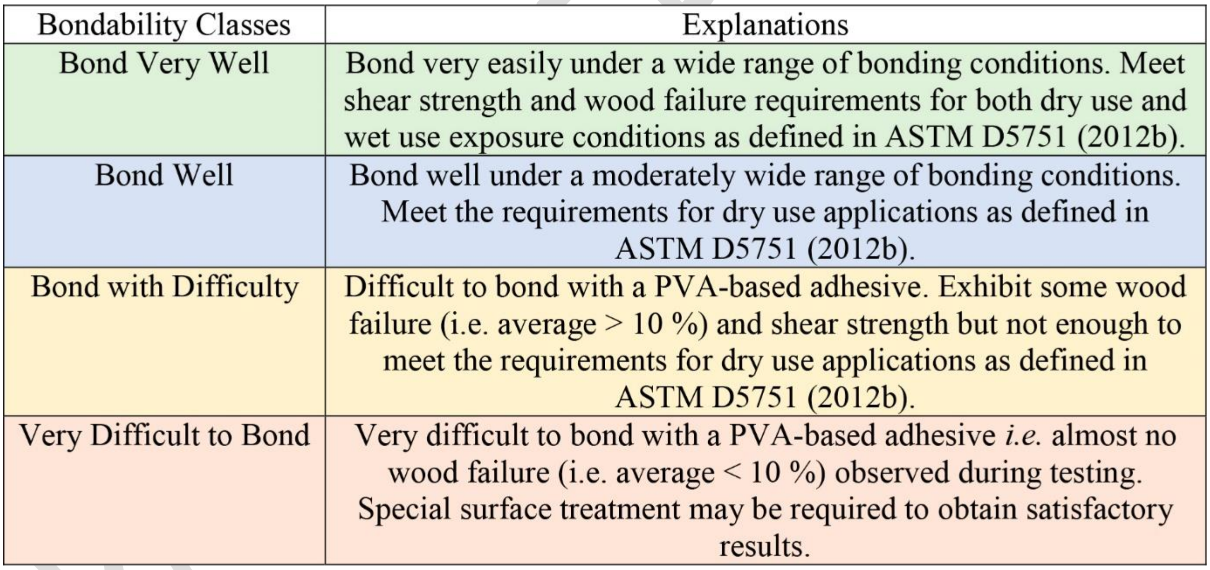
Results and discussion

Laboratory testing of glue-bond strength and performance of 24 PNG timber species has been conducted in various climatic conditions to simulate a large range of service conditions. Twenty-one laminate assemblies and 105 block shear specimens have been prepared for each species. Five different exposure conditions have been considered to determine the gluability of each species for non-structural applications.

Based on the testing results, each of the 24-selected species has been classified based on their bondability as per Table 3 and Table 4. To be considered to “bond very well” a species is able to meet or exceed shear strength and wood failure requirements for both dry use and wet use exposure conditions i.e. all five exposure conditions listed in Table

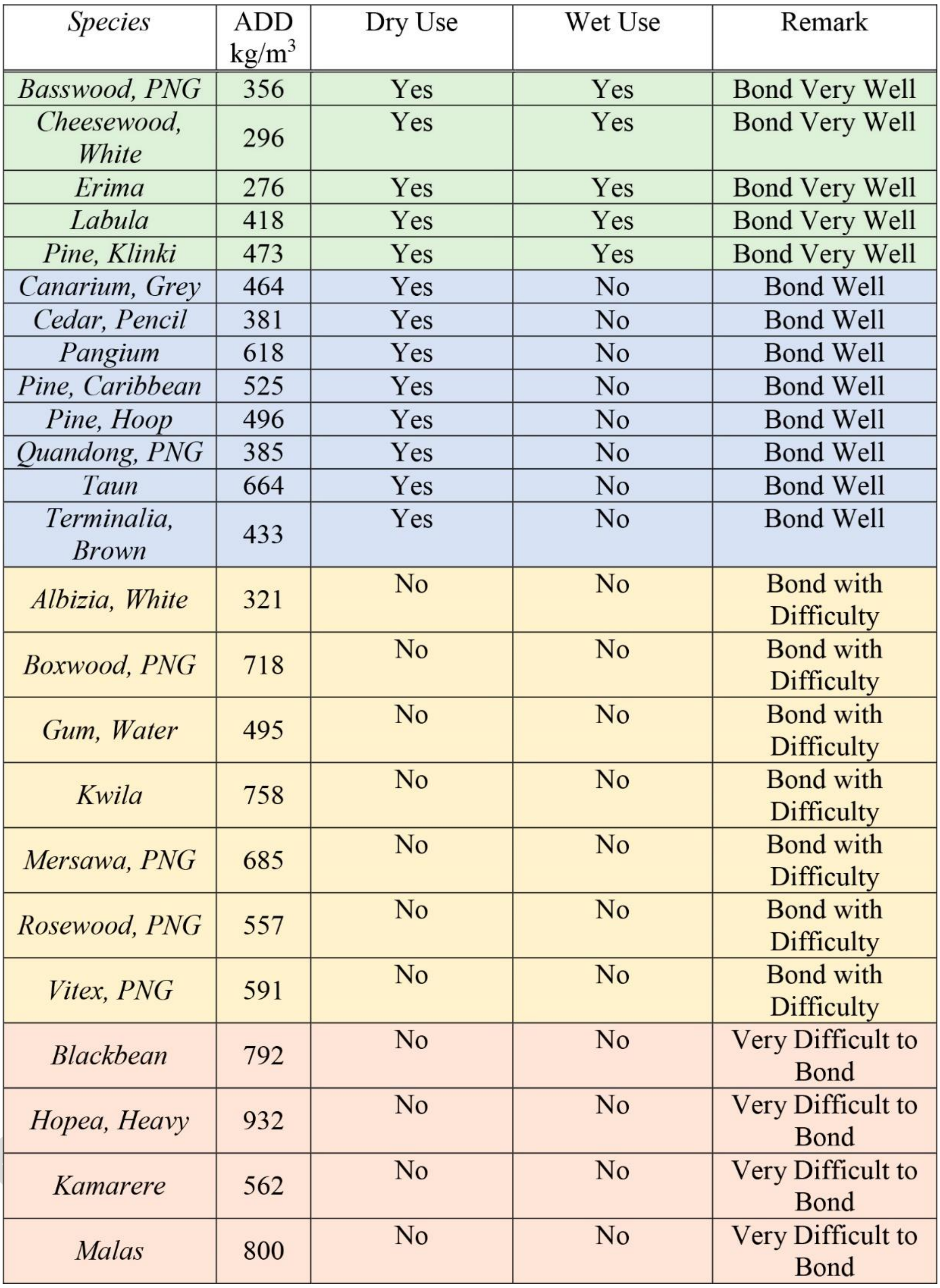
1. A species that “bond well” is able of meeting or exceeding the requirements for dry use applications i.e. cured, high temperature and 3-cycle soak exposure conditions. A species that “bond with difficulty” is usually exhibiting some wood failure and shear strength but not enough to meet the requirements for dry use applications. A species considered to be “very difficult to bond” could not manage to meet the shear strength requirements for dry use applications and provided very little wood failure (i.e. average < 10 %) across all exposure conditions no matter which adhesive is used. Such species would require careful selection of adhesives and very close control of bonding conditions. Special surface treatments may be required to achieve satisfactory results.

Table 3: Bondability classes used in the present study with explanations.



Bondability Classes	Explanations
Bond Very Well	Bond very easily under a wide range of bonding conditions. Meet shear strength and wood failure requirements for both dry use and wet use exposure conditions as defined in ASTM D5751 (2012b).
Bond Well	Bond well under a moderately wide range of bonding conditions. Meet the requirements for dry use applications as defined in ASTM D5751 (2012b).
Bond with Difficulty	Difficult to bond with a PVA-based adhesive. Exhibit some wood failure (i.e. average > 10 %) and shear strength but not enough to meet the requirements for dry use applications as defined in ASTM D5751 (2012b).
Very Difficult to Bond	Very difficult to bond with a PVA-based adhesive *i.e.* almost no wood failure (i.e. average < 10 %) observed during testing. Special surface treatment may be required to obtain satisfactory results.

Table 4: Bondability groupings for selected PNG species.



Species	ADD kg/m^3	Dry Use	Wet Use	Remark
Basswood, PNG	356	Yes	Yes	Bond Very Well
Cheesewood, White	296	Yes	Yes	Bond Very Well
Erima	276	Yes	Yes	Bond Very Well
Labula	418	Yes	Yes	Bond Very Well
Pine, Klinki	473	Yes	Yes	Bond Very Well
Canarium, Grey	464	Yes	No	Bond Well
Cedar, Pencil	381	Yes	No	Bond Well
Pangium	618	Yes	No	Bond Well
Pine, Caribbean	525	Yes	No	Bond Well
Pine, Hoop	496	Yes	No	Bond Well
Quandong, PNG	385	Yes	No	Bond Well
Taun	664	Yes	No	Bond Well
Terminalia, Brown	433	Yes	No	Bond Well
Albizia, White	321	No	No	Bond with Difficulty
Boxwood, PNG	718	No	No	Bond with Difficulty
Gum, Water	495	No	No	Bond with Difficulty
Kwila	758	No	No	Bond with Difficulty
Mersawa, PNG	685	No	No	Bond with Difficulty
Rosewood, PNG	557	No	No	Bond with Difficulty
Vitex, PNG	591	No	No	Bond with Difficulty
Blackbean	792	No	No	Very Difficult to Bond
Hopea, Heavy	932	No	No	Very Difficult to Bond
Kamarere	562	No	No	Very Difficult to Bond
Malas	800	No	No	Very Difficult to Bond

A first group of species composed of PNG basswood, white cheesewood, erima, labula, and klinki pine showed to bond very well. A second group of species provided results satisfying or able of satisfying the requirements for dry use applications: grey canarium, pencil cedar, pangium, caribbean pine, hoop pine, PNG quandong, taun, and brown terminalia. While PNG boxwood, kwila, PNG mersawa, PNG rosewood, white albizia, water gum, and PNG vitex could not meet the requirements for dry use applications with a PVAc. Four species provided low shear strength results and very limited wood failure resulting in them being classified as very difficult to bond: blackbean, heavy hopea, kamarere, and malas.

Not surprisingly, most of difficult and very difficult species to bond are high or very high-density species. Higher concentration of extractives that may interfere with the cure of adhesives is common in high-density species, particularly tropical hardwoods (Frihart and Hunt 2010). They are typically concentrated in the heartwood and are often produced by the standing tree as defensive compounds to environmental stresses (Taylor *et al*. 2002). They can interfere with the direct adhesive contact, leading to a chemically weak boundary effect and poor bond strength (Frihart and Hunt 2010). As noted by Roffael (2016), extractives can contribute to or determine the bonding relevant properties of wood such as acidity and wettability. The presence of hydrophobic extractives like resins on the surface of wood can have a detrimental influence on the wettability of wood towards adhesives (Chen 1970). Extractives may also affect bonding through their pH value and buffering capacity (Roffael and Dix 1994). The extent of adhesion failure tends to be greater in species with an extractive content than it is in groups with lower content (Nussbaum and Sterley 2002).

Additional tests with dense species would be recommended to fully assess their suitability for non-structural applications. As noted by Frihart and Hunt (2010), a species that bonds poorly with one adhesive may develop better bonds with another adhesive. A similar type of adhesive with somewhat different working, penetration, curing, and even strength properties can often dramatically improve bondability of a given species. Such species could also need some mechanical or chemical surface treatment to improve adhesion.

Successful adhesion between non-bondable or hard-to-bond materials has been achieved through the combinations of physical and chemical treatment methods. Gutowksi *et al*. (2015) demonstrated that chemical grafting can improve adhesion of coatings on façade materials and provide excellent adhesion. The technology has been used successfully to achieve long-term adhesion and bondline durability with difficult-to-bond Australian hardwoods species (Li *et al*. 2018). The roughness of wood surfaces has also shown to affect the wettability by bonding formulations and ultimately the strength of bonding. Qin *et al*. (2015) improved the wettability of wood surfaces by removing some of the material by sanding and it is known that sanding of the wood surface removes hydrophobic extractives, which can lead to more hydrophilic surfaces (Aydin 2004). Whether or not a beneficial result is achieved can be expected to depend on the chemical composition of the species. It is difficult to generalize whether a rough wood surface has a positive or negative impact on adhesive bonding performance. On one hand, roughness is a disadvantage because it contains failure initiation sites and hinders adhesives and coatings to penetrate into the wood substrate (Landry and Blanchet 2012) and anchor to the intact wood material (Özçifçi and Yapici 2008). On the other hand, roughness appears, to some extent, to improve the adhesive joint performance because crushed fibres can mechanically interlock with adhesives (Kuljich *et al*. 2013). It seems likely that an optimum combination of treatment and adhesion promotion exists, for different species and adhesive systems. However, more research is needed to overcome this situation and to allow the use of optimized techniques at a commercial level.

Klinki pine provided significantly higher glue-bond shear strength testing results than any other species across all selected timber species, together with sound wood failure results (Figure 3a, Figure 3b, Figure 3c, Figure 3d, Figure 3e, Figure 3f, Figure 3g, Figure 3h). On the other hand, erima provided significantly higher wood failure testing results than any other species across all selected timber species, together with sound glue-bond shear strength results (Figure 3a, Figure 3b, Figure 3c, Figure 3d, Figure 3e, Figure 3f, Figure 3g, Figure 3h).

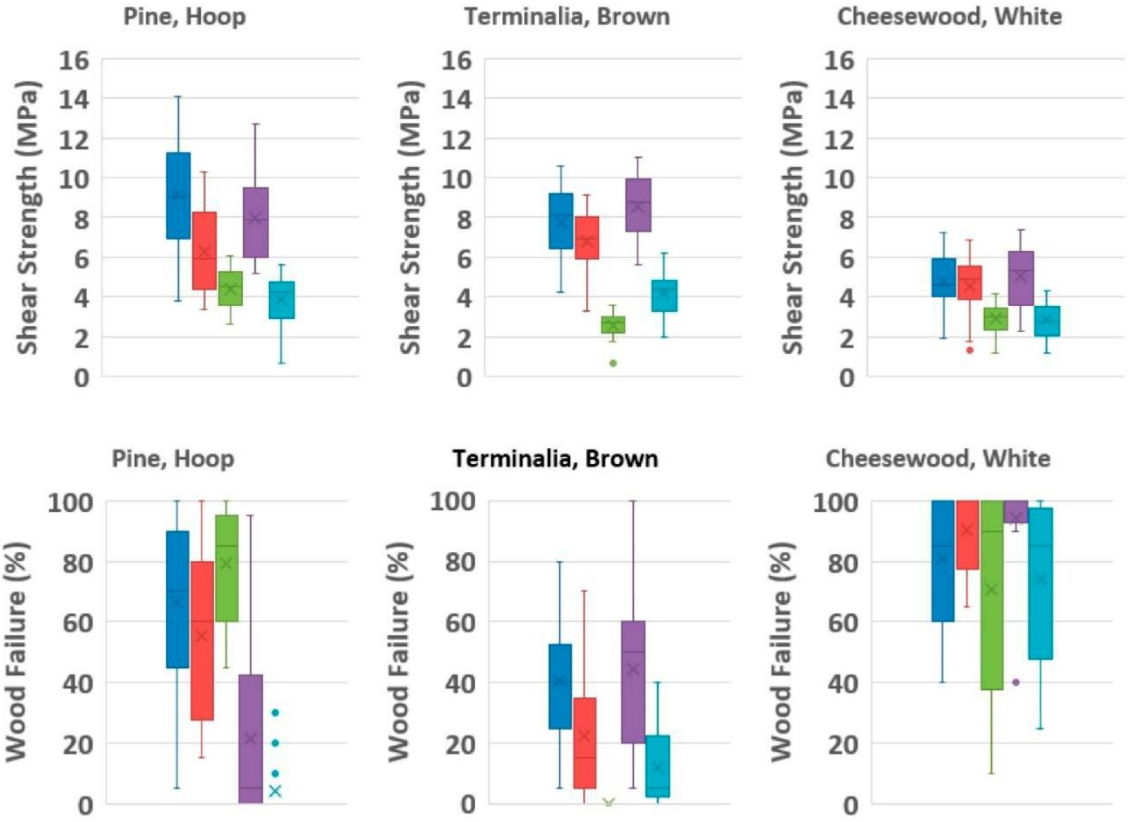


Figure 3a: Summary of shear strength and wood failure per species and exposure condition.

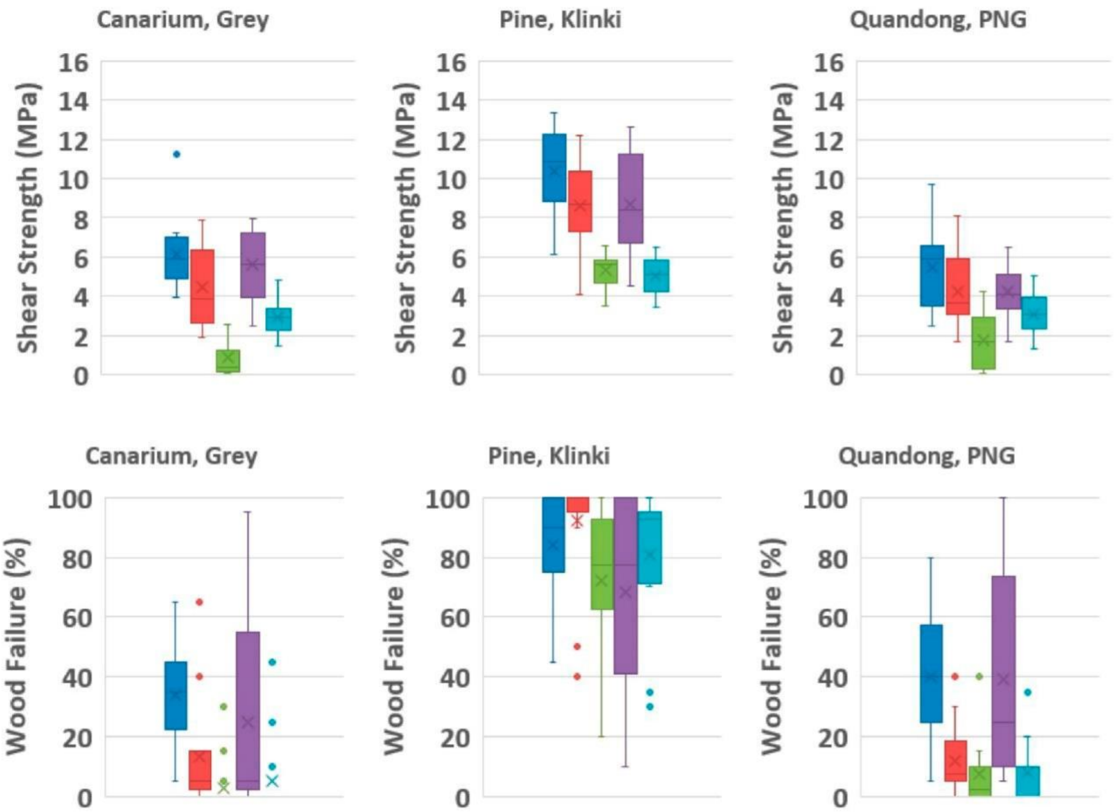


Figure 3b: Summary of shear strength and wood failure per species and exposure condition.

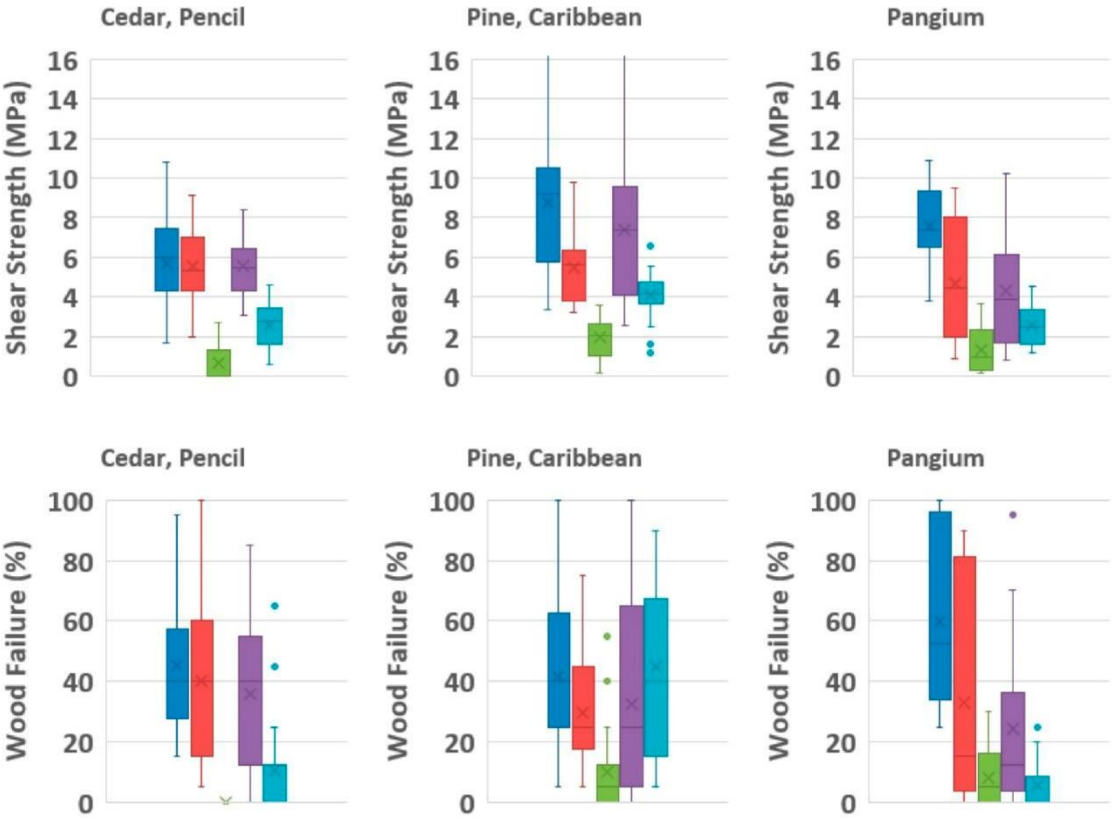


Figure 3c: Summary of shear strength and wood failure per species and exposure condition.

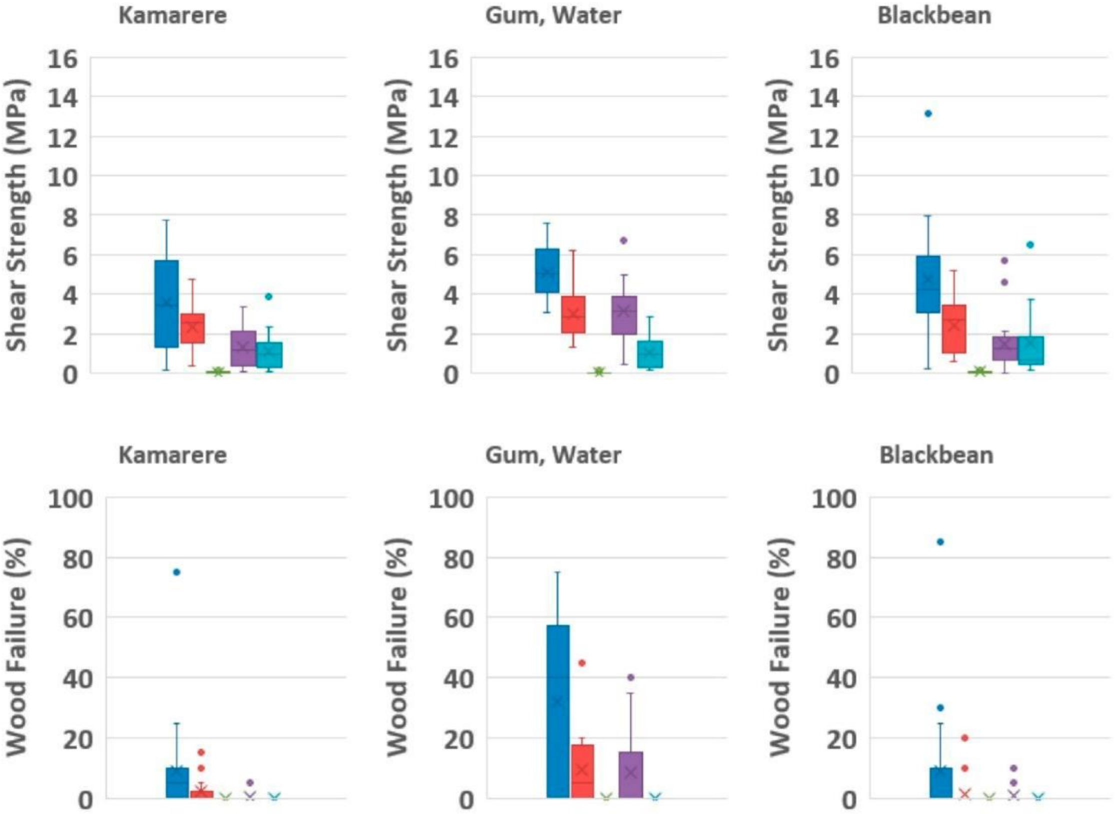


Figure 3d: Summary of shear strength and wood failure per species and exposure condition.

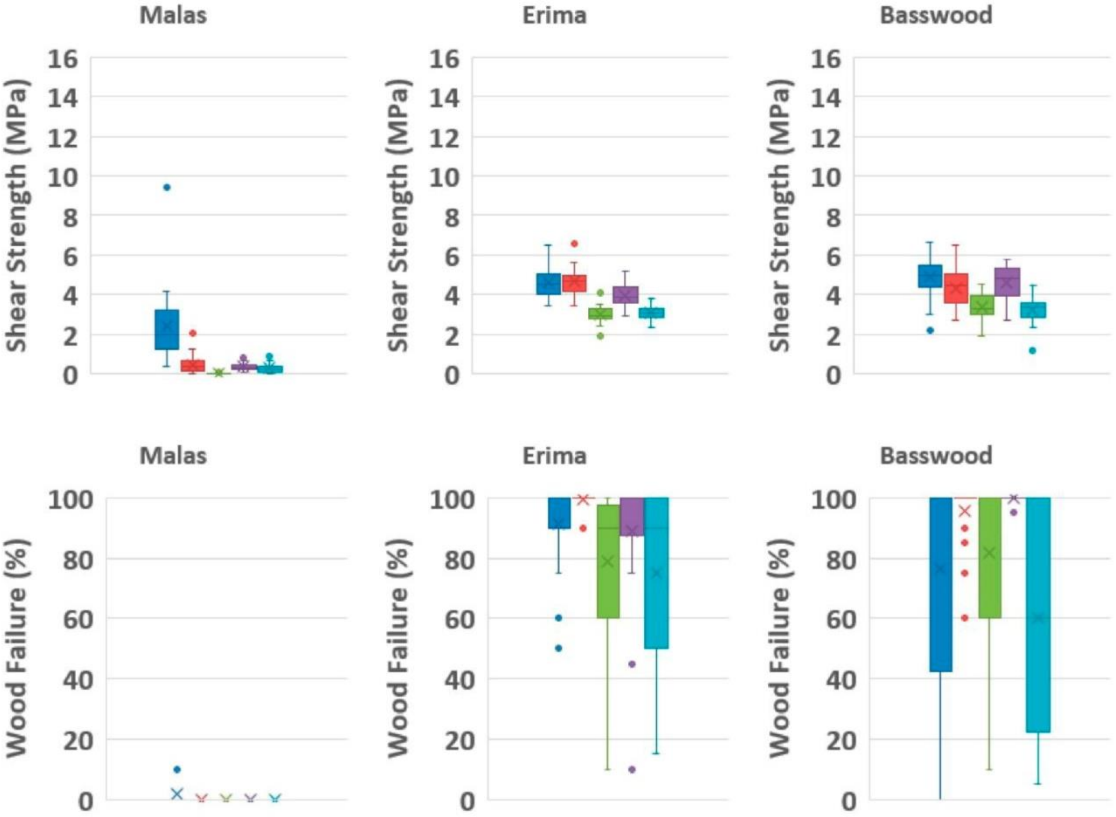


Figure 3e: Summary of shear strength and wood failure per species and exposure condition.

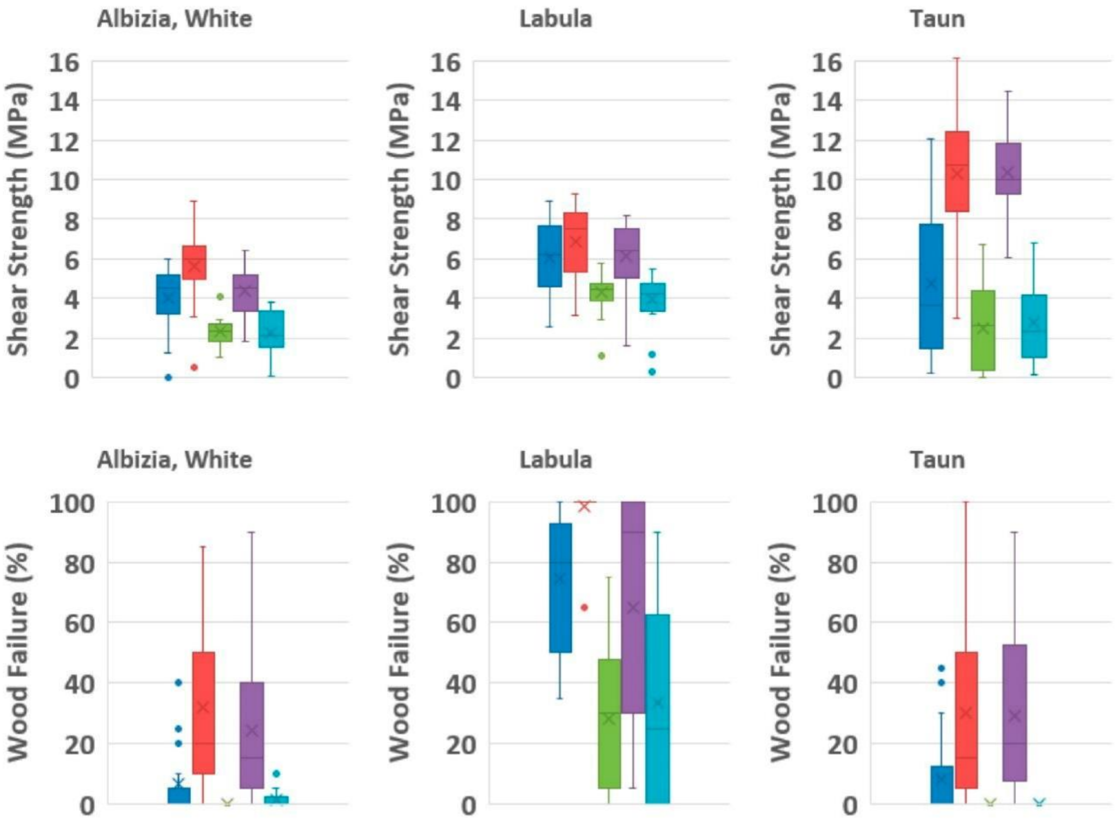


Figure 3f: Summary of shear strength and wood failure per species and exposure condition.

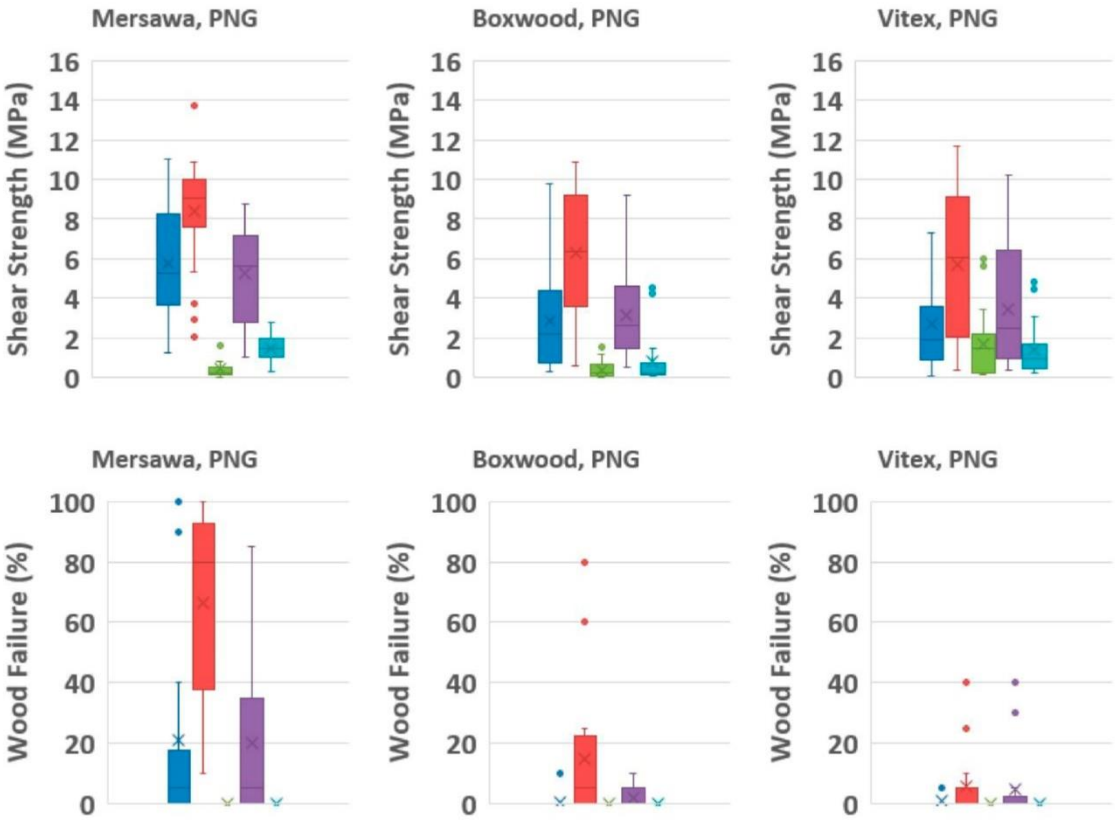


Figure 3g: Summary of shear strength and wood failure per species and exposure condition.

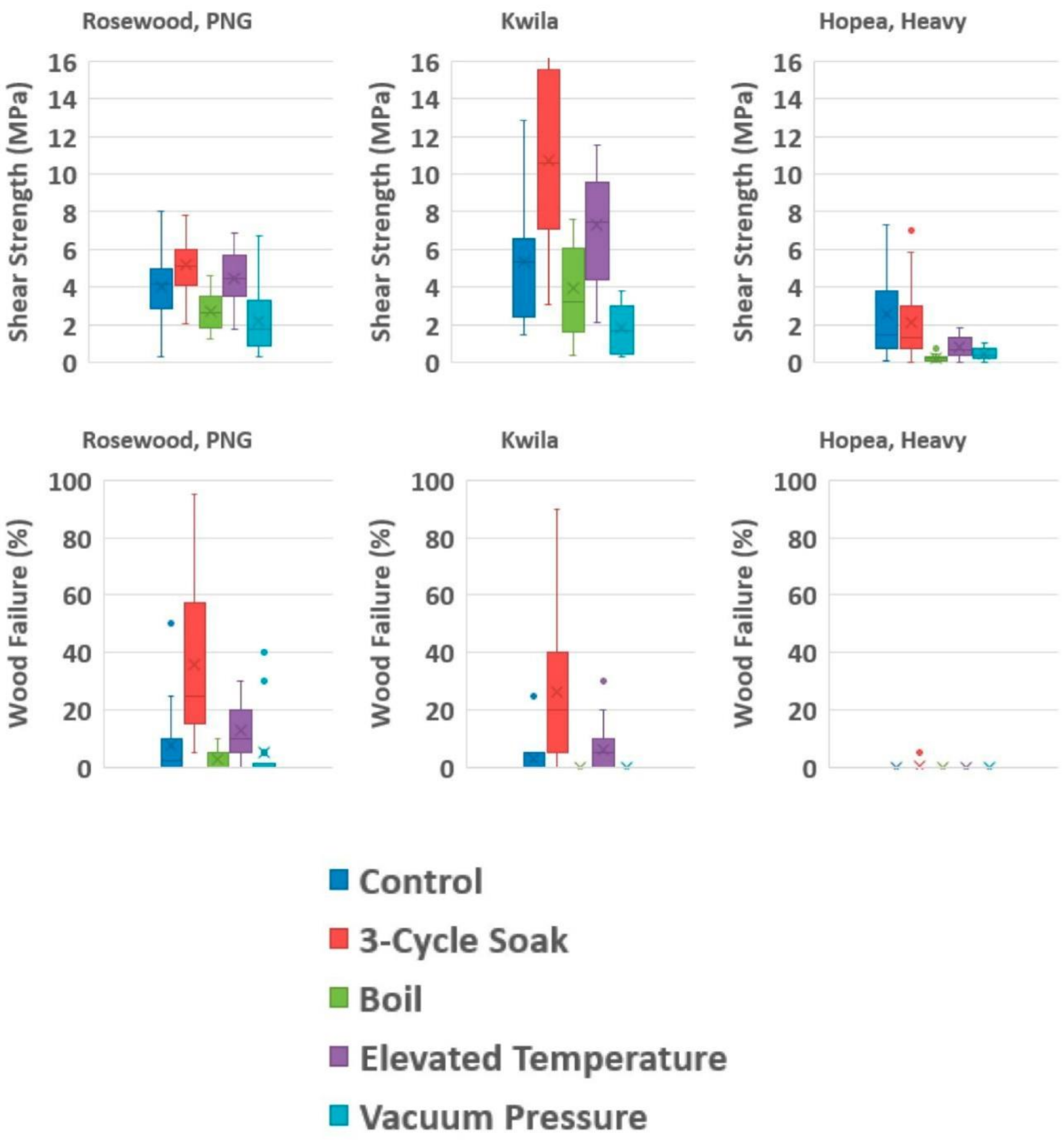


Figure 3h: Summary of shear strength and wood failure per species and exposure condition.

The statistical analysis demonstrated a highly significant between-group variance of the main effect (*P* < 0,001) between species, exposure conditions (treatments), ADD and MC on the glue-bond shear strength as well as the wood failure. It also demonstrated a highly significance ($P < 0,001$) interaction effect between treatments and MC on both the shear strength and wood failure.

Factorial analysis of covariance is a combination of a factorial ANOVA and a regression analysis thus showing linear regression relationship of ADD as a covariate on dependent variable (shear strength and wood failure) (Figure 4).

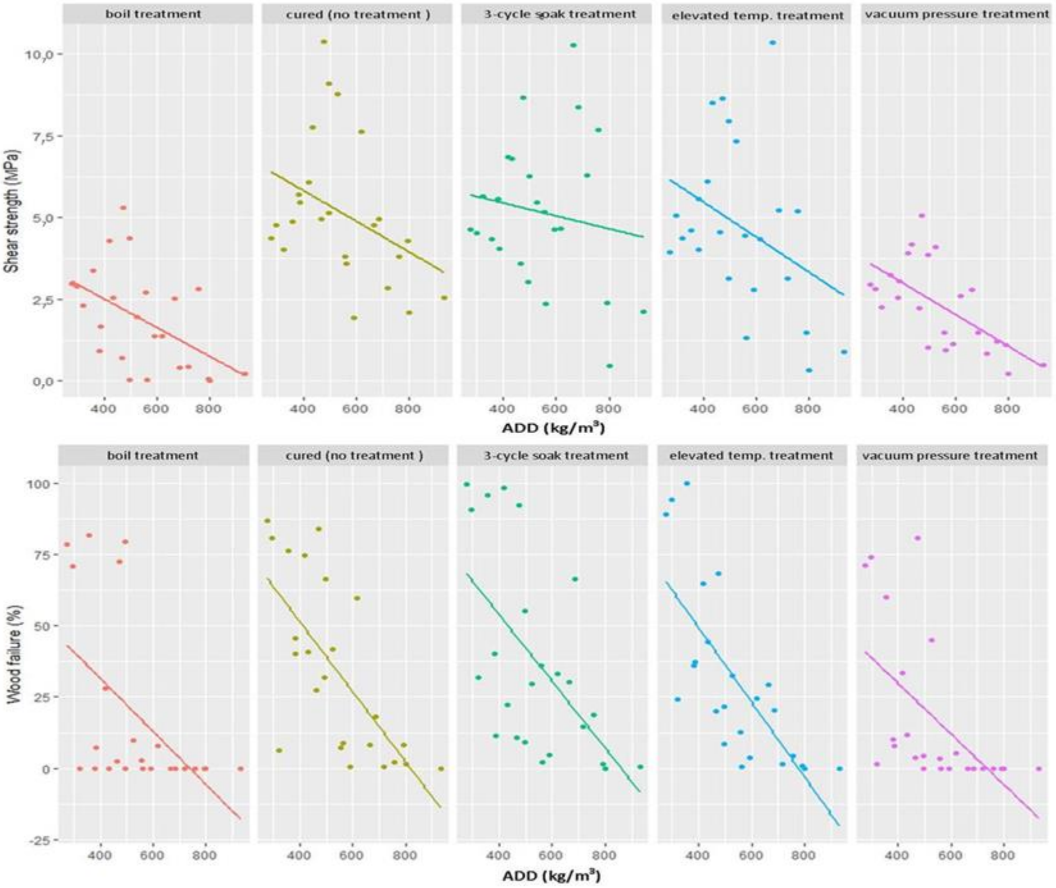


Figure 4: Relationship between air-dry density (ADD) and shear strength (top) and wood failure (bottom).

The wood physical properties that affect the bondability are particularly ADD, porosity, MC and dimensional movement i.e., shrinkage or swelling when exposed to different exposure conditions as stated by Vick (1999). ADD at 12 % MC as a wood property factor and MC as a product service factor does affect the shear strength (highly significant $P <$

0,001) and wood failure (ADD highly significant (*P* < 0,001) of the PNG timber species across all the exposure conditions as shown on Figure 5 and Figure 6. As the ADD and MC increases, high shear strength with high wood failure is more difficult to achieve consistently. Wood failure in laminated wood specimen tends to increase as the wood density and moisture content decrease (Frihart and Beecher (2016)). High-density wood species are difficult to bond because of thicker cell walls and less lumen volume as essential mechanical interlocking of adhesives is limited to one or two cells deep because adhesives do not penetrate easily (Vick 1999).

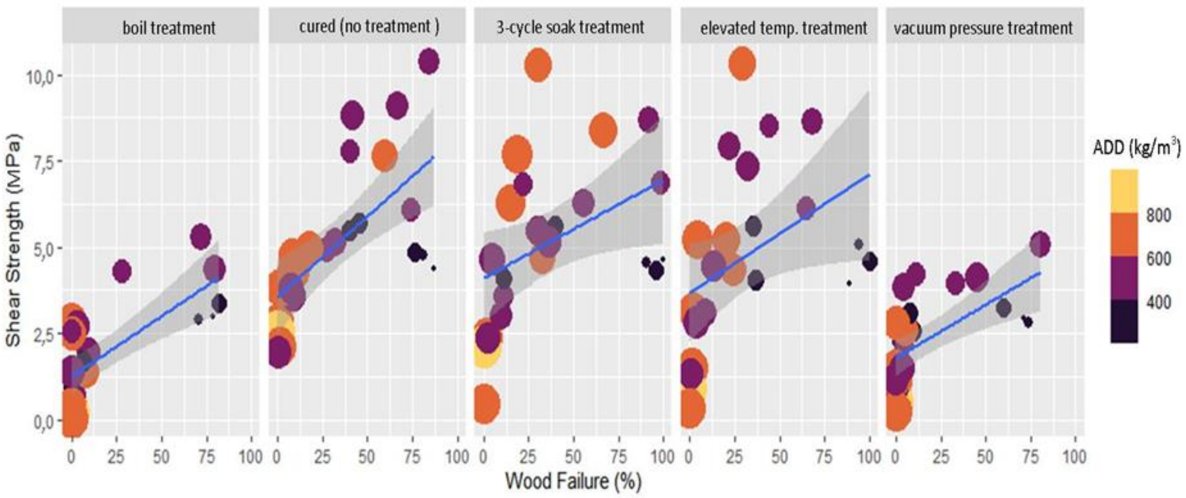


Figure 5: Showing the effect of air-dry density (ADD) on shear strength and wood failure of all the tested species across the different exposure conditions.

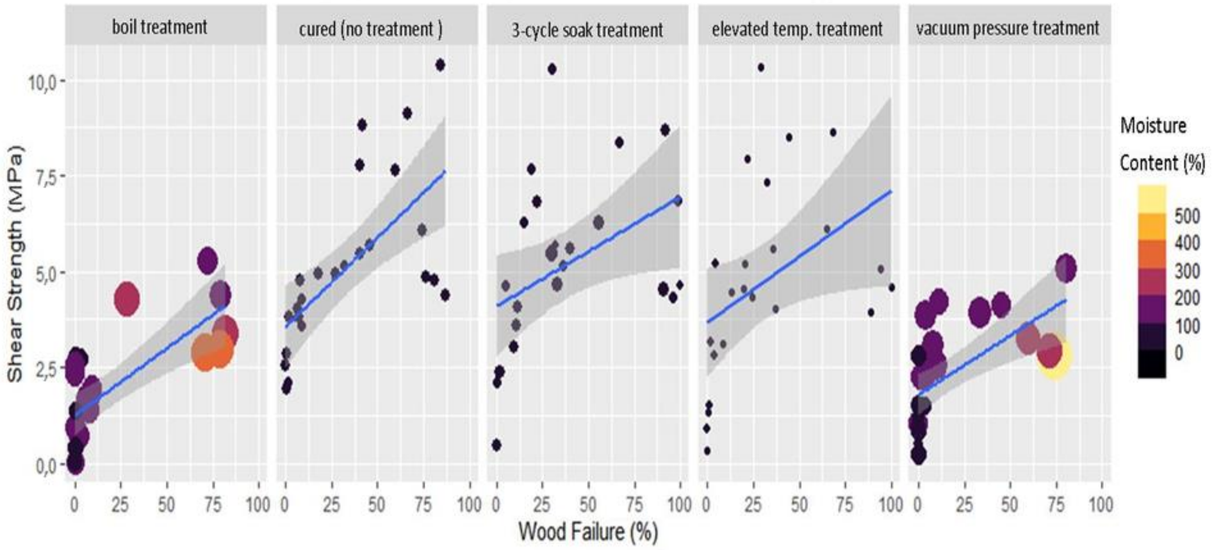


Figure 6: Showing the effect of wood moisture content (MC, %) on shear strength and wood failure of all the tested species across the different exposure conditions.

With the MC interaction with density, the curing treatment which is a control treatment at 12 % MC, the 3-cycle soaking treatment and elevated temperature treatment all of which their EMC ≤ 16 % (dry-use application) show that some timber species of ADD between 450-700 kg/m^3 sheared off with wood failure ranging between 0 and 40 %. These timber species are grey canarium, pangiun, caribbean pine, hoop pine and taun because they bond well meeting the standard for the dry-use application only and not the wet-use application as seen on the above Figures.

On the other hand, low-density species with an ADD of 200-450 kg/m^3 with high MC do bond very well with 50-80 % wood failure in boiling treatment and vacuum pressure treatment of which their EMC >16 % (wet-use application). They satisfy both the dry-use and wet-use application and these species are PNG basswood, white cheesewood, erima, labula, and klinki pine. However, other low-density species within similar range of 200-450 kg/m^3 bond with difficulty and not satisfying the wet-use application. These species are pencil cedar, quandong and brown terminalia and other high-density species of ADD range 500-900 kg/m^3 bonds with difficulty or even very difficult to bond and not satisfying both dry- and wet-use applications. Density is perhaps a crude indicator, but it is useful for estimating the bondability of a great variety of wood species (Vick 1999) in conjunction with other factors such as the concentration of extractives.

Conclusions

The overall aim of the project was to increase the contribution that utilization of forest resources makes to national and local economies, including landowners and processors, through the development of domestic value-added wood processing methods.

Five species showed to bond very well i.e. achieved satisfactory results for both dry use and wet use applications: PNG basswood, white cheesewood, erima, labula, and klinki pine. A second group of seven species provided results satisfying or able of satisfying the requirements for dry use applications: grey canarium, pencil cedar, pangium, caribbean pine, hoop pine, PNG quandong, Taun, and brown terminalia.

While PNG boxwood, kwila, PNG mersawa, PNG rosewood, and PNG vitex could not meet the requirements for dry use applications using a standard cross-linking PVA. Six species provided low shear strength results and very limited wood failure resulting in them being classified as very difficult to bond: blackbean, heavy hopea, kamarere, white albizia, water gum, and malas. Most high or very high-density species proved to be very difficult to bond.

Overall, the testing of gluing characteristics of PNG timbers provides data that will be of great value to both the scientific community and timber industry. The results will be particularly important to the companies which are involved in manufacturing value-added solid wood products and engineered wood products (EWPs) where bonding of timber components (solid and veneer) is a pivotal part of the manufacturing process.

Authorship contributions

B. B.: Conceptualization, data curation, formal analysis, methodology, project administration, Software, supervision, validation, visualization, writing – original draft, writing – review & editing. K. L.: Data curation, formal analysis, investigation, software, visualization, writing – original draft. E. G.: Data curation, investigation, project administration, visualization. J. F.: Data curation, investigation. B. O.: Conceptualization, funding acquisition, project administration, resources, supervision, writing – review & editing.

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