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High-Tech Modular Building Components with High Contents of Australian Hardwoods

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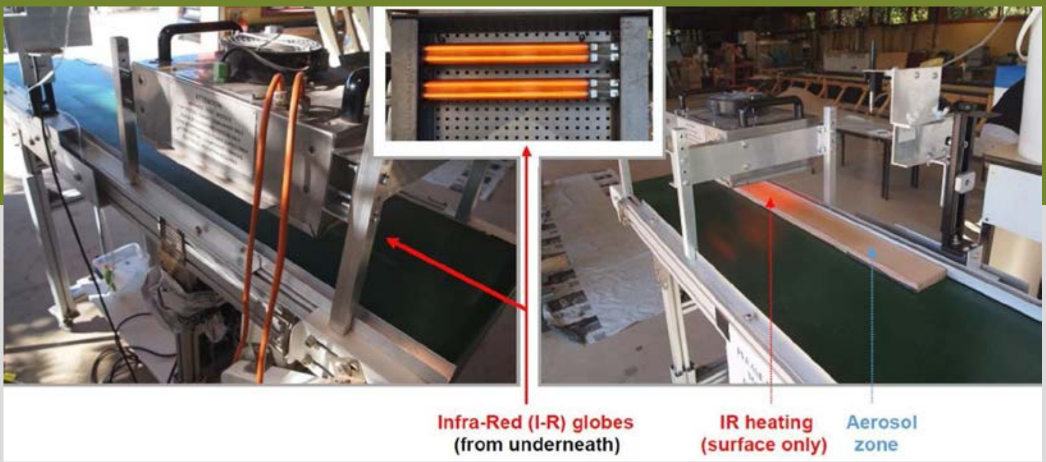

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Forest & Wood Products Australia

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Executive Summary

This collaborative project involving CSIRO, University of Melbourne and Swinburne University aims to develop a competitive technology platform enabling significant increase of hardwood usage in Australian building and construction sector. The principal approaches utilised in the project are: (i) to incorporate a reactive interface onto hardwood surface to enhance bonding performance of bonded products for accommodating interfacial stresses arising from hydrothermal movements, (ii) to provide strong and durable bond with exterior durable coatings for maintaining coating adhesion and hardwood natural appearance, and (iii) to provide design recommendations for exterior hardwood products. These will enable fabrication of high-value added engineered products with the aim of achieving excellent long-term durability for bonded and coated hardwood products and retention of initial decorative-visual attributes of natural timber for the time that may reach, as estimated preliminarily, up to ~ 15 years.

The R&D results have demonstrated that using CSIRO's surface modification technology can significantly improve bond strength and durability of bonded and coated Australian hardwood products. For product manufacture involving hardwood bonding using PU (polyurethane) adhesives, a thin layer of CSIRO Surf-BOND, a water-based low-hazard adhesion promoter formulation (~20ml/m^2) spray-applied on hardwood surface prior to bonding process, can generate a significant improvement of bond strength (by up to 100-300%), which is attributed to high level of wood failure for several typical hardwood species. Such benefits become even more pronounced when bond performance was assessed after exposure to severe cyclical environmental exposure conditions such as: high temperature, extreme wet & dry cycles (boiling + 104°C oven drying), or exposure to high temperatures reaching those generated by fire. The strong bonding behaviour is also maintained after H1 or H3 "True-Core" preservative treatment of the bonded product. These results were validated throughout entire technology scale-up process, from laboratory-scale testing through to pilot-scale trials and final demonstration at industrial trials conducted at the ASH Heyfield manufacturing plant.

Several commercially available automotive clear coatings have been identified in application for surface finishing of exterior hardwood products. As validated through long-term accelerated weathering assessment, selected high-gloss and low-gloss (matt) clearcoats from PPG Australia survived up to 2000 hours of Q-Sun or 4000 hours of QUV testing when used on various hardwood species. The weathered coating layer, devoid of surface voids and fractures, still retained optical clarity, continuity, flexibility and high strength of adhesion to the hardwood surface, while the wood products also maintained natural appearance after completion of accelerated weathering. Various surface- and interface-modifying underlayer coatings developed at CSIRO have provided additional benefits in enhancing coating adhesion, improving UV resistance and reduction of colour change, as demonstrated by accelerated weathering realistically simulating their potential long-term outdoor performance.

Such results provide promising solution for coated hardwoods in outdoor applications by overcoming surface damage (including discoloration) upon solar exposure and alleviating high-cost maintenance associated with poor durability of currently used coatings on exterior wood products, typically necessitating short repainting cycles due to poor paint adhesion, wood surface decomposition and resultant delamination. Although there is no direct correlation between the number of '*survived*' hours of Q-Sun or QUV simulated weathering exposure and the years of coating durability in real life, surviving 2000 hours of Q-Sun or 3000-4000 hours of QUV testing might imply some 15-*plus* years of coating durability, although this prediction needs further validation in scale-up and industrial trials.

A fundamental set of guidelines/stipulations has also been developed for designing outwardly facing surfaces of hardwood cladding components, irrespective of their rear (inward-facing) mounting systems, to maximise their effectiveness in preventing the rain- or condensation-related water accumulation on cladding surfaces. It has been demonstrated that besides the long-term UV resistance, coated hardwood cladding panels exhibit effective water-shedding ability at implementable angles in cladding panel profile designs, and prevent formation or retention of pooling stagnant water and capillary bridges in the gaps between adjacent panel surfaces (when needed due to engineering and design or styling requirements) when the gaps are greater than approximately 5 mm. The effectiveness of water-shedding ability of external timber cladding elements can potentially be even further enhanced by applying additional super-hydrophobic coatings, which have in the course of this research shown (in some instances) to increase the effectiveness of gravity upon removing water droplets.

The outcome of this project provides a promising technology combining remarkable enhancement of long-term performance of bonded and coated hardwood, whilst product design recommendations for Australian hardwood products manufacturers enable development of engineered designer-products for buildings' exterior and interior applications, e.g. prefabricated cladding modular components, *in-built* functional, decorative and structural hardwood products that has significantly increased their ability to meet relevant essential long-term performance standards. The outcomes also create potential for further innovation in hardwood-based modular building and architectural systems manufactured, surface finished and assembled off-site, and ready for installation at the designated construction site.

All surface-modification chemicals utilized in the project are low-cost, water-based, low-hazard and commercially available materials. The polyurethane adhesives and coatings are also commercially available. The process is robust and easy to implement and operate in existing industrial facilities utilising commodity industrial equipment and operational procedures. The technology can be further extended (through customisation or further R&D) to a broad range of Australian wood products to maximise benefits achievable to the entire wood products sector, allowing timber to be promoted and reliably utilised as a sustainable and highly reliable engineering material in a much broader range of applications, thus maximizing the use of Australian wood-based materials.

The project team highly recommends further R&D, consulting or other forms of assistance in further technology development, validation, product design and technology transition and productionising in the entire wood products industry as well as the building and construction sector.

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Introduction

Wood-based construction products such as façade cladding, doors, windows, decking and floors feature important advantages over metallic or plastic equivalents including attractive wood-grain aesthetics, eco-sustainability, excellent thermal insulation, fabrication ease and high strength. Regardless of this, while 10 – 20 years ago the wooden products such as windows and doors represented 50% of the total market in Australia, USA and Germany [1], today's sales are just about 25% or less of the overall numbers in these product categories [Friebel: http://www.coatings.de/radcure/reading/friebel]. Such huge market share loss is due to low durability of wood products against low-maintenance substitutes made of metals, plastics and wood-plastic composites which offer up to 20 years of maintenance-free service performance. As the current commodity wood-based materials and traditional methods of construction are struggling to deliver quality outcomes, it is critical to develop alternative high-performance materials able to retain wood's natural appearance for up to 20 years combining their use with advanced construction means based on modular systems driven by economic and practical advantages.

Australia has unique resources of native hardwoods producing aesthetically attractive and structurally viable timbers for high-strength structural applications in joists, posts, roof beams, decking, and for other products potentially suitable for exterior architectural elements such as façade panels, windows, doors, balconies, decks, balustrades, etc. These are manufactured from sawn planks, boards or laminated veneer products converted into engineered products through bonding by lamination and finger-jointing followed by surface coating, where required, for aesthetic or durability requirements. Many of these products, whilst suitable for interior applications, are inadequate for exterior use due to poor durability of hardwoods on exposure to moisture, solar radiation and lignicolous fungi.

Broadening the use of Australian hardwoods to engineered architectural products is, however, severely limited due to their poor bondability [2-12]. Many commercially important and visually attractive hardwoods: *Corymbia maculata* (Spotted gum), *Eucalyptus globulus* (Blue gum), *Eucalyptus piluralis* (Blackbutt), and *Eucalyptus microcorys* (Tallowwood) suffer from poor adhesion due to inherent content of low molecular weight mobile extractives; lipophillic (oily) and phenolic. Migrating to the surface they form a barrier on the surface of wood preventing formation of molecular bonds between cellulosic backbone of the substrate and adhesives or coatings. Some medium density hardwoods, e.g.: *Eucalyptus regnans, Eucalyptus obliqua* or *Eucalyptus delegatensis* (known as Mountain ash or Tasmanian oak, depending on the source) are relatively easy to bond by commodity adhesives and hence, are broadly used for high strength structural or engineered timber products for internal joinery, flooring systems, furniture and staircases. However, the products made of these species have not been suitable for outdoor applications due to insufficient performance of uncoated systems due to: (i) rapid surface discoloration upon solar exposure, and (ii) non-performing coating systems which, when used on these products, require high-cost maintenance, i.e. 3-year repainting cycles due to poor paints adhesion and resultant delamination.

With reduced supplies of hardwood logs produced in Australia overall, the domestic producers of traditional high value solid wood products such as flooring and structural timber, who get access to higher value species such as Blackbutt, Spotted Gum, Blue Gum and Tallow wood, will continue to be able to profitably service the reduced local demand for traditional flooring products. It needs to be emphasised that the superior strength, hardness, durability and sustainability characteristics of Australian hardwood timber species, including tableland species, could attract higher prices and outcompete existing feedstocks such as the

American and European Oaks. This however, necessitates the availability and/or development of appropriate technologies and manufacturing processes facilitating bonding of these difficult-to-bond Australian species to facilitate profitable processing, manufacturing and marketing for re-constituted products involving lamination, finger joining, and high-value added engineered products.[13] The additional challenge for industry, which will drive increases in profitability overall, is to develop processing options for less desirable species and lower quality logs produced as by-products of harvesting the higher quality logs. Hence, the need for development of high-value added engineered wood products exhibiting guaranteed high performance, long term durability, low maintenance whilst offering an aesthetically pleasing *'good-look of natural timber'* achieved through naturally durable hardwood species permanently bonded to the surface of exterior architectural products and systems.

This project builds on earlier CSIRO research resulting in development of technology for surface engineering of lignocellulosic materials to achieve enhanced adhesion of coatings and adhesives.[14-18] The outcomes as validated through adhesive bonding of selected Australian hardwoods with polyurethane structural adhesive demonstrated a significant increase in bond tensile strength compared with those of unmodified samples. This project aims to create competitive platform enabling significant increase of hardwoods use by Australian building and construction sector. The study will develop and validate high-value durable hybrid materials for the manufacture of engineered designer-products for building's exterior and interior applications which will meet essential performance standards. Prefabricated modular components designed for nominated applications are the principal target.

With an overarching view of maximising the use of Australian hardwoods through utilization of their inherent or designer *in-built* functional, decorative and structural aspects, the principal objective is to demonstrate improved bonding strength and durability of adhesion and long-term performance of clear coatings on nominated Australian hardwood products. This will be validated through demonstrating feasibility of fabrication and long-term performance of prototype hybrid materials (with high hardwoods content) for manufacturing designer-engineered exterior/interior modular products nominated by industrial collaborators.

The key drivers for this project from industrial design and construction companies are:

- encouraging the use of renewable Australian hardwoods within mainstream, larger scale building projects;
- developing modular and prefabricated construction systems for larger span and irregular shaped products using hybrid timber components, cladding and structures;
- meeting the durability and maintenance requirements of clients on large scale building projects.

On completion, with an overall aim of satisfying a diverse range of industry and market requirements, the project will:

- Create new high-value added hardwood-based hybrid materials and products for designer-engineered exterior and interior architectural and structural building components suiting modular components manufacture.
- Demonstrate high performance, long-term durability and low-maintenance attributes of new hardwood-based products which should be able to regain competitive advantage versus substitute materials such as metals and wood-plastic composites replacing wood in exterior building applications.

- Deliver a validated, commercially attractive, technically feasible technology platform facilitating significant broadening and diversification of the range of wood-based products generating economic benefits to the timber products industry and creating new job opportunities.

To ascertain project focus and delivery of project objectives with the aim of developing industrially relevant technology platform, a multi-disciplinary team (Figure 1) involved in this project comprises representatives of wood products industry, designers, architects and construction companies as collaborators in addition to researchers from CSIRO (hybrid materials development), Swinburne University (design, equipment prototyping/optimisation and products conceptualisation & modelling) and University of Melbourne (assessment of products performance and durability). The project has been over-sought by an expert panel (steering committee) selected from amongst reputable industrial and scientific leaders.

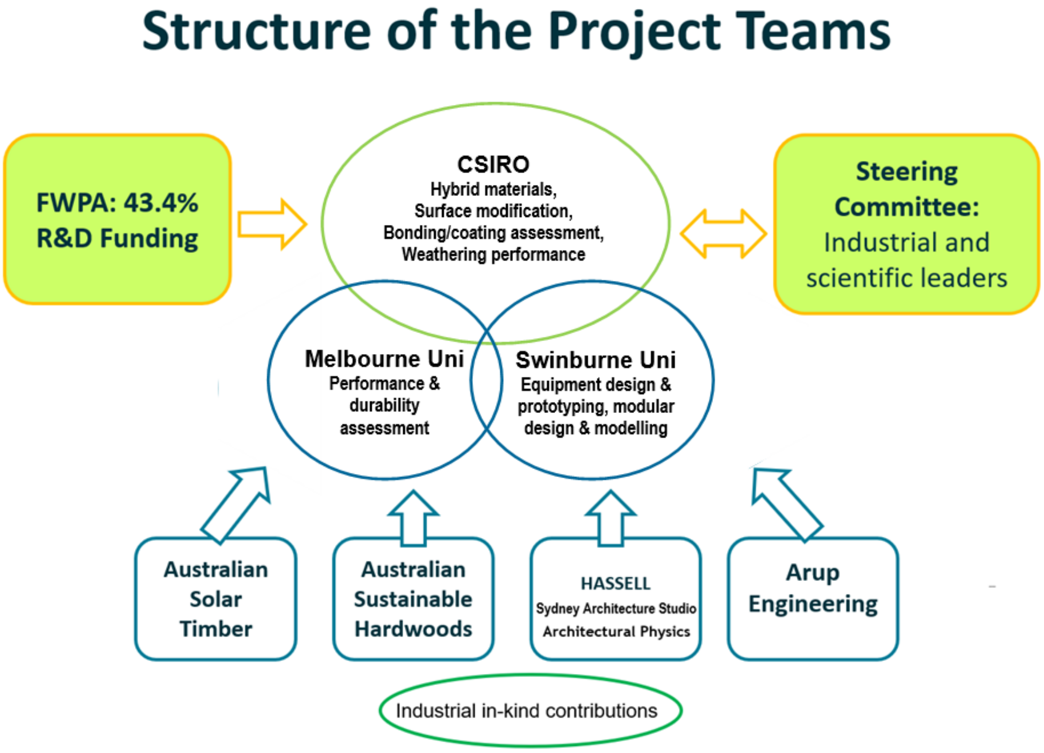


Figure 1. Structure and interactions of the project teams.

This project technical report summaries the R&D results including lab research, scale-up assessment and industrial trials, and acts as the deliverable to FWPA and project industrial partners.

Methodology

1. Wood Adhesion Performance Assessment

1.1. Hardwood and adhesive samples

A series of hardwood species selected from hardwood manufacturing industry are used in the project to validate the effectiveness of CSIRO's surface modification technology on hardwood bonding strength and durability, including:

- ASH: Vic ash (VA)
- AST: Blue gum (BG), Blackbutt (BBT), Tallow wood (TWD), Spotted gum (SG)

Two polyurethane-based adhesives (PU) used for the project are:

- Henkel Purbond: Loctite Purbond HBS series, one part PU - 30 min assembly time.
- Bostik AV515: solvent free, moisture curing, quick setting, and high water resistant.

1.2. CSIRO's surface modification chemicals

CSIRO Surf-Bond#(1-4) as listed in Table 1 were developed to enhance wood adhesion especially for hardwood.

Table 1. CSIRO's surface modification Surf-BOND formulations

Code	Description
Surf-BOND#1	Surface modification polymer additives 1: 3-5 wt% in water
Surf-BOND#2	Surface modification polymer additives 2: 3-5 wt% in water
Surf-BOND#3	Surface modification polymer additives 3: 3-5 wt% in water
Surf-BOND#4	Surface modification polymer additives 4: 3-5 wt% in water

1.3. Creep loading (constant stress) adhesion test method

Tensile adhesion strength of untreated or CSIRO surface treated timber bonded with PU was determined by the creep loading (constant stress) test method described in [19]. Pre-conditioned timber boards (from ASH and AST) were planned and cut into specimen blocks with the size of 13 x 13 x 50 mm. The specimens were then surface treated within two hours after planning and bonded, after air drying (within 1 hour) with moisture cured PU adhesives. Test specimens in the form of cross-lap joints (over 40 for each experimental point) for all wood species were prepared as illustrated in Figures 2 and 3 using clamping pressure between 0.75 to 1 MPa applied to the glue line through adjustable compression spring placed in the assembly jig shown in Figure 2. The PU adhesive was cured overnight.

The tensile adhesion strength was determined by exposing bonded specimens to creep loading conditions in condensing humidity environment produced above the surface of 60°C water bath [19], as shown in Figure 3. The protocol of testing involves loading bonded assemblies under incrementally increasing constant stress levels for 24 hours under condensing humidity at 60°C. The stress level is controlled by loads applied through a system of levers in stress increments corresponding to 0.0394 MPa. For screening assessment, at the least five replicate tests were performed at each stress level. The average tensile bonding strength (τ_{AV}) was calculated out from the numbers of specimens surviving the applied stress levels for 24 hours under constant loading, using the equation below:

$$\tau_{AV} = (\sum n_i \times \tau_i)/\sum n_i),$$

where: τ_i is the actual stress applied a surviving individual specimen, and n_i is the number of specimens passing (surviving) the stress loading τ_i for 24 hours.

Figure 2: Preparation of specimen (cross-lap joints) for constant stress (creep loading) tests

Figure 3: Cross-lap joints for constant stress (creep loading) testing and the creep loading facility at CSIRO Laboratory.

For a more comprehensive assessment, after the above screening test, at least 10 replicates are tested, and the bond strength is determined as the stress level at which approximately ≥ 50% ($\tau_{50\%}$) or 80% ($\tau_{80\%}$) of specimens survive 24 hours constant loading test.

1.4. Requirements and standards used for adhesion performance assessment

Many standards provide specifications and test methods for determining the strength of adhesion of bonded products, based on the category of wood product. Since all adhesively bonded structures (in automotive, aerospace, construction and other industrial applications) are designed for applications relying on transfer of shear stresses, shear is the most commonly used principal loading, and hence failure mode analysed and investigated for determining the joint strength levels. A quick perusal of international standards reveals a multitude of shear test geometries, each with the objective of producing a state of pure uniform shear in the bulk adhesive or within an adhesive layer. Performance requirements are very different for different climatic conditions in service and types of applications (Figure 4).

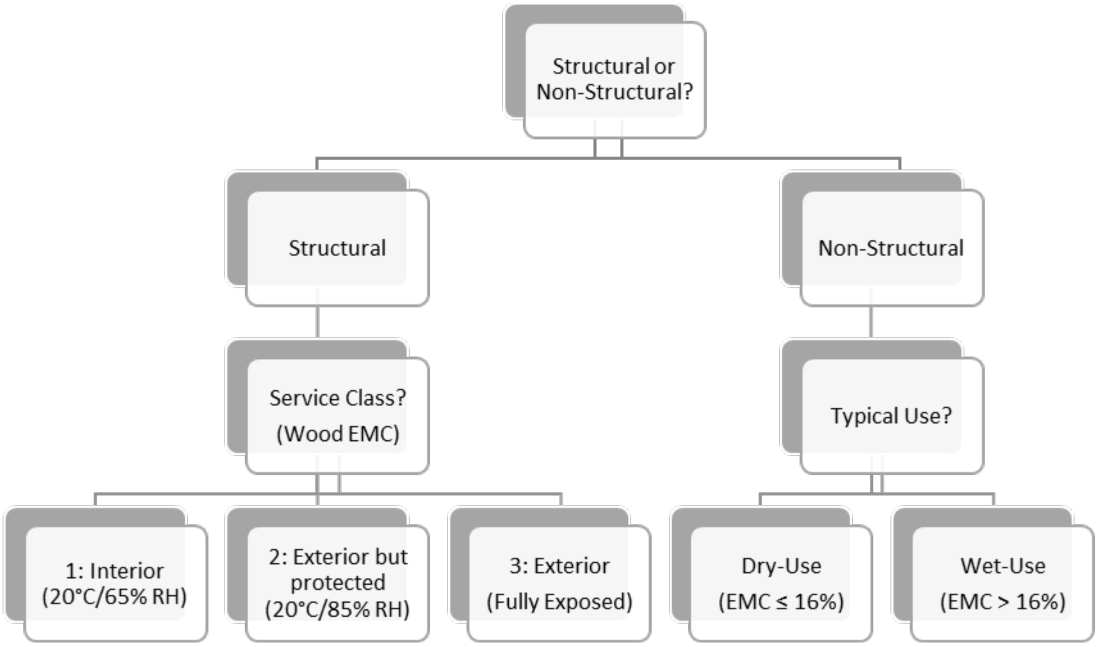


Figure 4. Exposure requirements for determining adhesives performance according to suitability for specific use in defined environmental conditions.

No Australian standard proposes requirements for non-structural applications where the bond is not required to permanently provide high mechanical properties necessary in load-bearing products. ASTM standard D5751 covers performance levels for all types of adhesives used in laminated joints in non-structural lumber products (ASTM 2012). This standard may be used to evaluate adhesive bonds in laminated joints present in industrial end-products. This specification is the only one listed that provides a method for determining the requirements for a specific wood species based on the species' mechanical properties and their bondability grouping, as defined in the Wood Handbook (FPL 2010), whilst other standards provide a single set of test requirements not influenced by the tested wood species.

Two categories of adhesives were identified based on their end-use:

1) Dry-use non-structural adhesives capable of producing sufficient strength and durability to make the bonded lumber product serviceable in non-structural applications, under conditions in which the equilibrium moisture content (EMC) of the wood does not exceed 16%, and
2) Wet-use non-structural adhesives capable of producing sufficient strength and durability to make the bonded lumber product serviceable in non-structural applications, under conditions in which the EMC of the wood may be 16% or higher.

Two performance criteria: shear strength [MPa] and wood failure percentage [%] across the bond area are used to determine if an adhesive meets the minimum requirements for either category.

The common measures used to assess the performance of bonded wood joints are the strength, wood failure, and delamination. A procedure for determining shear strength and wood failure is detailed in ASTM D905 (2008) and ASTM D5266 (1999). For the shear strength determination, a specimen is placed in the shearing tool whilst shear load is applied along the bondline to achieve failure (Figure 5).

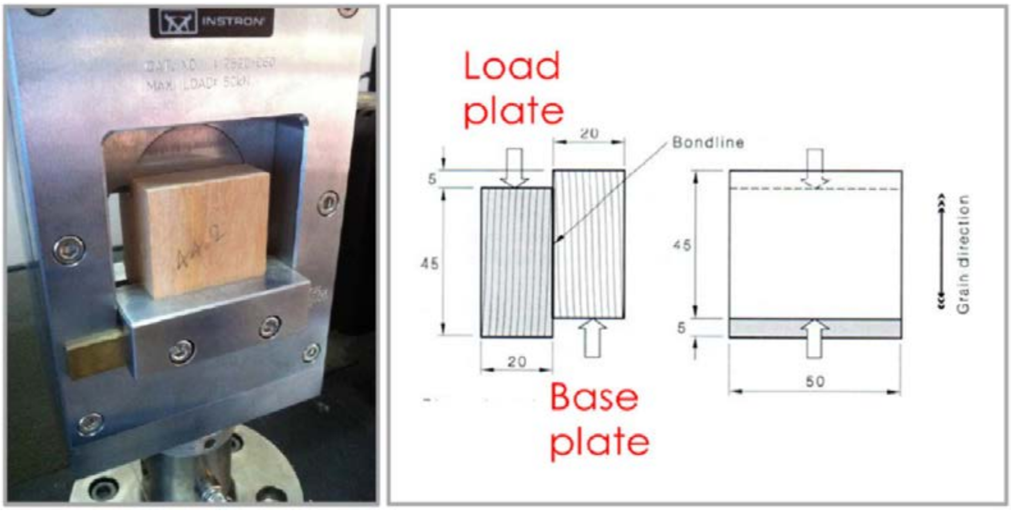


Figure 5. A universal testing machine equipped with a shearing tool testing a glued specimen.

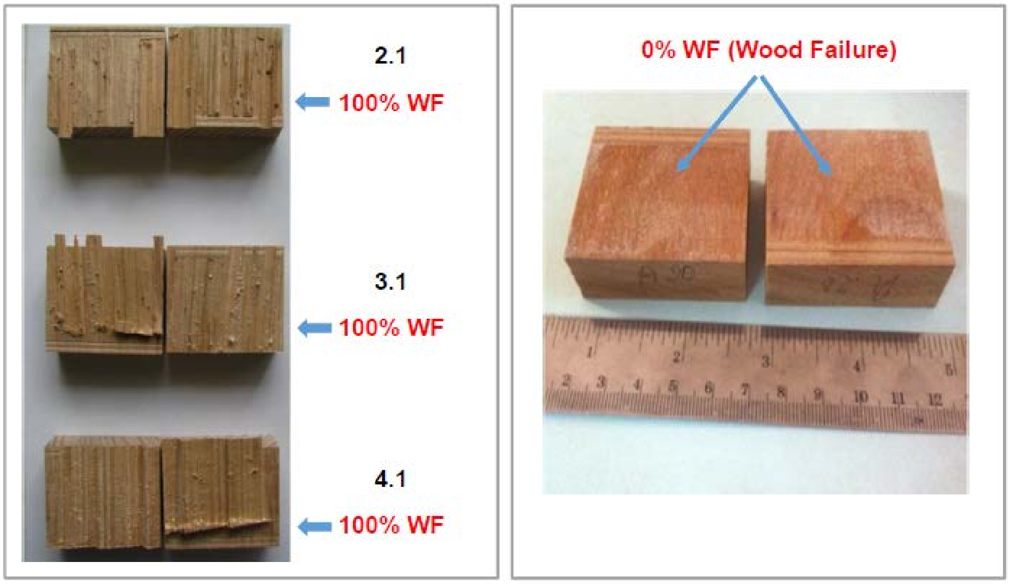


Figure 6. Examples of block shear specimen and wood failure (%) estimation following the shear strength test.

The percentage of wood failure represents the amount of wood that fails through cohesive rupture along the bondline zone, as a percentage of the area of the bonded joint (Figure 6). It is usually expressed as the percentage of ruptured wood fibres on the total area of a bonded specimen. The assessment of bonded joints performance is based on 5 different exposure conditions, as presented in Table 2.

Table 2: Exposure conditions for block shear strength test prior to testing.

No.	**Exposure condition**	**Treatment**
1	Cured (No Treatment)	23˚C / 65% RH for 14 d (curing period)
2	Elevated Temperature	Curing Period + 104°C for 6 h
3	Three-Cycle Soak	Curing Period + 3 “Water + Oven” Cycles
4	Boil	Curing Period + 2 “Boiling + Oven” Cycles
5	Vacuum Pressure	Curing Period + Vacuum (85 kPa) + Pressure (517 kPa)

The minimum wood shear strength requirements for laminated joints of Vic ash, as calculated based on ASTM D5751, are presented in Table 3. The shear strength used to determine the specific gluing requirements for that species was obtained from Bolza and Kloot (1963).

Table 3: Minimum shear strength requirements for Vic ash* (*E. regnans*) laminated joint in non-structural as per ASTM D5751.

Performance classification and exposure conditions [A]	**Laminate joint in shear [C]**			
	Strength [B]		**Wood failure [D]**	
	Average (MPa)	Individual minimum (MPa)	Group average (%)	Individual minimum (%)
Dry use				
Cured (dry)	7.3	3.7	30	No requirement
Three-cycle soak	3.7	1.8	No requirement	No requirement
Elevated temp.	4.9	2.4	20	No requirement
Wet use				
Cured (dry)	7.3	3.7	30	No requirement
Boil	6.1	3.1	25	No requirement
Elevated temp.	4.9	2.4	20	No requirement
Vacuum pressure	6.1	3.1	25	No requirement

Twenty specimens are required for each classification and exposure; B Using an average shear strength parallel to the grain of 12.2 MPa at 12% MC from Bolza and Kloot (1963). C Parallel to the grain; D Wood failure for group 3 hardwoods that bond satisfactorily is listed at 50 % of the softwood value, with no requirement if the wood failure value calculates to 15% or less. * Victorian ash can refer to the wood of either of the trees *Eucalyptus regnans* or *Eucalyptus delegatensis*, when it is sourced from Victoria. While there are some minor differences between the two types of timber, there are a remarkable number of similarities, making them often interchangeable.

The requirements for structural adhesives as per Australian/New Zealand standard AS/NZS 4364 (2010) are presented in Table 4. Both ASTM D5751 and AS/NZS 4364 use the same shear test method to determine the strength properties of adhesive bonds. However, some exposure conditions and treatments between these two specifications either differ or are not applied.

Table 4: Requirements for structural adhesives as per Australian standard AS/NZS 4364.

Performance classification and exposure conditions	Median Strength Requirements	Wood Failure Requirements	
	(MPa)	Lower Quartile	Median
Dry (Cured)	19	15%	60%
Wet → Vacuum Pressure	11	55%	80%
Wet → Boil-Dry-Freeze	6.9	---	---

Glued laminated timber (glulam) is obtained by bonding together several laminations having their grain essentially parallel. In this way, a member with a rectangular solid cross section can be produced. In Australia, glulam performance requirements and requirements for glueline integrity are specified in AS/NZS 1328.1 (1998).

The requirements for glueline integrity are to be based on testing of the glueline in a full cross-sectional specimen, which should be cut from the manufactured glulam member. Qualification tests should be undertaken whenever a new process or process change, such as a new adhesive/species combination is introduced. Qualification and routine tests (see Figure 5) depend on the product service class and the type of adhesive used.

1.5. Methodologies used for adhesion performance assessment

The assessment of performance and durability of new hybrid components and products developed within the project (*e.g.* stair treads, posts) has been conducted at the University of Melbourne wood technology laboratory. The tasks included:

- Preliminary trials and optimisation of a timber treatment pilot plant designed by Swinburne University;
- Optimisation of a bonding pilot;
- Assessing the bond strength and durability of adhesion of new hybrid hardwood materials and components using product performance criteria for exterior building applications, defined in relevant Australian standards and specifications provided by designers, architects, and construction company collaborators (*i.e.* laboratory trials);
- Testing and comparing the performance of surface-modified samples of new products and samples of unmodified ‘traditional’ products (*i.e.* in-factory trials).

1.5.1. Wood bonding testing for pilot scale-up trials

(1) Development and optimisation of a timber treatment pilot plant and bonding

The primary objective of this task conducted at the University of Melbourne wood technology laboratory was to establish an appropriate methodology (see protocol outline in Figure 7) for conducting hardwood gluing trials with wood surface treatment and application of adhesive to achieve required evenness, application rate, open assembly time, etc., prior to fabrication of samples for adhesion testing.

The initial surface treatment trials conducted using a commodity hand-held spray gun uncovered inadequate level of control of spray application conditions, *i.e.*: spray atomization, and air- and/or liquid flow rate. These deficiencies contributed to excessive volume of liquid applied to the timber surface (see right-hand panel in Figure 9) which increased the thickness of water-based graft chemical film. The above problems prompted the research team to develop a semi-automated treatment pilot plant utilising: (1) variable-speed conveyor for moving treated wood through the spray zone, and (2) air brush spray system allowing precise control of liquid atomisation and surface distribution of aerosol.

Based on this concept, a pilot plant for continuous surface treatment of hardwoods (see photo in Figure 8), designed and manufactured by Swinburne University, was subsequently optimised by the joint Uni Melbourne and Uni Swinburne Team to suite the requirements of ASH Heyfield production line.

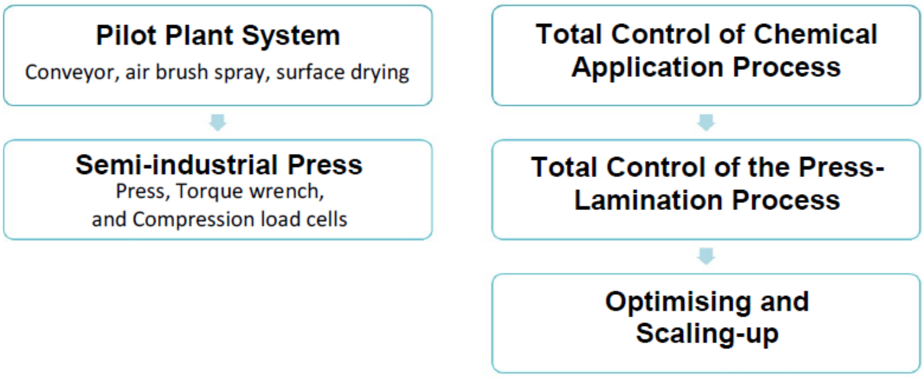


Figure 7. Schematic plan of the pilot plant process development and scale-up for surface treatment and fabrication of hardwood-based, press-laminated products.

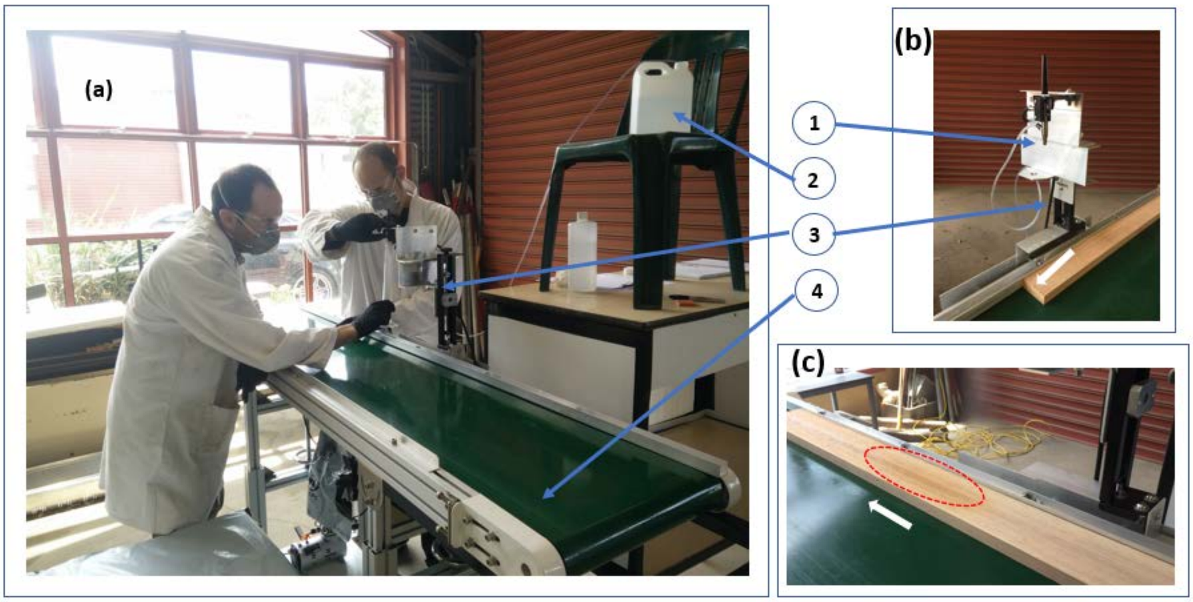


Figure 8. (**a**) Initial stages of the development and calibration of the prototype pilot plant for hardwood surface treatment: (1) airbrush nozzle; (2) chemical solution container; (3) nozzle height adjustment mechanism; (4) controlled-speed conveyor; (**b**) air brush system details; (**c**) aerosol spray cone and adhesion promoting chemical coating deposited on the hardwood surface (Vic ash) during conveyor movement direction [→].

Figure 9. Optimisation of adhesion promoting chemical spray, and drying time. From left to right: wet surface following chemical spray using airbrush (after 0, 10, 20 and 30 min of room temperature air drying) versus hand-held spray gun (far right, after 0 min).

(2) Assessing the bond strength and durability of adhesion

Step 1 - Preliminary trials

The objectives of the preliminary trials were to:

- Optimise the chemical application for the scale-up stage;
- Collect preliminary bond strength data allowing a comparison between surface-treated and untreated assemblies.

CSIRO water-based Surf-BOND#3 was applied to both surfaces of dressed hardwood boards (100 mm x 38 mm) to be glued using a pilot plant depicted in Figure 8 comprising a controlled-speed conveyor and airbrush system. Vic ash (*E. regnans*), blackbutt (*E. pilularis*), and blue gum (*E. saligna*) were selected as they all suffer from poor adhesion due to: (i) high inherent content of extractives, (ii) high density, and (iii) high hydrothermal movements in response to changes in the atmospheric moisture.

All hardwood specimens have been conditioned (1 week) at 23°C and 65% relative humidity (RH). The boards were dressed within 1 h of the chemical surface treatment. Three conveyor speeds *i.e.* 3.7, 5.0, and 6.3 m/min were selected. Following a 30-minute air-drying period, a type single-component polyurethane (PUR) adhesive (Purbond® HB S309) was applied one-sided at a rate of 150 g/m^2 using a V-serrated comb applicator (Figure 10).

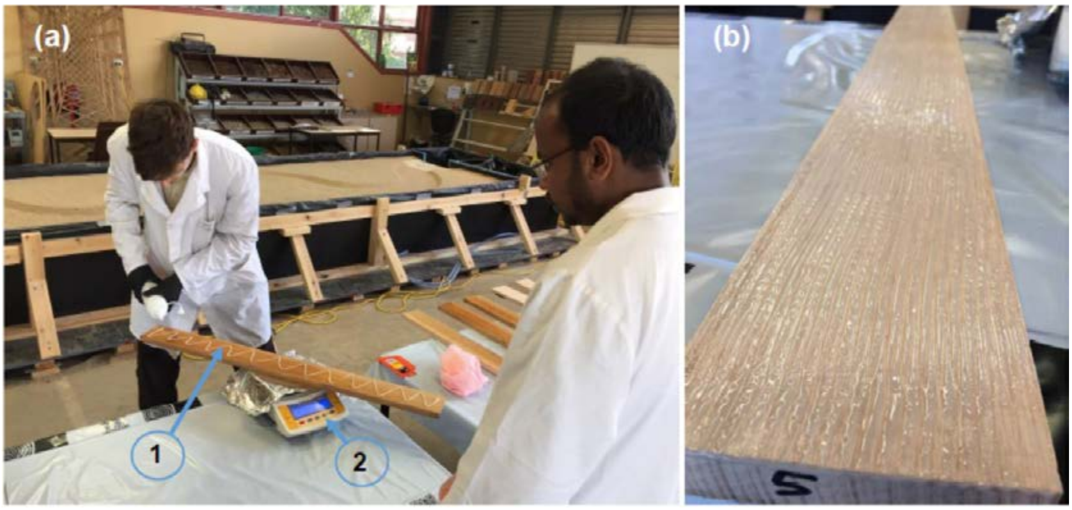


Figure 10. Adhesive application on the wood surface: (a) [1] initially extruded adhesive bead, [2] digital scale for controlling the weight of applied adhesive; (b) final glueline appearance.

A control group (untreated) and a treated group, each composed of 2 different laminates, were prepared. The assembled laminates were then pressed for 2 hours at a clamping pressure of 1 MPa using a semi-industrial mechanical press (Figure 11) supplied by ASH Heyfield.

Figure 11. Laminates being pressed in a semi-industrial mechanical press.

From each laminate, 10 to 12 block shear specimens were prepared (Figures 12 and 13). Following a conditioning period of two weeks at 23°C and 65% RH, the block shear specimens have been tested in accordance with ASTM D5751 (2012) using an Instron testing machine (Model 5569). The selected exposure conditions prior to testing are listed in Table 5.

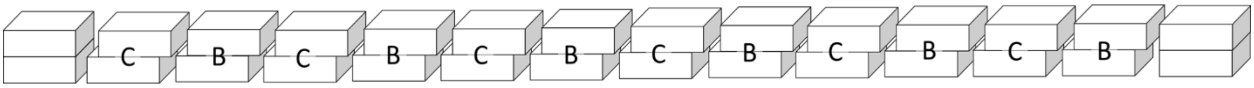


Figure 12. Laminate joint showing method of cutting block shear specimens for preliminary trials. C: Cured test specimen; B: Boiling water test specimen.

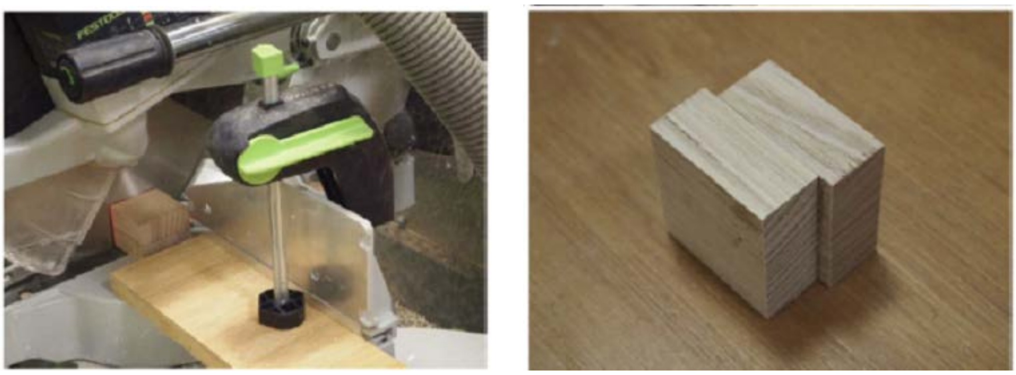


Figure 13. Machining block shear specimens from a laminate.

Table 5. Exposure conditions prior to testing for the preliminary trials.

Exposure Condition	**Description**	**Relevant Standard(s)**
Cured or "*as is*"	Specimens are conditioned at 23°C and 65% RH for 14 days (curing period).	AS/NZS 4364 ASTM D5751
Boiling water	Following the curing period, specimens are: (1) placed in boiling water for 4 hours; (2) dried for 20 hours at 63°C; (3) placed in boiling water for another 4 hours; (4) cooled in running water for 1 hour.	ASTM D5751

RH: Relative humidity; AS/NZS 4364: Timber-Bond performance of structural adhesives; ASTM D5751: Adhesives used for laminate joints in non-structural lumber products.

Step 2 - Scale up trials

The objectives of the scaling up trials were to:

- validate the preliminary results using a statistically representative population (*i.e.* going from 2 to 7 assemblies per species) and
- compare between treated and untreated assemblies following different exposure conditions.

The exposure conditions were selected in accordance with the relevant international standards. Seven assemblies per category (*i.e.* treated and untreated) and species have been prepared as specified above. Four different exposure conditions have been identified and selected to properly assess the bonding quality (Table 6, Figure 14).

Table 6. Exposure conditions prior to testing for the scaling up trials.

Exposure Condition	**Description**	**Relevant Standard(s)**
Cured or "*as is*"	Specimens are conditioned at 23°C and 65% RH for 14 days (known as curing period).	AS/NZS 4364 ASTM D5751
High temperature	Following the curing period, specimens are exposed to 103°C for 6 hours.	ASTM D5751
Vacuum/Pressure	Following the curing period, specimens are placed in a pressure vessel and submerged in water. A vacuum is then drawn (75 kPa, 30 min), followed by pressurisation (540 kPa, 2 hours) for a total of 2 cycles.	AS/NZS 4364
Boil/Dry/Freeze	Following the curing period, specimens are: 1) placed in boiling water for 4 hours; 2) dried in an oven at 63°C for 19 hours; 3) placed in a freezer at -20°C for 4 hours. The cycle is then repeated seven more times.	AS/NZS 4364

RH: Relative humidity; AS/NZS 4364: Timber-Bond performance of structural adhesives; ASTM D5751: Adhesives used for laminate joints in non-structural lumber products.

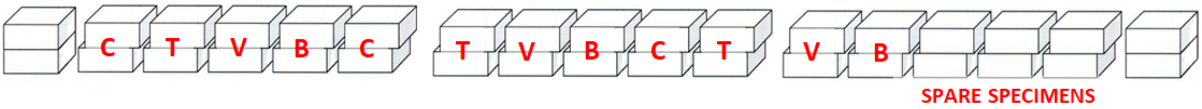


Figure 14. Laminate joint showing method of cutting block shear specimens during scaling up trials. [**C**] Cured test specimen; [**T**] High temperature specimen; [**V**]: Vacuum/pressure specimen; [**B**]: Boil/Dry/Freeze test specimen.

1.5.2. Wood bonding testing for industrial trials

Reducing the surface drying time to less than 30 seconds was identified by the industrial partner, ASH, as a critical factor essential for the implementation of the CSIRO surface modification technology in their current hardwood products manufacturing facility. To achieve this, an infrared (IR) drying system was investigated and optimised to accelerate water film drying time after hardwoods surface modification via spraying water-based chemicals (Surf-BOND#3) onto boards surface, from 30 minutes (natural air-drying) to less than 30 seconds, without adversely affecting the bond line strength.

An IR system with carbon-filament globes (see insert in Figure 15) was identified for the proposed purpose as these emit IR radiation at wavelengths critical to providing only the surface heating of water-based film, causing its rapid evaporation without relying on heating the bulk of the underlying substrate, i.e. wood board.

The IR module was mounted above the existing conveyor after the chemicals-spraying airbrush system (Figure 15), so that the heat generated by the IR lamps would allow rapid water evaporation of the chemical coating from wood surface whilst meeting the drying speed (< 30 seconds) requirement, as advised by industry partner. Thermal decomposition of both, sprayed chemicals and wood surface must also be avoided, specifically the upper limit temperature of the bond-enhancing solution's constituents, which begin to lose their effectiveness when approaching or exceeding 210°C.

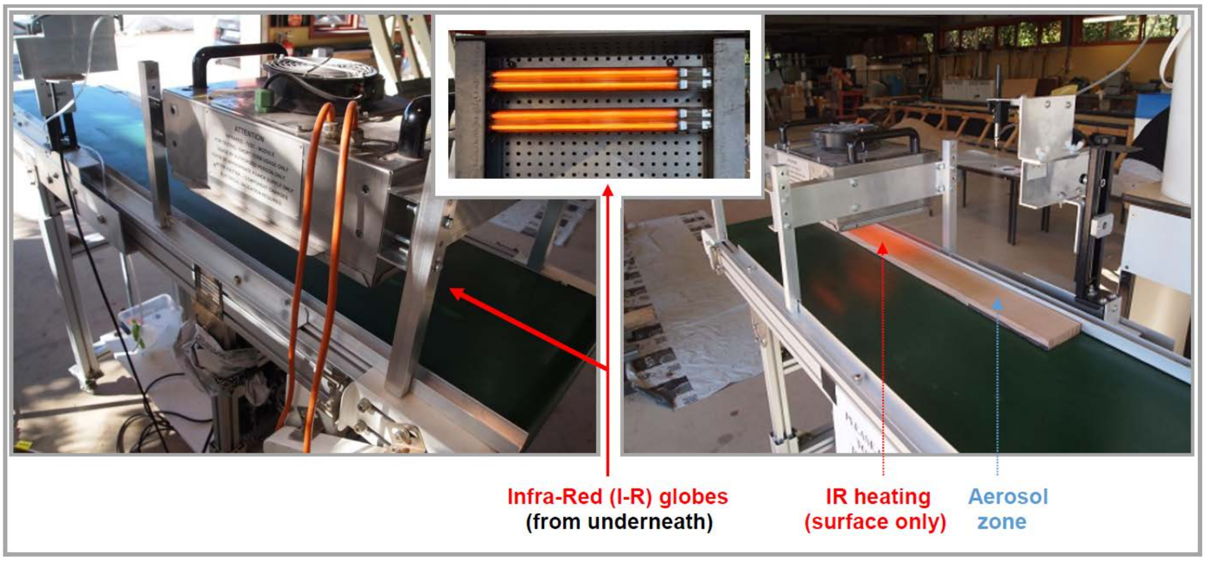


Figure 15. Infrared (I-R) surface heating system above conveyor for rapid drying (< 30 s) of water-based film of adhesion-promoting chemicals sprayed by airbrush-formed aerosol.

The shear testing of laminated hardwood assemblies confirmed that IR drying equipment integration could significantly reduce the drying period following chemicals application from

30 minutes (original ambient air-drying time) to less than 30 seconds without adversely affecting the bond strength. Bringing the IR lamps closer to the wood surface (*i.e.* subsequently increasing timber surface temperature) showed to negatively affect the glueline strength of treated laminates. However, the observed trend (re the strength reduction) was not statistically significant. The IR drying methodology was adopted for ASH industrial trails.

The testing methodology of glued laminated Vic Ash timber samples (see Figure 16) collected from industrial trial at ASH in September 2019 was based on the assessment of the durability of laminated products to be used in fabrication of non-structural components, *i.e.*:

- Stair treads or edge-laminated boards;
- Posts or face-laminated boards.

The stair treads were made up of three 100 mm x 38 mm dressed pieces (2 gluelines, edge-laminated). The posts were also laminated from three 100 mm x 38 mm dressed pieces (2 gluelines, face-laminated). Standard cleavage and delamination tests on both treated and untreated laminations have been performed in accordance with AS/NZS 1328.1 (1998) to assess the products manufactured during the ASH industrial trials.

Figure 16. Edge-laminated (bottom shelf) and face-laminated (top shelf) boards from the in-factory trials.

(1). Cleavage of glued joints

Cleavage characteristics of face- and edge-bonded glued joints parallel to the direction of the grain in glulam have been determined. Specimens consisting of a full cross section of glulam were cleaved apart in the plane of the glueline and the percentage of wood failure was recorded.

Prior to wet conditioning, a notch along each glueline of each specimen has been cut uniformly to a depth of 10 mm, as shown in Figure 17. The test specimens were then placed in an autoclave and immersed in water. A vacuum pressure was first applied (65 kPa) and maintained for 1.5 hours. A pressure of 500 kPa was then applied for 1.5 hours. This vacuum-pressure cycle was then repeated once more prior to cleaving each glue line by means of a chisel (Figure 18). Each individual glueline wood failure percentage was then assessed to the nearest 5%.

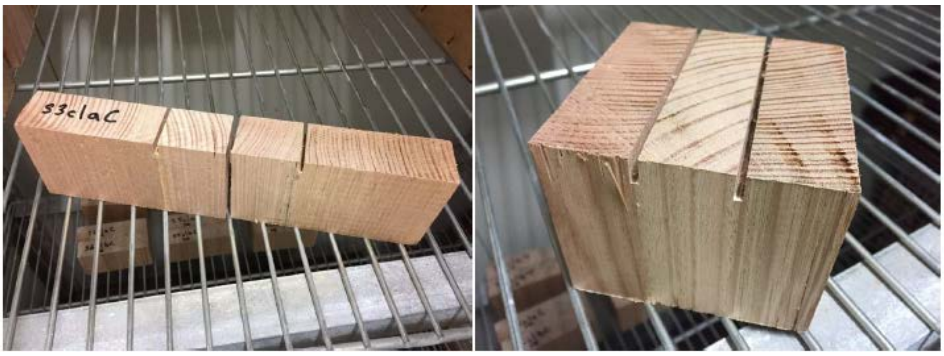


Figure 17. Examples of edge-laminated (left) and face-laminated (right) samples for the cleavage test.

Figure 18. Glueline cleaved by means of a chisel.

(2). Delamination of glued joints

A delamination test of gluelines has been conducted to assess the glueline integrity of the glued laminated samples. The test specimens were placed in a pressure vessel and completely submerged in water. A vacuum of 70 kPa was first drawn and held for 5 min. Then, samples were pressurised at 500 kPa for 1 h. This vacuum-pressure cycle was repeated once more. The samples were finally dried for a period 22 h in air at 60°C and 15% RH, and circulating at a velocity of 2 m/s to 3 m/s. The total delamination percentage of each test specimen was determined following the drying period (Figure 19).

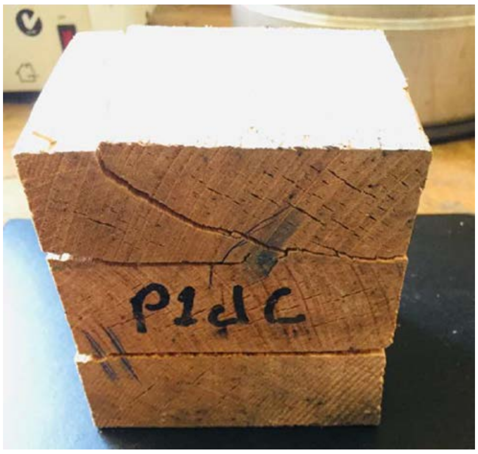


Figure 19. Example of face-laminated sample ready for delamination assessment.

2. Coatings on Hardwood and Performance Assessment

2.1. Wood species and types of coatings

The hardwood species supplied by Australian Solar Timber (AST) and Australian Sustainable Hardwoods (ASH) (identical to those used in wood adhesion assessment) were used for coating performance examination:

- ASH: Vic ash (VA)
- AST: Blue gum (BG), Blackbutt (BBT), Tallow wood (TWD), Spotted gum (SG)

Clear coatings traditionally applied as clear topcoats over the solid colour paints (coatings) for automotive (PPG), and building (Cabot) industries were selected and used in the project. The PPG's coatings are solvent-based two-part (2k) polyurethane (PU) coatings while that from Cabot is one-part (1K) PU, marine grade clear coating, as listed in Table 7.

Table 7: List of clear coatings selected from Cabot and PPG

Coatings	**Description**
Cabot Exterior Clearcoat	1K PU, marine-grade durable exterior clear coating
PPG high-gloss Carmaster	2K acrylic urethane Carmaster HS clearcoat CC-9240 / CH-5200 HS Clearcoat with Protec Flex Add AA-5656
PPG high-gloss D800	2K acrylic urethane D800 / D841 Deltron clearcoat with plasticizer D814
PPG Mattcoat Maxmeyer	2K PU low-gloss clearcoat Maxmeyer VOC low gloss Clearcoat
PPG Mattcoat GPSP1	2K PU low-gloss clearcoat GPSP-485-51-1 with extra flexible additives
PPG mattcoat GPSP2	2K PU low-gloss clearcoat GPSP-485-52-2 with extra flexible additives

2.2. CSIRO's surface modification formulations

A series of chemical formulations developed at CSIRO were used as underlayer coating for improvement of the adhesion strength between wood and coating, as listed in Table 8. A PPG primer was also used as a reference primer, which is also listed in Table 8.

The purpose of these underlayer coatings or primers is to provide one or more of the following performance attributes:

(1) Interfacial adhesion promotion

(2) Reducing the UV degradation

(3) Reducing interfacial stress caused by thermal- and moisture-related materials deformation during accelerative weathering, and/or under real-life service conditions.

(4) Sealing the pore structure of timber intended to be coated with more cost-effective commodity coatings.

Table 8: List of surface modification formulations as underlayer coatings

Underlayer	Description
1	Ionic Polymer
2	Ionic Polymer + Lignostab1198 + ZnO
3	Ionic Polymer + Lignostab1198 + FeOOH
4	PU D101 + Lignostab1198
5	PU D101 + Lignostab1198 + ZnO
6	PU D101 + Lignostab1198 + FeOOH
7	PU D101 + Lignostab1198 + ZnO + FeOOH
8	PVOH + Lignostab1198
9	PVOH + Lignostab1198 + ZnO
10	PVOH + Lignostab1198 + FeOOH
11	PVOH + Lignostab1198 + ZnO + FeOOH
12	PVOH + Lignostab1198 + XFast Yellow
13	PVOH + Lignostab1198 + Tinuvin-5333
14	PVOH + Lignostab1198 + Tinuvin-123DW
15	PVOH + Lignostab1198 + Tinuvin-123DW + Tinuvin-400DW
16 – PPG	Protec Ultraseal AP-6000 (transparent sealer adhesion promoter)

2.3. Wood sample preparation equipment

Planer: Plana 3.0: feed speed: 5m/min, thickness capacity 250 x 210mm (W x H), see Figure 20,

Band saw: BP-310 (Figure 20).

Figure 20. Left: Planer; Right: Band saw.

2.4. Coated wood sample preparation

The wood samples for chemical treatment and Q-Sun or QUV accelerated weathering exposure were prepared using the following procedures:

(1) Pre-cut 1m lengths of wood boards were inspected for defects and colour variations. Samples with smooth and defect-free surface were selected ensuring the least colour variation under naked eye. Similar wood grain orientation across the width were sought for experiments.

(2) The boards were planned twice, removing the surface of approximately 1.0 mm (in total) to ensure smooth, defect-free surface chosen for treatment, coating and UV exposure. Gloves were always used to ensure the absence of contaminants on the wood surface.

(3) Samples for accelerated weathering coating and coating performance assessment were pre-cut to lengths depending on designated weathering equipment: for Q-Sun samples 110 x 50 mm, and for QUV: 150 x 65 mm. Oil-free compressed air was used to clean the surface from debris.

Surface treatment procedure was conducted using the following procedures:

(1) All wood surfaces were cleaned from debris and dust using oil-free compressed air.
(2) Chemical solution was applied using paint roller to ensure uniform surface coverage.
(3) Samples, chemically treated as above, were left overnight for drying at 23°C.

Figure 21. Automated Spray – Yamaha robot (Yamaha SXYx KT8-46D731) positioned in a spray booth.

The coating of wood surface was conducted as follows:

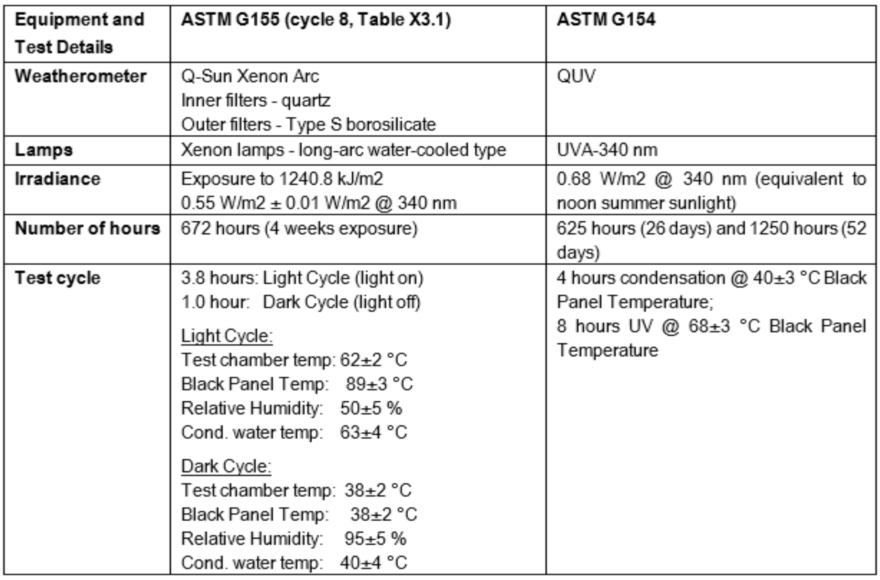
(1) Automated spray gun, HVLP, was calibrated (by preliminary coating tests) according to the desired coverage area and coat thickness (per single pass) prior to inserting to the gun holding fixture of a robotised spray system depicted in a photo in Figure 21.
(2) The selected nozzle diameter was 1.4 mm.
(3) Samples were placed on supporting aluminium strips using double-sided tape before fixing them onto a sample holder (see Figure 21).
(4) The spraying pressure was adjusted at 3 bar.
(5) All paints were mixed and applied as per manufacturer’s recommendations. The required coating thickness was controlled by the number of spray passes (robotised).
(6) Painted samples were subsequently placed in the oven and dried in accordance to manufacturer’s data sheet.

The samples prepared as above were ready for assessment of initial properties of coatings (adhesion quality, surface colour) prior to, and then - after designated time of Q-Sun or QUV accelerated exposure procedures.

2.5. Accelerated weathering exposure

The UV Exposure Standards used for Q-Sun and QUV accelerated weathering are shown in Table 9 below.

Table 9. Details of accelerated weathering protocols for assessing long-term performance of exterior coatings, according to ASTM Standards G155 and G154**.**



Equipment and Test Details	**ASTM G155 (cycle 8, Table X3.1)**	**ASTM G154**
Weatherometer	Q-Sun Xenon Arc Inner filters - quartz Outer filters - Type S borosilicate	QUV
Lamps	Xenon lamps - long-arc water-cooled type	UVA-340 nm
Irradiance	Exposure to 1240.8 kJ/m2 0.55 W/m2 ± 0.01 W/m2 @ 340 nm	0.68 W/m2 @ 340 nm (equivalent to noon summer sunlight)
Number of hours	672 hours (4 weeks exposure)	625 hours (26 days) and 1250 hours (52 days)
Test cycle	3.8 hours: Light Cycle (light on) 1.0 hour: Dark Cycle (light off) Light Cycle: Test chamber temp: 62±2 °C Black Panel Temp: 89±3 °C Relative Humidity: 50±5 % Cond. water temp: 63±4 °C Dark Cycle: Test chamber temp: 38±2 °C Black Panel Temp: 38±2 °C Relative Humidity: 95±5 % Cond. water temp: 40±4 °C	4 hours condensation @ 40±3 °C Black Panel Temperature; 8 hours UV @ 68±3 °C Black Panel Temperature

The Q-Sun and QUV testing facilities are shown in Figures 22 and 23.

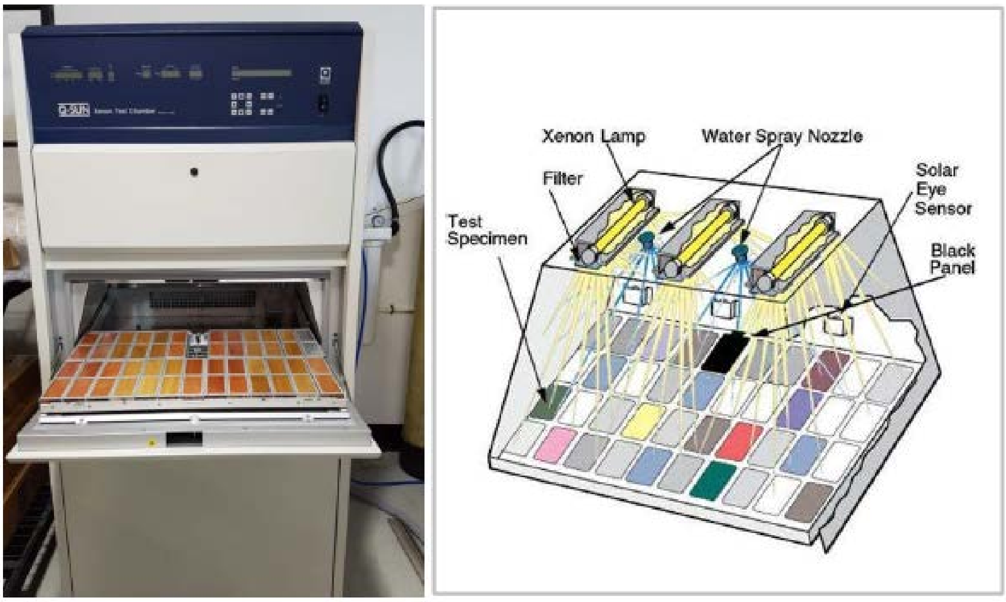


Figure 22. Q-Sun weathering facility with Xenon Test Chamber model XE-3-HBS

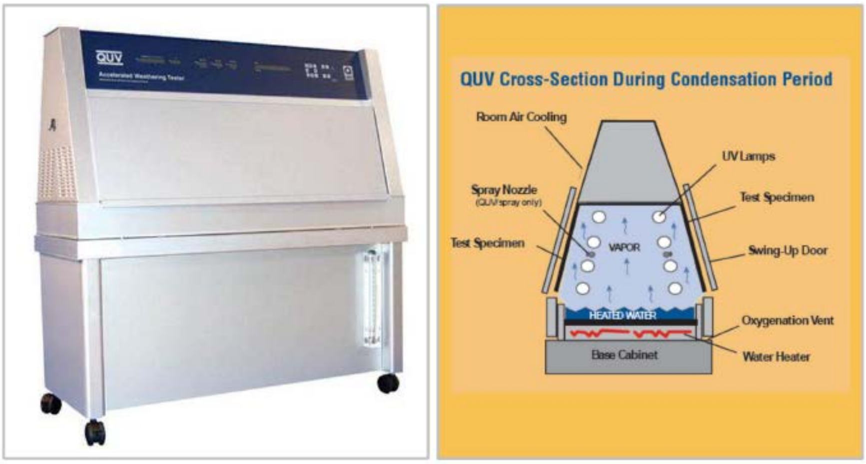


Figure 23. QUV weathering facility.

Q-Sun and QUV accelerated weathering was conducted using the following procedures:

(1) All coated samples were aligned with exposed surface facing up, or towards the light source ensuring there was no gap between samples.
(2) testing parameters were setup according to its ASTM Standard (G155 for Q-Sun and G154 for QUV).
(3) At the end of each weathering cycle or desired exposure duration, samples were taken from the chamber for adhesion and/or colour/gloss testing.

2.6. Wood coating adhesion testing

The standard cross-hatch test commonly used for assessing adhesion of coatings applied to metallic or polymeric substrates, as based on ASTM D 3359-95a, was fund inappropriate for coatings applied to the surface of wood. The key reason for this is the fact that a square-grid pattern (crosshatch) of parallel cuts (5 to 6 cuts approx. 2 mm from each other) that needs to be cut through the paint layer using a cross-hatch cutting tool causes damage to underlying wood substrate, and so to the coating layer, thus distorting the reliability of test results.

Considering the above deficiency of crosshatch test when used for coated wood, in this project the coating adhesion test was carried out in accordance to an aviation industry standard BSS7225 using the following procedure:

1. The coated wood specimen was scribed using a sharp blade in the manner shown in Figure 24 below with three scribes applied: two parallel scribes, 25.4 mm apart plus a diagonal scribe (at 45° angle).
2. One-inch wide strip of a high-grip self-adhesive tape (3M 8981 tape) was pressed onto the scribed area to ensure good contact between the adhesive and paint film,
3. The tape surface was rubbed with a piece of rubber to ensure firm contact between the tape and the scribed area.
4. After the above, the tape was rapidly peeled off the in one abrupt motion by pulling it perpendicular to the specimen.

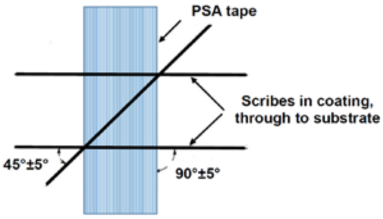


Figure 24. Paint adhesion test (coating on wood substrate) according to aviation industry standard BSS 7225.

The adhesion performance is reported based on the de-bonding pattern/area after tape was applied and lifted off, rating from 1 to 10 as specified in Figure 25. It is considered as "pass" when the rating $\geq$7, while "fail" for the rating $\leq$ 6.

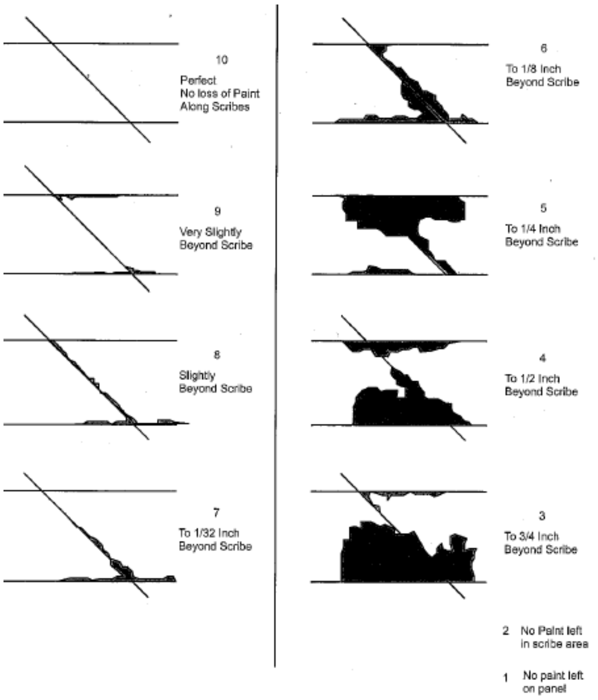


Figure 25. Adhesion performance rating methodology used for this project.

2.7. Colour and gloss testing

The surface of each coated wood sample was cleaned to remove dirt and debris, and then the colour and gloss meter (Figure 26) was placed on the sample. A setting of D65/2 was used to scan surface colour and gloss, and reading results were recorded. Colour change (ΔE) was calculated from the colour reading after Q-Sun or QUV accelerated weathering exposure.

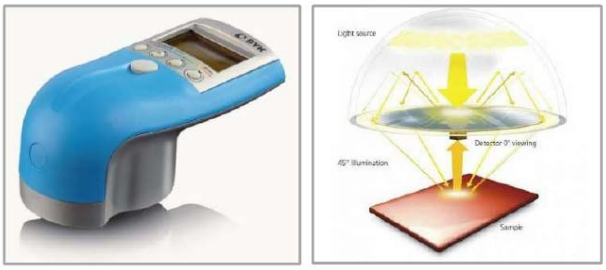


Figure 26. Colour and gloss meter: BYK Gardner Spectro-Guide 45/0 Spectrophotometer.

Results and Discussion

1. Surface Modification influence on Hardwood Adhesion Performance

1.1. CSIRO laboratory scale adhesion performance assessment

Based on the assessment methodology for wood-wood adhesion performance using PU-based glue as described in previous section, the tensile adhesion strength data obtained under creep loading conditions in exposure to condensing water vapour environment for Vic ash (VA) wood specimens without applying any CSIRO's surface modification are shown in Table 10. The data plot of pass (%) vs. stress applied is shown in Figure 27.

Table 10. Raw data of tensile adhesion testing for VA without surface modification

Load stress (MPa)	Number of specimens	Number of specimens passing the test	Number of specimens failing the test	Percentage of samples passing the test (%)
0.74	11	9	2	82
0.90	11	3	9	27
1.06	26	15	11	58
1.14	13	5	8	38
1.22	16	5	11	31
1.31	14	4	10	29
1.39	18	9	9	50
1.47	13	4	9	31
1.55	16	3	13	19
1.63	14	2	12	14
1.71	14	4	10	29
1.87	13	2	11	15
1.95	6	0	6	0
2.03	13	0	13	0
Total	198	65	133	---

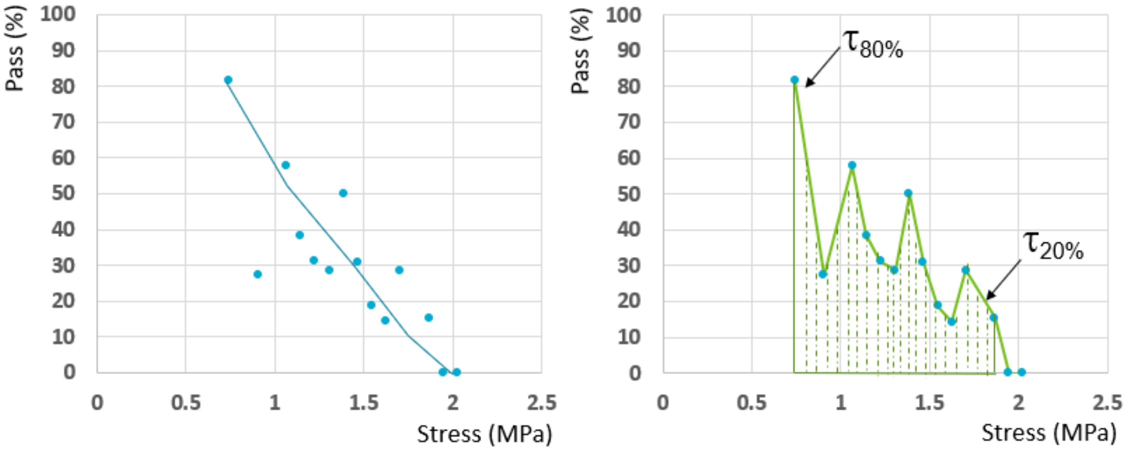


Figure 27. Tensile adhesion testing data for VA without surface modification: the data plot of Pass (%) vs. Stress applied.

The adhesion performance of VA specimens bonded after using CSIRO's surface modification methodology with Surf-BOND#3, as examined by the above method using all experimental data is shown in Figure 28 in comparison to the data re VA without surface modification. Note, that the tensile adhesion strength was significantly increased after using CSIRO Surf-BOND#3 treatement with significantly more fibres fracture observed – see the photos in Figure 28.

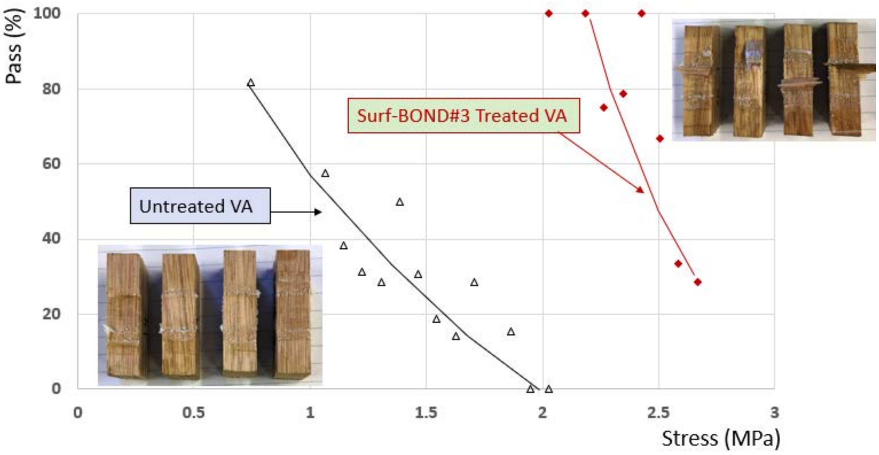


Figure 28. Comparison of VA adhesion strength for the VA using CSIRO Surf-BOND#3 treatement, in comparison with VA samples without the treatement.

The preservative treatment is commonly used to protect timber from borers & termite attacks and rot (moderate decay) in outdoor applications. However, the wood adhesion strength was thought to be weaker, if bonding would be carried out on preservative-treated wood boards, i.e. after the H3 (and other) preservative treatment.

Considering the above issue, the project team was requested to investigate if the CSIRO surface treatment technology can maintain the initial high-quality bond performance, if the H3 preservative treatment is carried out on already bonded wood specimens. Thus, a batch of VA wood samples supplied by ASH was surface-modified by Surf-BOND#3 and bonded by Purbond glue at CSIRO, and was then sent back to ASH for H3 treatment, and eventually returned to CSIRO to conduct the standard CSIRO creep loading performance assessment. The results obtained are shown in Figure 29 and in Table 11.

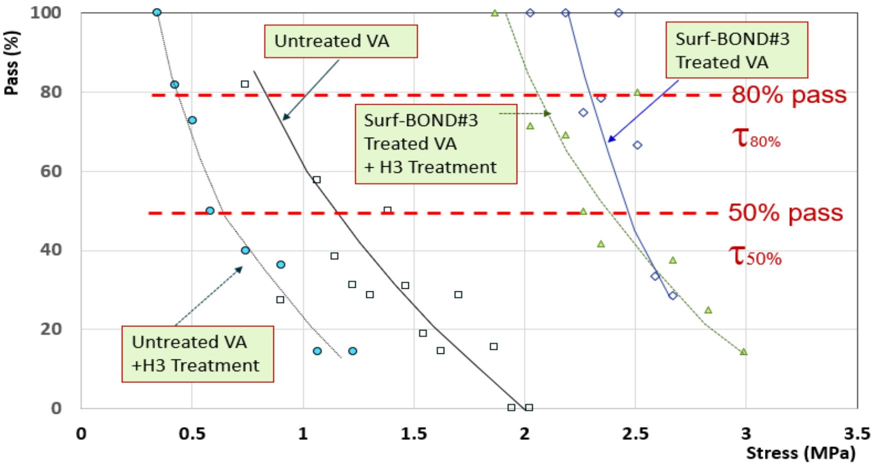


Figure 29. Comparison of VA adhesion strength for untreated VA and (VA+H3) treated samples and those using CSIRO Surf-BOND#3 treatement for 2 alternative scenarios: (1) CSIRO Surf-BOND#3 treatment & bonding of H3-treated timber, and (2) CSIRO treatment & bonding of as-received VA, followed by H3-treatment of adhesively bonded timber assemblies.

Note that for wood samples without the CSIRO's surface modification, H3 treatment did reduce the adhesion strength $\tau_{50\%}$ from 1.19 MPa (VA with no H3) to 0.65MPa, i.e. only 55% of the original strength. However, after H3 treatment of already bonded with CSIRO surface modified VA, the adhesion strength almost remained at the initial (i.e. significantly improved level), as indicated by the $\tau_{50\%}$ dropped slightly only from 2.44 MPa (no H3) to 2.36 MPa (with H3). A similar trend is shown in Table 11 for assembles modified using CSIRO Surf-BOND#4, although Surf-BOND#4 seems less effective when compared to #3. The significant benefits of the CSIRO technology were clearly demonstrated in hardwood adhesion enhancement when H3 treatement is applied.

Table 11. The tensile adhesion strength of VA using CSIRO's surface modification technology for various sequence of adhesive bonding and preservative-treatment (H3).

Samples	**No. of samples tested**	**Tensile adhesion strength (MPa)**	
		$\tau_{50\%}$ (50% Pass) /Improvement%	**$\tau_{80\%}$ (80% Pass) /Improvement%**
VA	198	1.20 / reference	0.78 / reference
VA + Surf-BOND#3	67	2.44 / 103%	2.28 / 192%
VA + Surf-BOND#4	46	2.42 / 102%	2.21 / 183%
VA/H3 Treatment	81	0.62 / reference	0.42 / reference
VA/H3 + Surf-BOND#3	84	2.36 / 281%	2.09 / 398%
VA/H3 + Surf-BOND#4	53	2.03 / 227%	1.92 / 357%

The same surface modification methodology as above was applied to other hardwood species, with Bostik PU AV515 used in some cases as it was more suitable for those species. The tensile adhesion strength data are summarized in Table 12. Note that the H1-treatment of Spotted gum and Tallow wood was conducted at AST prior to sending to CSIRO for surface modification, adhesive bonding and bond strength testing at CSIRO. This was a different approach from VA H3-treatment, where the VA H3-treatment was done at ASH after CSIRO surface modification and bonding.

Table 12. The average tensile adhesion strength τ_{AV} (MPa) of various hardwoods using CSIRO's surface modification technology, bonded with Purboond or Bostik PU adhesives.

Surface treatment/Glue	**Blackbutt**	**Blue Gum**	**Spotted Gum**	**Spotted Gum (H1-Treated)**	**Tallow Wood**	**Tallow Wood (H1-Treated)**
Untreated/Purbond	0.52	1.0	0.5	< 0.45	0.5	0.53
Untreated/Bostik PU	---	---	---	0.53	---	< 0.35
Surf-Bond#1/Bostik PU	---	---	---	0.94	---	---
Surf-Bond#2/Purbond	1.41	---	1.59	0.58	---	0.51
Surf-Bond#2/Bostik PU	---	---	---	1.06	---	0.61
Surf-Bond#3/Purbond	---	---	---	< 0.45	1.58	1.09
Surf-Bond#3/Bostik PU	---	---	---	0.94	---	---
Surf-Bond#4/Purbond	---	1.8	---	---	---	---

Note that the bonding performance of these hardwood species is not as good as that of VA, with lower tensile adhesion strengths achieved when compared to VA. The results are also related to the type of surface modification used in conjunction with the type of glue applied.

The CSIRO surface modification technology did, however, always generate improvement in tensile adhesion strength and in some cases the improvement was significant (up to 220%). For H1-treated Spotted gum and Tallow wood, approximately 100% improvement in adhesion strength was achieved when using Surf-BOND#3 or #2 for surface treatment.

The best adhesion strength improvements for different hardwood species using CSIRO's surface modification technologies are summarized in Table 13, which can be used as a guideline for further scale-up assessment and optimisation for these hardwood species targeting potential industrial applications in production of modular building components, and other structural engineering products for exterior and interior applications.

Table 13. Adhesion improvement by CSIRO Technology for a range of Australian hardwoods

Hardwood species	**Adhesives used**	**Surface modification**	**τ_{AV} (MPa)**	**Improvement***
Vic Ash	Henkel Purbond	Surf-BOND#3	2.44	103%
Vic Ash, H3-Treated		Surf-BOND#3	2.36	281%
Blackbutt		Surf-BOND#2	1.41	171%
Blue Gum		Surf-BOND#4	1.80	80%
Tallow Wood		Surf-BOND#3	1.58	216%
Tallow Wood, H1-Treated		Surf-BOND#3	1.09	98%
Spotted Gum		Surf-BOND#2	1.59	218%
Spotted Gum, H1-Treated	Bostik PU	Surf-BOND#2	1.06	100%

*Improvement relative to the strength without using CSIRO surface modification technology

1.2. Hardwood adhesion assessment at high temperatures

Based on the significant benefits regarding hardwood adhesion enhancement demonstrated by CSIRO's surface modification technologies, the Project Team received additional request from hardwood products manufacturing industry re investigation of a question on *whether the CSIRO technology can improve bonded hardwoods performance when using polyurethane adhesives with gluelines exposed to high-temperature HEAT or fire conditions*.

The global timber products industry competes with concrete and steel in numerous engineering and architectural finishes applications (i.e.: as a principal structural and/or cladding material) for the same buildings. Timber offers unquestionable advantages in virtually all areas: costs, aesthetics, construction time and design and manufacturing flexibility. However, the critical area in which timber is perceived as a substandard or unsuitable material under fire.

Although the above issue poses a complex challenge, timber is commonly used in structural applications in situations where it has been demonstrated that the structural properties of timber-based components such as columns or trusses are retained for a required period of fire exposure dur to the fact that charred timber creates insulating layer protecting the core of structural members against further (deeper) burning and/or decomposition that would lead to catastrophic failure. In these applications an experimentally proven char rate must be used, and is currently utilised by structural engineers, and regulated by the European standards regarding charring performance (char factors) for designated product categories. Such an approach, offering safe applications structural products, is being utilised by softwoods industry. This approach is being mimicked by the European hardwoods industry.

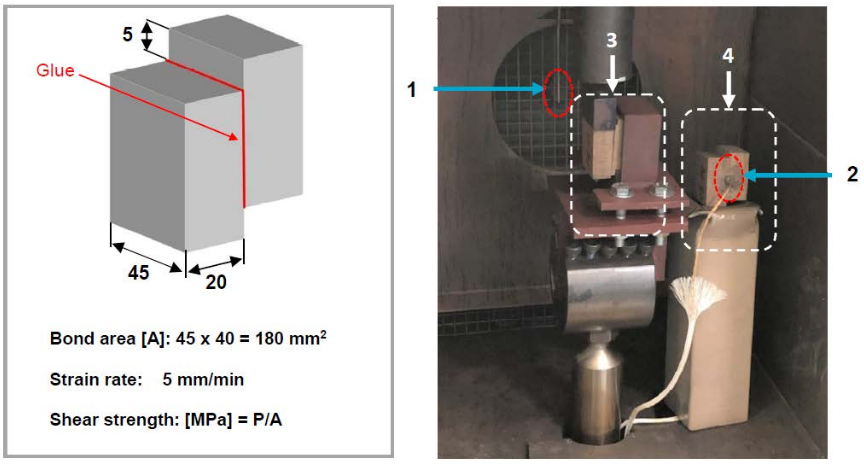
A fire testing of a commercial-size engineering timber product, e.g. a 400 x 400 mm structural column is very expensive regarding both aspects of testing and certification, i.e. the cost of full-size product and the cost of testing.

It is desirable thus that some indicative test could be carried out on a laboratory-scale sample at high temperatures simulating fire conditions for assessing the adhesive performance (e.g. measured by retention of laminated product integrity and shear strength across the entire bond area) before a next-level decision can be made easier to undertake regarding next step testing of a commercial-scale product.

Considering the above issue it was thought that if the CSIRO technology can deliver substantially better performance of hardwood products under heat/fire conditions (e.g. measured by the retention of laminated product integrity, and retention of required shear strength across the entire bond area), then this technology would become a "*game-changer*" for the industry, with the huge and world-wide implications.

1.2.1. Testing methodology

Currently there is no suitable lab-testing standard that can be used directly for the task, as identified above. In close collaboration with ASH, FWPA and Monash University Civil Engineering Department, the CSIRO research team took the challenge of developing a method for conducting the task. The ASTM D7247-07a "Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperature" was used to determine the specimen size and establish testing facility set-up, as illustrated in Figure 30.



(a) (b)

Figure 30. (a) Bonded block-shear specimen, and (b) testing set-up in the elevated temperature chamber of a mechanical tester, including: [1] thermocouple in the chamber for continuous monitoring of the exposure temperature; [2] thermocouples inserted into glueline area of the unloaded (reference) specimen [4], and [3] block-shear test specimen undergoing shear stress loading during temperature increase.

The facilities and testing procedures used are listed below:

<u>Test facilities</u>

- *Universal mechanical tester Shimadzu AG-X 300kN.*
- *Instron high-temperature chamber (RT to 600°C, 10°C/min).*
- *Thermocouples and data recorders.*

Customised test rig for accommodating CSIRO specimens under shear stress loading

Target parameters re determination of the operational window for conducting the tests

- *optimum specimen configuration and rigging.*
- *strain rate (load head rate: 5mm/min).*
- *optimum temperature range.*
- *kinetics of temperature increase.*
- *kinetics of shear stress increase (stress vs time).*

The above methodology facilitates time-effective testing of bonded assemblies under high-temperature exposure with continuous temperature monitoring at specified glueline locations at pre-determined rate of temperature increase during shear stress application.

Vic Ash samples from ASH bonded by Henkel Perbond PU adhesive at the University of Melbourne [initially fabricated for scaled-up (pilot plant) assessment of bond performance in glue-laminated products] were used for the testing. 20 specimens were examined in two groups: (1) with, and (2) without CSIRO's surface modification (10 replicates in each group). Additionally, specimens (with and without the surface modification) with continuous temperature monitoring with no mechanical stress applied to the glueline were placed next to the shear-stress loaded test specimens in the elevated temperature chamber (Figure 30), thus mirroring the glueline temperature of specimens subjected to mechanical loading. Such test set-up configuration allowed avoiding disturbance and mechanical damage to thermocouples during the shear strength testing.

1.2.2. High temperature testing results

The correlation between chamber temperature and glueline temperature at heating rate of 10°C/min was established as shown in Figure 31.

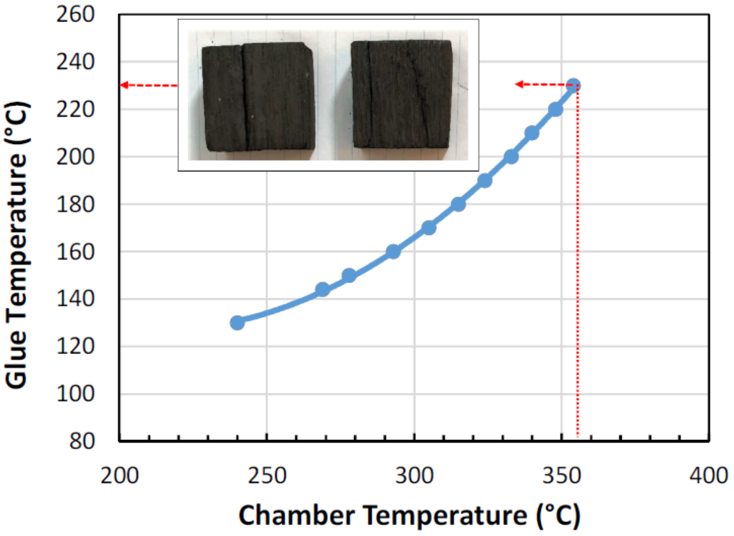


Figure 31. Correlation between chamber temperature and glueline temperature during experiments carried out at the heating rate of 10°C/min. [Insert]: The appearance of Vic Ash specimen (no CSIRO's surface modification) at the chamber temperature of 360°C (glueline temperature 230°C).

When the chamber temperature reached 360°C (at 10°C/min) at the corresponding glueline temperature of 230°C, significant volume of smoke was released causing safety concern, thus preventing further increase of the temperature. At this point, the bonded specimen (with no surface modification) was charred, as depicted in the insert of Figure 31, with significant wood cracking and fragmentation, and glue failure observed.

To alleviate the above problem, an alternative approach was developed to determine a suitable temperature (for both, the chamber and glueline) at which the bond shear strength could be tested, as per the task objective. This involved a step-wise procedure involving the chamber temperature increase to 220 – 250°C with 10 – 20 min ramping time, which allowed the glueline temperature reaching 190 – 200°C whilst measuring bond shear strength with reproduceable results and noticeable difference in failure modes could be observed i.e.: glue failure and wood failure (Figure 32).

Figure 32. VA specimens at glueline temperature 200°C after shear testing.

After several trials, the shear test was decided to be conducted immediately when increasing the chamber temperature to 250°C at the heating rate of 10°C/min, and then holding it at 250°C for 10min while the glueline temperature reached 200°C. The test strain rate (head speed) was 5mm/min and the duration of test was around 1 minute. The testing results are summarized in Table 14.

Table 14. Shear adhesion test results at 200°C (glueline temperature): strength [MPa] and failure mode (% of Glue Failure/Wood Failure).

Vic Ash Samples (VA)	Sample ID	Shear Strength [MPa]	Glue Failure /Wood Failure	Overall adhesion behaviour [average value]
Reference sample: No CSIRO's surface modification	9.15	2.40	0 / 100	Shear strength: **2.3 ±0.5 MPa** Glue Failure % /Wood Failure % **60 / 40**
	12.16	3.10	40 / 60	
	13.15	2.97	100 / 0	
	14.16	1.96	80 / 20	
	8.15	1.32	90 / 10	
	12.15	2.11	50 / 50	
Surf-BOND#3 for surface modification	6.16	3.55	0 / 100	Shear strength: **2.7 ±0.9 MPa** Glue Failure % /Wood Failure % **25 / 75**
	6.15	2.48	20 / 80	
	3.15	4.55	30 / 70	
	5.15	1.86	30 / 70	
	5.16	1.93	20 / 80	
	7.15	1.82	50 / 50	

As seen from Table 14, the average shear strength of PU-bonded VA specimens treated with CSIRO surface modification chemicals shows higher value (2.7±0.9MPa as compared to 2.3±0.5MPa for those no surface modification) and displayed larger wood failure proportion (75% as compared to 40% for those no surface modification). Additionally, the variation of wood failure (6 specimens for each sample) with CSIRO's surface modification was smaller, within 50 – 100% wood failure, as compared to 0 – 100% for unmodified substrates.

The above results provide additional evidence indicating that the CSIRO hardwood surface modification technology can significantly improve the bond performance under severe conditions - at glueline temperature as high as 200°C.

1.3. Pilot Scale Treatment Process: Adhesion Performance Assessment

1.3.1. Preliminary bonding tests on hardwood samples without cyclic exposure

The bonded hardwoods performance based on shear test results for Vic ash (VA), Blue gum (BG) and Blackbutt (BBT) hardwood species has been assessed by analysis of data listed in Table 15 under "cured" or "boiling water" conditions specified earlier in Table 5.

Table 15. Bond shear strength and wood failure assessment of Australian hardwood species – preliminary trials of untreated and treated [T] hardwoods.

Wood	**Pilot line treatment conditions**	**"Cured"**				**"Boiling Water"**			
		Shear strength (MPa)	Wood failure (%)			Shear strength (MPa)	Wood failure (%)		
			Average	Max	Min		Average	Max	Min
VA	Untreated	12.88±0.53^{B}	87^{A}	100	50	5.85±0.37^{B}	41^{B}	70	20
	T: 6.3m/min	13.87±0.63^{AB}	95^{A}	100	65	7.50±0.17^{A}	65^{BA}	100	20
	T: 5.0m/min	14.28±0.74^{AB}	91^{A}	100	75	8.07±0.39^{AB}	69^{A}	100	35
BG	Untreated	13.35±2.42^{B}	28^{B}	95	5	3.95±1.07^{C}	1^{C}	5	0
	T: 6.3m/min	15.63±2.15^{AB}	60^{A}	95	15	6.08±2.96^{B}	25^{B}	70	0
	T: 5.0m/min	16.60±2.96^{A}	70^{A}	100	20	9.09±1.38^{A}	45^{A}	85	5
BBT	Untreated	13.84±2.46^{B}	7^{B}	25	0	0.07±0.06^{C}	0^{C}	0	0
	T: 6.3m/min	15.48±3.22^{AB}	45^{A}	75	5	8.54±1.22^{A}	20^{A}	45	5
	T: 5.0m/min	17.48±2.02^{A}	43^{A}	100	10	5.29±2.55^{B}	15^{A}	45	0

* Means with the same letter are not significantly different. Average of 10 specimens.

Significant bond strength improvement was obtained for all hardwood species investigated in this project, especially those exposed at boiling water when hardwood surface was modified using CSIRO SurfBOND#3 at a conveyor speed of either 6.3 or 5.0m/min.

It is seen that shear strength of bonded VA increased from 5.85 to 8.07 MPa, for BG from 3.95 to 9.09 MPa, and for BBT from 0.07 to 8.54 MPa. The treatment also significantly increased wood failure under the same exposure condition (boiling water); for bonded VA it increased from 41% to 69%, for BG from 1% to 45%, and for BBT from 0% to 15%. When shear-tested under "cured" condition, *i.e.* without any exposure treatment prior to testing, the same conclusions could be drawn for all three hardwood species, although the difference for VA was not statistically significant.

Note that using a conveyor speed of 5.0m/min for spraying Surf-BOND#3 resulted in more significant improvement in bonding performance in most cases than those using a speed of 6.3m/min. A slow conveyor speed of 3.7m/min was also tried, but no significant benefits were obtained. The results from the above preliminary trials allowed identifying a conveyor speed of 5.0 m/min as the most appropriate across all the selected species for the scaling up trials.

1.3.2. Bonding tests on hardwood samples subjected to accelerated exposure

Selected Australian hardwoods (VA, BG, BBT) laminated after continuous surface treatment on a prototype pilot plant presented in Section 1.5.1 were subjected to exhaustive testing involving accelerated artificial exposure conditions based on international standards (AS/NZS 4364 and ASTM D5751), as outlined in detail in Table 6.

The results obtained from the above pilot-scale trials corroborated the results obtained during preliminary trials for VA, BG, and BBT hardwood species. Overall, applying CSIRO's Surf-BOND#3 for hardwood surface treatment improved glueline durability by increasing bond shear strength and percentage of wood failure for all studied species. The treatment also helped to prevent complete delamination for blackbutt and blue gum. The complete set of results is summarized in Table 16.

Table 16. Shear bonding strength and wood failure assessment of hardwood specimens – Scale-up trials.

Wood Type	**Accelerated Exposure Type Before Testing**	**Untreated**				**Surf-Bond#3: 5m/min**			
		Strength (MPa)	Wood failure (%)			Strength (MPa)	Wood failure (%)		
			Average	Max	Min		Average	Max	Min
VA	Cured	12.64 ± 1.80^{A}	72^{A}	100	30	12.57 ± 1.63^{A}	79^{A}	100	45
	High Temp	8.44 ± 1.79^{B}	59^{B}	100	15	9.87 ± 1.97^{A}	79^{A}	100	45
	Vacuum/Pressure	5.93 ± 0.71^{B}	99^{A}	100	90	6.77 ± 0.95^{A}	100^{A}	100	100
	Boil/dry/freeze	3.98 ± 0.81^{A}	46^{B}	100	0	4.35 ± 0.74^{A}	89^{A}	100	50
BG	Cured	14.22 ± 1.61^{B}	53^{B}	100	10	15.28 ± 1.51^{A}	85^{A}	100	10
	High Temp	5.96 ± 1.70^{B}	5^{B}	55	0	9.36 ± 2.68^{A}	43^{A}	100	0
	Vacuum/Pressure	6.40 ± 2.17^{A}	5^{A}	60	0	8.05 ± 1.47^{A}	6^{A}	25	0
	Boil/dry/freeze	2.39 ± 1.60^{B}	11^{B}	90	0	5.20 ± 2.46^{A}	57^{A}	95	0
BBT	Cured	14.88 ± 1.36^{B}	5^{B}	20	0	17.41 ± 1.69^{A}	50^{A}	100	0
	High Temp	3.85 ± 0.87^{B}	0^{A}	0	0	7.14 ± 1.33^{A}	2^{A}	25	0
	Vacuum/Pressure	2.27 ± 1.35^{B}	0^{A}	0	0	7.66 ± 1.21^{A}	0^{A}	0	0
	Boil/dry/freeze	0.09 ± 0.07^{B}	0^{B}	0	0	3.17 ± 1.70^{A}	1^{A}	10	0

*Means with the same letter are not significantly different. Average of 21 specimens.

At a cured stage (room temperature curing only), no significant difference has been observed between the treated and untreated VA, in accordance with results obtained during the preliminary trials. After exposure to high temperature, the VA bonding performance was significantly improved by the surface treatment, both shear strength and wood failure were increased by 17% and 34% respectively. Such an improvement was maintained when the hardwood specimens exposed to vacuum/pressure or boil/dry/freeze conditions.

It is noticeable that although the shear strength was increased only from 3.98MPa to 4.35MPa following the boil/dry/freeze testing, significant improvement in wood failure was observed (from 46% to 89%) in assemblies with CSIRO-treated hardwoods. As seen in the photos presented in Figure 33, that the bulk of solid wood samples shows extensive cracking due to cyclical moisture/drying/freezing exposure in both treated and untreated samples, but the glueline in laminates fabricated with the use of CSIRO surface treatment technology maintained its structural integrity.

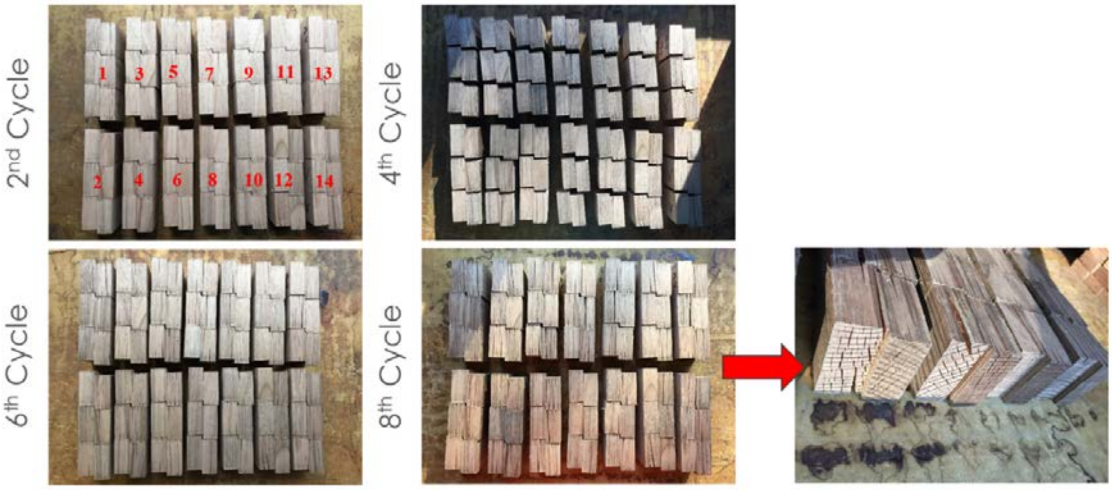


Figure 33. VA assemblies exposed to the boil/dry/freeze cyclic testing after cycle #2, #4, #6, and #8 show internal checks due to damage caused by repetitive shrinkage and swelling. CSIRO surface-treated assemblies: 1 to 7; Untreated assemblies: 8 to 14.

The improvement of bond performance for BG was significant for cured condition (overnight cure at RT), as marked by increase of wood fracture (from 53% in untreated to 85% for surface-treated) and drastically better after severe cyclical exposure (high temperature and boil/dry/freeze conditions), achieving about 60% to 120% shear strength improvement and wood failure increase from just 5-10% in untreated to 40-50% for treated wood.

A remarkable bond performance improvement was also observed for BBT (Blackbutt): although the glueline failure (delamination) is the predominant failure mode, the assemblies with BBT surface treated with CSIRO treatment exhibit shear strength at least twice of that achievable on an untreated BBT (see data in Table 16), even after severe exposure conditions (High Temperature; Vacuum/Pressure; Boil/dry/freeze). It is also noticeable that whilst untreated samples of BG (Figure 34) and BBT (Figure 35) fully delaminate during the boil/dry/freeze test (*i.e.* before shear testing), all CSIRO treated samples stayed glued together after all 8 cycles.

Figure 34. BG assemblies exposed to the boil/dry/freeze test after cycle #8 with one assembly (#8, untreated) missing as all 3 specimens delaminated during one of the conditioning cycles. Treated assemblies: 1 to 7; Untreated assemblies: 8 to 14 (see Figure 33 for assemblies numbering).

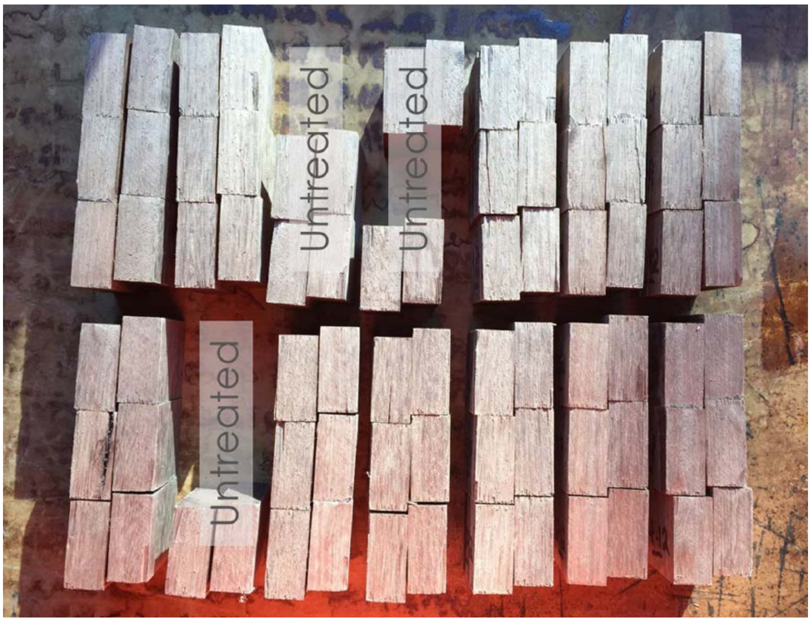


Figure 35. BBT assemblies exposed to the boil/dry/freeze test after cycle #8 with specimens from untreated assemblies #4, #5, and #7 missing as they delaminated during one of the conditioning cycles. Untreated assemblies: 1 to 7; Treated assemblies: 8 to 14 (see Figure 33 for assemblies numbering).

The pilot-plant scale-up trial results, as discussed above, confirmed that:

1. The CSIRO's surface modification technology significantly enhances the hardwood bonding ability and product performance in exposure to severe cyclical loads (e.g. environment-driven), where hardwood laminated/bonded components experience very high tangential and radial shrinkage due to quick change of exposure conditions such as temperature (boiling to freeze) and water content (wet to dry).

2. The CSIRO's technology can be effectively applied in the continuous (on-line) processing, and easily integrated with production facilities operating in hardwood manufacturing industry.

It is also worthwhile to mention that the VA specimens prepared in the pilot-plant facility were also used for high-temperature testing simulating exposure fire conditions (see: Results and Discussion Section 1.2), where enhanced bond performance was also observed.

The overall promising results are very encouraging and lead to building up strong confidence of our industrial partner ASH to commit capital investment for purchasing dedicated manufacturing equipment for forthcoming industrial trials.

2. ASH Industrial Trials of Hardwood Treatment and Bonding

2.1 Processing plant trial details

An industrial trial of surface modification technology investigated and scaled-up in this project was conducted at ASH Heyfield site on 10th September 2019. Vic ash (VA) was used as an input material for laminating with Henkel Purbond adhesive. The processing speed of 27m/min was used to synchronise the processing line with existing ASH processing procedures. The general outline of the processing plant is illustrated in a photo in Figure 36.

Figure 36. ASH industrial processing trails: (1) spray booth for Surf-BOND#3 application; (2) Infra-red (IR) surface drying oven; (3) the flow of surface treated VA boards form treatment line to laminating line; (4) transport of treated VA boards to a laminating press. [**Insert]**: products laminated during the ASH trial (LH: edge-laminated stringers; RH: face-laminated posts).

In order to assess the quality of the surface-treatment process trialled in ASH manufacturing plant in Heyfield, the VA laminated products without using surface-treatment (as reference) and with surface-treatment using CSIRO Surf-BOND#3 on the bonding surface were fabricated by ASH during the trial. Four (4) sets of wood samples (stringers and posts, with and without Surf-BOND#3) collected from the trials were cut into the designed testing size and passed on to University of Melbourne for assessment of bonding properties in accordance with principal standards, i.e.: AS/NZS 4364, and ASTM D5751.

2.2 Technical issues requiring pre-production rectification

Some technical issues were identified during the initial trail, which require further action:

(1). **IR lamps** provided by the supplier were not the same as those investigated and validated at pilot plant trials for rapid drying of moisture in Surf-BOND#3, and then recommended for the industrial plant. Consequently, inappropriate IR waveband of IR might cause overheating of wood surface reaching ~250°C which was much higher than recommended for the optimum processing. Effort was made to minimize the over-heating during the trial, however, the outcome was still not ideal.

(2). **Aerosol spray** by atomising spray nozzles, applied in the form of a diffused cone of water-based solution of adhesion-promoting chemical (CSIRO Surf-BOND#3), at a specific rate of atomisation, is the recommended spray method investigated and validated at pilot plant trials.

Two commodity air spray guns were installed in the spray booth (see Figure 36) instead of the recommended nozzle system to spray Surf-BOND#3 on VA surfaces. Unevenness, overspray and inapropriate drying were observed before the beams travelled to the PU adhesive application and wood lamination stages, resulting in deficency of bonding. The recommended spray system (able to create the required atomisation and spray pattern) should be used in future for precise spray-control and minimisation of the chemical usage.

(3) **The OH&S process operating procedure** needs to be developed for maintaining long-term safe production environment at ASH production facility regardless of the fact that the Surf-BOND#3 is a low hazard classification chemical.

2.3 Adhesion results of the VA laminates obtained from industrial trials

As outlined in Section 2.1, four (4) sets of laminated product samples (stringers and posts, with and without Surf-BOND#3) were collected from the trials, cut into the designated test specimen sizes (see insert in Figure 36 for illustration) and tested at the University of Melbourne in accordance with international standards re assessment of laminated products (AS/NZS 4364, and ASTM D5751).

Cleavage tests

The stringers with Surf-BOND#3 outperformed the control ones (without surface treatment) with 40% wood failure versus 0%. However, the results have shown to be inconsistent *i.e.* 1st glueline scored a 70% wood failure whilst the 2nd glueline scored only 10% (2 samples showed such a pattern). The above problem is most likely caused by uneven, excessively of spray of Surf-BOND#3 and covering just one side of VA boards, plus the inappropriate IR lamps for heating/drying (see comments above in 2.2).

For the posts, the Surf-BOND#3 treated samples also outperformed the untreated ones with 68% wood failure versus 29%. Again, the 1st glueline of the treated sample showed to be very good (95% wood failure) but the 2nd one offered no wood failure at all (due to the same reason as discussed above). The results also confirmed that edge-lamination had no negative impact on wood failure or delamination.

Delamination assessment

The delamination results corroborated the cleavage results. The average delamination for untreated stringers was 39% vs 13% for the treated stringers. There was not much difference between treated and untreated posts (treated: 26%; untreated: 23%).

Summary of the trial outcomes

Although the ASH industrial trial was an initial one with many technical aspects not meeting the plan and design requirements, it did demonstrate the application feasibility and robustness of the CSIRO's surface modification technology. The spray process was relatively easy to operate. Although the spray of Surf-BOND#3 was not properly controlled, and the treated timber surface was not properly dried, an overall positive result was still obtained with high level of wood failure for both VA products (stringers and posts) with the surface treatment. Additionally, the delamination for treated stringers is lower than that on untreated ones. Although in laminated posts the bond performance was similar for both treated and untreated ones, no negative impact of treatment was observed.

As advised by ASH, the originally designed/ordered IR lamps have been recently received, and another industrial trial has been planned. The OH&S procedure for spray of Surf-BOND#3 was also re-designed and proper personal protection equipment (PPE) (protective latex gloves and mask) was identified for ASH operators (Figure 37).

Figure 37. Personal protection equipment (PPE) for the spray booth operators at ASH.

3. Hardwood Coating Performance Improvement

3.1. CSIRO’s surface modification strategy for improving coating performance

Due to low durability of wood products against low-maintenance substitutes made of metals, plastics and wood-plastic composites which offer up to 20 years of maintenance-free (no repainting) performance, the current wood-based materials and traditional wood-protective coatings are not able to compete with these alternative materials. It has thus been realised that unless a breakthrough approach offering high-performance of coated wood, able to retain its natural appearance whilst eliminating the commonly observed coatings delamination and breaking off/peeling off from the coated surface for up to at least 10 – 15 years, wood as an exterior material is facing relegation to low-end products, or near-extinction as a viable exterior material for building and construction products.

An in-depth analysis of long-term performance of exterior coatings on surfaces of engineering structures by the original project proponents identified some critical factors, which allowed identification of principal platforms for proposing and undertaking this project, with the aim of alleviating or eliminating problems causing poor reputation of wood, which is currently considered as a non-performing, low durability exterior material:

(1). The polyurethane (PU) clearcoats commonly used by the manufacturers of automotive and aerospace structures have been applied as the uppermost, transparent UV-protective coatings exhibiting outstanding durability determined by: (i) the retention of original coating flexibility and adhesion; (ii) prevention of discolouration of solid colour paints and undercoats; (iii) no coating chipping-off or peeling-off, and thus, (iv) retaining coating performance (unless vehicle is accident-damaged) during its lifetime, which in automotive applications currently exceeds 15 – 20 years.

(2). The best clear coating types currently available for surface-finishing and protecting wood against environmental damage in exterior applications are solvent-based or water-based acrylic coatings filled with various types of UV absorbers improving their resistance against damaging effects of solar radiation.

(3). For the propose of improving long-term performance and durability of hardwood-coating system on real-life wood-based products maintaining coating adhesion strength, flexibility and natural appearance of hardwood, selection of long-term durable coating is of the critical importance.

Considering the above, the key objectives of this project re hardwoods coating task were:

- To validate the applicability and anticipated benefits listed in (1) above, as inherently offered by the polyurethane (PU) clear coatings currently used in the automotive or aircraft industries.
- To modify, with the input of selected PU coatings manufacturers, their composition to enhance and/or eliminate any uncovered/observed coatings deficiencies.
- To enhance the long-term adhesion performance of coatings on hardwoods by further developing durable interfaces between hardwoods and coatings by a series of chemical

formulations of underlayer coatings, as listed in Table 8, with the aim that they could server one, or a combination of the following additional purposes:

- Interfacial adhesion promotion,
- Reducing the UV degradation,
- Reducing interfacial stress caused by hydro-thermal movement and deformation of materials during accelerated and real-life weathering and service conditions,
- Sealing the pore structure of timber intended to be coated with more cost-effective commodity coatings.

The underlayer coatings usually comprise: (i) a base polymer that could enhance the bonding between hardwood surface and PU coatings, e.g. ionic polymer solutions, water solution or dispersion of polyvinyl alcohol (PVOH), or polyurethane with additional functional groups (e.g. PU D101), (ii) inorganic and/or organic UV absorbers such as zinc oxide (ZnO), iron oxide hydrate (FeOOH), transparent iron oxide (XFast Yellow or XFast red), and encapsulated UV stabilizers Tinuvin 5333, 1230-DW or 400-DW, and (iii) in some cases, a free radical scavenger Lignostab-1198 (L1198).

The UV-Visible light absorption spectra of some of these additives are shown in Figure 38.

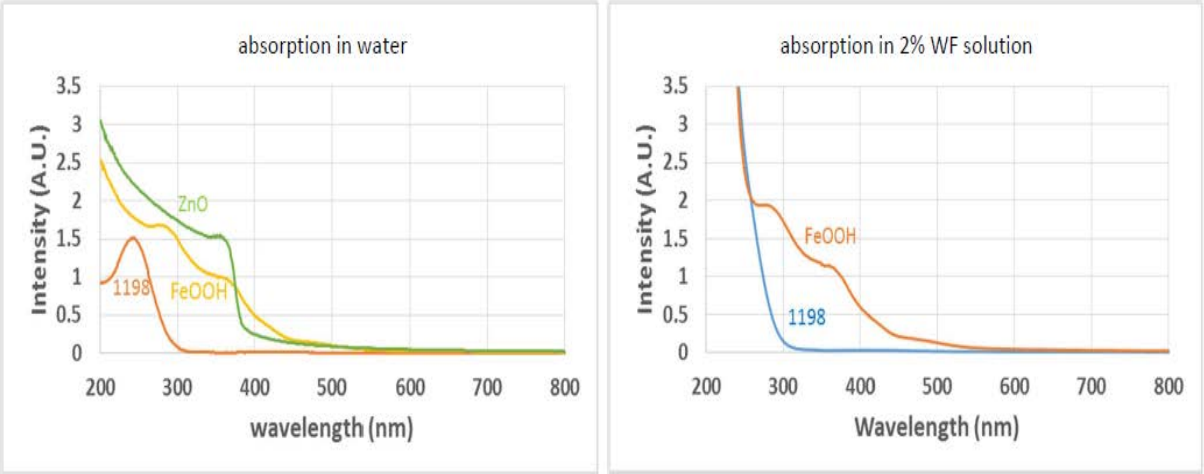


Figure 38. The UV-Visible light absorption spectrum of ZnO, FeOOH and Lignostab1198 (1198).

The long-term hardwood coating performance was assessed via accelerated weathering testing using Q-Sun or QUV, as described in Section 2.5. The coating adhesion behaviour and colour/gloss changes were examined for the coated hardwood samples after prolonged Q-Sun or QUV exposure. The results for a range of coatings and surface modification formulations are reported below.

3.2. Coating performance using Cabot exterior clearcoat

BG and TWD hardwood samples coated with Cabot exterior clearcoat using various surface treatment methods before Q-Sun exposure are shown in Figure 39 while those after 774 hours Q-Sun accelerated weathering exposure in Figure 40 respectively.

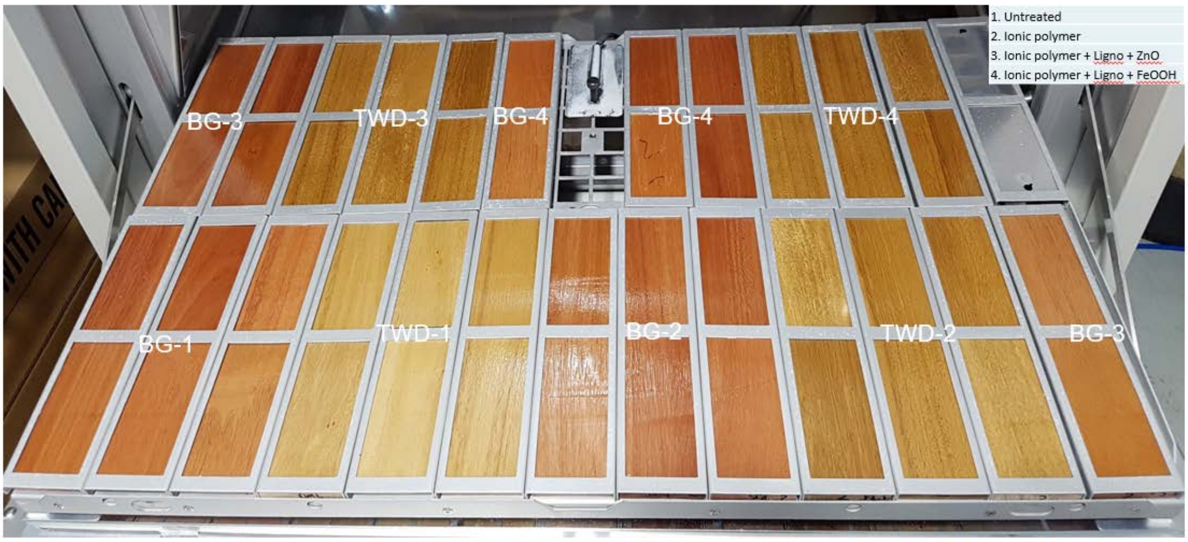


Figure 39. BG and TWD samples coated with Cabot exterior clearcoat before Q-Sun exposure.

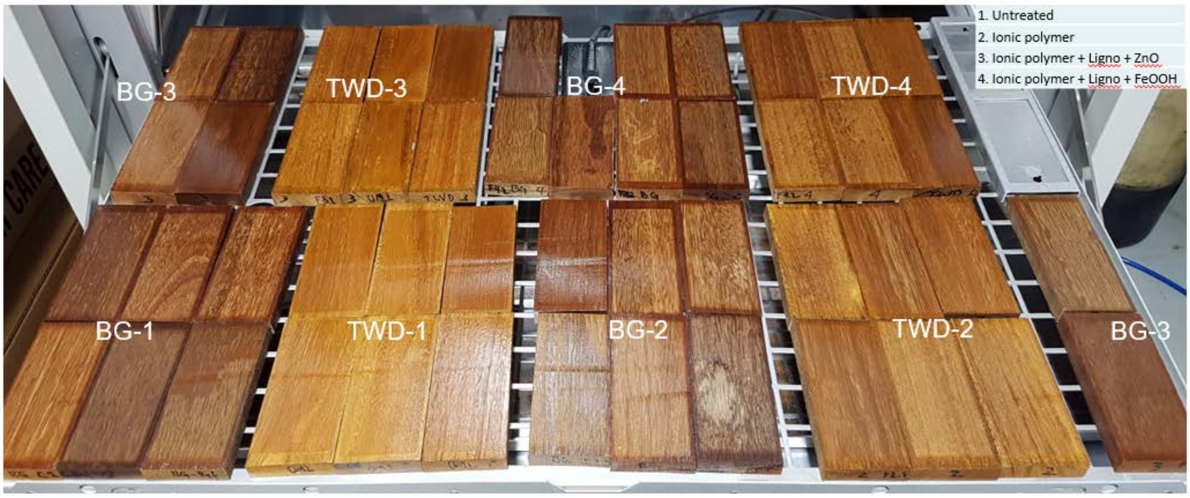


Figure 40. BG and TWD samples coated with Cabot exterior clearcoat after 774 hours Q-Sun exposure.

Table 17. Colour shift (ΔE) of hardwoods coated with Cabot exterior clearcoat after 774 hours Q-Sun exposure.

Surface modification / underlayer coating composition	**Blue Gum (BG)**	**Tallow Wood (TWD)**
Untreated	14.8	12.5
Ionic Polymer	11.0	14.4
Ionic Polymer + L1198 + ZnO	6.7	15.9
Ionic Polymer + L1198 + FeOOH	9.3	15.7

Colour shift (ΔE) data for Cabot clearcoat on BG and TWD in Table 17 demonstrate that a noticeable colour change occurred during relatively short (774 hours) Q-Sun weathering for all BG and TWD samples. More importantly, severe degradation of coating occurred after the

Q-Sun weathering, with coating adhesion strength significantly weakened, resulting in failure on all samples subjected to adhesion testing.

Since Cabot exterior clearcoat could not survive even 774 hours of Q-Sun weathering, it was deemed not suitable for exterior coating applications aiming the wood surface to survive undamaged by long-term real-life weathering (solar radiation, rain & humidity, temperature variations, etc), and therefore, no further accelerated weathering was conducted using Cabot clearcoat.

3.3. Coating performance using PPG PU high-gloss D800 clearcoat

Vic ash (VA) and Blackbutt (BBT) samples coated with PPG high-gloss D800 Deltron clearcoat using various surface treatment methods before exposure to Q-Sun weathering are shown in Figure 41, while those after 3098 hours weathering are shown in Figures 42 to 45 respectively.

Figure 41. VA and BBT samples coated by PPG high-gloss D800 clearcoat before Q-Sun testing.

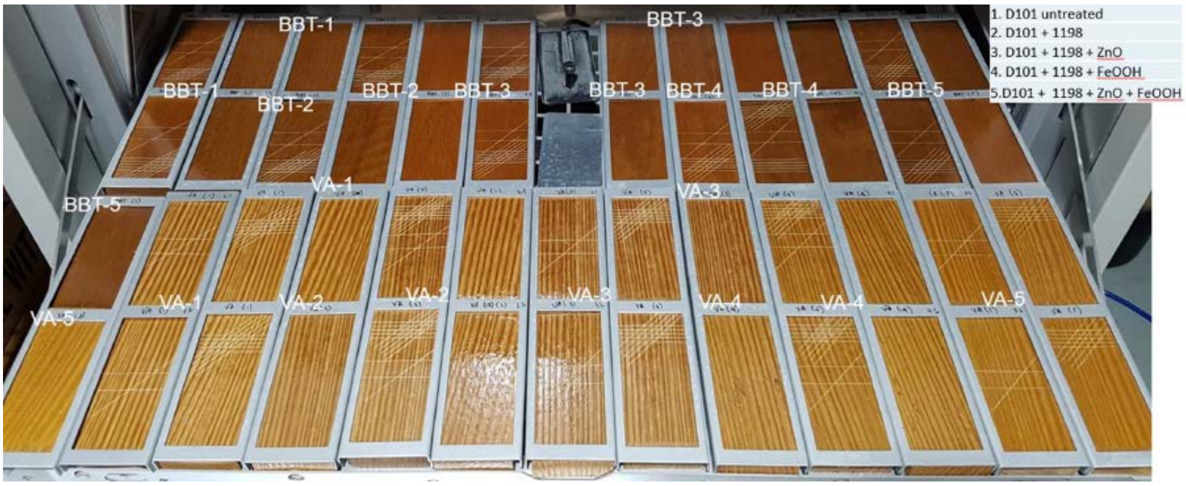


Figure 42. VA and BBT samples coated by PPG high-gloss D800 clearcoat after 642 hours Q-Sun testing.

Figure 43. VA and BBT samples coated by PPG high-gloss D800 clearcoat after 1344 hours Q-Sun testing.

Figure 44. VA and BBT samples coated by PPG high-gloss D800 clearcoat after 1898 hours Q-Sun testing.

Figure 45. VA and BBT samples coated by PPG high-gloss D800 clearcoat after 3098 hours Q-Sun testing.

The results of PPG D800 coating adhesion and colour shift (ΔE) after Q-Sun exposure periods up to 2688 hours are presented in Table 18 (coating adhesion) and Table 19 (colour shift [ΔE]).

Table 18. Adhesion of PPG D800 clearcoat (see Figure 24 for ranking scale in accordance with BSS 7225 standard) on VA and BBT surface after Q-Sun weathering.

Hardwood type	**Surface treatment/ underlayer coating composition**	**Q-Sun exposure hours**				
		0	**672**	**1344**	**2016**	**2688**
Vic Ash (VA)	Untreated	10	10	4-5	3	2
	PU D101+L1198	10	10	8	2-6	2-3
	PU D101+L1198+ZnO	10	6-10	4-5	3-5	2
	PU D101+L1198+FeOOH	10	10	8	2-4	2
	PU D101+L1198+ZnO+FeOOH	10	10	8	6-7	2-3
Blackbutt (BBT)	Untreated	10	10	8	6-7	5-6
	PU D101+L1198	10	10	7	6-7	4-6
	PU D101+L1198+ZnO	10	10	8	4-6	3-4
	PU D101+L1198+FeOOH	10	10	7-8	6-7	3-5
	PU D101+L1198+ZnO+FeOOH	10	10	7-8	6	3

Table 19. Colour shift (ΔE) of VA and BBT with PPG D800 clearcoat after Q-Sun weathering.

Hardwood	**Surface treatment**	**Q-Sun exposure hours**				
		0	**672**	**1344**	**2016**	**2688**
Vic Ash (VA)	Untreated	0	14.8	19.9	25.2	28.9
	PU D101+L1198	0	12.1	15.4	19.1	24.4
	PU D101+L1198+ZnO	0	11.1	15.4	18.7	23.6
	PU D101+L1198+FeOOH	0	6.0	9.0	11.9	17.4
	PU D101+L1198+ZnO+FeOOH	0	7.4	10.0	12.1	15.8
Blackbutt (BBT)	Untreated	0	9.0	12.6	16.5	20.8
	PU D101+L1198	0	19.4	24.4	27.4	30.0
	PU D101+L1198+ZnO	0	11.6	16.8	21.3	25.3
	PU D101+L1198+FeOOH	0	4.9	7.1	9.5	12.4
	PU D101+L1198+ZnO+FeOOH	0	5.2	11.2	14.1	16.8

Using a surface modification (underlayer coating) formulation containg a combination of PU D101 dispersion, Lignostab-1198 (L1198), ZnO and FeOOH (as highlighted by green font in Tables 18 and 19) resulted in coated VA specimens passing 2000 hours of Q-Sun weathering exposure regarding coating adhesion, while other underlayer coatings on VA samples failed the testing.

On the other hand, most of coated BBT samples passed 2000 hours of Q-Sun weathering exposure re coating adhesion regardless of with/without surface modification. Some of the BBT specimens also showed low colour shift value (e.g. using FeOOH in surface modification, as highlighted in green in the Table 19). All VA and BBT specimens fail coating adhesion test after 2688 hours of Q-Sun exposure.

The accelerated weathering testing was also conducted via QUV for BBT and TWD coated with PPG high-gloss D800 clearcoat, with the results summaried in Table 20.

Table 20. Adhesion of with PPG D800 clearcoat on BBT and TWD after QUV weathering.

Hardwood type	**Surface treatment/ underlayer coating composition**	**QUV exposure hours**				
		0	**646**	**1257**	**2501**	**4344**
Blue Gum (BG)	Untreated	10	10	10	10	7
	PU D101+L1198	10	10	10	10	7
	PU D101+L1198+ZnO	10	10	10	10	7
	PU D101+L1198+FeOOH	10	10	10	10	6-7
	PU D101+L1198+ZnO+FeOOH	10	10	10	10	7-8
Tallow Wood (TWD)	Untreated	10	10	10	10	6
	PU D101+L1198	10	10	10	10	6-7
	PU D101+L1198+ZnO	10	10	10	10	6
	PU D101+L1198+FeOOH	10	10	10	10	6
	PU D101+L1198+ZnO+FeOOH	10	10	10	10	6

It is noticeable from the data presented in Table 20 that excellent coating adhesion performance (rating 10) was retained through to 2501 hours of QUV weathering exposure, whilst a reasonable adhesion rating (6 – 7) was retained until as long as 4344 hours of such exposure. These are outstanding results considering the fact that surviving 1240 hours of QUV weathering in the automotive coatings testing protocols [General Motors, HN 1664 (Test 4.2/2 and 4.2/3) and ASTM G 53, Method b, High Temperature, UVB-313 tubes] has long been considered by automotive coatings experts as an equivalent of at least 5 years of lifetime under Arizona, Texas or Florida weather conditions, thus implicitly indicating that PPG high-glass D800 clearcoat is an excellent candidate for hardwood coating on exterior products, with long-term prospective durability.

A set of D800 clear-coated TWD samples with various underlayer coating compositions after 2501 and 4344 hours of QUV weathering is shown in photos in Figure 46. It is seen that, as it can be anticipated, the colour of TWD after long-term UV exposure becomes darker, in line with the colour shift (ΔE) data shown in Figure 47.

Figure 46. The TWD samples after 2501 and 4344 hours QUV testing.

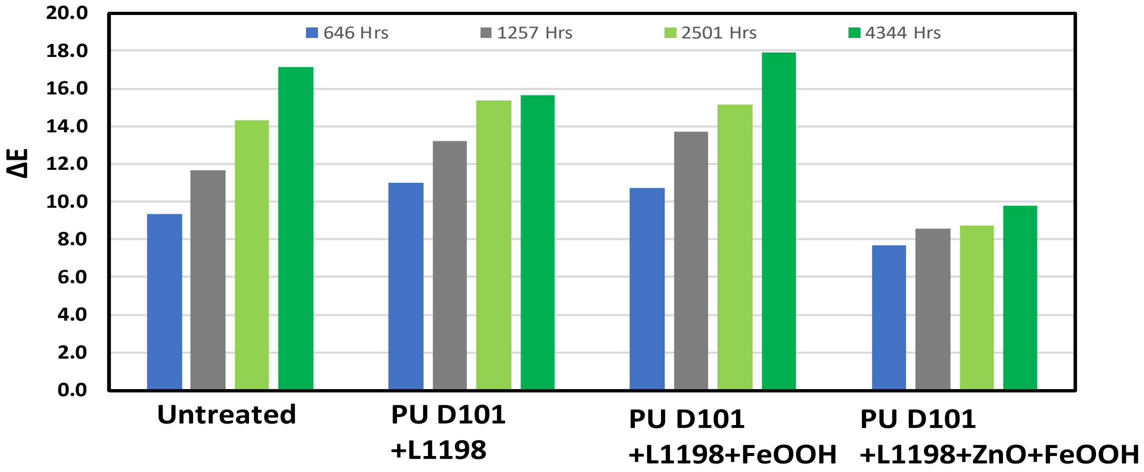


Figure 47. Colour shift (ΔE) of TWD surface coated with PPG D800 clearcoat applied onto various underlayer coatings after up to 4344 hours QUV exposure weathering

The most interesting outcome is observed for undercoat system comprising PU D101, Lignostab1198 (L1198), ZnO and FeOOH, which exhibits less further colour change with incresing UV exposure time beyond 646 hours, in contrast with ΔE increase for other undercoat types. It is also intersting to see that the performance of each specific surface modifying formulation can be quite different when applied to different hardwood species, even whilst using the same coating.

3.4. Coating performance using PPG Maxmeyer mattcoat

Vic ash (VA) and Blackbutt (BBT) coated with PPG Maxmeyer mattcoat using CSIRO’s surface modification methods before Q-Sun artificial weathering are shown in Figure 48, while those after 672 and 1344 hours testing are shown in Figures 49 and 50. In order to avoid moisture penetration into the specimens during artificial weathering through the remaining (uncoated) five (5) specimen surfaces, water-proof flexible PU sealant was used to seal all of these uncoated surfaces.

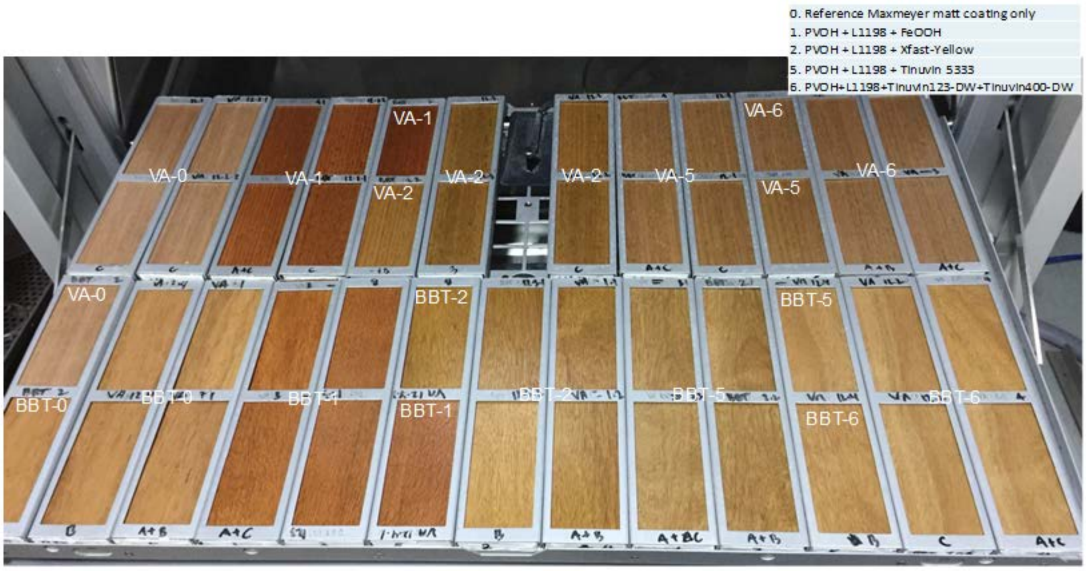


Figure 48. VA and BBT samples coated by PPG Maxmeyer mattcoat before Q-Sun testing.

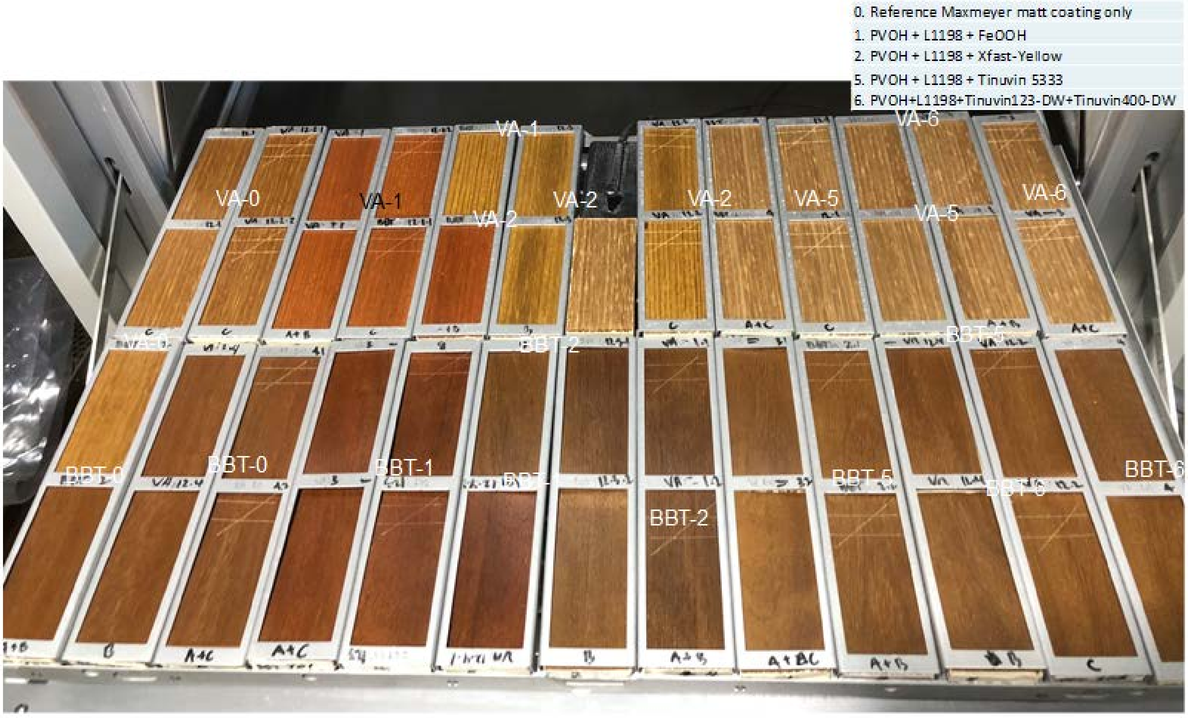


Figure 49. VA and BBT samples coated by PPG Maxmeyer mattcoat after 672 hours Q-Sun testing.

Figure 50. VA and BBT samples coated by PPG Maxmeyer mattcoat after 1344 hours Q-Sun testing.

The coating adhesion and colour shift results after long-term Q-Sun and QUV artificial weathering are listed in Tables 21 – 23 respectively.

Table 21. Coating adhesion of VA and BBT coated with PPG Maxmeyer mattcoat after Q-Sun weathering

Hardwood type	**Surface treatment/ underlayer coating composition**	**Q-Sun exposure hours**			
		0	**672**	**1344**	**2016**
Vic Ash (VA)	Untreated	10, 10	8, 8	8, 8	6, 6
	PVOH+L1198+FeOOH	10, 10	9, 9	9, 9	7, 7
	PVOH+L1198+XFast	10, 10	9, 9	9, 9	5, 4
	PVOH+L1198+Tinuvin5333	10, 10	9, 9	9, 8	5, 6
	PVOH+L1198+Tinuvin123DW+Tinuvin400DW	10, 10	9, 9	9, 9	6, 5
Blackbutt (BBT)	Untreated	10, 10	7, 7	6, 6	5, 5
	PVOH+L1198+FeOOH	10, 10	8, 8	8, 8	6, 6
	PVOH+L1198+XFast	10, 10	8, 8	6, 6	4, 4
	PVOH+L1198+Tinuvin5333	10, 10	9, 9	9, 9	7, 6
	PVOH+L1198+Tinuvin123DW+Tinuvin400DW	10, 10	9, 9	9, 9	7, 6

Table 22. Colour shift (ΔE) of VA and BBT coated with PPG Maxmeyer mattcoat after Q-Sun artificial weathering

Hardwood	**Surface treatment**	**Q-Sun exposure hours**			
		0	**672**	**1344**	**2016**
Vic Ash (VA)	Untreated	0	4.9	7.7	12.1
	PVOH+L1198+FeOOH	0	14.2	15.8	18.4
	PVOH+L1198+XFast	0	9.2	11.0	12.3
	PVOH+L1198+Tinuvin5333	0	6.1	9.3	10.9
	PVOH+L1198+Tinuvin123DW+Tinuvin400DW	0	6.6	9.0	10.4
Blackbutt (BBT)	Untreated	0	17.7	21.5	26.6
	PVOH+L1198+FeOOH	0	8.1	12.9	14.6
	PVOH+L1198+XFast	0	10.5	15.8	19.2
	PVOH+L1198+Tinuvin5333	0	5.4	6.8	7.9
	PVOH+L1198+Tinuvin123DW+Tinuvin400DW	0	12.4	13.6	16.7

Table 23. Coating adhesion and colour shift (ΔE) of BBT coated with PPG mattcoat Maxmeyer after long-term QUV artificial weathering.

Surface treatment/ underlayer coating composition	**QUV 0h**		**QUV 1250h**		**QUV 2500h**		**QUV 3340h**	
	Adhesion	ΔE	Adhesion	ΔE	Adhesion	ΔE	Adhesion	ΔE
Untreated	10, 10	0	9, 9	12.6	8, 8	15.1	7, 7	18.9
PVOH+L1198+FeOOH	10, 10	0	9, 9	4.6	8, 8	7.5	8, 8	13.2
PVOH+L1198+XFast	10, 10	0	9, 9	6.1	8, 8	9.1	8, 9	19.2
PVOH+L1198+Tinuvin5333	10, 10	0	9, 9	4.3	9, 8	6.8	8, 8	11.5
PVOH+L1198+Tinuvin123DW + Tinuvin400DW	10, 10	0	10, 10	8.3	9, 8	10.9	8, 8	17.1

As highlighted in green in Tables 21 and 22, at least one CSIRO surface modification formulation produces coating adhesion passing 2000 hours Q-Sun artificial weathering with relatively less colour change simutaneously recorded for both VA and BBT coated using PPG Maxmeyer mattcoat.

It also needs highlighting that all BBT specimens coated by mattcoat Maxmeyer, as listed in Table 23, passed adhesion tests after 3340 hours QUV exposure, with many specimens also showing relatively low colour shift.

3.5. Comparison of coating performance using PPG high-gloss and matt coatings

Based on the outcome of work analysed above, both PPG high-gloss and low-gloss mattcoat appear to exhibit performance attributes making them suitable for potential use as clearcoats for hardwoods due to their long-term durability regarding coating adhesion and retention of natural wood appearance. In order to examine the effect of PPG's Ultraseal underlayer coatings, accelerated weathering tests were conducted for VA and BBT hardwood coated with PPG high-gloss Carmaster or mattcoat Maxmeyer. The specimens utilising the PPG Ultraseal underlayer (1&2 or 1&3), or not using this underlayer material (VA-2 or VA-3 or BBT-2 or BBT-3) before Q-Sun exposure are shown in Figure 51, while those after weathering are shown in Figures 52 and 53.

Figure 51. VA and BBT samples coated by PPG high-gloss Carmaster or mattcoat Maxmeyer with, and without Ultraseal underlayer before Q-Sun artificial weathering exposure.

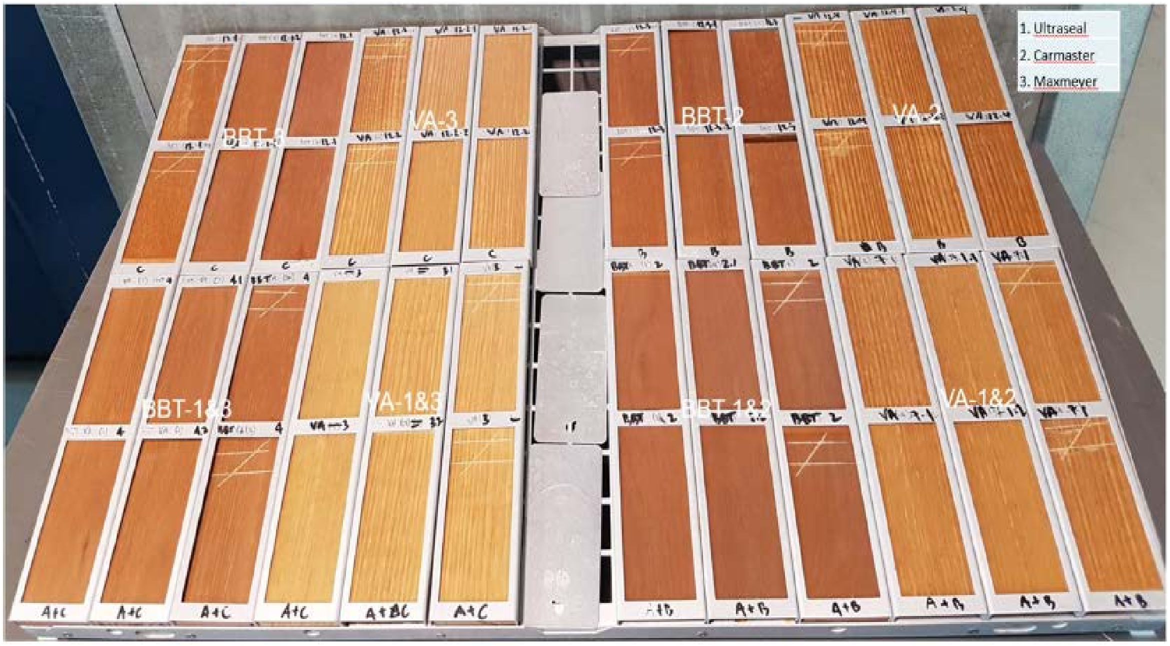


Figure 52. VA and BBT samples coated by PPG high-gloss Carmaster or mattcoat Maxmeyer with and without Ultraseal underlayer after 672 hours Q-Sun artificial weathering exposure.

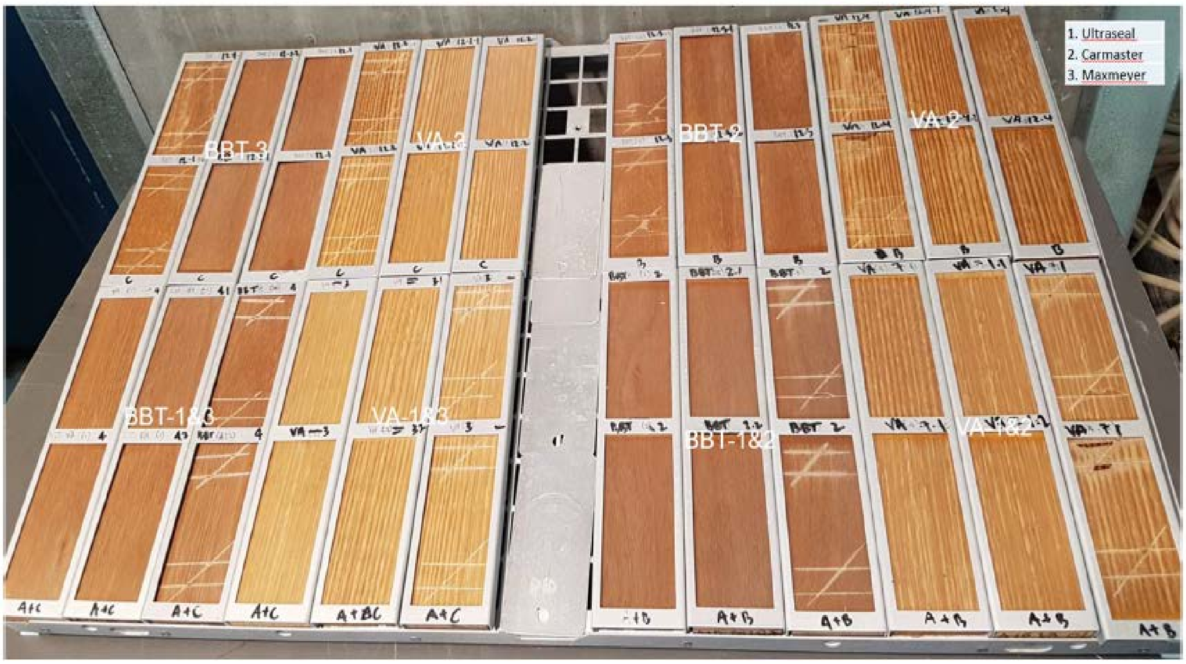


Figure 53. VA and BBT samples coated by PPG high-gloss Carmaster or mattcoat Maxmeyer with, and without Ultraseal underlayer after 1344 hours Q-Sun artificial weathering exposure.

The coating adhesion and colour shift data after Q-Sun artificial weathering exposure are summaried in Tables 24 and 25 respectively. It is seen through the data that PPG mattcoat Maxmeyer has better coating adhesion as compared to PPG high-gloss Carmaster coat, while the Ultraseal undercoat improved the adhesion performance. However, the colour change values are relatively higher in comparrison to some CSIRO surface modification methods, e.g.: PVOH+L1198+FeOOH for VA, or PVOH+L1198+Tinuvin5333 for BBT.

Table 24. Coating adhesion of VA and BBT coated with PPG high-gloss Carmaster or mattcoat Maxmeyer with/without Ultraseal underlayer after long-term Q-Sun artificial weathering exposure.

Hardwood	**Surface treatment**	**Q-Sun exposure hours**				
		0	**672**	**1344**	**2016**	**2688**
Vic Ash (VA)	Carmaster CC9240	10, 10	6, 5	2, 2	2, 2	---
	Maxmeyer	10, 10	8, 8	7, 6	6, 6	6, 6
	Ultraseal/Carmaster CC9240	10, 10	9, 6	7, 7	7, 7	1, 1
	Ultraseal/Maxmeyer	10, 10	9, 9	7, 8	7, 7	3, 3
Blackbutt (BBT)	Carmaster CC9240	10, 10	8, 9	4, 5	2, 2	---
	Maxmeyer	10, 10	8, 8	7, 8	7, 7	1, 1
	Ultraseal/Carmaster CC9240	10, 10	8, 8	7, 8	7, 7	1, 1
	Ultrseal/Maxmeyer	10, 10	8, 8	7, 7	6, 6	5, 6

Table 25. Colour shift (ΔE) of VA and BBT coated with PPG high-gloss Carmaster or mattcoat Maxmeyer with/without Ultraseal underlayer after long-term Q-Sun artificial weathering exposure.

Hardwood	**Surface treatment**	**Q-Sun exposure hours**				
		0	**672**	**1344**	**2016**	**2688**
Vic Ash (VA)	Carmaster CC9240	0	17.1	21.5	27.1	--
	Maxmeyer	0	15.1	18.9	21.7	24.7
	Ultraseal/Carmaster CC9240	0	15.7	20.8	27.3	31.1
	Ultraseal/Maxmeyer	0	14.2	18.1	22.1	25.0
Blackbutt (BBT)	Carmaster CC9240	0	7.9	12.4	15.7	--
	Maxmeyer	0	19.2	24.0	30.5	33.6
	Ultraseal/Carmaster CC9240	0	14.5	19.0	23.5	25.6
	Ultraseal/Maxmeyer	0	17.8	20.8	23.6	26.7

3.6. Coating performance using PPG GPSP mattcoat

Towards the end of 2018, two additional formulations of PPG GPSP mattcoats were obtained for coating performance assessment. These were applied to VA and BBT hardwood samples either with or without PPG Ultraseal underlayer for Q-Sun artificial weathering exposure up to 2900 hours (Figure 54). The coating adhesion and colour shift results after the long-term Q-Sun exposure are summarized in Tables 26 and 27.

Figure 54. VA and BBT samples coated by PPG GPSP Matt coat after 2900 hours Q-Sun testing.

Table 26. Coating adhesion of VA and BBT with PPG GPSP mattcoat after Q-Sun artificial weathering exposure.

Hardwood	**Surface treatment**	**Q-Sun exposure hours**			
		0	**672**	**1344**	**2027**
Vic Ash (VA)	GPSP-485-51-1	10, 10	8, 7	3, 3	3, 3
	Ultraseal + GPSP-485-51-1	10, 10	8, 7	8, 8	6, 6
	GPSP-485-52-2	10, 10	8, 8	7, 7	6, 6
	Ultraseal + GPSP-485-52-2	10, 10	10, 9	8, 8	8, 7
Blackbutt (BBT)	GPSP-485-51-1	10, 10	8, 7	7, 7	5, 6
	Ultraseal + GPSP-485-51-1	10, 10	9, 9	9, 9	8, 7
	GPSP-485-52-2	10, 10	8, 8	7, 7	7, 7
	Ultraseal + GPSP-485-52-2	10, 10	9, 9	8, 7	6, 6

Table 27. Colour shift (ΔE) of VA and BBT with PPG GPSP mattcoat after Q-Sun artificial weathering exposure.

Hardwood	**Surface treatment**	**Q-Sun exposure hours**			
		0	**672**	**1344**	**2027**
Vic Ash (VA)	GPSP-485-51-1	0	17.5	22.1	26.4
	Ultraseal + GPSP-485-51-1	0	14.3	17.4	20.6
	GPSP-485-52-2	0	14.7	16.0	17.4
	Ultraseal + GPSP-485-52-2	0	15.0	22.0	24.6
Blackbutt (BBT)	GPSP-485-51-1	0	19.2	26.3	30.7
	Ultraseal + GPSP-485-51-1	0	14.5	19.8	23.5
	GPSP-485-52-2	0	6.2	10.6	14.0
	Ultraseal + GPSP-485-52-2	0	9.6	14.1	18.0

The results presented in Table 26 and 27 are relatively consistent with those obtained for using PPG mattcoat Maxmeyer. For VA, the best coating adhesion was achieved by using GPSP-2 and Ultraseal, which passed 2000 hours of Q-Sun artificial weathering exposure. However, it was surprising to observe that the colour shift was lower when Ultraseal was not used.

For BBT, the best coating adhesion was achieved by using GPSP-1 and Ultraseal, which passed 2000 hours Q-Sun artificial weathering exposure, with the colour shift also being lower when GPSP-2 was used without Ultraseal.

It is also seen in photos presented in Figure 54 that PPG mattcoat performed well during the harsh Q-Sun exposure assessment exhibiting good coating film flexibility beneficial in coping with the wood expanding/shrinking under the cyclical wet/dry/UV conditions over the long-period testing. The retention of natural appearance of wood samples was also good.

3.7. Summary of hardwood coating performance

As indicated earlier, in order to provide long-term performing coating system for hardwoods, able to maintain durable strength of coating's adhesion and retain natural appearance of hardwood, two approaches followed in this project were:

- Identification and validation of long-term durable coatings for hardwood products, and
- Development of underlayer coating formulations to enhance adhesion performance and UV resistance of coated hardwood products.

3.7.1. Identification and validation of long-term durable coatings for hardwoods

The data presented in this report demonstrate that both PPG high-gloss and low-gloss (matt) clearcoats exhibit excellent long-term durability and UV resistance for hardwood coating. Analysis of photos of coated hardwood specimens presented in Section 3 of this report reveals that most of the coatings retain appropriate strength and flexibility with no much degradation observed after over 2000 hours Q-Sun or 4000 hours QUV accelerated weathering exposure. Such result is consistent with long-term performance and excellent durability of identical coatings used as clearcoats in the global automotive industry over the length of real-life service, which in our approximate estimations could potentially be in excess of 15 years.

This estimation is based on the paradigm of automotive coatings engineers (Ford and GM) stipulating that the survival of 1240 hours of QUV weathering of automotive coatings upon meeting performance criteria established in a General Motors protocol HN 1664 (Test 4.2/2 and 4.2/3) and ASTM G 53 (Method b, High Temperature, UVB-313 tubes) is considered as an equivalent of such coating surviving at least 5 years of service life under Florida/US weather conditions.

The above outcome implicitly indicates that both PPG high-gloss D800 and low-gloss clearcoat are excellent candidates for hardwood coating on exterior products, with long-term prospective durability.

3.7.2. Underlayer coatings enhancing adhesion performance and UV resistance of coated hardwood products

A series of surface modification formulations were developed as underlayer coatings for hardwood, with several of them demonstrating 2-pronged benefits in: (i) improving the coating adhesion between hardwood and coatings, and (ii) reducing the colour change over the long-term Q-Sun or QUV artificial weathering exposure.

However, the performance is still not consistent for different hardwood species; it seems difficult to identify a master formulation working satisfactorily for different hardwood species or using different coatings. Table 28 lists the best formulations for each hardwood investigated in this work, when using specific types of clear coatings.

Overall, there seems to be no clear trend and thus, no general guideline can be formulated yet for predicting the performance for new hardwood/coating/underlayer systems. Therefore, further investigation is needed to develop optimum underlay coating providing universally satisfactory performance and long-term durability.

Table 28. Hardwood/Underlayer/Coating Systems with Best Coating Performance

Hardwood	**Coatings***	**Underlayer surface modification**	**Q-Sun/QUV**	**Colour shift (ΔE)**
Vic Ash	HG D800	PU D101+L1198+ZnO+FeOOH	Q-Sun 2000h	15.8
	Matt-M	PVOH+L1198+Tinuvin123DW +Tinuvin400DW	Q-Sun 2000h	10.4
	Matt-GPSP2	PPG Ultraseal	Q-Sun 2000h	24.6
Blackbutt	HG D800	PU D101+L1198+FeOOH	Q-Sun 2000h	12.4
	Matt-M	PVOH+L1198+Tinuvin5333	Q-Sun 2000h	7.9
	Matt-GPSP1	PPG Ultraseal	Q-Sun 2000h	23.5
Blue Gum	HG D800	PU D101+L1198	QUV 4000h	11.1
Tallow Wood	HG D800	PU D101+L1198+ZnO	QUV 4000h	8.1

*HG=high-gloss clearcoat M=Maxmeyer

It needs to be further emphasized here that although it can be expected that the longer hours a coating can survive under Q-Sun or QUV accelerated weathering, the longer the years of durability of the coating performance in real life, there is no direct correlation between the number of Q-Sun or QUV accelerated weathering hours and the number of coating durability years in real life of coated hardwood products due to many complicated issues such as unpredictable synergies of weathering factors, including those related to the actual composition of coatings and interactions between various ingredients of coatings and hardwood surface/structures. The accelerated weathering results presented in this project report can only be used as a rough indication regarding assessment of coating lifetime of hardwood products. As outlined in Section 3.7.1 – surviving 2000 hours of Q-Sun or 3000-4000 hours of QUV accelerated weathering might correlate to approximately 10-15 years of hardwood coating durability in real life. This, however, needs further validation through scale-up and industrial trials, combined with rigorous assessment of any predictions including the use of global standards and specifications.

4. Improvement of Hardwood Product Performance by Design

The objective of Swinburne University as part of this project was to provide design outcomes that help mitigate the primary factors causing timber to degrade and/or be less suitable, due to compromised durability in external cladding and bonded applications, than low-maintenance substitutes made of metals, plastics and wood-plastic composites offering up to 20 years of maintenance-free service performance.

The improvement of performance of timber for external uses such as structural columns, trusses, or cladding systems was achieved through developing technological and design-based solutions facilitating elimination, or significant lowering of the speed and extent of wood degradation from moisture accumulation and UV light exposure, which subsequently extends the lifetime of timber in these applications closer to the time-span traditionally associated with plastics or painted metals.

This was done in conjunction with technological breakthroughs developed and validated by CSIRO via accelerated (artificial) weathering carried out by Q-Sun or QUV exposure of selected Australian hardwood species coated with selected types of commercially available automotive clear coatings. This, in turn, allowed the identification of coatings shown to perform significantly better than currently available transparent wood coatings (e.g. Cabot or Dulux water-based acrylics or polyurethanes). These novel approaches were utilised in design-based prototype conceptualisation aiming for further improvement of exterior wood products' performance by systematically investigating and improving their inherent water-retention properties.

The improvement of performance of timber in the form of structural products fabricated as multi-component bonded composite structures was conducted in conjunction with Melbourne University. The overall aim of this work was to develop and optimise equipment and processes facilitating continuous on-line processing (surface modification) and lamination for achieving consistently improved property-performance characteristics of bonded and coated timber, and subsequently to scale-up the equipment and technology for implementation in commercial production by the project industry partner, ASH.

4.1. Factors to be considered in hardwood product design

4.1.1. Water management in design and engineering of wood-based façades

Building façades, and other exterior wood-based structures are continually exposed to fluctuating environmental conditions, including the presence of water droplets and films, condensation and airborne moisture. Consequently, the relationship between the properties of water and hydrophilic wood is the dominant factor influencing this material's performance and durability. All these issues necessitate novel design approaches to exterior components re. development and validation of new concepts targeting effective mitigation of water stagnation on surfaces of wood products.

The upper level of moisture content in externally exposed wood components is always influenced by rainfall intensity, relative humidity and the temperature gradient between the surface and that of the surrounding environment (which control moisture condensation). If the product surface becomes covered with a continuous and stable film of rainwater or condensation residing for a sufficiently long-enough time, the surface of wood attains the equivalent of 100% relative humidity (RH). It will also depend strongly on whether the surface is raw, or coated by a protective coating, and on its geometry which may either, promote long-term retention of the water film when it is flat and horizontal, rough or porous, or conversely, potentially be able to shed it off, if it has been surface-finished with a coating resembling (at the micro-level) the Lotus leaves, which exhibit a specific property known as super-hydrophobicity.

Developing an in-depth understanding of water behaviour on model façade substrates is essential for uncovering and establishing a clearly defined set of fundamental physical attributes which, when combined with appropriately selected coatings, should provide multi-faceted embodiments effectively facilitating reduction of harmful effects of undissipated (stagnant) water and moisture.

4.1.2. Water repellent super-hydrophobic surfaces in nature

Observations of behaviour of water droplets from rain and agricultural sprays (plants watering and pesticides delivery) in contact with surfaces of plant leaves revealed that many of these (e.g. leaves of Lotus) are completely cleaned from any surface-attached dust deposits by rain. Such leaves were denoted as “super-hydrophobic” because water droplets spontaneously form spheres with very little adhesion to the leaf surface and roll off very quickly even at negligible angle of inclination [20-25].

A main feature of super-hydrophobic surfaces (water repellence and self-cleaning behaviour) is their roughness on the micro and nanometre scales, as shown in Figure 56. Water droplets and dirt particles on such surfaces are only able to contact the tips of these micro and nano-sized asperities. Therefore, due to a negligibly small contact area, the contaminating particles develop negligible adhesion forces to such surfaces and can be effectively removed by rain.

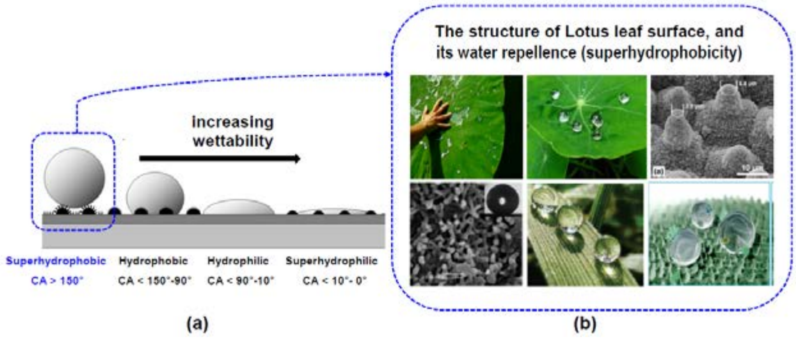


Figure 56. (a) Four categories of surface wettability and their characteristic shapes of sessile water droplets with associated static contact angles (adapted from [21]), and (b) images of super-hydrophobic lotus (Nelumbo nucifera) and rice grass (Oryza sativa) leaves with self-cleaning properties, shown here at different magnifications [21, 23].

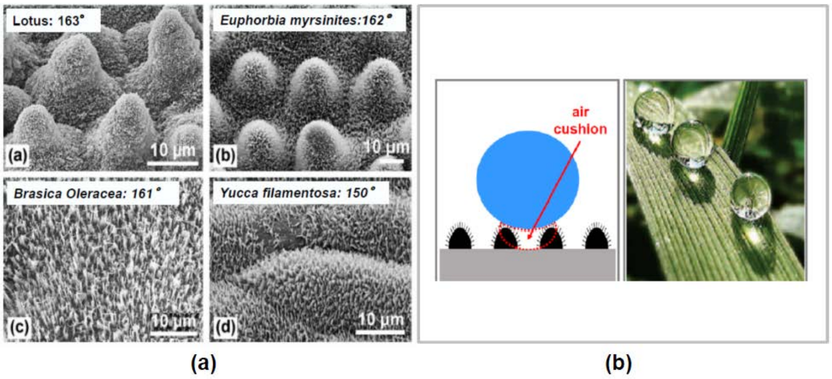


Figure 57. (a) The structure of a super-hydrophobic surface (SHS) of some plant leaves; (b) illustration of the mechanism of a nature-made SHS on the rice grass leaf.

The ability of these natural surfaces to spontaneously shed off a water bead, as illustrated in Figure 57 (b), and to effectively wash off any surface contamination has been named the "Lotus effect", although it is observed not only on the leaves of the Lotus (Nelumbo nucifera) but also on many other species, such as garden Nasturtium (Tropaeolum majus) or Eucalypts, and on thousands of other plants, some of which are listed as examples in the pioneering publication of Neinhuis & Barthlott [25].

4.1.3. Water and moisture in building cladding

Raindrops driven against the windward facade of buildings, commonly known as wind driven rain (WDR), are one of the most important sources of moisture penetrating building facades and affecting their performance and durability.

Figure 58 schematically depicts the key effects of wind-driven, façade impinging, rain drops.

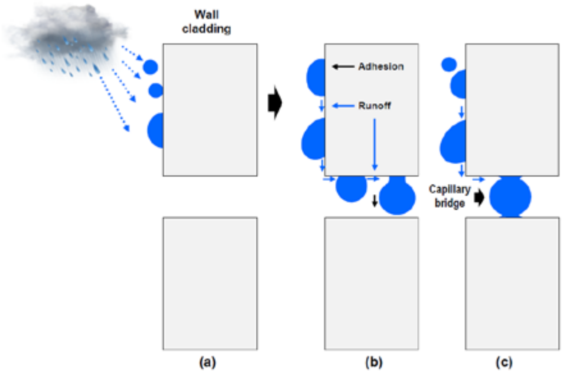


Figure 58. Schematic effects of wind-driven rain drops: (a) surface impinging; (b) drops coalescence, followed by runoff after gravity forces exceeding adhesion and surface tension effects result in drops sliding down and then forming pendant drops at the bottom edge of cladding panels; (c) excessive volume of pendent drops resulting in formation of capillary bridges in the gaps between cladding panels.

Prolonged accumulation of water at façade panel surfaces leads to its migration and diffusion into porous substrates such as wood, which can consequently lead to water penetration through the building envelope [26-29]. This, in turn, depending on the environmental conditions, can lead to further substrate damage by frost, biological and chemical degradation of the facade material, and may ultimately cause the surface- or bulk-related structural cracking of cladding panels and protective coatings due to severe thermal and moisture-related gradients [30] commonly occurring on moisture-sensitive materials such as wood.

4.1.4. Factors influencing physical design aspects

Water, in the form of rain drops or condensation constitutes one of the most damaging factors affecting performance and durability of coated wood.

The stagnant water, which is present as stationary droplets of various volumes, or as film of condensed moisture formed from coalescing micro-droplets of dew, diffuses through the surface of coating into the wood cells causing swelling and shrinking of the wood upon cyclical increase or reduction of its moisture contents [31,32]. This, in turn, depending on the environmental conditions can lead to further damage by frost, biological and chemical degradation of the facade material and may ultimately cause structural cracking of the cladding panels and coatings due to repetitive thermal and moisture gradients, and resultant stresses [33].

In addition to the above, the infrared (IR) fraction of solar radiation (constituting about 51-52% of solar energy) delivers irradiated heat to materials surfaces, significantly increasing their surface temperature. The sum of both factors: water and heat in all forms “complement” each other in producing cyclic hydro-thermal movements of wood (swelling and shrinking), including its surface, resulting in severe interfacial stresses between the surface of wood and the coating. These stresses, which can reach the magnitude of more than 10-15 MPa [34-36], often exceed the strength of coating, creating its cracking if the coating does not have sufficient flexibility able to accommodate these movements. Due to their cyclical nature, the prolonged cyclical fatigue stresses initiate and continually progress the delamination of coatings from the substrate surfaces.

As schematically shown in Figure 58, the key effects of impinging rain drops are: (i) coalescence of individual drops, (ii) subsequent runoff, once the size of the drop exceeds the threshold value upon which gravity forces exceed adhesion and surface tension effects, causing the sliding of drops across the face of cladding panels, (iii) forming pendant drops at the bottom edge of such panels, and finally, (iv) formation of capillary bridges in the gaps between cladding panels when pendent drops reach excessive volume resulting in drop stretching followed by gap bridging.

The most relevant of the above phenomena require development of an in-depth understanding of the mechanism(s) of their individual or interactive action(s), which can then be attempted to be managed by purposeful utilisation of the properties of functional coatings, and more importantly, specific features of façade panels design, by the purposeful arrangement and configuration of as many of the physical aspects of the geometry of timber elements to assist with the effective removal of water.

4.2. Experimental results

Based on the outcomes of the project conducted at CSIRO, three types of exterior clearcoats were used in the experiments:

(1). Cabot Exterior Clearcoat, gloss (1K PU, water-based): a commodity wood coating,

(2). PPG high-gloss D800(2K acrylic-urethane): automotive repair/re-spray (low-temp. cure),

(3). PPG matt-coat Maxmeyer (2K PU): automotive clearcoat, low-temperature cure.

4.2.1. Mitigation of water accumulation through design outcomes

A series of tests were selected to investigate and interpret simultaneous interactions of the water-accumulation/shedding properties of the following:

(1). timber substrates which were coated with the CSIRO-selected best performing coatings (see Table 28 and discussion in Section 3.7) providing best long-term durability and UV protection of clear-coated wood, and

(2). the physico-geometrical parameters of designed components that could potentially work in conjunction with the coatings,

with the overall aim to develop a general (all-encompassing) approach for mitigating water accumulation, i.e. achieve the best possible water-shedding behaviour of architectural surfaces.

The tests selected and conducted were:

- Contact angle of sessile water droplets on flat surface,
- Water droplet behaviour on timber surface tilted at all angles from 0 to 90°,
- Gap distance for water droplet capillary bridge breakage.

In order to reliably determine the principal factors controlling water behaviour, the following matrix of parameters was considered in experiments:

(1). Substrates categories: a smooth reference substrate (Aluminium) and machined wood:

- Reference substrate: geometrically smooth aluminium (Al),
- Timber (Vic ash): face-grain surface,
- Timber (Vic ash): end-grain surface.

(2). Surface finish:

- Uncoated substrates,
- Substrates (all categories: see item 1 above) coated with all selected coatings.

Based on the above, the complete set of substrate-coating combinations (24 in total) for investigating water behaviour were as follows:

a. **Uncoated substrates: as per (1) above**

b. **substrates coated with**:
   - Cabot gloss clear
   - PPG D800 gloss clear
   - Maxmeyer matt clear
   - Super-hydrophobic only

c. **substrates, as per (b) + superhydrophobic coating, i.e.:**
   - Cabot gloss clear + Super-hydrophobic
   - PPG D800 gloss clear + Super-hydrophobic
   - Maxmeyer matt clear + Super-hydrophobic.

The conversion of outcomes of this work into physical and geometrical design parameters necessitates investigation of factors controlling: (i) behaviour of water droplets on substrate surfaces, and (ii) gap distance causing capillary bridge breakage between adjacent substrates.

(1) Sessile water droplets behaviour on inclined timber surfaces

The behaviour of sessile water droplets on timber surfaces tilted at variable angles (using gradually increasing tilt angle from 0° to 90°) was investigated using a Ramé Hart contact angle goniometer utilising the Automated Tilting Base mechanism (100-25-A) and automated microsyringe system (p/n 100-22) for precise deployment of water volume in 10 microlitre (µL) increments. Distilled water was used in all testing, as recommended in standards.

Each substrate sample was tested beginning with the droplet volume of 10 µL and tested at gradually increasing tilt angles ranging from 0° through to 90°. The water droplet volume was increased in 10 uL increments and tested through to 90°, or until reaching the respective (minimum) volume at which the droplet had spontaneously and completely rolled-off from the sample's surface and lower edge (See Figure 59).

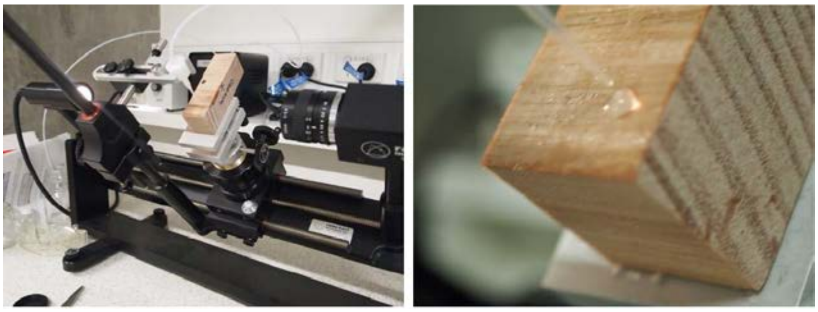


Figure 59. Ramé Hart contact angle goniometer with tilting base with attached timber (Vic Ash species) substrate sample, showing a surface-attached distilled water droplet.

The complete set of results of this investigation presenting water droplets behaviour in terms of their *'rolling volume'* on all substrate types selected for this study), i.e.: aluminium; timber face-surface; timber end-grain surface (uncoated and with all coatings applied) at angles from 0 to 90° is illustrated in Figures 60- 62.

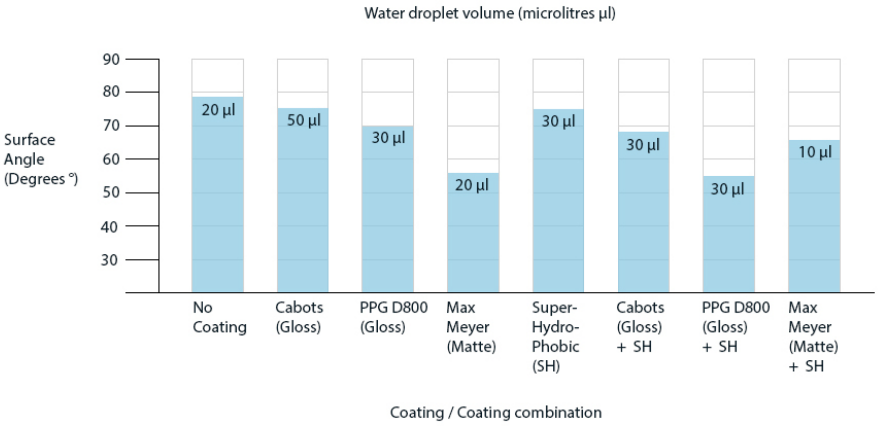


Figure 60. Tilt angles of geometrically smooth reference substrate (aluminium) with/without coating combinations, at respective water rolling volumes (minimum volume at which droplets completely roll-off from the sample surface).

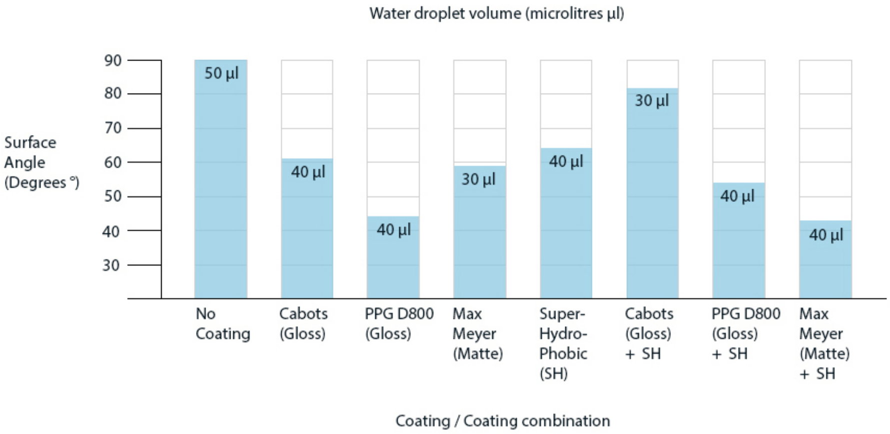


Figure 61. Tilt angles of timber (Vic Ash) face surface, at respective water rolling volumes (minimum volume at which droplets completely roll-off from the sample surface).

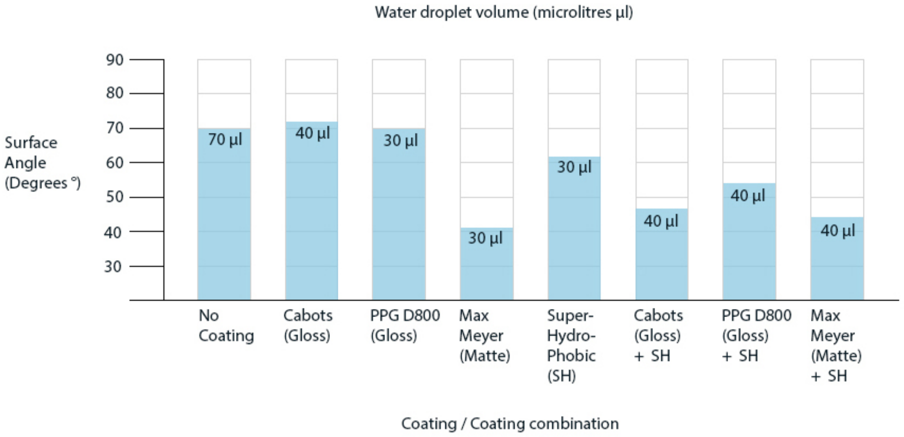


Figure 62. Tilt angles of timber (Vic Ash) end-grain surface, at respective water rolling volumes (minimum volume at which droplets completely roll-off from the sample surface).

The results (in respect to timber substrates) indicate that for some of the coatings tested, the angle that a 30 µL or 40 µL water droplet completely rolls-off from the surface could be as high as around 70°. However, a consistent angle of at least 70° for any given surface to exhibit is not feasibly implementable as a property of an external timber design element.

Based on these initial results, it was decided to utilise the most common volumes at which the majority of water droplets rolled-off completely from the tilted surfaces (i.e.: 30 µL and 40 µL) for testing at what distance between a flat lower and upper timber (Vic ash species) substrate a water capillary bridge would disengage. This test was performed with the same substrate/coating combination set as in the previous test, using the Ramé Hart contact angle goniometer, and utilising height-adjustable platforms. Substrate samples were placed above and below each other (see Figure 63), with the water droplet placed on the lower flat surface. The upper sample was slowly lowered until its lower surface made contact with the top of the water droplet, subsequently forming a capillary bridge, and was then slowly raised until the capillary bridge disengaged. The resulting gap was then measured (see Figure 63).

Figure 63. Timber substrate samples with identical coating combination and grain orientation attached to the Ramé Hart goniometer height-adjustable platforms, showing distilled water droplet prior to capillary bridge formation, as upper sample is lowered.

The tests carried out in accordance with an example illustrated in Figure 63 yielded the following results, whilst utilising water droplets of 30 and 40 µL (Figures 64, 65).

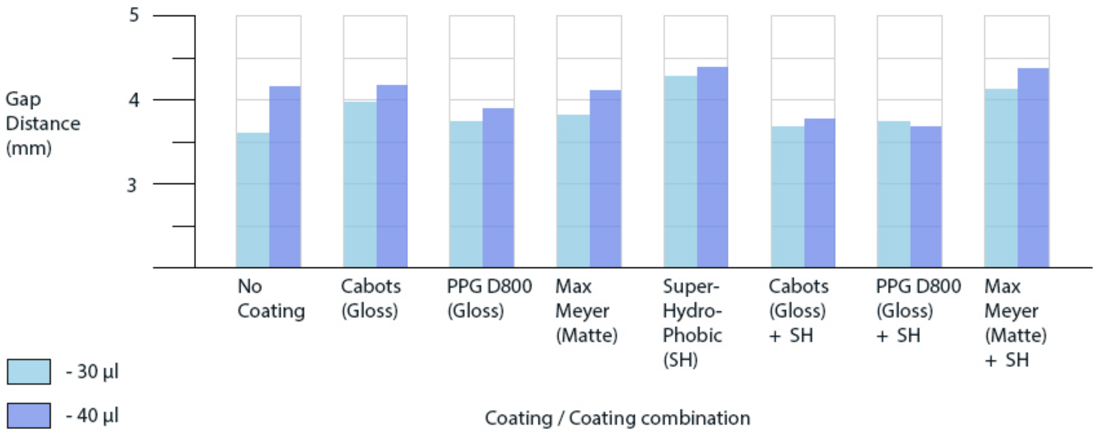


Figure 64. Capillary bridge breaking distances: Timber (Vic ash) face surface.

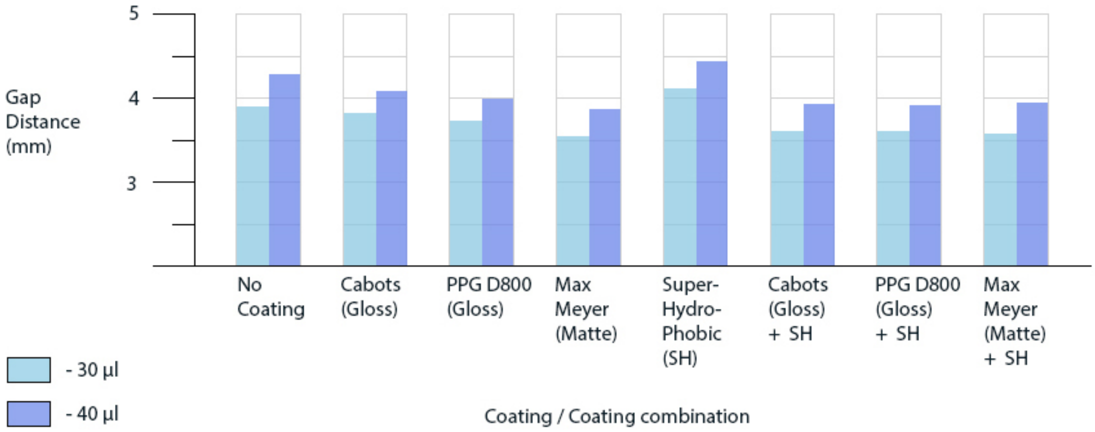


Figure 65. Capillary bridge breaking distances: Timber (Vic ash) end-grain surface.

The results of this investigation of capillary bridge formation and breaking demonstrate that water droplets of up to 40 µL cannot maintain a connection with an adjacent parallel (and placed above) surface (for any of the coating combinations) at a gap of approximately 4.5mm or greater.

4.3. Discussion and recommendations for hardwood product design

Through the above investigation of water behaviour and data, a fundamental set of design guidelines/stipulations can be offered:

(1). The upper surface of external cladding elements should not have an angle of less than 45° (slope declining outward from the curtain wall), and have

(2). The physical gaps between each adjacent and independent (coated) element should be no less than 5mm.

The above physical design parameters are recommended to be used as a foundation for fundamental prerequisites when designing any outwardly facing cladding components, irrespective of their rear, inward-facing mounting systems, to maximise each element's effectiveness at preventing water accumulation or stagnant water deposits formation.

The effectiveness of water shed-off by external timber cladding elements can be further improved (in conjunction with the above physical design parameters) by utilising some of the external automotive clear coatings that have been shown through Q-Sun or QUV weathering at CSIRO to be more effective at extending the time that UV damage occurs, in conjunction with the interpretation of data from the above water behaviour testing.

The analysis of all results as above, leads to the following observations pertaining to external coatings:

(1). Within the scope of this project, the best-case scenario observed through research data is the timber coated with either the PPG Maxmeyer matt or D800 high-gloss clearcoat (plus potentially additional combinations that also include a super-hydrophobic external layer) which yielded improved water-dissipating physical properties via a 40 µL droplet (diameter, D = 4.242mm) completely rolling off the surface and edge at a maximum tilt of around 45°. These should thus be further investigated via arrays of coated timber panels to map-out and optimise these properties and parameters. These are the fundamental (design/material) features of importance, although (at this stage) inferred only from the interpretation of data.

(2). The water droplets roll-off when the force of gravity [F] acting on droplets residing on surface tilted at the angle (α) overcomes adhesion forces between the droplet and the substrate surface: [$F = \rho V g \sin \alpha$], where V - the droplet volume; ρ the density of water; $g = 9.81\text{ms}^{-2}$ is the gravity acceleration; α is the rolling or sliding angle.

Assuming that the force of adhesion between nearly spherical water droplets and the same substrate (or coating type) remains nearly constant, it can be reasonably deduced that increasing the volume of droplets [which increases the gravity force ($F = \rho V g \sin \alpha$)] should result in larger droplets roll-off at lower tilt angles. This, if/when confirmed experimentally, may significantly broaden the flexibility of design achieving good water shedding ability of architectural elements to be used in building façades.

The coatings that showed to be the most effective at removing water droplets via gravity alone was primarily the Maxmeyer Matt-finish coating, which has the additional benefit of its matt finish resembling that of natural timber. If a gloss finish is preferred, then it is suggested to use the PPG D800 gloss-finish. Both coatings have shown through the data analysis to not only create a layer that can block the UV damage for longer than existing timber coatings, but also are sufficiently effective at shedding-off water at an implementable edge angle in cladding designs. This effective water shed-off can potentially be enhanced (based on some of the data collected in this investigation) by adding an additional super-hydrophobic coating, which has shown, in some instances, to increase the effectiveness of gravity upon removing water droplets. Preferably, however, a more effective SHC should be found than that used in this project.

Further testing (to commence after this project completion) should include all the above sample sets arranged into external cladding arrays encompassing all above recommendations, and exposed to artificial rain, to further evaluate and reinforce the above findings.

Conclusions

This collaborative project aimed to develop a competitive platform technology enabling significant increase of hardwood usage by Australian building and construction sector. The principal approaches utilised in the project are: (i) to incorporate a reactive interface onto hardwood surface to enhance bonding performance of bonded products for accommodating interfacial stresses arising from hydrothermal movements, (ii) to provide strong bond with exterior durable coatings for maintaining coating adhesion and hardwood natural appearance, and (iii) to provide design recommendations for exterior hardwood products.

The project R&D results have demonstrated that the CSIRO's surface modification technology can improve bonding strength and durability of hardwood adhesion, and long-term performance of clear coatings on Australian hardwood products.

CSIRO's Surf-BOND is a water-based, low-cost, low-hazard surface-modification formulation and easy to apply on the hardwood surface prior to bonding or coating. For hardwood bonding using polyurethane adhesives in product manufacture, a small amount of thin-layer spray coating (~20ml/m^2) of Surf-BOND can generate a significant improvement of bonding strength (100 – 300%) and a higher level of wood failure for several typical hardwood species. Such benefit became more pronounced when bonding performance was assessed after exposure of specimens to severe conditions such as high temperatures, going through extreme wet to dry cycles, or even under a condition similar to fire. The strong bonding behaviour could also be maintained after H1 or H3 "True-Core" treatment. This result was validated by lab testing at CSIRO, scale-up assessed at University of Melbourne and finally demonstrated in an industrial trial at ASH for Vic ash timber. For other hardwood species, scale-up assessment and industrial trials are still needed to confirm the result, test the application feasibility and robustness, and optimize the procedures in industrial production.

Commercially available clear coatings were identified as suitable industrial coatings with long-term durability and solar exposure resistivity for hardwood. As validated through long-term accelerated weathering assessment, both high-gloss and low-gloss (matt) clearcoats from PPG could survive up to 2000 hours Q-Sun or 4000 hours QUV testing when used for coating on various hardwood species; the continuous coating layer was still flexible with sufficient bonding strength and the hardwood specimens still maintained natural appearance attributes (wood texture pattern and minimal surface discolouration).

Various underlayer surface-modification coatings developed at CSIRO have provided benefits in enhancing coating adhesion, improving UV resistance and reduction of colour change as observed in the long-term accelerated weathering assessment. The results have provided a promising solution for coated hardwood products in outdoor applications to overcome surface discoloration upon solar exposure and high maintenance costs caused by short repainting cycles due to poor paints adhesion and resultant delamination. Although there seems no direct correlation between the number of Q-Sun or QUV testing hours and the number of coating durability years in real life, surviving 2000 hours Q-Sun or 3000 – 4000 hours QUV testing might imply some 10 – 15 years coating durability, which needs further validation in scale-up and industrial trials and assessment.

However, it seems that the underlayer coating performance is critically important and needs to be further developed to provide additional improvement of long-term performance. Some fundamental research is needed in understanding the general relationship between underlayer formulation and long-term coating performance for developing general guidelines for predicting the performance for new hardwood/underlayer/coating systems, and then further validation would be needed to improve the overall coating durability.

In accordance with the aim (iii) of this project, Swinburne University has quantified a fundamental set of physical parameters which may be used as design guideline for external cladding components. Suitable equipment and processes were also established allowing a consistent repeatable application of the CSIRO's Surf-BOND to facilitate the increase of bond performance in potential composite timber (e.g. structural beams and columns) products. It can be scaled up to allow commercial manufacture of the products, especially relating to large cross-section structural timber beams that have been stated to be one of the most in-demand products by the architectural and building industry. The main advantage coming from this successful commercial bond-enhanced structural timber beam manufacturing is the great sustainability as achieved through utilisation of smaller timber elements that would otherwise have less commercial value, as well as anticipated increased production and revenue from mitigating the current difficulty in manufacturing solid-timber structural beams due to hard-to-find suitably large trees.

The outcome of this project provides a promising technology in combination of hardwood bonding/coating enhancement and design methodologies for Australian hardwood product manufacturers to develop engineered designer-products for building's exterior and interior applications to meet essential long-term performance standards. It also provides a potential for further innovation of building modular systems manufactured and assembled off-site ready for full installation within the architectural projects specific to the use of softwood and hardwood materials. The proposed surface-modification in bonding/coating process is easy to operate/robust, and was demonstrated to be easy to integrate with existing industrial facilities.

The technology can be further extended (through customisation or further research) to a broad range of Australian wood products to maximise significant benefits achievable to the entire wood products sector, allowing timber to be promoted and reliably utilised as a sustainable and highly reliable engineering material in a much broader range of applications than currently, thus maximizing the use of wood-based materials.

Recommendations

With an overarching view of maximising the use of Australian hardwoods through utilization of their inherent or designer *in-built* functional, decorative and structural aspects, the principal objective of this project was to demonstrate improved bond strength and durability of adhesion and long-term performance of clear coatings on Australian hardwood following optimum product design. Based on the R&D outcomes achieved in the project, recommendations are made as below.

1. Using CSIRO's Surface Modification Technology to Enhance Hardwood Adhesion Performance

Based on the laboratory- and pilot-scale assessment following the industrial trial conducted at ASH, Surf-Bond#3 is recommended to be used in surface modification of Vic ash wood in production of hardwood products especially when H3 "True-Core" treatment is applied. Surf-Bond#3 can be easily sprayed or coated onto the wood surface to be bonded at ~ 20g/m^2, followed by the wood subjected to rapid drying to achieve "touch-dry" surface, followed by standard wood bonding process using Henkel Purbond adhesives.

A similar surface modification process can be utilised for other hardwood species with specific Surf-Bond in conjunction with polyurethane adhesives as listed in Table R1 below. However, CSIRO's laboratory-scale assessment was conducted only for Blackbutt, Blue gum and Tallow wood and hence, further scale-up and industrial trials are needed to confirm the enhanced bond performance, assess the application feasibility and robustness, and optimize the procedure in industrial production conditions.

Table R1: Hardwood Adhesion Performance Using CSIRO's Technology

Hardwood species	Adhesives used	Surface modification	$\tau_{50\%}$ (MPa)	Improvement*
Vic Ash	Henkel Purbond	Surf-BOND#3	2.44	103%
Vic Ash "H3 Treat"		Surf-BOND#3	2.36	281%
Blackbutt		Surf-BOND#2	1.41	171%
Blue Gum		Surf-BOND#4	1.80	80%
Tallow Wood		Surf-BOND#3	1.58	216%
Tallow Wood "H1 Treat"		Surf-BOND#3	1.09	98%
Spotted Gum		Surf-BOND#2	1.59	218%
Spotted Gum "H1 Treat"	Bostik PU	Surf-BOND#2	1.06	100%

*Improvement relative to those without using CSIRO's surface modification technology

2. The Methodology to Improve Hardwood Coating Performance

Identification of a suitable industrial coating exhibiting long-term durability and resistance to solar exposure for hardwood in conjunction with effective surface modification technology on wood surface to enhance the coating adhesion are the combining strategies to achieve sufficient long-term coating performance of hardwood products in outdoor applications overcoming surface discoloration upon solar exposure and high-cost in maintenance, i.e. short repainting cycles due to poor paints adhesion and resultant delamination.

Commercially available PPG coatings have demonstrated long-term coating durability used for hardwood products for maintaining natural appearance of hardwood. As validated via this project, both high-gloss and low-gloss (matt) clearcoats obtained from PPG can survive up to

2000 hours Q-Sun or 4000 hours QUV accelerated weathering testing when used for coating various hardwood species. Figure R1 shows the Vic ash hardwood coated with PPG GPSP mattcoat after 2900 hours Q-Sun testing. The continuous coating layer was still flexible with sufficient strength and the wood specimens still maintained natural wood appearance with minimal discolouration.

Figure R1. Vic-ash samples coated with PPG GPSP mattcoat after 2900 hours Q-sun testing.

Various underlayer surface-modification coatings developed at CSIRO have demonstrated benefits through enhanced coating adhesion, improved UV resistance and reduced colour change over long-term Q-Sun or QUV testing. The best-performing systems listed in Table R2 are recommended for further scale-up assessment or industrial trials.

Table R2. Hardwood/Underlayer/Coating Systems with Best Coating Performance

Hardwood	Coatings*	Underlayer surface modification	Q-Sun/QUV	Colour shift
Vic Ash	HG D800	PU D101+L1198+ZnO+FeOOH	Q-Sun 2000h	15.8
	Matt-M	PVOH+L1198+Tinuvin123DW +Tinuvin400DW	Q-Sun 2000h	10.4
	Matt-GPSP2	PPG Ultraseal	Q-Sun 2000h	24.6
Blackbutt	HG D800	PU D101+L1198+FeOOH	Q-Sun 2000h	12.4
	Matt-M	PVOH+L1198+Tinuvin5333	Q-Sun 2000h	7.9
	Matt-GPSP1	PPG Ultraseal	Q-Sun 2000h	23.5
Blue Gum	HG D800	PU D101+L1198	QUV 4000h	11.1
Tallow Wood	HG D800	PU D101+L1198+ZnO	QUV 4000h	8.1

*HG=high-gloss clearcoat M=Maxmeyer

Although there is no direct correlation between the number of Q-Sun or QUV hours of accelerated weathering exposure and the number of years of hardwood coating durability in real life, the accelerated weathering results presented here might still be taken as a rough estimation: surviving 2000 hours of Q-Sun or 3000-4000 hours of QUV exposure might correlate to approximately 10 – 15 years of recommended automotive coating durability in real life.

3. Design Recommendations for Exterior Hardwood Products

A fundamental set of guidelines/stipulations for application to exterior architectural product design is also offered: any upper surfaces of external cladding element should not have an angle of less than 45° (slope declining outward from the curtain wall), and for physical gaps (where gaps are necessary) between each independent, coated element to be no less than 5mm. These physical parameters are recommended to be used as a foundation when designing any outwardly facing physical cladding components, irrespective of their rear, inward-facing mounting systems, to maximise each element's effectiveness at preventing water accumulation or stagnant water formation. The external timber cladding elements' water shedding-off effectiveness can be further improved by utilising external automotive clear coatings that have been shown through Q-Sun or QUV weathering tests at CSIRO to be significantly more effective at extending the time that UV damage occurs. These coated hardwoods are subsequently more effective at shedding-off water when combined with an implementable angle in cladding designs besides the long-term UV resistance. The effectiveness of water shedding-off may be even further enhanced by adding an additional super-hydrophobic coating. However, determining this was beyond the scope of this project and warrants further investigation.

It needs to be emphasized that the above recommendations are only for further validation in scale-up and industrial trials, rather than for immediate implementation and production. The project team is willing to provide further R&D, consulting or other form of assistance in further technology development, methodology validation, product development or technology transition to the general timber manufacturing industry.

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Appendix

PUBLICATION LIST:

1. B. Kuys, M. Gutowski, S. Li, W.S. Gutowski, A. Cerra, *“Modular Design and Assembly of Automotive and Architectural Structures: Product Integration through Adhesive Bonding”,* Advances In Manufacturing Science and Technology, Vol. 40, No. 3, 2016. DOI: 10.2478/amst-2016-0013.

2. S. Li, B. Belleville, M. Gutowski, B. Ozarska, *“Achieving long-term adhesion and bondline durability with difficult-to-bond Australian hardwoods species”.* Proceedings of the 61st International Convention of Society of Wood Science and Technology, Nov. 5-9, (2018) Nagoya, Japan. DOI: 10.13140/RG.2.2.29358.56648.
3. S. Li, B. Belleville, M. Gutowski, B. Ozarska, *Poster Presentation: “Achieving long-term adhesion and bondline durability with difficult-to-bond Australian hardwoods species”.* International Convention of Society of Wood Science and Technology, Nov. 5-9, (2018) Nagoya, Japan.

4. B. Kuys, M. Gutowski, S. Li, W.S. Gutowski, *“Novel technologies for improving adhesion and durability of architectural coatings to wood-based substrates and wood-plastic composites (WPC)”.* Proceedings of 13th International Conference *„Advances in Coatings Technology - ACT’18*”, Paper No. 29, Sosnowiec 13-15th November 2018.

5. M. Gutowski, B. Kuys, S. Li, *“Factors controlling adhesion and durability of architectural coatings on bio-composite substrates”.* Accepted for publication in Journal of Machine Construction and Maintenance, 2/2019 (113). ISSN 1232-9312.