Bond Strength/Disbonding Behavior and Dimensional Stability of Wood Materials with Different Adhesives

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ABSTRACT: In this study, we aimed to describe the effects of adhesives [poly(vinyl acetate) (PVAc), Desmodur vinyl trie ketonol acetate, and urea formaldehyde (UF)] on wooden materials (Scotch pine and oriental beech) cut tangentially and radially impregnated with Protim Solignum, chromate copper arsenate (CCA), and Celcure AC 500 and exposed to humidity and water and heat-resistance, heating, and cooling tests. For the adhesives, the highest swelling (4.3%) was obtained for oriental beech bonded with UF and cut radially, and the lowest swelling (1%) was obtained for Scotch pine bonded with PVAc and cut radially. For the control samples, the humidity-resistance, water-resistance, heat-resistance, and heating and cooling tests decreased the bonding strength. J Appl Polym Sci 115: 438–450, 2010

Key words: adhesion; adhesives; composites; degradation

INTRODUCTION

Wood is a hygroscopic material that loses and gains moisture as a result of changes in humidity. Hygroscopic materials such as wood and other lignocellulosic materials change their dimensions with fluctuations in the relative humidity (RH). On the basis of the current moisture content of the wood and its surrounding conditions, dimensional changes in wood as a construction material will influence its effectiveness.[1]

One should appreciate that every application of wood in its natural or unprocessed state is potentially affected by its tendency toward relatively large cross-grain dimensional changes whenever significant moisture content changes in service are expected. For example, the performance of every structural connection in wood, with the possible exception of a glued joint, can be affected by different dimensional changes in the members. Even simple glued joints, including those in laminated wood members, show shrinkage or swelling stresses if the pieces put together do not have identical moisture-response properties.[2]

Today, synthetic resins are being produced for wood materials used in dry and damp conditions. They are also convenient for use in workshops and in straight manufacturing. To prevent material scraps and increase the quality, research studies have been carried out on the development of glue and its new application areas.[3]

The demand for engineered wood products, such as oriented strand board, glulam, and laminated veneer lumber (LVL), has increased because of a constant increase in the global population. The grain of each layer of veneer assembled into LVL runs parallel with each adjacent ply.[4] Being a homogeneous and dimensionally stable building material, LVL can be used where strength and stability are required.[5]

LVL panels, such as plywood, are manufactured with different synthetic resins, depending on where they are used. Phenol formaldehyde resins are generally used as a binder for exterior-grade panel production. Melamine–urea formaldehyde (UF) resins are also used for panels evaluated in damp conditions. However, it was reported that panels bonded with UF resins under exterior conditions were not as resistant as panels bonded with phenol formaldehyde resin.[6] To increase water repellency, the addition of melamine to a UF–glue mixture was found by Cremonini et al.[7] to be quite effective.

Dry shear strength and wood failure values have indicated that one-part polyurethane adhesive bonds are at least as strong as bonds of a resorcinol formaldehyde structural adhesive on yellow birch and Douglas fir. Wet shear strengths, measured after three different water-saturating test procedures, indicated that polyurethane bonds are as strong as those of resorcinol. A moderately severe two-cycle boil test indicated that the resistance to delamination of polyurethane bonds vary from high to low, whereas resorcinol bonds are completely resistant to delamination.[8]

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Uysal[9] conducted a study to determine the effects of wood pretreatment on the bonding strength of wood materials. Beech, Scotch pine, oak, and chestnut were impregnated with Tanalith-C, creosote, and Protim 230 WR paraffin by full-cell methods according to ASTM D 1413-76 standards. After impregnation, shear strength tests were performed for samples bonded with poly(vinyl acetate) (PVAc), Desmodur vinyl trie ketonol acetate (D-VTKA), and Pattex fast. The highest shear strength was obtained for the nonimpregnated (control) and PVAc glued oak (5.328 N/mm^2), and the lowest shear strength was obtained for chestnut glued with Protim 230 WR paraffin and Pattex fast (0.169 N/mm^2). The impregnation process negatively affected the adhesive bonding strength.[9]

Because there has not been enough study on the disbonding behavior of different adhesives, the aim of this study was to compare the effects of adhesives (PVAc, D-VTKA, and UF) on wooden materials (Scotch pine and oriental beech) cut tangentially, radially impregnated with Protim Solignum, CCA, and Celcure AC 500, and exposed to humidity-, water-, and heat resistance and heating and cooling tests.

EXPERIMENTAL

Wood species

Scotch pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) were chosen randomly from a timber supplier in Ankara, Turkey. A special emphasis was put on the selection of the wood material. Accordingly, nondeficient, whole, knotless, normally grown (without a zone line, reaction wood, decay, insects, or fungal infection) wood materials were selected.

Adhesives

The following adhesives were used in this experiment. PVAc adhesive is usually preferable for the assembly process in the furniture industry. According to the producer's recommendations, the adhesive was applied in the amount of 180–190 g/m^2 to the surfaces of the test samples. Its viscosity was −16,000 ± 3000 mPa s at 25°C, its density was 1.1 ± 0.02 g/cm^3 at 20°C, and 20 min for cold pressing was recommended at 6–15% humidity. The TS 3891[10] standard procedure was used to apply the PVAc adhesive supplied by Polisan (Izmit, Turkey).

The producing firm[11] described D-VTKA as a polyurethane-based, one-component, solvent-free adhesive that is widely used for the assembly process in the furniture industry. It is used for gluing wood, metals, polyester, stone, glass, ceramic, PVC, and other plastic materials. Its application is specially recommended in locations that are subjected to high levels of humidity. The gluing process was carried out at 20°C and 65% RH. According to the producer's recommendations, the adhesive was applied in the amount of 180–190 g/m^2. Its viscosity was 14,000 ± 3000 mPa s at 25°C; its density was 1.11 ± 0.02 g/cm^3. After the application of the adhesive to the surfaces at 20°C and 65% RH, it took 30 min to dry.

UF is an amine resin made from the polycondensation of urea (carbamide) with formaldehyde. It is shipped to engineered wood product plants as a colloidal aqueous solution with a solid content of about 65%. This adhesive is usually applied to the surfaces in concentrations of 100–150 g/m^2. If cold pressure is applied at 20°C, the period of pressing is 3–5 h. In hot pressing, this period decreases to 3–5 min. According to the producing firm's procedure, this adhesive is opaque, the density is between 1.270–1.275 kg/m^3 at 20°C, the viscosity is 300–500 cP at 20°C, the gel time is 30–35 s, and the pH value is 7.5–8.5. The UF adhesive was supplied by POLISAN (Izmit, Turkey).[11]

Impregnation chemicals

The following impregnation chemicals were used in this experiment:

Celcure AC-500 was supplied by Senkron A. Ş. (Istanbul, Turkey). According to the manufacturer, Celcure AC-500, the density of which is 1.23 g/cm^3 at 20°C, is a water-based, slightly ammoniacal amine at pH:10.6, and a wood preservative containing an alkaline copper quaternary system, including an organic cobiocide (a quaternary compound), and boric acid is supplied as a liquid concentrate, and diluted solutions are applied to timber in an industrial, controlled treatment process with vacuum pressure impregnation.

Protim 230 WR is a pretreatment material based on an organic solvent. It is easily applied to wood material by a dipping method, and when necessary, it is applied in factories. It has high resistance against fungus, insects that cause damage, and termites. Because it is water free, it does not cause any swelling or changes in the dimensions of the wood. It contains water-repellent additives that decrease changes in the dimensions of wood materials. It does not cause corrosion in metal connection elements. Protim 230 WR was supplied by Senkron A. Ş. (Istanbul, Turkey). According to the manufacturer, its active components are Tributil stannum naphtanat and permetrin, it is straw colored, its ash point is at least at 36°C, its density is 0.8 g/cm^3, and it is ready for instant use and must not be diluted. The usage amount of this material changes between 15 and 40 L/m^3, depending on the wood species and type of impregnation.

Tanalith-C at a 1% concentration was used in this study. It was supplied by Hemel (Istanbul, Turkey). The contents of Tanalith-C were 30.2% and 52.8 g/L of chromium trioxide, 11.2% and 196 g/L of copper oxide, and 17.3% and 303 g/L of arsenic pentoxide. The pressure impregnation of timber with waterborne preservatives, such as Tanalith-C, of CCA by the full-cell process is an important method for increasing the natural durability of wood against deteriorating organisms and, hence, increasing its service life. Efficient penetration and uniform distribution of the preservative salt is achieved by pressure impregnation, as the preservative is driven via the wood capillary system. Factors of prime consideration governing the flow are the amount of pressure, fluid viscosity, solvent contact angle, wood pore radius, and wood capillary length.

CCA is a wood preservative formulation containing copper, chromium, and arsenic. The copper acts as the main fungicide and provides some protection against termites. Arsenic provides protection against termites and copper-tolerant decay fungus. Chromium helps to bond and fix the chemical components to the wood.

Determination of the density

The dry densities of the wood materials used for the preparation of the treatment samples were determined according to TS 2472.[12] Accordingly, air-dried samples were oven-dried up to 103 ± 2°C until they reached constant weights. Then, the samples were cooled in a desiccator containing calcium chloride and weighed in an analytic balance with ±0.01-g sensitivity. Afterward, the dimensions of the wood materials were measured by a compass with ±0.001-mm sensitivity, and the volumes were determined by the stereometric method. The perfect dry density (δ_0) was calculated with the following equation:

$$\delta_0 = M_0/V_0 \quad (1)$$

where M_0 is the perfect dry weight (g) and V_0 is the dry volume (g/cm^3) of the wood material.

Surface roughness

To determine the surface roughness, a TIME TR-200 (Shimadzu, Tokyo, Japan) surface roughness tester measuring the changes in successive profiles was used according to TS 6956 standards.[13]

Preparation of the experimental samples

We conditioned the wood samples cut from sap wood at 20 ± 2°C and 65 ± 3% RH until they reached a constant weight by holding them for 3 months in a climatization room. There were 4800 test samples with 12% average moisture with dimensions of 55 × 20 × 10 mm^3 according to the procedure in BS EN 204 for each wood species.[14]

The impregnation process was carried out according to the principles of ASTM D 1413-76.[15] A vacuum, which was equal to 60 cmHg, was applied to the samples. They were then dipped for 60 min in a solution and subject to open-air pressure. Before the impregnation process, all samples were weighed and then kiln-dried at 103 ± 2°C until they reached a constant weight. Then, the samples were weighed in an analytic balance with 0.01-g sensitivity. After impregnation, all of the impregnated samples were held for 15 days in circulating air to evaporate the solvent.

After this period, the impregnated samples were kiln-dried at 103 ± 2°C until they reached a constant weight. After cooling, all dried samples in the desiccator were weighed on the scale. The dry weights of the samples were determined and recorded. The amount of retention [R (kg/m^3)] and the ratio of retention [R (%)] were calculated as follows:

$$R = \frac{GC}{V} \times 10^3 \ (\text{kg/m}^3) \quad (2)$$

$$R\ (\%) = \frac{M_{di} - M_d}{M_d} \times 100 \quad (3)$$

where G is the mass of the sample after impregnation (T2, kg) minus the mass of the sample before impregnation (T1, kg), M_{di} is the dry mass after impregnation (kg), M_d is the dry mass before impregnation (kg), V is the volume of the sample (m^3), and C is the concentration of the solution (%).

The characteristic features of the impregnation chemicals were determined before and after the impregnation processes. All of the processes were carried out at 20 ± 2°C. The impregnated test samples were kept at 20 ± 2°C and 65 ± 3% RH until they reached a constant weight. Afterward, approximately 180 g/m^2 adhesive was applied to the bonding surfaces of the samples, on the basis of TS 5430.[16] Bonding was obtained with a 0.5-N/mm^2 press pressure and a 24-h pressing time. The press temperature was applied as 110°C for the UF adhesive, with the general curing temperature recommended by the manufacturer taken into consideration. The perspective of the test specimen is shown in Figure 1.

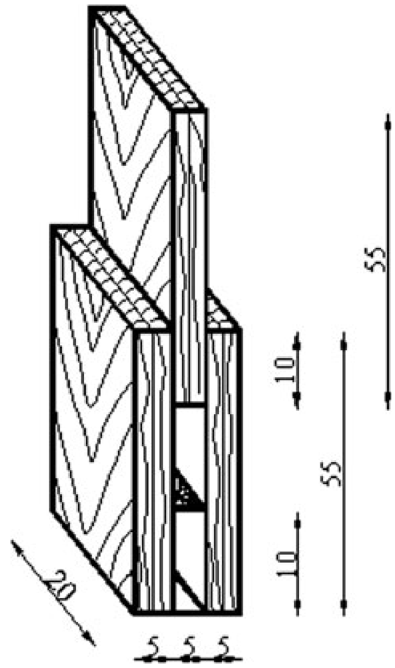

Figure 1 Test sample (sizes given in millimeters).

Execution of the test

Before the following measurements were made, the test samples were kept at 60°C and 95% RH for 2 h, 60°C and 95% RH for 6 h, 60°C and 95% RH for 12 h, 60°C and 95% RH for 24 h, 60°C and 95% RH for 48 h, 60°C and 95% RH for 96 h, 60°C and 95% RH for 30 days, 20°C in water for 7 days, 60°C for 30 days, 60°C for 8 h, and −20°C for 8 h.

Weight increases

The absorbed water of the samples was calculated as a percentage according to the procedure TS 4086.[17] An analytic balance with 0.01-g sensitivity was used. The amount of absorbed water (A) was calculated with the following equation:

$$A = (M_{1\ldots6} - M_b) \times 100/M_b \qquad (4)$$

where M_b is the weight before the test (g) and $M_{1\ldots6}$ is the weight at measurement (g).

Radial (thickness) swelling

Radial (thickness) swelling was measured at four different locations, and their average value was recorded as a single value. The radial swelling of the samples (R) was expressed as a percentage and was calculated with the following equation according to the procedure of TS 4084.[18]

A micrometer with a ±0.01-mm sensitivity was used:

$$R = (a_{1\ldots6} - a_b) \times 100/a_b \qquad (5)$$

where a_b is the initial thickness (mm) and $a_{1\ldots6}$ is the change in thickness (mm).

Tangential swelling

The tangential swelling of the samples (T) was expressed as percentage and was calculated with the following equation. A micrometer with a ±0.01-mm sensitivity was used:[18]

$$T = (a_{1\ldots6} - a_b) \times 100/a_b \qquad (6)$$

where a_b is the initial width (mm) and $a_{1\ldots6}$ is the change in width (mm).

Shear strength test

The test of shear strength was carried out in a universal testing machine, the loading speed of which was 50 mm/min. The loading was carried out until a break or separation occurred on the surface of the test samples.[19] The shear strength [σ_k (N/mm^2)] was calculated with the observed load (F_{max}) and bonding surface of the sample [A (mm^2)] as follows:

$$\sigma_k = F_{max}/2A = F_{max}/2(ab) \qquad (7)$$

where a is the width of the glued face (10 mm) and b is the length of the glued face (20 mm).

Data analyses

By using three different types of glue, three impregnation chemicals and one control sample, one kind of process, two wood types, two directions (tangential and radial), and 10 different test methods as parameters, we prepared a total of 4800 samples (3 × 4 × 2 × 2 × 10 × 10) using 10 samples for each parameter. Multiple analyses of variance were used to determine the differences between the bonding strengths of the jointing surfaces of the prepared samples. The Duncan test was used to determine whether there was a significant difference between the groups.

RESULTS AND DISCUSSION

The average densities are given in Table I. The highest densities (0.561 g/cm^3 for Scotch pine and 0.700 g/cm^3 for oriental beech) were determined for both wood species prepared radially with CCA impregnation chemicals.

The highest retention amounts are given in Table II. The highest retention amounts (6.96% for Scotch pine and 9.01% for oriental beech) were determined for both wood species prepared radially with CCA impregnation chemicals.

TABLE I
Average Densities (g/cm^3)

Wood species	Scotch pine								Oriental beech							
	Control		Protim Solignum		CCA		Celcure AC 500		Control		Protim Solignum		CCA		Celcure AC 500	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Tangential	0.508	0.032	0.523	0.043	0.538	0.051	0.528	0.052	0.634	0.043	0.656	0.033	0.684	0.060	0.660	0.070
Radial	0.525	0.042	0.544	0.025	0.561	0.023	0.556	0.060	0.642	0.034	0.667	0.050	0.700	0.047	0.674	0.032

SD = standard deviation.

The average values of the surface roughness are given in Table III. After the impregnation process, for the surface roughness values obtained before the bonding of the samples, the highest roughness value (11.235 μm) was determined for the oriental beech samples cut tangentially and impregnated with Celcure AC 500. The smoothest surface value was found in the control samples.

The mean values of the radial and tangential swelling (%) are given in Table IV. For the adhesives, the highest swelling (4.3%) was obtained for Oriental beech bonded with UF and cut radially, and the lowest swelling (1%) was obtained for Scotch pine bonded with PVAc and cut radially.

For the impregnation chemicals, the highest swelling (4.2%) was obtained for Oriental beech prepared radially and impregnated with CCA, and the lowest swelling (−0.1%) was obtained for Scotch pine prepared radially and impregnated with CCA.

With these methods, the highest swelling (7%) was obtained for Oriental beech prepared radially and kept at 60°C and 95% RH for 30 days, and the lowest swelling (−1.6%) was obtained for both Oriental beech and Scotch pine prepared tangentially and kept at 60°C for 30 days.

The radial and tangential thickness increases in Scotch Pine (%) are given in Table V. The highest tangential thickness swelling (7.2%) was obtained for Scotch pine samples cut tangentially, impregnated with CCA, bonded with PVAc adhesive, and exposed to water for 7 days at 20°C. The highest shrinkage (−2.7%) was obtained for control Scotch pine samples bonded with UF adhesive and kept at 60°C for 30 days. The highest radial swelling (7%) was obtained for Scotch pine control samples cut radially, bonded with vinyl trie ketonol acetate (VTKA) adhesive, and exposed to water for 7 days at 20°C. The highest shrinkage (−1.5%) was obtained for Scotch pine impregnated with CCA, bonded with UF, and kept at 60°C for 30 days.

The radial and tangential thickness increases in Oriental beech (%) are given in Table VI. The highest tangential thickness swelling (8.4%) was obtained for Oriental beech control samples cut tangentially, bonded with PVAc adhesive, and exposed to water for 7 days at 20°C. The highest shrinkage (−1.7%) was obtained for Oriental beech control samples cut tangentially, bonded with UF adhesive, and kept at 60°C for 30 days. The highest radial swelling (8.7%) was obtained for Oriental beech cut radially, impregnated with Protim 230 WR, bonded with PVAc adhesive, and exposed to water for 7 days at 20°C. The highest shrinkage (−1.4%) was obtained for Oriental beech samples cut radially, impregnated with Protim WR, bonded with UF, and kept at 60°C for 30 days.

The tangential and radial width increases in Scotch Pine (%) are given in Table VII. The highest tangential width increase (4.8%) was obtained for Scotch pine samples cut tangentially, impregnated with Celcure AC-500, and bonded with PVAc; control samples bonded with UF adhesive, two of which were exposed to water for 7 days at 20°C; and

TABLE II
Amount of Retention (%)

Wood species	Scotch pine						Oriental beech					
	Protim Solignum		CCA		Celcure AC 500		Protim Solignum		CCA		Celcure AC 500	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Tangential	3.08	0.132	6.02	0.151	4.00	0.202	3.46	0.133	8.01	0.260	4.22	0.070
Radial	3.7	0.914	6.96	0.323	6.01	0.260	4.01	0.170	9.01	0.347	5.08	0.132

SD = standard deviation.

TABLE III
Average Surface Roughness Values (μm)

Wood species	Scotch pine: Protim Solignum	Scotch pine: CCA	Scotch pine: Celcure AC 500	Scotch pine: Control	Oriental beech: Protim Solignum	Oriental beech: CCA	Oriental beech: Celcure AC 500	Oriental beech: Control
Tangential	5.197	8.111	9.327	4.977	7.122	10.621	11.235	6.612
Radial	5.411	9.404	8.288	4.905	6.627	8.554	10.854	7.042

samples impregnated with Celcure AC-500, bonded with UF adhesive, and kept at 60°C and 95% RH for 30 days. The highest tangential width shrinkage (−2.7%) was obtained for control samples cut tangentially, bonded with UF adhesive, and kept at 60°C for 30 days. The highest radial width increase (4.8%) was obtained for Scotch pine control samples cut radially, impregnated with CCA, bonded with VTKA adhesive, and exposed to water for 7 days at 20°C. The highest radial width shrinkage (−1.4%) was obtained for Scotch pine samples impregnated with CCA and bonded with PVAc; samples impregnated with CCA with UF adhesive, two of which were kept at 60°C for 30 days; and samples impregnated with CCA with PVAc adhesive kept at 60°C and 95% RH for 6 h.

The tangential and radial width increases (%) in Oriental beech are given in Table VIII. The highest tangential width increase (4.6%) was obtained for Oriental beech control samples cut tangentially and samples impregnated with CCA, bonded with VTKA, and exposed to water at 20°C for 7 days. The highest tangential width shrinkage (−4.6%) was obtained for control samples cut tangentially, bonded with UF adhesive, and kept at 60°C for 30 days. The highest radial width increase (4.4%) was obtained for Oriental beech samples cut radially, impregnated with Protim 230 WR, bonded with UF adhesive, and exposed to water at 20°C for 7 days. The highest radial width shrinkage (−1.4%) was obtained for Oriental beech samples impregnated with Protim 230 WR, bonded with PVAc, and kept at 60°C for 30 days.

The average values of bond strength (N/mm^2) are given in Table IX. When the wood species were compared according to their bonding strengths; the

TABLE IV
Mean Radial and Tangential Swelling Values (%)

	Tangential				Radial			
	Radial swelling (%)		Tangential swelling (%)		Radial swelling (%)		Tangential swelling (%)	
	Oriental beech	Pine	Oriental beech	Pine	Oriental beech	Pine	Oriental beech	Pine
Adhesive								
PVAc	2	1	2	1.8	4.3	2.2	3	2
VTKA	2.5	2.3	2	2	3.6	2.6	2.8	2.5
UF	2.7	1.6	1.7	2	3.8	2.6	2.8	2.7
Impregnation chemical								
Protim Solignum	3.3	3.1	1.9	1.8	1.5	2.1	2.9	3.3
CCA	1.6	−0.1	1.7	1.7	4.2	3.7	2.7	1.6
Celcure AC 500	3.7	1.5	2.2	2.1	5	2	3	3.7
Method								
60°C and 95% RH for 2 h	0.7	0.7	0.3	0.1	3.3	2.7	0.7	0.7
60°C and 95% RH for 6 h	1.3	0.6	0.1	0.2	2.1	1.5	1.1	1.3
60°C and 95% RH for 12 h	3.8	4.2	2.8	3.5	5	4.3	2.7	3.8
60°C and 95% RH for 24 h	2.7	0.1	3.4	2.9	5.1	2.9	3.7	2.7
60°C and 95% RH for 48 h	5.1	2.3	3.9	3.9	6.5	1.8	6.1	5.1
60°C and 95% RH for 96 h	3.7	1	2.7	3.2	4.4	2.8	4.8	3.7
60°C and 95% RH for 30 days	6.5	3.6	5.2	5.5	7	3	6.4	6.5
20°C in water for 7 days	4.3	5.2	4.4	4.3	5.7	4.3	5.8	4.3
60°C for 30 days	0.5	−0.7	−1.6	−1.6	1.7	1.4	−0.3	0.5
60°C for 8 h and −20°C for 8 h	0.6	1	−0.1	−0.1	2	2.8	0.6	0.6

TABLE V
Radial and Tangential Thickness Increases in Scotch Pine (%)

Wood	Scotch pine												Scotch pine											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	−0.3	−0.1	0.1	−0.5	0.2	−0.4	0.2	0.1	0.2	−0.4	0	0	0.1	0.1	3.4	0.7	0.2	0.2	0.8	−0.3	0.3	0.7	−0.2	0.7
2	−0.1	0.1	0.4	−0.2	0.3	0.6	0.4	0.4	0.1	−0.7	0.4	−0.2	0.3	0.7	1.2	2	0.3	0.3	1.3	0.5	0.5	1.4	−0.4	0.5
3	2	1.4	1.2	2	1.7	1.0	2.3	1	1.8	1.4	2.7	3	2.5	1.2	1.7	3	0.9	1	2.2	2.6	2	2.3	2.4	3
4	2.6	2.3	1.8	2.6	2	1.1	3.1	1.4	2.5	2.3	4.3	3.9	3.3	1.7	2.4	4.5	3.7	2.5	3.8	3	3.8	3.1	2.9	3.1
5	5	4.6	2.3	2.6	2.3	1.3	5.1	3.2	3.4	3.9	5	4.5	4.1	2.1	2.9	4.6	3.8	2.8	4.3	3.5	5.2	3.3	3.9	4
6	5.5	6.7	3.5	2.7	4.2	3.4	5.8	3.4	3.8	4.2	5.8	5.1	3.9	2.1	3	4.7	3.8	3.5	5.5	3.9	5.8	4.1	4.3	4.1
7	6	7.1	5.7	5.8	6.8	4.5	5.9	5.7	4.9	5.1	6.2	5.4	4.3	2.7	4.2	5.2	6.4	5.5	5.6	5	6.1	5.1	4.7	4.2
8	6.3	7.2	5.8	6.7	7	6.2	6	6.6	5.7	6.1	6.1	6.8	5.5	5.5	4.4	6	6.7	6.8	6.7	7	6.1	5.4	5.1	5.5
9	−0.5	−0.7	−0.8	−0.1	−0.5	−0.3	−0.5	−1.9	−1.3	−0.5	−0.9	−2.7	−0.5	−1.4	0.1	−0.4	0	−0.2	−0.1	0.2	−0.5	−1.5	−0.2	1.3
10	−0.1	−0.1	−0.7	−0.5	0.4	−0.7	0	0.7	0	−0.3	0.2	1.3	−0.9	−0.4	−0.4	−0.1	−0.2	0	0.2	2	−1.1	1.2	0.8	1.2
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE VI
Radial and Tangential Thickness Increases in Oriental Beech (%)

Wood	Orientel beech												Orientel beech											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	0.8	0	0.4	0.1	0.3	−0.4	0.2	0.5	0.4	−0.3	0.1	−0.7	1.1	0.9	0.6	0.2	−0.2	0.6	0.9	0.8	0	−0.5	0.8	0.5
2	1	−0.8	−0.3	1	1.1	0.7	1.7	−0.2	0.6	2.2	1.5	0	2.8	1.3	1.6	3.3	0.2	−0.1	1.6	2	−0.7	2.6	1.3	1.1
3	1.9	2	2.5	1.8	3.1	1.7	2.1	3.8	1.3	2.7	2.2	2.9	3.3	3.2	1.8	3.7	1.3	3.2	2.3	3.1	0.6	3.4	2.1	3
4	2	2.4	3.2	2.5	3.5	1.8	2.8	4	1.9	2.7	2.8	3.2	4	3.3	2.3	3.8	3.3	3.5	4.5	3	3.6	5.2	2.8	3.6
5	3.1	2.7	3.5	5.4	4	2.4	3	5	2.4	3	3.6	3.9	5	3.5	5.1	3.9	3.7	3.6	7.3	3.2	4	7.2	3.6	5.8
6	4	3.1	4.6	5.7	5.5	3.7	3.5	6.4	3.8	3.5	3.9	4.2	4.3	3.5	6	6.2	5.6	6.5	7.2	6.6	4.3	7.7	4.6	5.9
7	4.6	5.4	6.9	7.5	6.7	6.2	6.8	6.7	7.8	4.2	4.1	4.7	5.2	4.1	6.9	7.5	5.7	7.8	6.9	7.3	4.4	8.1	5.2	7.5
8	6.4	7.4	7.6	8.4	7.5	7.2	7.3	7.8	38	4.3	5.9	5.9	8.7	5.4	6.8	8.2	5.7	8	4.9	7.4	4.6	8.5	6.6	6
9	−0.9	−1.4	0.1	0.2	−1.6	0.8	1.4	−1.5	0.8	0.9	0.5	−1.7	−0.9	−1	6.8	2.6	0.6	0.2	1.5	0.5	−1.4	1.7	−1.3	−0.5
10	0.3	0.2	0.4	0.5	0.8	−1.2	−0.4	0.2	1.5	−0.1	1.6	0.8	0.8	−1.1	1.5	4.2	−3.4	0.5	0.6	0	−1.2	5.7	0.8	0.4
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE VII
Tangential and Radial Width Increases in Scotch Pine (%)

Wood	Scotch pine												Scotch pine											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	−0.2	−1.1	0	−1.4	0.1	−1.3	0.7	0.4	0.2	−0.4	0	0	0.1	0	3.4	0.7	1.1	0.2	0.8	−0.3	2.3	0.7	−0.7	0.7
2	0	−0.8	0.4	−0.2	0.1	0.6	0.4	0	0.1	−0.7	0.4	−0.1	0.2	−1.4	1.2	1	0.2	0.2	1.2	0.4	−0.1	1.3	−0.4	0.5
3	2	2.3	1.2	2	1.6	1.3	2.3	1.5	1.7	2.3	2.6	2	1.8	0.6	1.6	1.9	0.9	1.9	2.1	1.6	1.9	1.2	1.4	1.9
4	2.6	3.3	1.7	2.5	2	1.4	3.1	2.4	2.2	2.3	3.3	2.9	2.3	1.2	2.4	2.5	2.7	2.5	2.7	2	2.7	2	1.6	2
5	3.1	3.5	2.2	2.6	2.2	2.3	3.1	4.2	2.3	3.1	3.5	3.5	3.1	1.6	2.8	2.6	2.8	2.7	3.2	3.4	3.1	3.2	1.8	3
6	3.5	3.8	3.4	2.7	4.2	3.3	3.8	4.4	2.5	3.2	4.1	3.8	3.8	2.3	3	3.7	3.7	3.5	3.4	3.9	3.7	3.5	2.2	4
7	4	4.1	4.7	4.5	4.7	4.5	3.9	4.7	4.2	4	4.8	4.4	4.2	2.6	3.1	4.2	4.4	4.6	4.5	3.9	4	3.6	2.7	4.2
8	4.1	4.1	4.8	4.7	2.9	4.6	4	4.6	3.6	4.1	4.7	4.8	4.5	4.4	4.3	4.4	4.7	4.8	2.6	4.5	4.1	3.8	3.1	4.5
9	−1.5	−1.6	−1.8	−2	−1.5	−2.2	−1.5	−1.9	−1.3	−0.4	−0.9	−2.7	−0.4	−1.4	2.9	−0.3	−0.1	−1.1	−0.1	0.1	−0.4	−1.4	−1.1	0.2
10	−0.1	0	−1.6	−0.5	0.3	−0.7	0	0.7	0	−0.3	0.2	1.3	−0.9	−0.4	−0.4	−0.1	−0.2	0	0.2	2	−1.1	4.2	0.7	1.8
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE VIII
Tangential and Radial Width Increases in Oriental Beech (%)

Wood	Oriental beech												Oriental beech											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	0	−0.2	0	−3.3	1.5	−0.4	5.8	1.4	0.5	0.3	−1.2	−0.2	0.2	0.9	3.2	0.7	0.6	0.5	0.8	1	−0.1	0.3	0	0
2	0.5	0.2	0.3	−0.2	0.1	−0.3	0.5	0.9	0.3	0.1	0.8	0.2	0.7	1.2	1	1.2	1.7	0	1.3	0.8	0.7	1.8	0.9	0.5
3	2.1	2.1	1.5	4	2.5	1.8	2.1	1.8	1.7	2.8	−0.5	1.5	1.8	2.5	1.2	2.2	2.1	2	2.1	2.5	1	2.7	2.1	2
4	2.2	2.2	1.6	2.2	1.3	2.1	3.1	1.9	2.1	1.7	1.2	2.2	2.7	3	1.5	1.6	2.7	2.3	2.8	2.6	2.4	3.3	2.3	2.5
5	3.1	2.6	1.8	2.5	2.1	2.8	3.3	2	2.6	2.2	2.2	3	3.2	3.5	2.5	1.8	2.8	2.4	3.1	3.1	2.5	3.5	2.6	2.8
6	3.5	2.8	3.2	2.7	3	3.2	3.1	2.5	2.9	2.7	2.7	3.2	3.5	3.7	3.2	3.7	4.1	4.2	3.6	3.8	3.6	3.7	3.4	3.3
7	3.8	3.9	3.5	3.8	3.4	3.3	3.7	3.1	3.3	3.9	3.5	3.6	3.9	3.7	3.2	3.8	4.2	4.5	4.1	4.2	4.1	4.2	3.8	4.2
8	4.2	4.5	4.2	4.6	4.2	4.6	4.5	4.4	4.3	4.2	2.6	2.5	4.2	4.1	4.2	4	4.3	3.6	4.1	4.1	4.4	4.3	4.2	4.2
9	−0.6	−1.8	−1.2	−1.7	−0.8	−2	−2.4	−1	−1.6	−2	−0.3	−4.6	−1.4	−0.9	0.1	−0.2	−1	−1	−0.5	−0.3	−0.6	−0.7	−1.3	−0.8
10	0.1	0.1	−1.4	0.4	0.2	−0.4	0.1	0.4	−0.4	−0.7	−0.5	1.5	0.8	0.1	0.1	0.5	0.2	−0.7	1.4	0.1	−0.2	4.1	0.5	0.8
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE IX
Average Bond Strength Values (N/mm^2)

Variable		Bond strength (N/mm^2)
Wood type	Scotch pine	7.03
	Oriental beech	8.80
Direction	Tangential	7.79
	Radial	8.05
Impregnation chemical	Protim Solignum	7.99
	CCA	6.95
	Celcure AC 500	7.66
	Control	9.07
Adhesive type	PVAc	7.91
	D-VTKA	8.99
	UF	6.85
Control	Control	11.34
Humidity-resistance test	60°C and 95% RH for 2 h	9.66
	60°C and 95% RH for 6 h	9.74
	60°C and 95% RH for 12 h	9.37
	60°C and 95% RH for 24 h	8.87
	60°C and 95% RH for 48 h	8.00
	60°C and 95% RH for 96 h	6.65
	60°C and 95% RH for 30 days	1.27
Water-resistance test	20°C in water for 7 days	2.55
Heat-resistance test	60°C for 30 days	9.57
Heating and cooling tests	60°C for 8 h and at −20°C for 8 h	10.07

bonding strength of Oriental beech was higher than that of Scotch pine. For their directions, the samples cut radially gave higher bonding resistances than the ones cut tangentially. The impregnation chemicals decreased the bonding strength, and the control samples gave higher bonding strength values. For the adhesive types, the D-VTKA adhesive gave the highest bonding strength value. For the humidity-resistance test, the highest bonding strength was obtained at 60°C and 95% RH for 6 h, and the lowest value was determined at 60°C and 95% RH for 30 days. The longer the exposure to humidity was, the lower the bonding strength was. For the control samples, the humidity-resistance, water-resistance, heat-resistance, and heating and cooling tests decreased the bonding strength.

The bonding strength values of Scotch pine (N/mm^2) are given in Table X. For tangentially cut samples, the highest bonding strength (10.73 N/mm^2) was obtained for Scotch pine impregnated with Celcure AC500, bonded with PVAc, and kept at 60°C and 95% RH for 2 h. There was no bonding strength in the samples bonded with PVAc and UF adhesives kept at 60°C and 95% RH for 30 days. Although the PVAc and UF adhesives did not have resistance at 60°C and 95% RH for 30 days, the VTKA adhesive had good resistance under the same conditions.

For radially cut samples, the highest bonding strength (11.2 N/mm^2) was obtained for Scotch pine impregnated with Protim 230 WR, bonded with PVAc, and kept at 60°C for 30 days. There was no bonding strength in the samples bonded with PVAc and UF adhesives and kept at 60°C and 95% RH for 30 days. However, the VTKA adhesive gave better results under the same conditions. The PVAc adhesive also lost its resistance at 20°C in water for 7 days.

The bonding strength values of oriental beech (N/mm^2) are given in Table XI. For tangentially cut samples, the highest bonding strength (13.45 N/mm^2) was obtained for Oriental beech impregnated with CCA, bonded with VTKA, and kept at 60°C for 8 h and −20°C for 8 h. There was no bonding strength in the samples bonded with the PVAc and UF adhesives kept at 60°C and 95% RH for 30 days. Although the PVAc and UF adhesives did not have resistance at 60°C and 95% RH for 30 days, the VTKA adhesive had good resistance under the same conditions.

For radially cut samples, the highest bonding strength (13.28 N/mm^2) was obtained for Oriental beech impregnated with Celcure AC 500, bonded with UF, and kept at 60°C and 95% RH for 12 h. There was no bonding strength in the samples bonded with PVAc and UF adhesives and kept at 60°C and 95% RH for 30 days. However, the VTKA adhesive gave better results under the same conditions. The PVAc adhesive also lost its resistance at 20°C in water for 7 days.

The results of the multivariance analyses are given Table XII.

TABLE X
Bonding Strength Values (N/mm^2) of Scotch Pine

Wood	Scotch pine												Scotch pine											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	10.26	5.93	10.73	11.03	5.5	7.58	9.96	10.53	4.86	5.66	7.11	12.25	9.45	7.71	9.55	10.5	8.35	3.98	8.25	9.65	7	7.65	6.91	7.86
2	8.65	8.1	6.16	8.95	10.61	8.11	6.61	11.16	3.41	5.93	8.28	10.06	10.2	7.98	10.21	10.6	10.26	4.56	8.33	11.2	7.8	6.85	6.13	9.18
3	6.73	4.15	8.91	11	5.2	6.86	4.28	9.2	3.7	6.06	8.61	11.11	10.85	8.81	7.41	11.2	8.45	6.66	9.41	10.85	5.91	7.68	5.06	8.25
4	9.36	4.48	6.38	10.46	8.4	5.68	6.13	9.4	4.75	6.23	6.33	9	8.56	5.56	9.28	10.03	8.11	6.03	8.98	11.41	6.68	5.65	5.35	10.2
5	5.98	3.85	8	8.53	10.61	8.91	7.36	11.23	1.06	3	3.26	5.5	3.58	4.05	5.86	6.43	9.08	7.91	8.35	9.75	4.96	2.68	2.5	6.18
6	8.33	0.75	6.5	8.45	6.13	9.1	7.86	11.05	0.91	3.75	3.95	7.66	7.91	8.31	6.41	8.7	9.28	4.88	8.7	9.83	6.71	4.28	6.3	8.53
7	0	0	0	0	4.2	3.7	0.95	6	0	0	0	0	0	0	0	0	0.73	4.13	0.73	6.26	0	0	0	0
8	2.2	0.183	0	2.5	3.83	4.88	4.96	9.16	0.2	0.61	0.28	2.1	0.7	0	0	1.75	5.05	2.38	5.73	6.26	2	0.2	2.78	3.48
9	6.83	6.56	8.71	11.9	9.25	6.61	7.43	11.2	4.61	4.36	7.65	8.1	11.2	8.45	9.53	11.96	9.48	4.6	8.86	10.81	8.55	3.58	5.25	10.11
10	10.65	5.35	8.86	11.25	6.815	9.8	8.83	10.21	3.75	3.95	9.03	10.5	11.03	10.41	10.7	11.88	9.8	5.23	9.06	10.08	7.21	5.3	6.51	10.45
11	11.06	8.38	10.8	12.25	10.83	9.28	9.97	11.53	9.61	7.78	10.2	12.9	11.73	11.43	10.33	12.66	11.13	8.05	9.8	12.75	9.06	7.88	7.11	10.91

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE XI
Bonding Strength Values (N/mm^2) of Oriental Beech

Wood	Oriental beech												Oriental beech											
Direction	Tangential												Radial											
Adhesive	PVAc				VTKA				UF				PVAc				VTKA				UF			
Impregnated material	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control	Protim 230 WR	CCA	Celcure AC 500	Control
Method																								
1	10.85	11.36	10.43	12.73	10.83	11.66	12.25	13.48	9.7	9.68	8.58	8.26	12.95	11.28	9.8	13.41	9.15	10.41	7.25	10.78	10.7	7.7	7.31	11.76
2	12.58	10.95	10.75	13.1	12.05	12.23	12.26	12.76	6.9	8.48	8.78	11.11	11.25	8.45	11	11.86	12.33	6.33	10.31	12.51	10.45	9.15	8.25	11.5
3	11.76	10.08	11.53	12.38	11.18	8.38	10.81	11.48	5.56	11.33	9.33	10.05	7.55	6.25	8.83	9.58	11.63	7.38	8.86	11.78	9.46	9.11	13.28	11.81
4	9.71	8.66	9.15	14.78	10.58	10.5	11.6	11.6	9.11	7.05	9.68	11.1	10.08	10.4	10.31	11.25	9.43	3.61	10.26	10.98	10.41	6.68	10.36	12.55
5	4.65	4.41	8.18	8.41	10.11	9.16	7.11	10.55	4.73	2.33	4.25	6.9	5.015	6.1	6.01	7.11	9.7	9.23	5.75	11.8	4.4	2.96	10.5	13.03
6	11.21	4.4	8.33	13.21	12.2	10.1	9.75	12.23	5.3	7.2	6.86	9.26	11.66	7.13	6.58	9.76	10.26	11	10.66	11.68	11.05	5.86	9.73	12.5
7	0	0	0	0	4.41	5.9	2.01	6.76	0	0	0	0	0	0	0	0	1.23	5.86	1.56	6.6	0	0	0	0
8	2.26	0.6	0	2.5	4.9	7.48	3.06	7.83	0.5	0.3	3.16	1.71	1.53	0	0	2.25	7.53	6.11	3.73	7.81	0.91	0.3	6.05	6.25
9	10.95	8.43	9.8	12.25	11.61	11.71	12.86	13.26	6.43	8.43	10.93	6.55	11.63	9.13	11.58	11.71	11.48	10.53	11.38	12.48	11.25	7.73	12.16	13.1
10	10.15	12.28	11.91	13.16	10.16	13.45	12.38	13.5	7.25	8.65	11.3	11.8	11.83	11.8	11.53	12.5	10.46	11.26	9.41	12.48	11.4	10.56	9.7	11.86
11	12.6	12.53	12.13	15.13	14.76	13.58	13.03	15.38	10.01	11.68	11.58	11.86	12.15	11.91	12.38	12.81	12.53	11.45	11.66	12.9	11.15	11.46	13.11	13.2

The conditions were as follows: (1) 60°C and 95% RH for 2 h, (2) 60°C and 95% RH for 6 h, (3) 60°C and 95% RH for 12 h, (4) 60°C and 95% RH for 24 h, (5) 60°C and 95% RH for 48 h, (6) 60°C and 95% RH for 96 h, (7) 60°C and 95% RH for 30 days, (8) 20°C in water for 7 days, (9) 60°C for 30 days, (10) 60°C for 8 h and −20°C for 8 h, and (11) control.

TABLE XII
Results of Multivariance Analyses

Source	Type III sum of squares	*df*	Mean square	*F*	Significance
Factor A	313.267	1	313.267	85.369	0.000
Factor B	14,860.154	1	14,860.154	4,049.595	0.000
Factor C	7,400.220	3	2,466.740	672.220	0.000
Factor D	15,542.181	2	7,771.091	2,117.728	0.000
Factor E	161,969.175	10	16,196.918	4,413.881	0.000
A × B	380.970	1	380.970	103.820	0.000
A × C	2,890.603	3	963.534	262.576	0.000
B × C	100.537	3	33.512	9.133	0.000
A × B × C	808.216	3	269.405	73.417	0.000
A × D	2,034.144	2	1,017.072	277.166	0.000
B × D	289.027	2	144.514	39.382	0.000
A × B × D	922.084	2	461.042	125.640	0.000
C × D	6,936.411	6	1,156.069	315.044	0.000
A × C × D	5,632.397	6	938.733	255.818	0.000
B × C × D	1,608.227	6	268.038	73.044	0.000
A × B × C × D	4,243.561	6	707.260	192.738	0.000
A × E	1,117.654	10	111.765	30.458	0.000
B × E	3,715.710	10	371.571	101.258	0.000
A × B × E	677.699	10	67.770	18.468	0.000
C × E	4,625.746	30	154.192	42.019	0.000
A × C × E	4,426.228	30	147.541	40.207	0.000
B × C × E	2,132.599	30	71.087	19.372	0.000
A × B × C × E	1,553.440	30	51.781	14.111	0.000
D × E	15,816.262	20	790.813	215.507	0.000
A × D × E	1,774.021	20	88.701	24.172	0.000
B × D × E	1,504.539	20	75.227	20.500	0.000
A × B × D × E	1,816.286	20	90.814	24.748	0.000
C × D × E	9,307.659	60	155.128	42.274	0.000
A × C × D × E	7,129.907	60	118.832	32.383	0.000
B × C × D × E	4,239.890	60	70.665	19.257	0.000
A × B × C × D × E	3,721.896	60	62.032	16.904	0.000

df, degree of freedom; *F*, *P* value.
Factor A = wood direction (tangential and radial); factor B = wood species (Scotch pine and oriental beech); factor C = impregnated material (Protim Solignum, CCA, Celcure AC 500, and control); factor D = adhesive type (PVAc, VTKA, and UF); factor E = methods (control; samples kept at 60°C and 95% RH for 2, 6, 12, 24, 48, and 96 h; samples kept at 20°C in water for 7 days; samples kept at 60°C for 30 days; and samples kept at 60°C for 8 h and at −20°C for 8 h).

CONCLUSIONS

The highest densities (0.561 g/cm^3 for Scotch pine and 0.700 g/cm^3 for oriental beech) were determined in both wood species prepared radially with CCA impregnation chemicals.

The highest retention amounts (6.96% for Scotch pine and 9.01% for oriental beech) were determined in both wood species prepared radially with CCA impregnation chemicals.

After the impregnation process, for the surface roughness values obtained before the bonding of the samples, the highest roughness value (11.235 μm) was determined in oriental beech samples cut tangentially and impregnated with Celcure AC 500. The smoothest surface value was determined in the control samples. The surface roughness occurred as a result of the swelling of the fibrils after the impregnation process.

Among the adhesive types, the highest bonding strength was obtained for Oriental beech cut tangentially and bonded with D-VTKA, and the lowest bonding strength was obtained for Oriental beech cut tangentially and bonded with UF. The D-VTKA adhesive gave better results in both wood species (see Fig. 2).

D-VTKA had high dry and wet strengths, was resistant to water and damp atmospheres, and had a limited resistance to prolonged and repeated wetting and drying and gap filling.[20]

For the interaction given in Figure 3 between the adhesive types and impregnation chemicals, D-VTKA adhesive and Protim WR 230 gave the best results, and UF and CCA gave the lowest bonding strength values. For the control samples, all impregnation chemicals decreased the bonding strength of the wood materials. Preservative treatments and treatment methods generally reduce the mechanical properties of wood. The effects of preservative treatments on the mechanical properties are directly related to wood quality, size, and various pretreatment, treatment, and posttreatment processing factors.[9]

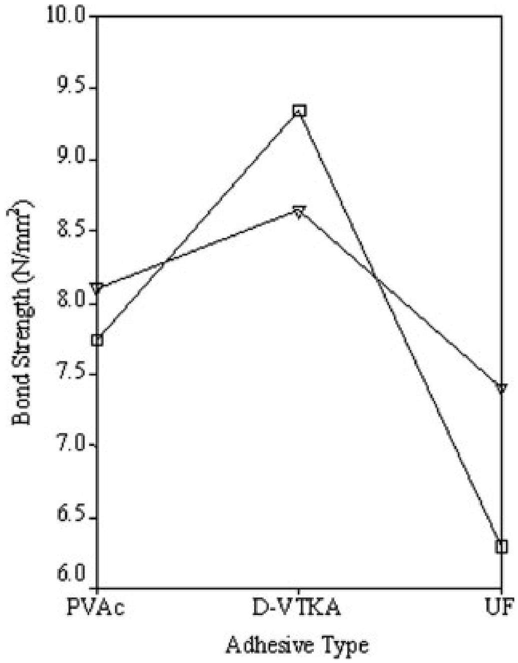

Figure 2 Effects of the types of adhesives and direction on the bond strength: (□) tangential and (▽) radial.

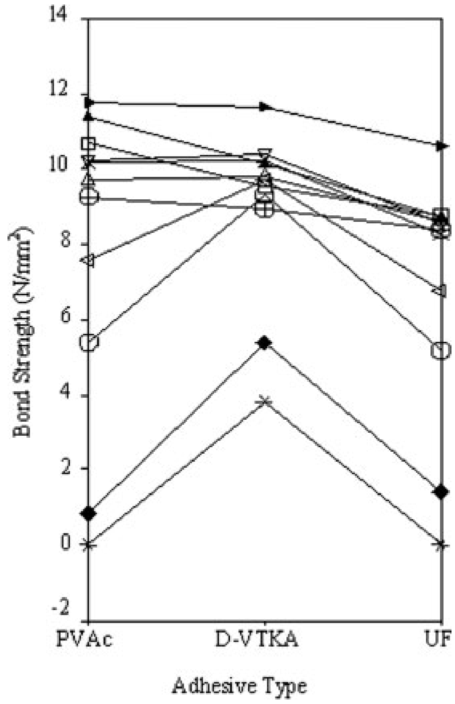

Figure 4 Effects of the types of adhesives and methods on the bond strength: (▶) control, (□) at 60°C and 95% RH for 2 h, (×) at 60°C for 30 days, (◆) at 20°C in water for 7 days, (▽) at 60°C and 95% RH for 6 h, (△) at 60°C and 95% RH for 12 h, (⊕) at 60°C and 95% RH for 24 h, (○) at 60°C and 95% RH for 96 h, (◁) at 60°C and 95% RH for 48 h, (*) at 60°C and 95% RH for 30 days, and (▲) at 60°C for 8 h and at −20°C for 8 h.

The highest bonding strength was obtained for control samples with PVAc and D-VTKA adhesive, and the lowest values were obtained for samples bonded with these three types of adhesives and conditioned at 60°C and 95% RH for 30 days. As shown in Figure 4, all methods caused a decrease in the bonding strength of the adhesives. The lowest bonding loss was observed in the D-VTKA adhesive as compared to the other two types of adhesives. After humidity-, water-, and heat resistance and heating and cooling tests, all types of impregnation chemicals and adhesives had lower bonding strengths than the control samples.

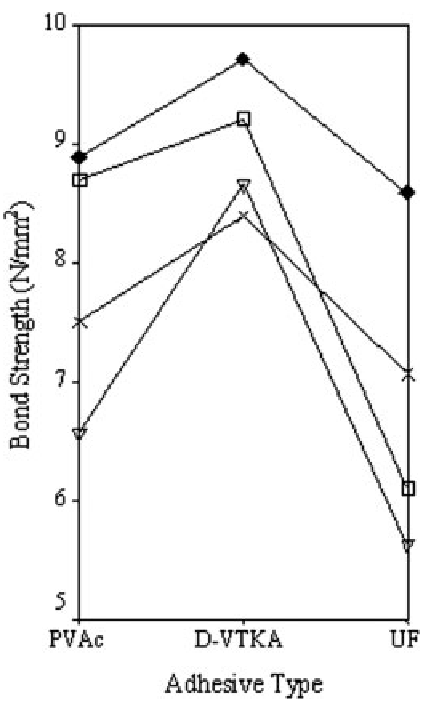

Figure 3 Effects of the types of adhesives and impregnated material on the bond strength: (□) Protim WR 230, (▽) CCA, (×) Celcure AC 500, and (◆) control.

In conclusion, Oriental beech wood cut tangentially, impregnated with Protim WR 230, and bonded with D-VTKA adhesive could be used as a material in damp conditions where strength is required.

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