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Full Length Research Paper

Comparison of bonding strengths of the sapwoods and heartwoods of tree species used in wooden shipboard building

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The aim of this study is to determine how tree species, their sapwood-to-heartwood ratios, adhesive type, and environmental conditions affect the bonding strength of the wood material. The bonding strengths formed by joining the sapwood and heartwood of chestnut (*Castanea sativa* Mill.), oak (*Quercus petrea* L.) and Scotch pine (*Pinus sylvestris L.*) with polyurethane, epoxy, and resorcinol formaldehyde adhesives are the focus of the study since these wood species and adhesives are used extensively in Turkey. The results of the study indicated that oak has the best bonding strength performance for all environmental conditions. It was determined that the bonding strengths of the sapwood specimens were higher than the bonding strength of the heartwood specimens for all environmental conditions. The best bonding strength was obtained by using the resorcinol formaldehyde adhesive, and this was followed by the epoxy and polyurethane adhesives for all environmental conditions. There were apparent decreases in the bonding strengths for all of the tree species and adhesives when the environmental conditions were more severe.

Key words: Adhesives for wood, epoxy, polyurethane, resorcinol formaldehyde, lap-shear.

INTRODUCTION

Today, the economic value of wood and wood products is apparent, because wooden raw material has approximately 6000 different usages. From the time the wood is cut in the forest, it goes through a series of processes, such as making it into a half-product, shipping it to the producer, and being used to make a wide range of products, that greatly increases its economic value (Kaygın, 1997).

Wooden shipboards are exposed to a number of negative effects due to their exposures to seawater and outdoor conditions. Therefore, they must be durable and made from high-quality materials. Also, the adhesive substances used are very important since the wooden materials must be strongly bonded together. So, great care must be exercised in selecting the adhesive to ensure that the desired performance is obtained. Otherwise, if the adhesive fails unexpectedly or prematurely, significant technical, economic, and qualitative loses are possible (Kaygın, 2002).

Wooden shipboard is also exposed to marine borers that damage and destroy wooden material. The most important marine borers are *Terodo navalis* L. and Limnoria *lignerum* Sars. For protection, wooden parts, especially those in contact with water must be impregnated by tar oil or epoxy resin to protect against damage from marine borers. Because of threats from various sources, the wooden material to be used in shipboard production must have a high quality of impregnation by protective substances (Toper-Kaygın, 2007). However, the relationship between the impregnation process and bonding resistance is also significant. Ozen et al. (2007) reported in their research, “The Affect of Impregnation Process to the Bonding Resistance,” that the impregnation process decreases bonding resistance. Meanwhile, the treating of wood composite lumbers with fire retardant chemicals causes delamination between the bonded wood strands; therefore, this significantly reduces the mechanical strength of the material (Denizli-Tankut et al., 2004).

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Table 1. Properties of trees used in the study

Properties	Tree species		
	Chestnut	Oak	Pine
Exposure	North	North	North
Altitude (m)	360	250	1200
Diameter at breast height (cm)	34	36	30
Sapwood width (cm)	2.5	3	6.5
Heartwood width (cm)	18	14	5.5
Number of annual rings in sapwood	10	22	40
Number of annual rings in heartwood	28	72	36

Also, Örs et al. (2004) investigated the bonding strength of wood impregnated with Imersol-Aqua. The aim of this experimental study was to determine the bonding resistance of Oriental beech (*F. orientalis lipsky*), Scotch pine (*P. sylvestris lipsky*), oak (*Quercus petreae liebl.*) and Toros cedar (*Cedrus libani A. Rich*), which were impregnated and used widely in furniture production, with the following adhesives: 1) polyvinylacetate (PVAc); 2) Klebit 303 (Klebchemie, M. G. Becker GmbH-Co. KG, Baden, Germany); 3) Kleiberit 305.0 (Klebchemie, M. G. Becker GmbH-Co. KG, Baden, Germany); 4) Super Lackleim 308 (Klebchemie, M. G. Becker GmbH-Co. KG, Baden, Germany); and 5) polyurethane (POLISAN, Gebze, Kocaeli, Turkey). Based on evaluations of shear strength, the results of the study showed that the best combination of process components was beech wood, short-term dipping for impregnation, using PU as the adhesive, and surface sanding after impregnation. Thus, beech wood, the short-term dipping method, PU adhesive, and surface sanding after impregnation could be proposed for furniture elements produced by solid wood materials (Ors et al., 2004).

The wood of tree species that have diffuse-porous structure has different bonding characteristics from the wood of tree species that have ring-porous structure. The wood of tree species with diffuse-porous structure has adhesive-layer resistance that is directly proportional to the specific gravity of the wood (McNamara and Waters, 1970).

Bonding wood species having high specific gravity is more difficult than bonding the ones having low specific gravity (Kilic, 1997).

EXPERIMENTAL

Wood materials

The woods of chestnut, oak, and pine were chosen randomly from Bartin Directorate of Forest District, Turkey. Special emphasis was given to the selection of the actual wood materials from which the samples would be prepared. Accordingly, non-deficient, proper, knotless, normally-grown wood materials were selected. This means that selected wood could not have zone lines, could not be reaction wood, and could not have any decay, insect damage, or fungus damage. The properties of the test trees are presented in Table 1.

Adhesives

Three different adhesives were used in the experiments, that is, polyurethane adhesive, epoxy adhesive, and resorcinol formaldehyde adhesive. The first two are used widely in the wooden shipboard building industry in Turkey, and resorcinol formaldehyde adhesive is used to a lesser extent. Polyurethane adhesive was supplied by DEVCON, a seller firm in Turkey; epoxy adhesive was supplied by WEST SYSTEM 105 RESIN, a seller firm in the United Kingdom; and resorcinol formaldehyde adhesive was supplied by HUMBROL EXTRAPHEN, a seller firm in the United Kingdom.

Viscosities, pH values, and dry substance amounts of these adhesives were determined according to TS EN 1066 (2000), TS EN 1067 (2000), TS EN 827 (1997) and TS EN 1245 (2002) before the adhesive process was initiated. Properties of the three adhesives used in the study are shown in Table 2.

Determining physical properties of wood species

Some physical and chemical properties of the wood trees used in the experiments must be determined in order to interpret the effects of their sapwood and heartwood on bonding resistance. It is estimated that, besides other factors, these properties of the wood species would affect the bonding resistances determined by the experiments.

According to TS 2472 (1976), wood samples were prepared in order to determine the physical properties of the sapwood and heartwood of the experimental wood species. Accordingly, after the sapwood and heartwood parts of wood species were carefully separated, the experimental samples, prepared with dimensions of 2 x 2 x 3 cm in groups of thirty each, were conditioned at 20 ± 2°C and at 65 ± 5% relative humidity for a month. Later, the weights of the air-dried samples, the weights of the air-dried samples, cell-wall intensity, and porosity were determined according to TS 2472.

Determining chemical properties of wood species

According to TAPPI T 11 m-45 standard, wood samples were prepared in order to determine the chemical properties. Disks with 5 cm diameters were taken in groups of three, from each of the tree species. Initially, all the disks were divided into two parts and later into four parts to form a right angle. At this stage, sapwood and heartwood parts were carefully separated. Later, these samples were chipped into pieces of matchstick size and ground in a laboratory-type Willey grinding machine. The samples were sifted through a 40-mesh sifter, and the wood remaining on a 60-mesh (250 micron) sifter after sifting in a shaking shifter was taken as a

Table 2. Properties of adhesives used in the study.

General properties	Polyurethane	Epoxy	Resorcinol formaldehyde
Commercial name	Devcon	West System 205	Extraphen
Contains	Difenilmetan 4,4 diizosiyanat	Bisfenol A-epiklorohidrin	Resorcinol phenol formaldehyde
Commercial form	Liquid	Liquid	Liquid
Shelf life (months)	6 - 9	12	3
Color	Light brown	Colorless	Dark brown
Technical properties			
Solids content (%)	35	40	55
Application amount (g/m^2)	120	120	120
Pressing time (h)	8	12	10
pH*	7	8	7.5
Hardener properties			
Commercial name	-	West System 105	Extraphen p. hardener
Contains	-	Triethylene tetramine	Paraformaldehyde
Commercial shape	-	Liquid	Powder
Mixing ratio (hardener/glue)	-	1/5 by weight	2/3 by volume
Color	-	Brown	White

* pH: pH level of glues before application.

test sample. The samples were placed in jars, and the jars were tightly closed. Then, pH values and the proportions of halo cellulose and alpha cellulose in the three tree species were determined.

Preparation of experimental samples

Experimental samples required for determining bonding resistances were prepared according to TS 5430 (1988) standard. First, logs were cut by a band saw for log and the sapwood and heartwood were separated and air dried. The surfaces of the samples were cleaned with a planer, and the samples were cut at the required size of 55 ± 1 x 20 ± 0.1 x 5 ± 0.1 mm using a table saw. According to the standard, experimental samples cannot have knots, splits, decay, a spiral grain, or discoloration. The samples were conditioned at a temperature of 20 ± 2°C and a relative humidity of 65 ± 5%, according to TS 642 (1997), until they reached constant weights.

Later, the bonding surfaces of the sample plates were cleaned carefully. Before bonding, the moisture content of the wooden samples was measured by a moisture meter and was determine to be approximately 8 - 10%. The adhesives were prepared according to the manufacturer's directions, and some measurements were made, including viscosity, percentage of solids content, and the pH of the adhesives.

The polyurethane adhesive was applied directly to the surfaces of the samples because this adhesive does not require a hardener. However, the epoxy and resorcinol formaldehyde adhesives were prepared by adding the recommended amounts of hardener. The bonding surfaces of the samples were coated uniformly with each adhesive by the amount of 120 - 150 g/m^2. To facilitate bonding, a press pressure of 0.5 N/mm^2 was applied for 24 h. The setup of the test specimens is shown in Figure 1. After the bonding process was completed, samples were conditioned at a temperature of 20 ± 2°C and a relative humidity of 65 ± 5% until the constant weight obtained.

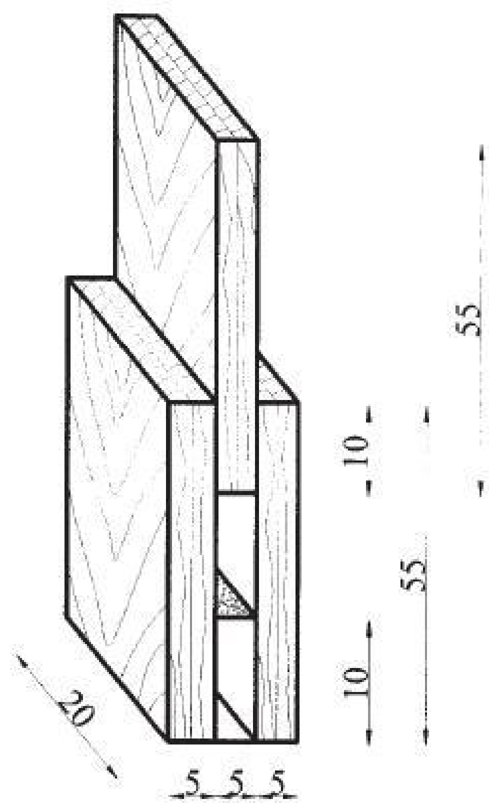


Figure 1. The test sample (dimensions in mm).

Application of experiment

Samples bonded according to TS 5430 regulations were exposed to the environmental conditions given in Table 3 before testing. Bonding strengths for four different environments were determined since the long-term durability of bonding, which is one of the most

Table 3. Test procedure of water resistance.

Conditioning procedure	Procedures
I (Control)	7 days conditioning at 20 ± 2°C and 65 ± 2% relative humidity
II (Cold water)	7 days conditioning at 20 ± 2°C and 65 ± 2% relative humidity, 24 h submerged in 20 ± 2°C water
III (Boiling water)	7 days conditioning at 20 ± 2°C and 65 ± 2% relative humidity, 2 h submerged in boiling water
IV (Sea water)	7 days conditioning at 20 ± 2°C and 65 ± 2% relative humidity, 24 h submerged in seawater

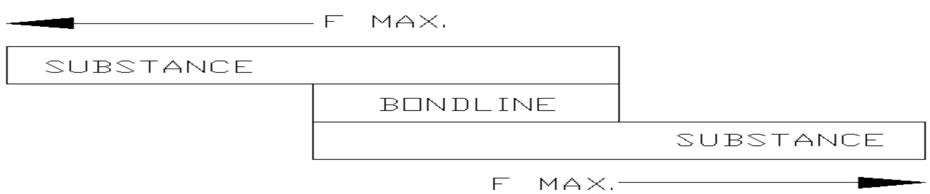


Figure 2. Tensile experiment apparatus.

important qualities of wood materials bonded with adhesives, must be known. The proportions of the adhesive layers that were spoiled were accelerated greatly in Environment II, Environment III, and Environment IV in order to simulate long-term exposures to actual environmental conditions. According to the literature three of these short-term experimental methods are generally accepted and applied in international standards like EN and ISO. In addition to the samples mentioned, bonded samples were also kept in Environment IV in order to determine the effect of seawater on bonding strength. Environment I represents the durability in a typical environment. Environment II represents the durability in conditions of high humidity, and Environment III represents the durability in the open air.

Shear strength was determined according to the procedure of BS EN 205 (1991) standards. As shown in Figure 2, the loading speed was 50 mm/min. The loading was continued until a break or separation occurred on the surface of the test samples; meanwhile, the observed load (F_{max}), the bonding surface area of the samples (A, in mm^2), and shear strength values (σ_k) were calculated as follows:

$$\sigma k = \frac{Fmax}{2A} = \frac{Fmax}{2(ab)} \, N/_{mm^2} \quad (1)$$

Where σ is the width of the face to which the adhesive was applied (10 mm), and b is the length of face to which the adhesive was applied (20 mm).

Data analyses

By using three different types of adhesive, three wood types, heartwood and sapwood of the wood types, and four different environmental conditions as parameters, a total of 720 samples (3 × 3 × 2 × 4 × 10) were prepared using 10 replications for each parameter. Multiple variance analysis (MANOVA) was used to determine the differences between the bonding strengths of the joined surfaces of the prepared samples. The Tukey test was used to determine whether there were significant differences between the groups.

RESULTS

Physical properties of tree species

The physical properties of the wood materials used in the study are given in Table 4.

Chemical properties of tree species

Chemical properties of wood materials used for the study are given in Table 5.

Shear strength

The bonding strength results obtained from the experiments are presented in Table 6. Statistical analysis of the results showed that "tree species used," "adhesive types preferred," "tree cut from sapwood or heartwood," and "environmental conditions in which wooden material is used" all had significant effects on bonding strength.

Bonding strength findings obtained in Environment I, Environment II, Environment III, and Environment IV were compared according to sapwood-heartwood and adhesive-type factors for each of the three tree species in Figures 3, 4, and 5.

DISCUSSION

When sapwood-heartwood factors are taken into consideration, these results show that the sapwoods of the three tree species have a better bonding strength than their heartwoods in all environments. Lower heartwood

Table 4. Physical properties of wood materials used in the study.

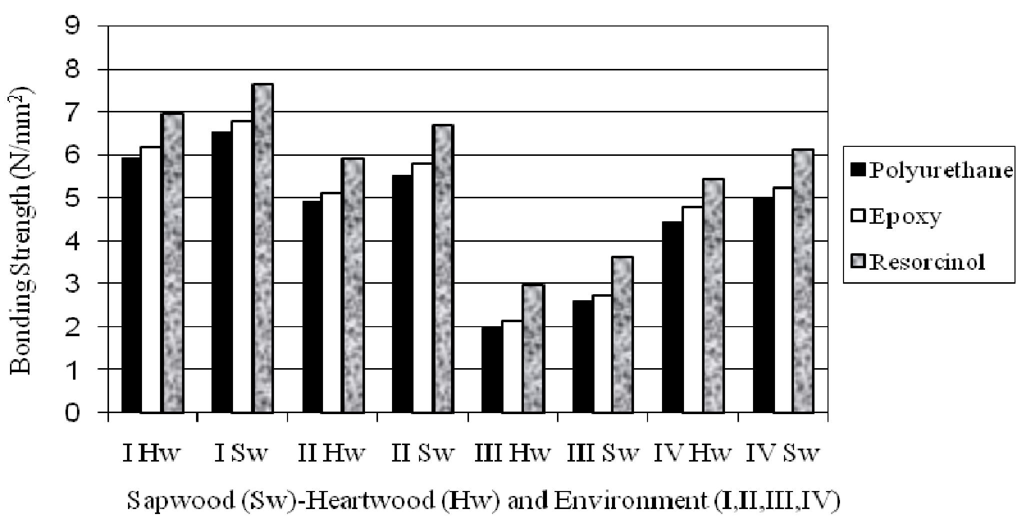
Wood species	Oak		Chestnut		Scotch Pine	
Physical properties	Sw*	Hw**	Sw*	Hw**	Sw*	Hw**
Average oven dry density (gram/cm^3)	0.654	0.618	0.576	0.554	0.455	0.492
Average air dry density (gram/cm^3)	0.693	0.654	0.591	0.580	0.496	0.528
Porosity (%)	56	59	62	63	70	67
Cell wall density (%)	44	41	38	37	30	33

*Sw: Sapwood; **Hw: Heartwood.

Table 5. Chemical properties of wood materials used in the study.

Wood Species	Oak		Chestnut		Scotch Pine	
Chemical properties	Sw*	Hw**	Sw*	Hw**	Sw*	Hw**
Moisture content (%)	15.71	14.51	12.67	11.52	17.20	13.50
Extractive substance (%)	1.26	3.35	3.70	5.04	4.19	9.15
Halo cellulose (%)	78.87	76.62	76.19	74.21	62.35	68.39
Alpha cellulose (%)	69.54	64.22	53.73	53.12	58.73	60.42
PH	3.98	3.95	3.34	3.31	5.14	5.12

*Sw: Sapwood; **Hw: Heartwood.

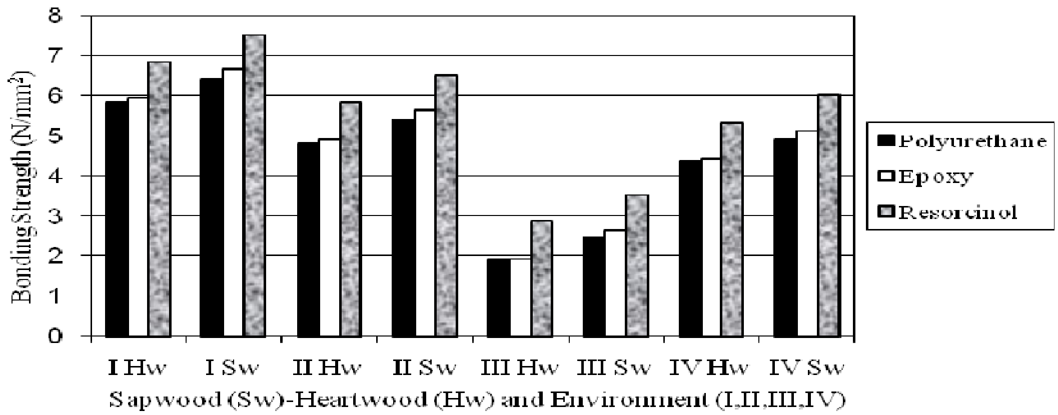


Figures 3. Bonding strength of oak wood according to the environment, sapwood-heartwood, and adhesive type.

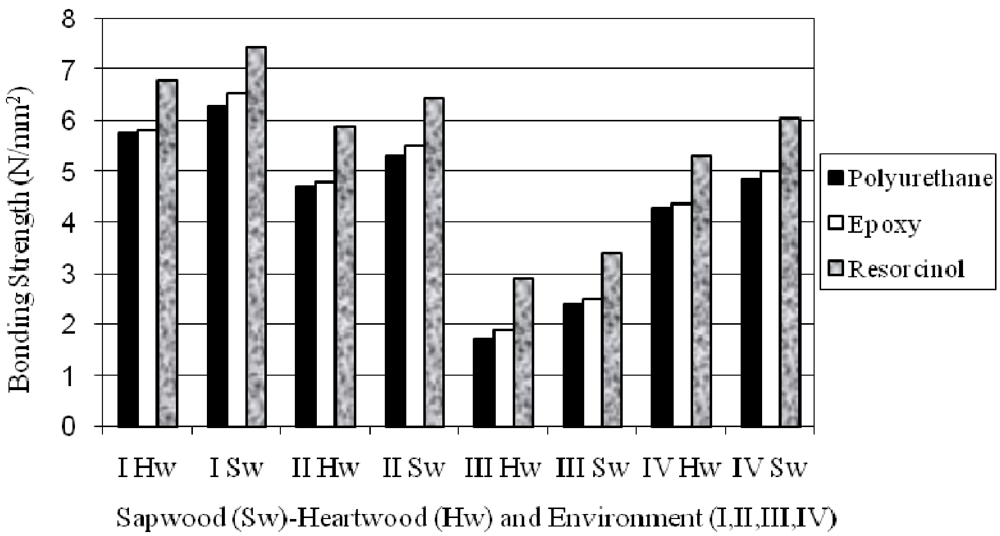
bonding strength is related to the extractive substances that heartwood contains. Extractive substance proportions of each tree species were determined before the experiments, and they were given in Table 5. The heartwoods of the three tree species have more extractive substances than their sapwoods have. These excessive extractive substances in the heartwoods affected the pH level, which had an effect on adhesive hardening, and, therefore, the bonding strengths were reduced compared to those of the sapwoods.

According to Chen (1970), when extractive substances are kept away from the wood, the pH value becomes normal and bonding capability increases. Therefore, the choice of sapwood or heartwood will affect the bonding strength of the adhesives.

The different bonding strengths of the three adhesive types were evaluated. The results of the study showed that resorcinol formaldehyde adhesive has a better bonding strength than the other two adhesives. The second strongest was the epoxy adhesive, and the third strongest was the polyurethane adhesive. It is assumed that these different bonding strength values of the adhesives



Figures 4. Bonding strength of chestnut wood according to the environment, sapwood-heartwood, and adhesive type.



Figures 5. Bonding strength of Scotch pine wood according to the environment, sapwood-heartwood, and adhesive type.

resulted from the differences between their technological structures, reaction mechanisms, and adhesive-cohesive bonding characteristics. Although all three adhesives were synthetic types, their bonding strengths were differrent. Resorcinol formaldehyde, which is representative of condensation adhesives and is expensive and is hard to produce, has the best bonding strength value since it has better bonding characteristics for adhesion and cohesion than the other two adhesives. Also, its reaction mechanism has better adaptation to tree species than the other two adhesives.

Epoxy and polyurethane adhesives belong to the polyadhesion type adhesives; the epoxy adhesive had better bonding strength than the polyurethane adhesive. The reason for this is that the epoxy adhesive has better technological and bonding qualities than the polyurethane adhesive.

Experiments to determine the effects of environmental conditions on bonding strength were applied in four differrent environments, and all bonded experimental samples succeeded in tests for all environments. However, as environmental conditions become harsher, that is, when the spoiling proportion of the adhesive line was accelerated, there was an apparent decrease in bonding strengths. The bonding strengths of the samples maintained in cold water decreased 16%, those in seawater decreased 22%, and those in boiling water decreased 60%, compared to the bonding strengths of the control samples maintained normal circumstances.

Oak wood had the best bonding strength with all three

Table 6. Average bonding strength results.

Environment I (Control)		Bonding strength (N/mm^2)		
		Polyurethane	Epoxy	Resorcinol formaldehyde
Oak	Sw*	6.5	6.7	7.6
	Hw**	5.9	6.1	6.9
Chestnut	Sw*	6.4	6.6	7.5
	Hw**	5.8	5.9	6.8
Scotch Pine	Sw*	6.2	6.5	7.4
	Hw**	5.7	5.8	6.7
Environment II (Cold water)				
Oak	Sw*	5.5	5.7	6.6
	Hw**	4.9	5.1	5.9
Chestnut	Sw*	5.4	5.6	6.5
	Hw**	4.8	4.9	5.8
Scotch Pine	Sw*	5.3	5.5	6.4
	Hw**	4.7	4.8	5.8
Environment III (Boiling water)				
Oak	Sw*	2.5	2.7	3.6
	Hw**	1.9	2.1	2.9
Chestnut	Sw*	2.4	2.6	3.5
	Hw**	1.8	1.9	2.8
Scotch Pine	Sw*	2.3	2.5	3.4
	Hw**	1.7	1.8	2.8
Environment VI (Sea water)				
Oak	Sw*	5.0	5.2	6.1
	Hw**	4.4	4.7	5.4
Chestnut	Sw*	4.9	5.1	6.0
	Hw**	4.3	4.4	5.3
Scotch Pine	Sw*	4.8	5.0	6.0
	Hw**	4.2	4.3	5.3

*Sw: Sapwood; **Hw: Heartwood.

adhesive types in all environments, and there was no significant difference between the bonding strengths of chestnut and Scotch pine woods. It is estimated that oak wood has better bonding strength because of its better physical and chemical adaptation to the adhesive types used. Physical and chemical properties of the wood species used in the study are given in Tables 4 and 5.

The information in these tables indicates that oak wood has higher air-dry density and oven-dry density than the other two woods. However, its porosity is lower, and it has less extractive substances in both its sapwood and heartwood than the other two wood species have. The pH level of the oak wood samples was approximately the same as the pH levels for the other two wood species.

Conclusion

The bonding strength values obtained from the study may assist shipboard manufacturers to improve the technical, economical, and qualitative aspects of their products. Based on the results of the study, the following conclusions can be drawn relative to the use of woods and adhesives for shipboard construction:

1. When wood is to be used as furniture in interior residences and in the ship's cabin where it will be exposed to normal moisture conditions, the priority order for choosing the wood is Oak sapwood, Chestnut sapwood, and Scotch Pine sapwood with adhesives in the preferred order of resorcinol formaldehyde, epoxy, and polyurethane. The heartwoods of these three wood species should not be used for these purposes.
2. When wood is to be used for the construction of interior shipboard residences, such as kitchens, bathrooms, outside doors, outside stairs, and windows exposed to high moisture, in order to have good bonding strength, the priority order for choosing the wood is Oak sapwood, Chestnut sapwood, and Scotch Pine sapwood with adhesives in the preferred order of resorcinol formal-

dehyde, epoxy, and polyurethane. The heartwoods of these three wood species should not be used for these purposes.

3. When wood is to be used in joints for the construction of supporting members of shipboards, such as back-bones, stems, ribs, and frames that are exposed to wind and seawater, Oak sapwood and resorcinol formaldehyde adhesive should be used.

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