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Use of Carbon and Basalt Fibers with Adhesives to Improve Physical and Mechanical Properties of Laminated Veneer Lumber

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Abstract: Climate change is one of the main factors influencing the research of environmentally friendly materials. This is why the use of engineering fibers as a reinforcement technique in wood, in order to increase its mechanical properties, has recently been investigated. This research presents the results obtained from the use of carbon and basalt fiber fabrics as a reinforcement for microlaminated Radiata Pine wood panels at a laboratory scale using the adhesives epoxy resin and polyvinyl acetate. Tests were carried out in comparison to the control boards, relating the physical properties obtained in terms of thickness swelling by 48 h-water immersion with a decrease of 19% for the polyvinyl acetate and carbon fiber matrix reinforcement, about the mechanical properties evaluated, a better performance was obtained for the epoxy resin and carbon fiber matrix reinforcement and in terms of flexural stiffness and strength (in flatwise), tensile strength and Janka hardness, with an increment of 31%, 38%, 56% and 41%, respectively.

Keywords: laminated veneer lumber; basalt fiber; carbon fiber; epoxy resin; polyvinyl acetate

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1. Introduction

In engineering, specifically in the field of construction, the aim is to use raw materials of the highest quality and at an affordable cost that allows for efficient construction. However, the materials commonly used in this sector (such as steel, concrete, and brick) emit more greenhouse gases than a design made of wood. Replacing these materials with wood could reduce global CO_2 emissions by 14–31% and global fossil fuel consumption by 12–19%, making a key contribution to the fight against climate change [1–3].

Solid wood is characterized by the presence of cracks, knots, growth stress, and limited length [4]. This is why wood composites were introduced, and among them, the creation of Laminated Veneer Lumber (LVL) arose from the need to upgrade solid wood's mechanical properties. LVL is an engineered wood-based product manufactured from veneers that are rotary peeled, dried, and laminated together with parallelly oriented grains under heat and pressure with a waterproof adhesive and whose veneer grain is usually oriented in a single direction, although cross-grained sections are also manufactured to offer tailored mechanical properties. Applications include beams, columns, headers, joists, rafters, scaffold planks, and truss chords [5–7]. LVL is a reconstituted dimensional timber that is usually twice the strength of dimensional timber of the same species manufactured from rotary peeled veneers of spruce, pine, or Douglas fir of 3 mm thickness; in general, their mechanical properties are more uniform compared with solid timber [5,8]. However, microlaminated boards produced from these tree species have low mechanical properties, and they attain good dimensional stability, good homogeneous mechanical properties, and great durability [4,7]. In order to generate an increase in LVL physical-mechanical and thermal properties and a high structural application, the addition of engineered fiber fabrics, such as carbon or basalt fiber, as reinforcement for LVL boards can be a great opportunity.

Nowadays, carbon fiber (CF) and basalt fiber (BF) are typical reinforcing materials in polymer composites, and recently, BF has been subjected to more investigation [9]. The advantages of carbon fiber (CF) compared to other reinforcement fibers are its low density, high tensile strength, stiffness, and chemical resistance [10]. Carbon fiber is a great option to use as reinforcement in structural terms, as well as in aerospace, automotive, and wind energy sectors, among others. Despite its great advantages, CF's main problem is a high production cost, which creates a considerable advantage for basalt fibers (BF), whose price is one-third that of carbon fiber. Among the benefits of basalt fiber are that it has high thermal resistance, high thermal insulation, high corrosion resistance and is environmentally friendly [10,11].

To generate the adhesion of the reinforcement fibers with wood, two types of adhesives will be studied. The first one is epoxy resin (ER), a thermosetting adhesive of high rigidity, resistance to chemicals, low shrinkage, and excellent thermo-mechanical characteristics [12]. The second one corresponds to a thermoplastic adhesive: Bicomponent Polyvinyl acetate (PVAc) type D4. Among its advantages are resistance to humidity under controlled environmental conditions, its price compared to epoxy resin, faster solidification, easier handling, cleanability, and lower environmental impact [13]. This last feature is related to the fact that, currently, most Fiber Reinforcement Polymers (FRPs) use epoxy or polyester resins as a matrix [14], but there are other adhesives that are less harsh to the environment than conventionally used resins, such as the PVAc adhesive that could substitute the polymeric matrix of FRP [13].

Since FRP materials have become popular, several authors have studied the reinforcement of different construction materials with engineering fibers, for example, in concrete mixtures [15], coral sand cement mortar [16], geopolymer concretes [17], geopolymers [18], oil well cement [19], solid wood [20,21], vintage wood [22], wood beams [23] and others, to improve their mechanical properties, restoring construction materials and finding environmentally friendly reinforcements.

Specifically in the case of wood-based panels, in 2023, Zhang et al. [24] proposed a hollow glulam beam design with stiffening plates in a hollow rectangular cross-section reinforced at the bottom with carbon and basalt reinforcement fibers. In 2022, Núñez-Decap et al. [11] reinforced plywood with carbon and basalt fiber combined with epoxy resin and polyvinyl acetate adhesives to enhance their physical and mechanical properties. During the same year, the authors Rescalvo et al. [25] also reinforced LVL with carbon and basalt fibers with polyurethane adhesive to enhance their mechanical properties under shear and compression stresses. In 2021, Gallego et al. [26] also reinforced LVL panels with carbon and basalt fibers to improve their bending properties, but in this case, the reinforcement fibers were placed between the last and the penultimate veneer of each side of the board. In 2021, Wdowiak-Postulak and Swit [27,28] studied the reinforcement of pine beams made from glued laminated timber with subsurface basalt fibers and basalt fiber reinforcement of bent heterogeneous glued laminated beams. In 2018, carbon fiber-reinforced LVL beams were tested to improve their bending properties by Globa et al. [29]. The effect of grain orientation on the carbon fiber reinforcement polymer (CFRP) to LVL bond has also been studied in order to analyze its behavior by Subhani et al. 2017 [30].

The main problem the present research tries to solve relates to the physical-mechanical low performance of wood veneers compared to the primary construction materials currently used, such as steel and concrete.

Given the foregoing, the main opportunity to be addressed in this research is to improve the physical-mechanical performance of LVL panels to structural applications through the incorporation of high-performance engineering fibers as reinforcement. Although PVAc adhesive does not have structural applications, we seek to compare it to epoxy resin to see if PVAc could be a non-toxic alternative to reinforcing LVL panels.

2. Materials and Methods

2.1. LVL Panels

The Laminated Veneer Lumber (LVL) panels were fabricated with five flawless veneers of *Pinus radiata* D. DON (with an average density of 456 kg/m^3 and an average moisture content of 6.90%) and bonded with Phenol Formaldehyde (PF) adhesive. The veneers' dimensions were 500 mm length × 500 mm width and a 2.2–3.6 mm thickness range. The difference in veneer thicknesses is due to raw material availability of common thicknesses used in Chile; however, all the samples were manufactured with the same configuration of veneer thicknesses (the thinner ones located towards the board surfaces, and the thicker ones were located in the center). The veneers used were donated by PRODIMA-LAB (Concepción, Chile).

2.2. Reinforcement Fibers

The engineering fibers used in the reinforcement of LVL panels were carbon fiber (CF) and basalt fiber (BF), both provided by Aura Industrial (Santiago, Chile). The fibers' properties, according to their data sheets, are listed in Table 1.

Table 1. Properties of the reinforcement fibers used by Aura Industrial data sheets [31].

Properties	Carbon Fiber	Basalt Fiber
Fabric	Bidirectional weaving	Bidirectional weaving
Thickness (mm)	0.28	0.18
Grammage (g/m^2)	200	200
Tensile Strength (MPa)	≥3500	≥1000

2.3. Adhesives

The fiber reinforcement polymer (FRP) panels FRP-LVL, were glued with polyvinyl acetate adhesive (PVAc-X016 D4 Franklin) supplied by SlipNaxos Chile S.A. (Santiago, Chile) and epoxy resin (ER) with its hardener (Aura 280 and its hardener Aradur 963) supplied by Aura Industrial and Comercial SpA (Santiago, Chile).

Two types of adhesives were used on each board because the manufacturer of the reinforcing fibers recommends using epoxy resin to adhere them to the wood veneer, and in search of a non-toxic replacement, it was decided to try PVAc.

2.4. Characterization of Adhesives

The adhesive viscosity was measured according to ASTM D1084-16R21 [32] with a Brookfield viscosimeter model LVF with a spindle N°6, 150 rpm to PF adhesive, and 200 rpm to PVAc adhesive.

The PF and PVAc adhesives' pH was measured according to ASTM E0070-19 [33] with a Hanna Instruments pH-meter model 211. The epoxy resin pH was measured with a pH-paper test. The electrical conductivity of the adhesives was measured with a multiparameter tester. And the adhesive's solid content was measured according to ASTM D1490-01R18 [34].

2.5. Reinforcement of LVL Panels

Three different types of LVL panels were configured, as shown in Figure 1. The first one corresponds to the control sample, composed of 5 veneers glued with phenol formaldehyde adhesive. The second one corresponds to the carbon fiber-reinforced LVL panel (CFRP-LVL), which have two layers of CF, one between the first and the second veneer and other one on the opposite surface (tension side), and the third panel corresponds to the basalt-reinforced LVL panel (BFRP-LVL), which have two layers of BF, one between the first and the second veneer and other one on the opposite surface (tension side). The purpose of the board being reinforced by only one surface is to allow the user to decide whether or not to leave the fiber exposed.

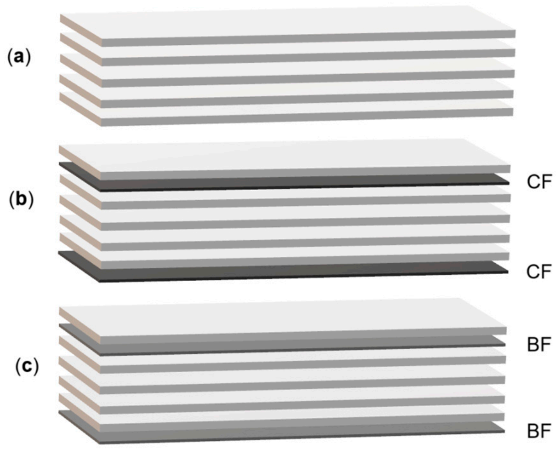


Figure 1. The control LVL panel, carbon fiber reinforced LVL, and basalt fiber reinforced LVL panel were configured as follows: (**a**) Control LVL panel; (**b**) LVL panel reinforced with carbon fiber; and (**c**) LVL panel reinforced with basalt fiber.

Both reinforcement fibers, CF and BF, were impregnated on both sides with ER and PVAc adhesives, forming different samples, while the rest of the veneers were glued with PF adhesive. The difference in the grammage used is due to the different solids content of the adhesives and also to the manufacturer's recommendations. (The experimental design is presented in Table 2).

Table 2. Design of experiment.

ID	N° LVL	Adhesive Grammage (g/m^2)
P	4	200
ER-CF	4	250
ER-BF	4	250
PVAc-CF	4	400
PVAc-BF	4	400

Once properly prepared, the panels were subjected to two pressing steps; the first step corresponded to high-temperature pressing, and the second step to cold pressing. The hot-pressing step consisted of subjecting the panels to a specific temperature of 130 °C, using a three-stage pressing cycle, as illustrated in Figure 2. The objective of the first cycle is to generate adhesion between the wood and the adhesive, the second cycle seeks to consolidate the adhesive, and the third cycle is to prevent the pressure decompensation from being abrupt and producing the breakage of the bonding chains (blowing).

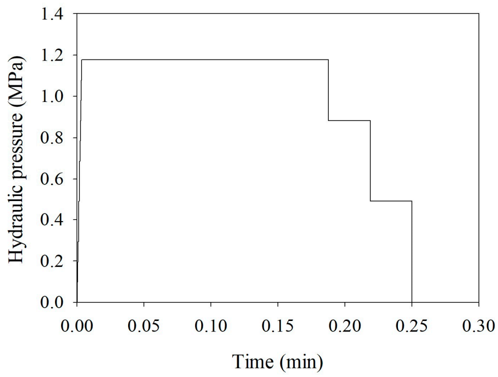


Figure 2. Three-stage pressing cycle for both hot and cold pressing.

After hot pressing, the panels were immediately subjected to the cold pressing stage at an ambient temperature of 20 °C, under the same pressure and time conditions of the first pressing step (Figure 2). The purpose of cold pressing is to accelerate the adhesive curing process.

After pressing, the LVL panels were conditioned for 7 days at 23 ± 3 °C and 65% relative humidity. Then, the LVL panels were formatted in 480 mm length × 480 mm width and a dimension range of 14.7–15.6 mm thickness and finally cut to the dimensions of each specimen according to European and American standards to determine their physical, mechanical, and thermal properties.

2.6. Physical Properties

Initially, density was assessed in a total of 40 specimens, with each specimen measuring 50 mm in length and 50 mm in width. The evaluation was conducted in accordance with the European standard UNE-EN 323 [35]. The Amersham plc AMCK6693 gamma-ray densimeter was employed to measure the density profile of the panel's specimens. The densimeter scanned directly through the sample's thickness with an incremental step of 0.1 mm. A total of 5 specimens from each LVL sample, measuring 50 mm in length and 50 mm in width, were subjected to density profiling.

To determine the moisture content, 20 specimens were assessed following the guidelines of the European standard UNE-EN 322 [36]. Furthermore, thickness swelling was evaluated in 40 specimens, each measuring 50 mm in length and 50 mm in width, by the conditions specified in the European standard EN 317 [37].

2.7. Mechanical Properties

2.7.1. Static Bending Tests

The bending properties of both the control and reinforced LVL panels were assessed through mechanical tests utilizing a four-point static bending setup. The positions tested included flatwise (FW) (oriented as shown in Figure 1) and edgewise (EW), following the specifications and methodology outlined in the European standard UNE-EN 408 [38]. For each LVL sample, a total of 10 specimens were subjected to testing.

In the flatwise position, the specimens measured 450 mm in length, 50 mm in width, and 15 mm in thickness. In the edgewise position, the specimens had dimensions of 450 mm in length, 20 mm in width, and 15 mm in thickness. The observed failures in the specimens were carefully noted and classified, adhering to the guidelines specified in the European standard EN 310 [39].

The bending properties were determined using an Instron 100-23 universal testing machine, which was equipped with BlueHill2 software for data analysis and recording.

2.7.2. Tensile Strength

A tensile strength test was conducted on both the control and reinforced LVL panels. A total of 12 specimens per sample were tested, following the dimensional requirements outlined in the American standards ASTM D3500—Method A [40].

2.7.3. Hardness Test

The Janka hardness test was carried out on both the control and reinforced boards. A total of 6 specimens per sample were used for the test, and they had dimensions of 76 mm in length and 52 mm in width, as specified by the American standard ASTM D1037-12 [41]. The hardness value per specimen corresponds to the average of 4 indentations, two on each side.

To measure the mechanical properties, a universal testing machine, specifically the Instron 100-23, was employed. The testing machine was equipped with BlueHill2 software, which facilitated the analysis and recording of the test results.

2.7.4. Thermal Properties

The thermal conductivity test was conducted on both the control and reinforced LVL boards. A total of 5 specimens were used for the test, and they had dimensions of 100 mm in length, 50 mm in width, and 15 mm in thickness, according to the specifications provided by the American standard ASTM D5334 [42].

The Decagon KD2 PRO equipment was utilized to perform the thermal conductivity measurements on the specimens.

2.7.5. Analysis of Data

After obtaining the results, an ANOVA was conducted to assess the differences between the averages. In this analysis, significance was accepted at a level of $p < 0.05$, indicating that the observed differences were considered statistically significant.

When the differences between the results of each tested specimen were found to be statistically significant, a multivariate analysis LSD test was employed. This test helps to identify specific pairwise differences between the results of the specimens. The Statgraphics Centurion 19 software was used to perform this analysis.

The outcomes of the data analysis, including the results of the ANOVA and the relevant tables indicating the statistically significant differences, are documented and marked accordingly.

3. Results and Discussion

3.1. Characterization of Adhesives

The characteristics of adhesives used in LVL production have an important role in the quality of the final product, which can be established based on the physical and mechanical properties of the boards [43].

The characterization of the adhesives used is presented in Table 3. According to the viscosity values of each adhesive, it can be seen that ER and PVAc viscosity values are very similar and around 75% lower than PF viscosity. These results are related to the penetration depth that each adhesive can achieve [44]; in this case, PF-wood penetration was more limited, which can also be related to a great bond quality.

Table 3. Characterization of adhesives.

ID	Viscosity (cP)	pH	Electrical Conductivity (mS)	Solid Content (%)
PF	4827	12.53	24.23	42.27
ER	1200	7.50	-	93.88
PVAc	1240	2.76	13.89	52.06

The pH has a significant influence on the glue-line formation as it affects the rate of adhesive curing [45]. Regarding the pH level results, PF and ER adhesives are in an alkaline condition, while PVAc is in an acidic condition. Anyways, the pH of the adhesives should not exceed the range of 2.5–11 because, beyond these limits, the resin causes degradation of the fibers of the wood, especially in the presence of moisture [46], a situation that could happen to veneers glued with PH adhesive. Normally, a low pH affects predominantly holocellulose, while a high pH affects mainly the lignin content of the wood. Therefore, a low pH may have a more negative effect on wood strength than a high pH.

PF adhesive is more conductor electrically than PVAc adhesive; this is probably because PF adhesive has more additives like fillers, which offer benefits like increased viscosity, better mechanical properties, increased electrical conductivity, achievement of higher thermal and dimensional stability, and others [47,48].

Regarding the content of solids, PF adhesive has the least solids in its composition, PVAc adhesive has almost half of the solids in its composition, while almost the entire composition of ER adhesive corresponds to solids; in other words, it has almost no liquid in its composition. When the panel is subjected to hot pressing, evaporation of the liquid component (cure), that is, the solidification of the adhesive, forms the glue line that is responsible for the bond between the substrates [49], so as the epoxy resin has a higher content of solids, in comparison to the other adhesives characterized, it may present a better bond quality.

3.2. Physical Properties

The FRP-LVL exhibited a higher density compared to the control panel, as indicated in Table 4. The density increase ranged from 6.23% for the ER-CF sample, with a density of 563 kg/m^3, to 10.38% for the PVAc-CF sample, with a density of 585 kg/m^3. However, these differences in density between the FRP-LVL samples were not found to be statistically significant.

Table 4. Results of physical properties.

ID	Density (kg/m^3)		Moisture Content (%)		Thickness (mm)		Thickness Swelling (%) 24 h		Thickness Swelling (%) 48 h	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
P	530 ^{a}	27.29	8 ^{a}	0.64	14.33 ^{a}	0.31	1.26 ^{a}	1.81	5.13 ^{ab}	0.93
ER-CF	563 ^{ab}	43.13	10 ^{b}	0.82	14.97 ^{b}	0.44	0.74 ^{a}	1.22	4.43 ^{bc}	0.45
ER-BF	570 ^{b}	31.81	11 ^{c}	0.28	14.41 ^{a}	0.20	0.66 ^{a}	1.88	5.32 ^{a}	0.41
PVAc-CF	585 ^{b}	14.14	12 ^{d}	0.14	15.03 ^{b}	0.23	0.60 ^{a}	1.70	4.16 ^{c}	0.64
PVAc-BF	568 ^{b}	41.92	12 ^{cd}	0.40	14.20 ^{a}	0.24	0.00 ^{a}	0.00	4.83 ^{abc}	1.03

Column means are indicated with different letters (a, b, c, and d) to indicate homogeneous groups from the multiple-range test by Fisher's LSD method. This means that different letters are statistically different from each other at a 95% confidence level.

Furthermore, the density profile of the FRP-LVL samples revealed variations, particularly with a noticeable peak on the surface where the carbon and basalt fibers were positioned. This suggests that the distribution of fibers impacted the density profile of the FRP-LVL panels. Basalt fiber-reinforced samples revealed the highest density peaks, but in smaller thickness, while carbon fiber-reinforced samples revealed the lowest density peaks, but in larger thickness (Figure 3). This is consistent with the fiber's properties presented in Table 1 and with [50], who says that BF density is higher than CF density. The difference in thicknesses observed in Figure 3 is due to the thicknesses of the engineering fibers, glue lines, and small differences between the veneers themselves.

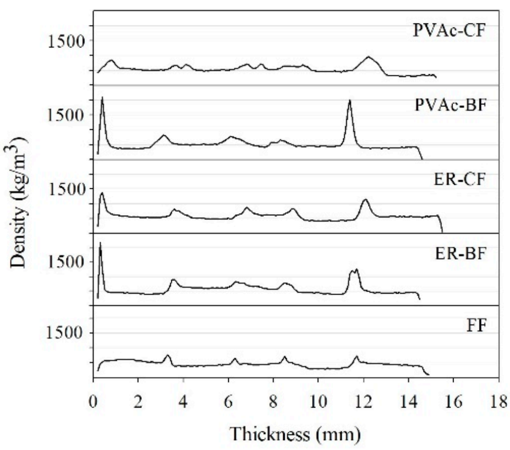


Figure 3. Density profile of the composite panels.

The density values of the FRP-LVL were found to be higher in comparison to LVL. This can be attributed to the incorporation of reinforcement fibers such as BF and CF, as well as the use of adhesives ER and PVAc, which have higher density values than wood. However, it was observed that there was no direct correlation between the type of reinforcement fiber or adhesive employed and the extent of density increase in the tested samples.

The moisture content (MC) values of the FRP-LVL samples were higher than the MC value of the control sample. Aside from the factors that are inherent to the wood itself, aspects related to the manufacturing processes of LVL influence its equilibrium MC [43]. All of the samples exhibited moisture content within the expected range for conditioning, ranging between 8% and 12%. This indicated that the samples were appropriately conditioned, and their moisture content levels were within the desired specifications.

The thickness swelling in 24 h of water immersion did not vary between the samples, but in 48 h, better dimensional stability was evidenced by the sample PVAc-CF (4.83%), which decreased by 18.91% compared to the control sample (5.13%). For the rest of the samples, there was no statistically significant difference, so in general, there was no difference in the dimensional stability between the FRP-LVL samples and the control sample, except for the sample PVAc-CF. The results of this property correspond to a percentage variation concerning the initial thickness (according to the standard indicated in the methodology).

3.3. Mechanical Properties

3.3.1. Strength and Stiffness Bending Properties

In general, the FRP-LVL samples glued with ER adhesive presented the highest results in stiffness (MOE) and strength (MOR).

In the flatwise position (Figure 4), the sample ER-CF (MOE: 8190 MPa; MOR: 86.27 MPa) presented an increase, about 30.53% and 37.61%, in MOE and MOR, respectively. For the rest of the samples, there were no statistically significant differences in comparison to the control sample.

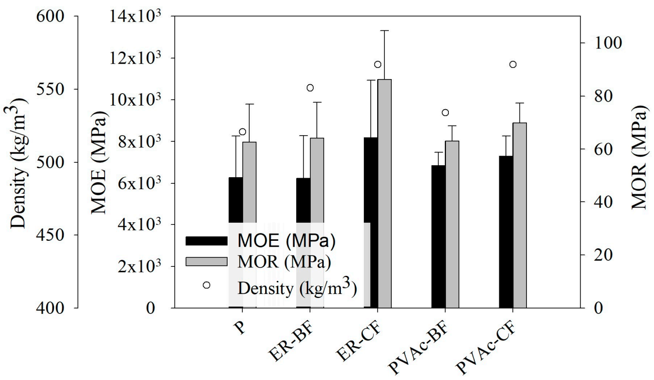


Figure 4. Results of strength (MOR) and stiffness (MOE) bending properties and density of each sample in the flatwise position (error bars indicate standard deviations).

In the edgewise position (Figure 5), there was an increase in MOE values, between ~14% and 35.93%, in the samples ER-CF; PVAc-CF (9626 MPa; 9754 MPa) and ER-BF (11,476 MPa), respectively. The MOR of the sample ER-BF (76.08 MPa) increased by 28.65%, while for the rest of the samples, in the MOR case, there were no statistically significant differences in comparison to the control sample.

In the investigations of Wang [51] and Rescalvo [25], CFRP-LVL samples presented higher values in bending properties compared to an unreinforced sample, which generally occurred in this investigation in MOE results. Furthermore, in the investigation of Wdowiak-Postulak [28], BFRP-glulam beam samples also presented higher values in bending properties compared to an unreinforced sample, which occurred in edgewise samples of this investigation.

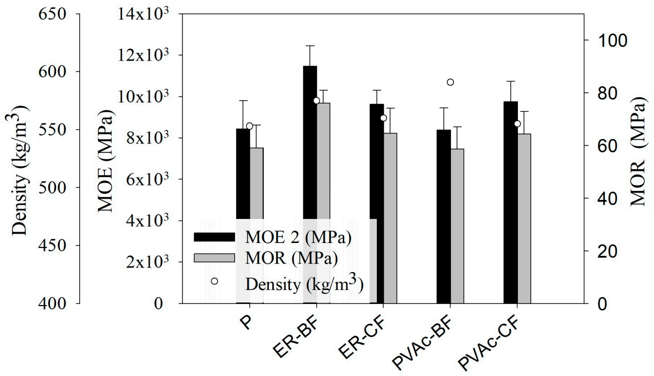
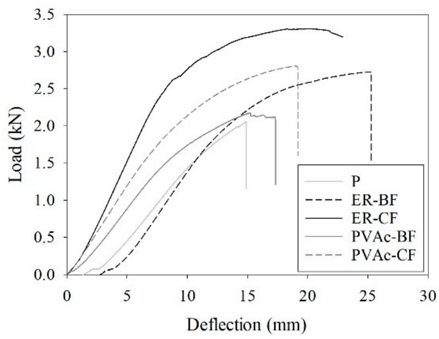


Figure 5. Results of strength (MOR) and stiffness (MOE) bending properties and density of each sample in the edgewise position (error bars indicate standard deviations).

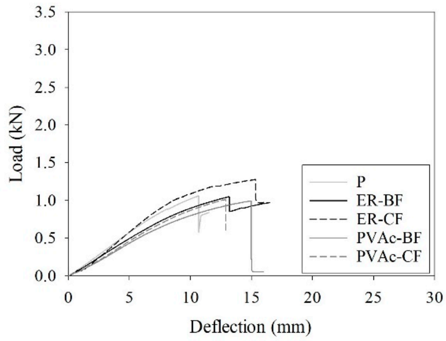
The bending test results indicated that the samples glued with ER have a higher stiffness and strength compared to the samples glued with PVAc adhesive. This might be associated with the ten-times-higher MOE of ER than that of wood [52], but also the cure temperature needed for each adhesive, because while PVAc was hot pressed, it could have lost its mechanical properties by the water evaporation and its less solid content percentage. On the other hand, thermosetting polymers of ER make excellent structural adhesives because they undergo irreversible chemical change when cured [53], and thermoset adhesives generally are stronger than thermoplastic adhesives (PVAc) [49]. Anyways, good results of ER adhesive in the matrix are not consistent with the ecological perspective of this study.

The highest bending test stiffness (MOE) results were obtained by the EW position samples, while the highest strength (MOR) results were obtained by the flatwise position samples. This result can be attributed to veneer classification and board assembly that prioritized more resistant veneers for the external layers of LVL [43]. Furthermore, all the samples tested mainly had tensile failure. However, in several cases, shear failure was observed, especially in the flatwise position tested samples. The reason lies in the fact that the flexural strength contribution of the FRP exceeds the shear strength of the veneer itself, causing this type of failure [25]. Thus, the flatwise position tested samples did not reach higher values than the edgewise position in MOE results.

The bending test load-deflection curves of the flatwise and edgewise positions samples demonstrated that the FRP-LVL panels exhibited increased maximum load and maximum deflection when compared to the LVL panels (Figures 6 and 7); these results are consistent with the results of the authors Bakalarz and Kossakowski [54] who also obtained higher maximum load and deflection values for FRP-LVL compared to the control LVL.



(**a**)



(**b**)

Figure 6. Load-deflection curves were obtained during the four-point bending test for the samples in the (**a**) flatwise position and in the (**b**) edgewise position. A characteristic curve for each sample was used as a representation of the behavior of each one.

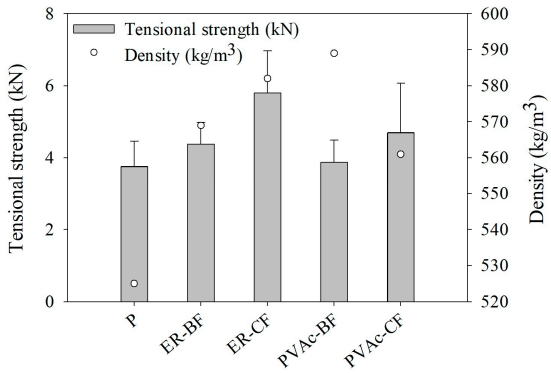


Figure 7. Results of tensile strength and density of each sample (error bars indicate standard deviations).

In both cases—flatwise and edgewise position—samples seem to present a more ductile performance than the control sample, especially samples glued with epoxy resin in the FW position. Results were also evidenced in the investigation of Rescalvo et al. [25] and probably obtained due to the high stiffness and strength properties of epoxy resin [12]. In the case of the EW position, there is not a clear patron.

About the reinforced fibers used, it can be noticed that samples reinforced with BF presented a higher deflection and a lower load than samples reinforced with CF, which evidenced the brittle property of CF and the high elongation property of BF [55]. The same results were reported by these authors.

3.3.2. Tensile Strength

The sample ER-CF (5.8 kN) increased by 54.30% compared to the control sample, while the rest of the samples did not present a statistically significant difference between them (Figure 7).

Figure 7 shows that samples reinforced with carbon fiber presented the highest values of tensile strength. In Table 1, the characteristics of each fiber used in this investigation are presented, and data sheets say that CF has a higher TS than BF. Furthermore, Wang et al. [51] explained in their investigation that the TS and MOE of CF are higher than for wood veneer, so using CF could improve the mechanical properties of LVL, and in this case, the tensile strength property. In addition, according to Dhand et al. [50], CF has a higher TS than BF.

3.3.3. Janka Hardness

The FRP-LVL increased the Janka Hardness results just in the samples reinforced with carbon fiber, between 31.52% and 41.43%, in the samples PVAc-CF (3.9 kN) and ER-CF (4.2 kN), respectively (Figure 8).

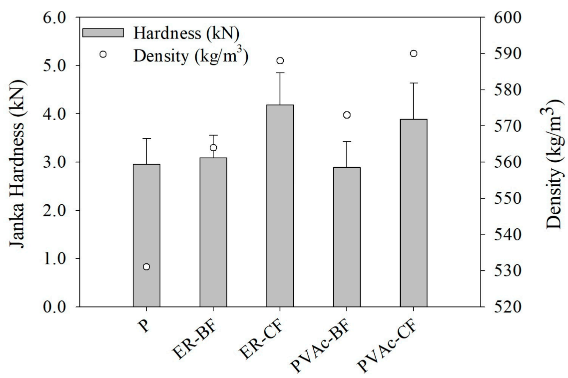


Figure 8. Results of Janka Hardness test and density of each sample (error bars indicate standard deviations).

Janka hardness is an important property in deciding the end use of FRP-LVL, especially when used as flooring components [56]. Carbon fiber-reinforced LVL showed a higher hardness than the rest of the samples, as in the study of Núñez-Decap et al. [11], probably because CF has the best mechanical properties in comparison to other kinds of reinforcement fibers.

3.4. Thermal Properties

In general, FRP-LVL maintained the thermal properties of LVL (Figure 9).

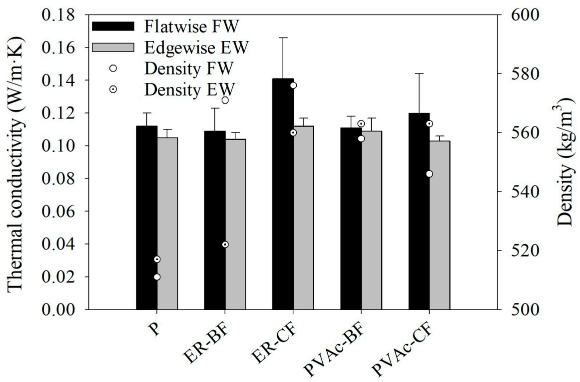


Figure 9. Results of the thermal conductivity test of each sample (error bars indicate standard deviations).

In the flatwise, the thermal conductivity of the sample ER-CF (0.14 W/m·K) increased by 25.78% compared to the control sample PF (0.11 W/m·K). This can be associated with the use of CF, as carbon-based materials, in general, present low density and high thermal conductivity [48]. On the contrary, one characteristic of the BF is its low thermal conductivity [57].

For the rest of the samples, in the flatwise and edgewise positions, there was no statistically significant difference in comparison to the control sample. Anyways, every sample in the flatwise and edgewise position presented thermal conductivity values between 0.10–0.14 W/m·K, which is the expected range, because the thermal conductivity values of panel boards, with a density of approximately 500 kg/m^3, should be around 0.13 W/m·K [58].

4. Conclusions

The tests performed evidenced that FRP-LVL modifies and, in general, improves LVL's physical and mechanical properties.

- In general, FRP-LVL increases their physical properties in 48 h water immersion when glued with PVAc adhesive. The sample PVAc-CF had the best performance, with a decrease in thickness swelling by 19%. These results introduce a good option for reinforced-LVL panels, as PVAc is a more environmentally friendly adhesive than epoxy resin and, in its case, evidenced good dimensional stability;
- FRP-LVL increase their flexural stiffness and strength properties when glued with ER adhesive; the samples ER-CF and ER-BF increased the MOE by 31% (FW), 36% (EW), and the MOR by 38% (FW) and 29% (EW), respectively;
- LVL panels, when reinforced with ER-CF, increase their tensile strength by 56% and their hardness by 41% in comparison to the control panel.

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