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HYBRID LVL PANELS MADE OF EUCALYPT AND PINE WOODS DECAYED BY WHITE-ROT FUNGUS

LVL panels have been employed for structural purposes on a large scale, replacing not only solid wood, but also other materials, due to their high mechanical properties combined with an ecological appeal. This study aimed to investigate the degradation which occurred in hybrid LVL panels composed of pine and eucalypts woods from fast-growing plantations, layered as six different combinations of five veneers. In order to evaluate the behaviour of the panels underwater immersion, some samples were subjected to an ageing process performed prior to mycological tests. For characterization, mass loss, colourimetric properties (CIELAB method) and Janka Hardness were the used parameters. The results indicated that the panels made with adjacent eucalypts veneers were more susceptible to water immersion. The panels made with pine veneers as cores showed lower hardness. The hybrid panels combined high durability and good water resistance.

Keywords: wood panels, *Trametes versicolour*, CIELAB method

Introduction

It is a historical fact that extractivism has caused the depletion of existing native forests in Brazil. On the other hand, since the 1960s, increasing government tax incentives have subsidized many plantations of exotic species, resulting in the current forestry scenario, wherein there is a great area of exotic forests, mainly of species from the *Pinus* and *Eucalyptus* genres.

Initially, the aim of these exotic species plantations was to supply sleepers for railway industries and charcoal for locomotives. Currently, their main use occurs in pulp and paper production. However, alternative purposes such as the

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lumber industry and reconstituted wood panels could provide products with greater added value [Müller et al. 2015; Delucis et al. 2016].

Regarding the production of panels, Laminated Veneer Lumber (LVL) can be considered a promising alternative, since it allows for the removal of the natural defects of wood growth, such as knots and irregular grain orientation [Aydin et al. 2004]. Another positive factor is that these panels do not present defects from growth stresses and drying, such as cracks and warping [Kiliç 2011; Ardalany et al. 2013].

LVL is a composite for external use, composed of multiple wood veneers with thicknesses ranging between 2 and 6.4 mm, which are glued together by a thermosetting adhesive. In these panels, the fibres of the veneers are preferably oriented in a lengthwise direction and phenol formaldehyde is the main adhesive used [Frąckowiak et al. 2014; Melo and Del Menezzi 2014].

Various studies showed that compared to solid wood of a specific species, LVL panels have more predictable and reliable properties, greater dimensional stability, higher mechanical properties and durability [Nzokou et al. 2005; Kurt et al. 2011; Xue and Hu 2012]. Other studies highlighted that, due to the low energy required for their manufacture, LVL panels could replace materials such as plastic, steel and concrete [Hashemi et al. 2010; Tenorio et al. 2011].

Various process variables, however, should be considered to obtain qualified panels, such as the layout position of the veneers. According to Aydin et al. [2004], from a classification method of the veneers, it is possible to save many resources because lower-cost veneers can be used and the disposal of manufactured panels with inadequate properties can be reduced.

Existing studies present few results about the effect of the veneer layout on the technological properties of LVL panels. Nevertheless, this information is very useful, as the available veneers in the panels industry present high heterogeneity due to factors, such as fast growth, genetics and climatic parameters, among others [Aydin et al. 2004; Müller et al. 2015].

Ozarska [1999] indicated that the mixture of veneers from different species can be a good strategy for obtaining LVL panels with a good cost-benefit relationship. The same author, when comparing softwoods with hardwoods, felt that the former is more susceptible to bonding, but the hardwoods provide increased strength and structural rigidity to the performed panel. For Ido et al. [2010], the choice of a hardwood or a softwood is very important for the price of the LVL panel due to the aesthetic and architectural aspects.

Using the same material as the present study, Müller et al. [2015] evaluated the mechanical properties of LVL panels with six different combinations of five veneers glued with *Pinus taeda* and *Eucalyptus saligna* by means of flexural tests. The authors found that the use of three or more veneers of *Pinus taeda* harmed the mechanical properties. On the other hand, the bonding between adjacent veneers of *Eucalyptus saligna* damages the grip of the panels. The present study evaluated the same material used in the study by Müller et al.

[2015] but focused on the biological resistance of these panels when subjected to accelerated ageing by a leaching procedure and fungal decay using white-rot fungus *Trametes versicolour.*

Materials and methods

Wood veneers

Six trees of *Eucalyptus saligna* and *Pinus taeda* were selected from homogeneous plantations overturned at 25 years in southern Brazil, according to procedure D5536 [ASTM D-5536:2014]. Soon after, baseline logs of 1.3 m in length which were sectioned, were subjected to a peeling process on a rotary lathe (spindleless lathe type), yielding veneers with dimensions of 1.3 m × 3.2 mm (width × thickness). Then, the veneers were radially cut to 0.8 m in length.

In order to prevent the premature attack of xylophagous organisms, the veneers were immediately artificially dried at a temperature of 102 ±3°C, obtaining a moisture content of about 5%. After that, in order to stabilize its equilibrium moisture content at 12%, the material was placed in a climate chamber (20°C and 65% RH) according to the recommendations proposed by procedure D4442 [ASTM D-4442:2016].

In order to reliably select the veneers that best represented the assembled products, the specific gravity and moisture content were evaluated for each veneer in accordance with procedure D2395 [ASTM D-2395:2014]. Then, based on the average values of these parameters, veneers with more disparate specific gravity and moisture content values and veneers that had visually identifiable defects were discarded.

Adhesive

The commercially-known Cascophen HL-2080 was used as the adhesive. This is a phenolic resin, resole type, alkaline in aqueous solution, with a phenol--formaldehyde basis. The resin had a solids content of between 49 and 51%, a Brookfield viscosity between 400 and 800 centipoises, pH between 11.5 and 13 and gel time between 6 and 9 minutes. Subsequently, a mixture was prepared with the phenolic resin (100 parts), a commercially purchased micro pulverized coconut shell as the filler (5 parts), wheat flour as the extender (5 parts), and water (5 parts).

Manufacture and properties of the LVL panels

The glue application used a glue spread rate of 200 $g \cdot m^{-2}$. Then, the panel composed of the veneers was cold-pressed for a period of 60 minutes. Thereafter, a press was used with 1.4 MPa, with plates heated at a temperature of 135°C for 15 minutes. Finally, the panels with the dimensions of 47 cm × 37 cm

× 1.6 cm (length × width × thickness) were placed in a climate chamber (20°C and 65% RH) in an upright position, until stabilization of their moisture content occurred.

In order to evaluate the effect of the layout of the veneers in the properties of the panels, the veneers of *Eucalyptus saligna* and *Pinus taeda* woods were combined in six different positions (fig. 1).

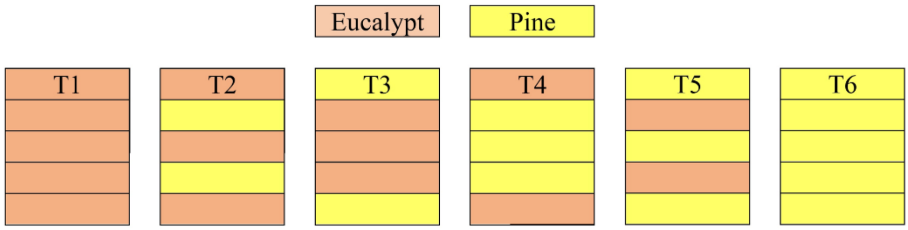

Fig. 1. Experimental plan proposed for the combinations between the eucalypt and pine veneers

Average and standard deviations for physicomechanical properties of the LVL panels are presented in table 1, based on the apparent density (as ASTM D-2395), flexure strength and modulus of flexure (both in flatwise position as ASTM D-3043), which were previously published in Müller et al. [2015].

Table 1. Physicomechanical properties of the six LVL panels before both the leaching and ageing tests

	T1	T2	T3	T4	T5	T6
Apparent density (kg·m^{-3})	898 ±2.74	793 ±2.71	778 ±2.33	739 ±2.92	726 ±3.10	639 ±2.97
Modulus of elasticity (MPa)	22385 ±6.44	20804 ±5.88	20367 ±4.14	16489 ±9.22	16384 ±13.5	15270 ±10.0
Flexure Strength (MPa)	168 ±10.4	151 ±5.58	146 ±9.23	139 ±11.8	131 ±9.05	100 ±18.8

Leaching test of samples

LVL panels were subjected to weathering cycles based on a modified EN-84 [BS-EN 84:1997] normative. Specimens were placed in separate containers (12 samples of each type of panel) and fixed with weights to avoid that samples float. Afterwards, water is poured into the containers until samples were submerged and a vacuum of 4 kPa for 20 min was applied; then, the water was renewed with fresh water totaling nine replacements over 14 days. The leached specimens were stored at 20°C and 50% relative humidity until they were tested. Specimens were weighed before and after leaching.

Decay tests

The laboratory test of resistance to fungal decay was carried out according to a modified EN 113 [EN 113:1996] using specimens of LVL panels (dimensions = 40 × 25 × 16 mm^3) previously leached and then inoculated with the rot fungi into Petri dishes with a diameter of 120 mm. To compare the LVL panels between type (six veneers combinations), leaching test (leached and unleached samples) and decay test (decayed and unexposed samples), five specimens for each condition were used.

The decay test of LVL panels was performed with the white-rot fungus *Trametes versicolour* (L.) Lloyd (TR489). The incubation period was 12 weeks at 23°C ±2°C and at a relative humidity of 60% ±5% to allow the colonization of the specimens by mycelium. Afterwards, colonised specimens were carefully removed from agar plates, taking away the surrounding mycelia of the samples. Finally, the specimens were conditioned in a climatic chamber at a temperature of 23°C ±2°C and a relative humidity of 50% ±5% until they achieved a stable mass.

Mass loss

In order to assess the grade of durability, the initial dry mass (m_i) and the final dry mass after incubation (m_f) were determined by oven drying the specimens at 103°C ±1°C. The mass loss (ML) due to a fungal attack of each specimen was calculated as a percentage of the initial dry mass according to the Equation: ML (%) = $((m_i - m_f) / m_i) \times 100$. Where: ML= mass loss (%); m_i = mass before decay test (g); m_f = mass after decay test (g).

Colour measurements

Changes in chromatic characteristics of the LVL panels was measured by means of a portable colourimeter Konica Minolta brand, CR-400 model, configured with a D45 source light at an observation angle of 2º, according to CIE-Lab colour space coordinate system L*, a*, and b*. For this procedure, colourimetric parameters were measured: brightness (L*), green-red (a*) and blue-yellow (b*) coordinates.

Janka Hardness test

The Hardness of the decayed samples and the healthy group was evaluated in accordance with the Janka method, using a universal testing machine, EMIC brand, DL 30000 model. In this test, a crosshead speed of 6 $mm \cdot s^{-1}$ was used.

Statistical analysis

All data (mass loss, colorimetric parameters and hardness) were subjected to multifactorial analysis of variance (MANOVA) tests prior to Fisher tests at levels of significance of 1% and 5%.

Results and discussion

Mass loss

A comparison between the mass loss averages (fig. 2) indicates the effect of the combinations between the six wood veneers made of eucalypt and pine led to specific decay processes, wherein the panels composed exclusively by wood veneers from the same species (T1 with eucalypt and T6 with pine) underwent a more prominent influence of the ageing process previously performed by leaching. Therefore, accounting for all the samples, there were no significant differences between aged and non-aged samples (F value = 0.43; $p > 0.05$) nor between the type of panel (F value = 1.59; $p > 0.05$).

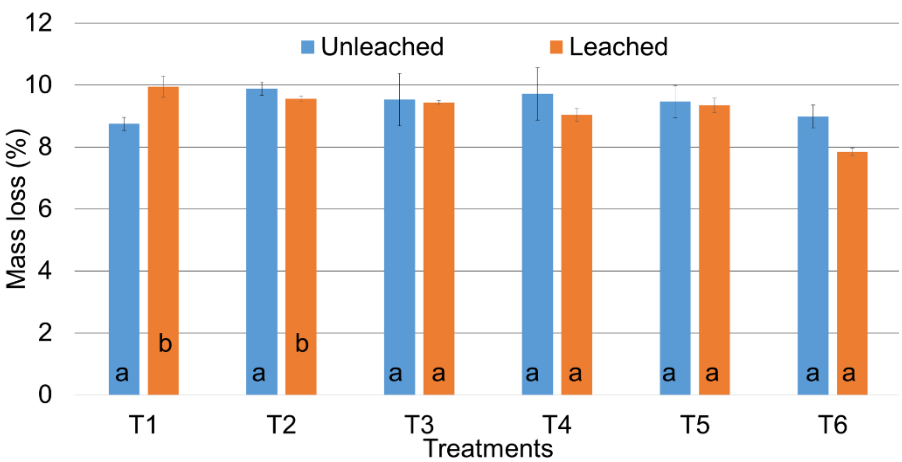

Fig. 2. Mass loss of both leached and unleached LVL panels after 12 weeks of exposure to *Trametes versicolour* fungus

Interesting results between panels combinations were found for the panels made exclusively with eucalypt veneers (T1), which presented a greater rate of mass loss up to 13% in a comparison to leached and unleached samples. On the other hand, the pine panels (T6) presented a much higher decay resistance. This infers a greater fragility to water contact related to the adhesion of adjacent eucalyptus veneers. Therefore, the water immersion possibly conditioned the mass loss levels by leaching of the extractable components from wood, which mainly consist of phenolic groups, flavonoids and proanthocyanidins [Vek et al. 2013]. According to background studies, there is a consensus about the important role of wood extractives in its natural resistance to xylophagous fungi, mainly due to phenolic and terpene compounds [Shultz et al. 1995; Antwi--Boasiako et al. 2010].

Regarding the hybrid panels (T2, T3, T4 and T5), differences in the mass loss levels were not evident, in a comparison between the veneers layout nor leached and unleached samples. Besides that, based on weight loss levels previously published for *Pinus* spp. (≈ 50%) and *Eucalyptus* spp. (≈ 60%) woods [Vivian et al. 2015], the studied LVL panels presented a greater biological resistance than the softwood and hardwood themselves when they were decayed by white-rot fungi.

Colour changes

As shown in figure 3, both the biodegradation caused by a fungal attack (F value = 149.52; $p < 0.01$) and that attributed to ageing by leaching (F value = 9.19; $p < 0.01$) implied a decrease in the averages for L*, although the former promoted a more significant effect. In this context, colour changes in the wood surfaces attributed to water immersion can be explained by the photochemical reactions which mainly occurred in the chromophores groups of the lignin [Sandak et al. 2014]. Regarding the biodegradation, white-rot fungi (like *Trametes versicolour*) performs an enzymatic process that affects both the lignocellulosic sugars and lignin. And hence, leading to changes in physicochemical characteristics of the wood, represented by noticeable effects on the wood surface, which becomes greyer and darker [Råberg et al. 2005; Herrera et al. 2015].

In a comparison between unexposed and decayed samples, high decreases in L* levels were found for panels T1, T2 and T4, which were of 27.66%, 19.32% and 26.61%, respectively. The same treatments (T1, T2 and T4) also presented high decreases in L* attributed to the ageing by leaching, which in percentage values were 13.89%, 19.72% and 12.33%, respectively. This indicates that the panels made with eucalyptus veneers at the extremities were more susceptible to surface depreciation. This can be attributed to the higher number of extractives and some carbohydrates possibly released by the eucalyptus veneers in comparison to the pine veneers [Lourençon et al. 2016].

Similar to the results discussed about the L* levels, the a* levels indicated that the panels made with eucalypts veneers placed at the extremities (T1, T2 and T4) showed higher changes in comparison to the others, which were not due to either the biodegradation (F value = 2.82; $p > 0.05$) or the leaching testing (F value = 0; $p > 0.05$). Therefore, these parameters did not significantly affect the a* levels. However, the biodegradation mechanism increased the a* levels in the panels made with pine veneers at the extremities, especially for panels T3 and T6.

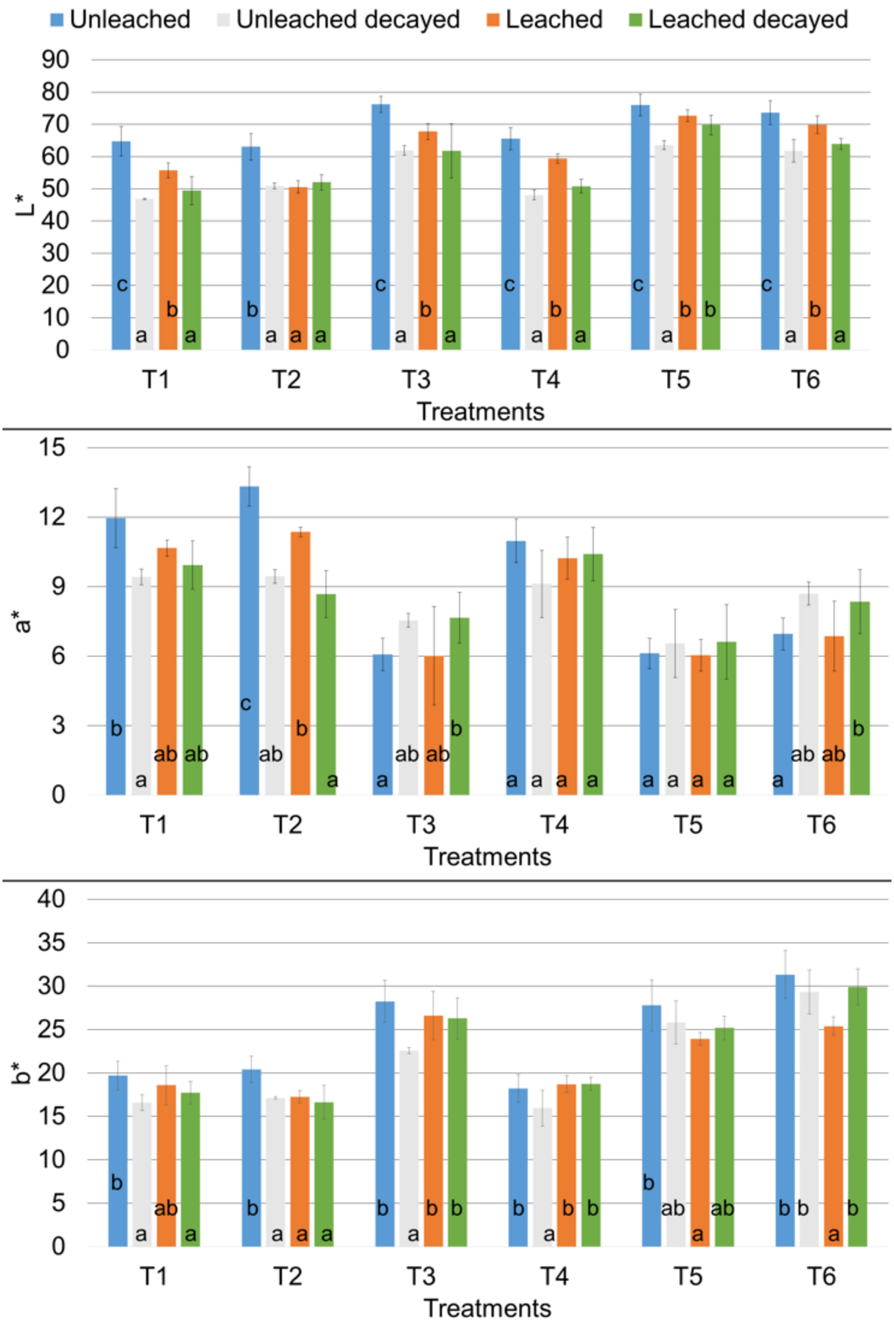

Fig. 3. Colourimetric parameters of both leached and unleached LVL panels after 12 weeks of exposure to *Trametes versicolour* fungus

Regarding the b* levels, similar to those discussed about the L* values, the biodegradation mechanism leads to decreases (F value = 6.63; $p < 0.05$). Moreover, similarly to the a* levels, the changes in b* levels were not sensitive enough to describe changes in wood colour attributed to the leaching tests in an isolated way (F value = 2.18; $p > 0.05$). According to Reinprecht and Hulla [2015], there are a number of competing and sometimes opposing factors that influence this property, including fungicide or modification agents present in the wood, the ageing history of the wood before the fungal attack, cellulolytic and other bio-mechanisms of decay, the degree of decay, the uniformity of decay, the colour of the fungal mycelia, and the distribution of the fungal mycelia in cells of wood.

Hardness

Regardless of the position of the different wood veneers, the decayed panels presented a decrease in their hardness compared to those unexposed, even though the equilibrium moisture content remained approximately constant (8-12%) (fig. 4). Similarly, although to a lower degree, there was a decline in hardness levels attributed to the prior ageing performed by leaching.

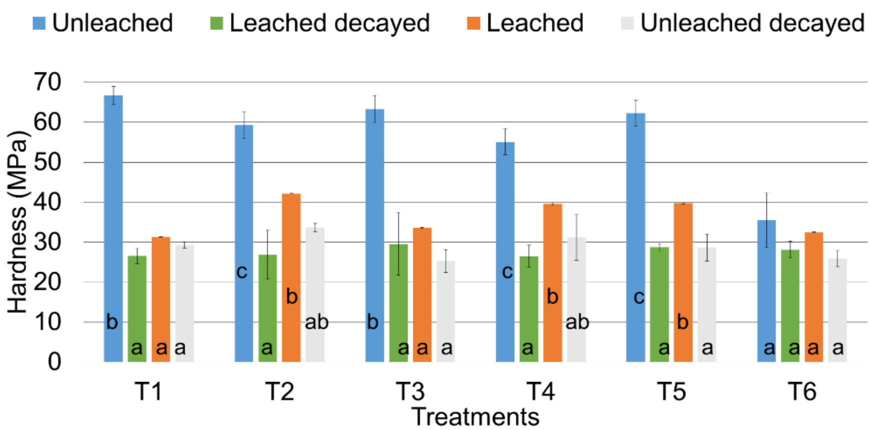

Fig. 4. Hardness of both leached and unleached LVL panels after 12 weeks of exposure to *Trametes versicolour* fungus

The unleached panels with cores comprised of two or more eucalypt veneers (T1, T3 and T5) presented higher hardness levels than the others. However, in a comparison between leached and unleached panels, it was found that the bonding between adjacent eucalypt veneers was highly suitable to water action. This also indicates that although Janka hardness is a mechanical test performed on the wood surface, the obtained results describe mechanisms (interactions in glue lines between the veneers) which occurred in internal layers of the panels. This can be attributed to the propagation of stresses through the interfaces of the veneers and the cracks formation, since the pull load carried out during the mechanical test also leads a compressive load, and thus, the overall stiffness plays an important role. Because of that, the higher the number of pine veneers, the lower the panel hardness.

Still based on the hardness levels, the aged panels with eucalypt veneers at the extremities (T1, T2 and T4) presented greater resistance to biodegradation than the unleached panels made with the same combination of veneers. The panels made exclusively with pine veneers (T6) presented a low initial hardness, which was almost unaffected by both the leaching and the decay tests. This also occurred for the L* changes and can be attributed to diverse influences related to the non-defined proportion of juvenile and mature woods, the effect of the leaching tests in wood extractives, the relatively low levels read and the modified hardness test conditions [Reinprecht and Zubková 2010].

For the panels with pine veneers as side layers (T3, T5 and T6), there is a sum of the effects related to leaching and decay. On the other hand, for the panels with eucalypt veneers as cover layers (T1, T2 and T4), both the panels leached and decayed presented averages between the panels only leached and only decayed. This indicates a diverse influence of the cover veneers from different wood species on the mechanical properties of the LVL panels in hardness.

As before, the hybrid panels (T2, T3, T4 and T5) presented intermediate properties in relation to the single panels formed only with eucalypts (T1) or pine (T6) veneers after the ageing process by leaching. In general, LVL panels with only eucalypts veneers (T1) presented both higher biological resistance and greater damage underwater action. Therefore, the hybrid panels T2 and T4 may be recommended for outdoor uses based on both their biological resistance and adhesion quality.

Conclusions

Although the panels made with the same species (T1 and T6) showed different mass losses, in a comparison between unexposed panels and those aged by leaching this parameter behaved as a somewhat useful tool for the evaluation of LVL hybrid panels subjected to decay tests.

The evaluation by means of colourimetric technique focused on the veneers used at the extremities, wherein the biodegradation caused higher discolouration compared with leaching. Colour depreciation was characterized by decreases in both L* and b* levels for the decayed panels, indicating these two parameters were most suitable to evaluate LVL panels under decay. Moreover, only L* was sensitive enough to indicate colour changes attributed to the leaching tests.

Among all the characterization techniques, hardness tests yielded the best parameter in order to distinguish unexposed panels from both those decayed by white-rot fungi and those deteriorated by leaching. Furthermore, mass loss results were capable of indicating wood decay for comparisons between leached and unleached single panels (T1 and T6).

Unexposed panels made with eucalypt veneers at the core presented higher hardness levels, although two or more adjacent veneers of this species formed glue lines more easily damaged by moisture. Based on their positive characteristics - adhesion resistance to moisture and high biological resistance – hybrid panels T2 and T4 appear suitable for outdoor uses.

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List of standards

ASTM D-2395:2014 Standard test methods for density and specific gravity (relative density) of wood and wood-based materials

ASTM D-4442:2016 Standard test methods for direct moisture content measurement of wood and wood-based materials

ASTM D-5536:2014 Standard practice for sampling forest trees for determination of clear wood properties

BS EN-84:1997 Wood preservatives. Accelerated ageing of treated wood prior to biological testing. Leaching procedure

BS EN 113:1996 Wood preservatives. Test method for determining the protective effectiveness against wood destroying basidiomycetes. Determination of the toxic values

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