Effect of Adhesives on Thermal Conductivity of Laminated Veneer Lumber

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ABSTRACT: In this study, it is aimed to describe the effect of adhesives (PVAc-polyurethane and urea formaldehyde) on wooden materials (Scotch pine and oriental beech) cut tangentially and radially and layers in laminated veneer lumber (LVL; 3, 4, 5) on thermal conductivity. The lowest thermal conductivity of 0.105 kcal/(m h °C) was obtained in Scotch pine, cut tangentially, bonded with polyurethane, and three-layer LVL. The highest thermal conductivity of 0.159 kcal/m h °C was obtained in oriental beech, cut radially, bonded with PVAc, and five-layer LVL. Consequently, oriental beech wood cut radially and bonded with PVAc adhesive and five layers in LVL can be used as a material in construction where the thermal conductivity is required. Scotch pine wood cut tangentially and bonded with polyurethane adhesive and three layers in LVL can be used as a material in construction where the insulation is required. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 1822–1827, 2008

Key words: laminated veneer lumber; adhesive; thermal conductivity; grain orientation

INTRODUCTION

Wood is an extremely versatile material with a wide range of physical and mechanical properties among the many species of wood. It is also a renewable resource with an exceptional strength-to-weight ratio. Wood is a desirable construction material because the energy requirements of wood for producing a usable end-product are much lower than those of competitive materials such as steel, concrete, or plastic.[1]

Thermal conductivity is expressed by the coefficient of thermal conductivity (k). This is a measure of the quantity of heat in calories that will flow during a unit of time (s) through a body 1 cm thick with a surface area of 1 cm^2, when a difference of 1°C is maintained between the two surfaces, i.e., k is measured in kcal/(m h °C).[2]

Some of the important thermal properties of wood are affected by its moisture content (MC). These include specific heat, thermal conductivity, and thermal diffusivity. The thermal conductivity of wood also increases greatly with its MC, as well as with other factors such as temperature and specific gravity.[3] The thermal conductivity of wood is affected by a number of basic factors: density, MC, extractive content, grain direction, structural irregularities such as checks and knots, fibril angle, and temperature. Thermal conductivity increases as the density, MC, temperature, or extractive content of the wood increases. Conductivity along the grain has been reported as 1.5–2.8 times greater than conductivity across the grain, with an average of about 1.8, but reported values vary widely. For MC levels below 25%, approximate coefficient of thermal conductivity k across the grain can be calculated with a linear equation of the form where M is the MC (%).[4]

Thermal conductivity (T_c) is influenced by various factors, such as wood structure, density, moisture, temperature, extractives, and defects (checks, knots, cross grain).[5] When moisture is increased or reduced below the fiber saturation point (FSP) by 1%, T_c is increased or reduced from 0.7% to 1.18%. Kollman determined the above the FSP, the increase or reduction is somewhat higher, and in general, wood with a MC higher than 40% has an approximately one-third higher conductivity than dry wood.[6] Furthermore, T_c is affected by temperature. Kanter determined the k [kcal/(m h °C)] for birch at temperatures between 20 and 80°C at different MCs, and found variations from 0.17 to 0.21 at 20% MC and from 0.22 to 0.27 at 40% MC.[7]

In general, the thermal conductivity of wood is low because its structure is porous. Dry wood is one of the poorest conductors of heat due in part to the low conductivity of the actual cell wall materials, and in part to the cellular nature of wood, which in its dry state contains within the cell cavities a large volume of air—one of the poorest conductors known.[8]

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TABLE I
Average Values of Density (g/cm^3)

Wood Type	Grain orientation	Layer	PVAc	D-VTKA	Urea formaldehyde
Scotch pine	Radial	5	0.649	0.616	0.649
		4	0.616	0.548	0.593
		3	0.593	0.526	0.571
		Control	0.514	0.514	0.514
	Tangential	5	0.722	0.660	0.711
		4	0.716	0.649	0.705
		3	0.660	0.639	0.672
		Control	0.627	0.627	0.627
Oriental beech	Radial	5	0.862	0.705	0.761
		4	0.784	0.716	0.750
		3	0.694	0.628	0.694
		Control	0.616	0.616	0.616
	Tangential	5	0.864	0.761	0.784
		4	0.840	0.761	0.828
		3	0.739	0.660	0.739
		Control	0.716	0.716	0.716

The demand for engineered wood products such as oriented strand board, glulam and laminated veneer lumber (LVL) has increased due to a constant increase in the global population. The grain of each layer of veneer assembled into LVL runs parallel with each adjacent ply.[9–11] Being a homogeneous and dimensionally stable building material, LVL can be used where strength and stability are required.[12]

Since there is not enough study on the thermal conductivity of LVLs, the aim of this study was to compare the effects of adhesives (PVAc-polyurethane and urea formaldehyde) on wooden materials (Scotch pine, oriental beech) cut tangentially and radially and layers (3, 4, 5) of LVL.

MATERIAL AND METHOD

Material

Wood species

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

Adhesives

Three different adhesives were used. The following adhesives were used in this experiment:

PVAc is an odorless, nonflammable adhesive. It can be used in cold temperatures and solidifies quickly. The application of this adhesive is very easy, and it does not damage the tools during the cutting process. However, the mechanical resistance of PVAc adhesive decreases by increasing the heat. It loses bonding resistance capacity over 70°C. Using 150–200 g/m^2, the adhesive seems to be suitable on the condition that it is applied to only one surface.[13] TS 3891 standard procedure was used for applying PVAc adhesive. The density of PVAc should be 1.1 g/cm^3, the viscosity 16,000 ± 3000 mPa s, and pH value and ash ratio should be 5 and 3%, respectively. A pressing time of 20 min for the cold process and 2 min and 80°C are recommended with 6–15% humidity for the jointing process. After a hot-pressing process, the materials should be attended until its normal temperature is reached.[14] PVAc adhesive was supplied from POLISAN, a producer firm in İzmit, Turkey.

Producer firm[15] describes polyurethane adhesive having one component polyurethane based and widely preferred for the assembly process in the furniture industry. It has a one component solvent-free adhesive. It is used for gluing wood, metal, polyester, stone, glass, ceramic, PVC, and other plastic materials. Its application is specially recommended in locations subject to high-level humidity. Gluing process was carried out at 20°C and 65% relative humidity. According to the producer firm's advice, adhesive was applied 180–190 g/m^2 to the surfaces. Its viscosity was −14,000 ± 3000 mPa s at 25°C; density 1.11 ± 0.02 g/cm^3 at 20°C, and it had resistance against cold air.

Urea–formaldehyde (UF) is an amine resin made from the polycondensation of urea (carbamide) with formaldehyde. The building blocks for UF are urea and formaldehyde. Urea is synthesized from ammonia NH_3 and carbon dioxide CO_2 under heat and pressure into $CO(NH_2)_2$ and water H_2O. Both ammonia and carbon dioxide are obtained from natural

TABLE II
Average Values of Thermal Conductivity Coefficients [kcal/(m h °C)]

Wood type	Grain orientation	Adhesive	Layer	Mean	Min.	Max.	Standard deviation
Scotch pine	Radial	PVAc	5	0.126	0.123	0.130	0.0076
			4	0.119	0.116	0.122	0.0028
			3	0.118	0.115	0.121	0.0028
			Control	0.118	0.115	0.121	0.0063
		D-VTKA	5	0.123	0.120	0.127	0.0041
			4	0.115	0.112	0.119	0.0036
			3	0.109	0.103	0.110	0.0029
			Control	0.118	0.115	0.121	0.0063
		Urea formaldehyde	5	0.117	0.113	0.120	0.0034
			4	0.114	0.110	0.117	0.0036
			3	0.110	0.107	0.114	0.0033
			Control	0.118	0.115	0.121	0.0063
	Tangential	PVAc	5	0.125	0.121	0.128	0.0021
			4	0.118	0.114	0.121	0.0029
			3	0.115	0.111	0.118	0.0033
			Control	0.115	0.112	0.118	0.0078
		D-VTKA	5	0.120	0.116	0.123	0.0014
			4	0.111	0.108	0.115	0.0038
			3	0.105	0.102	0.109	0.0033
			Control	0.115	0.112	0.118	0.0078
		Urea formaldehyde	5	0.114	0.110	0.117	0.0047
			4	0.114	0.111	0.118	0.0029
			3	0.115	0.111	0.118	0.0033
			Control	0.115	0.112	0.118	0.0078
Oriental beech	Radial	PVAc	5	0.159	0.157	0.161	0.0085
			4	0.157	0.153	0.159	0.0033
			3	0.157	0.153	0.159	0.0038
			Control	0.149	0.146	0.153	0.0026
		D-VTKA	5	0.155	0.153	0.160	0.0031
			4	0.151	0.147	0.154	0.0038
			3	0.151	0.148	0.155	0.0032
			Control	0.149	0.146	0.153	0.0026
		Urea formaldehyde	5	0.154	0.150	0.157	0.0038
			4	0.150	0.147	0.154	0.0038
			3	0.150	0.146	0.153	0.0032
			Control	0.149	0.146	0.153	0.0026
	Tangential	PVAc	5	0.154	0.150	0.157	0.0032
			4	0.154	0.149	0.156	0.0033
			3	0.152	0.149	0.155	0.0023
			Control	0.141	0.137	0.144	0.0036
		D-VTKA	5	0.149	0.146	0.153	0.0024
			4	0.149	0.146	0.153	0.0034
			3	0.146	0.142	0.149	0.0024
			Control	0.141	0.137	0.144	0.0036
		Urea formaldehyde	5	0.152	0.149	0.156	0.0033
			4	0.151	0.148	0.155	0.0038
			3	0.148	0.144	0.151	0.0033
			Control	0.141	0.137	0.144	0.0036

gas. Urea is a whitish crystal traded in pellet form. Urea is best known as fertilizer. Formaldehyde is synthesized from methane CH_4 and oxygen O into methanol CH_3OH. Methane is obtained from crude oil and oxygen from the air. With the help of a catalyst, methanol is converted into formaldehyde HCHO and hydrogen H_2. Formaldehyde is a colorless gas.

Urea and formaldehyde are combined in a reactor into UF resin. It is shipped to engineered wood product plants as a colloidal aqueous solution with a solid content of about 65%. This liquid is odorless, slightly opaque, and, of course, not flammable. When shipped, the UF resin is already polymerized and crosslinked to a certain degree. UF reacts with a wooden cell wall hydroxyl. Adhesive is usually applied on the surfaces 100–150 g/m^2. If cold press is applied at 20°C, the period of press is 3–5 h. In hot press, this period decreases to 3–5 min.[16]

TABLE III
Multiple Variance Analysis for the Effect of Wood Type, Grain Orientation, Adhesive Type, and Layer on Thermal Conductivity

Source	Type II sum of squares	df	Mean square	F	Significance
Factor A	3.688 E −04	2	1.844 E −05	10.130	0.000
Factor B	8.578 E −02	1	8.578 E −04	4712.526	0.000
Factor C	9.241 E −04	1	9.241 E −03	50.765	0.000
Factor D	3.681 E −03	3	1.227 E −04	67.100	0.000
A*B	4.356 E −04	2	2.178 E −05	11.965	0.000
A*C	2.194 E −05	2	1.097 E −05	0.603	0.548
B*C	1.688 E −04	1	1.688 E −04	9.275	0.003
A*B*C	1.963 E −05	2	9.815 E −03	0.539	0.584
A*D	1.110 E −03	6	1.851 E −04	10.167	0.000
B*D	1.862 E −03	3	6.207 E −05	34.096	0.000
A*B*D	3.608 E −04	6	6.013 E −04	3.303	0.004
C*D	2.009 E −04	3	6.698 E −03	3.679	0.013
A*C*D	7.879 E −05	6	1.313 E −04	0.721	0.633
B*C*D	7.407 E −05	3	2.469 E −03	1.356	0.257
A*B*C*D	2.564 E −04	6	4.273 E −04	2.347	0.032

Factor A = Adhesive type (PVAc, D-VTKA, and UF).
Factor B = Wood species (Scotch pine and oriental beech).
Factor C = Grain orientation (radial, tangential).
Factor D = Layer (3, 4, 5).

Method

Determination of density

Wood materials were kept in the room at 20°C ± 2°C and 65% ± 3% relative humidity until their weight became stable.[17] Air dry densities of wood materials used for the preparation of treatment samples were determined according to TS 2472.[18] Afterwards, the dimensions of wood materials were measured by a compass of ± 0.001 cm^3 sensitivity and volumes were determined by a stereometric method. The air dry density (δ_{12}) was calculated by using the following equation:

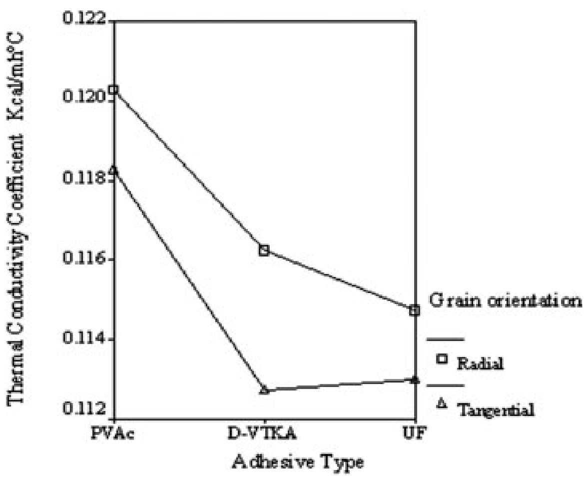

Figure 1 Effect of types of adhesives and grain orientation on thermal conductivity in Scotch pine.

$$\delta_{12} = \frac{M_{12}}{V_{12}} \text{g/cm}^3 \quad (1)$$

where M_{12} is the perfect air dry weight (g) and V_{12} is the volume (cm^3) of the wood material.

Preparation of experimental samples

The wood samples cut from sap wood were conditioned at 20°C ± 2°C and 65% ± 3% relative humidity until they reached a constant weight by holding them for 3 months in a climatization room. Air-dry specimens with a dimension of 4, 5, 7 mm ± 0.3 × 50 × 100 mm^3 were cut from the drafts. Afterward, ~ 180 g/m^2 adhesive was applied to the bonding surfaces of samples, based on TS 5430.[19] Bonding was obtained with 0.5 N/mm^2 press pressure and 24-h pressing time. Press temperatures were applied as 110°C for UF adhesive by taking the general curing temperatures recommended by their manufacturers into consideration. LVLs were prepared in a way to enable 3, 4, and 5 layers. There were 480 test samples with 12% average moisture with dimensions of 20 × 50 × 100 mm^3 according to the procedure of ASTM C 177/C 518 for each wood species.[20]

Execution of the test

A quick thermal conductivity meter based on ASTM C 1113-99 hot-wire method was used.[21] Variac (power supply) was used to supply constant electrical current to the resistance. QTM 500 device is a product of Kyoto Electronics Manufacturing, Japan. Measurement range is 0.0116–6 W/mK. Measurement precision is F5% of reading value per reference plate. Reproducibility is F3% of reading value per reference plate. Measurement temperature is −100 to 1000°C (external bath or electric furnace for temperature other than room). Sample size required is 20 × 50 × 100 mm^3. Measuring time is standard 100–120 s.[22]

Data analyses

By using three different types of glue, two wood types, directions (tangentially and radially) and three differences layer (3, 4, 5) and massive control as parameters, a total of 480 samples (3 × 2 × 2 × 4 × 10) were prepared using 10 samples for each parameter. Multiple analyses of variance were used to determine the differences between the thermal conductivity of the prepared samples.

RESULTS AND DISCUSSION

The averages of density are given in Table I. The highest density (0.864 g/cm^3) was obtained in oriental beech prepared tangentially, bonded with PVAc and five-layer LVL. The lowest density (0.514 g/cm^3) was obtained in Scotch pine prepared radially, massive control.

When the number of the layers are increased, the amount the adhesives is increased thus the highest density was obtained with five-layered samples.

The thermal conductivity value [kcal/(m h °C)] is given in Table II. The highest thermal conductivity of 0.159 kcal/(m h °C) was obtained in oriental beech, cut radially, bonded with PVAc, and 5-layer LVL. The lowest thermal conductivity of 0.105 kcal/(m h °C) was obtained in Scotch pine, cut tangentially, bonded with Polyurethane, and 3-layer LVL.

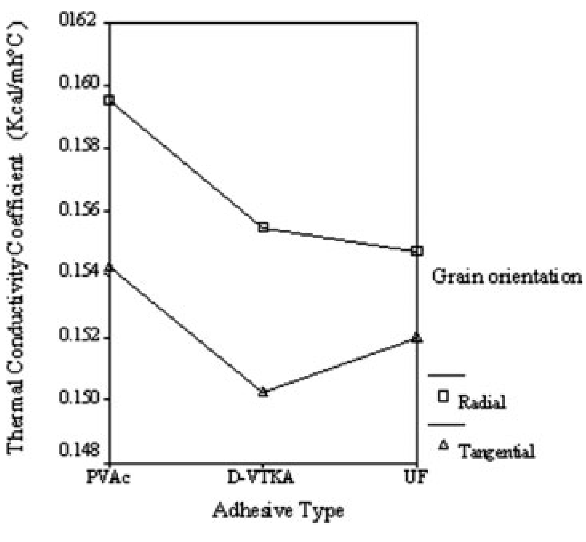

Figure 2 . Effect of types of adhesives and grain orientation on thermal conductivity in oriental beech.

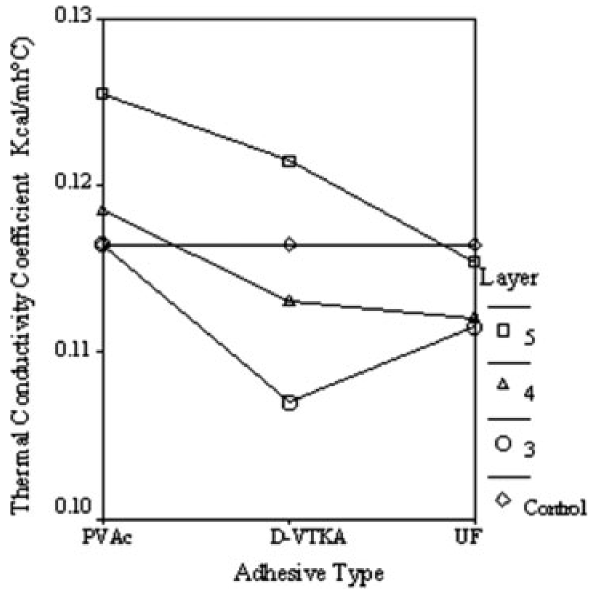

Figure 3 . Effect of types of adhesives and layer in LVL on thermal conductivity in Scotch pine.

Because the viscosity of the PVAc adhesive is high, the absorption of it into the wooden material is higher than the other adhesives. For this reason, the thermal conductivity of the samples bonded with PVAc is higher than the others.

As a wooden material, the thermal conductivity of oriental beech is higher than Scotch pine. This is because the density of oriental beech is higher than Scotch pine and the amount cell cavities in oriental beech is lower than Scotch pine.

As a conclusion, the more the number of the layers, the more is its thermal conductivity. On the contrary, when the number of the layers are increased, the more cell cavities occur on the bonded surfaces, the thermal conductivity of both materials are decreased due to the cell cavities. D-VTKA adhesive gave the lowest thermal conductivity, because it occurred to be more flexible on expanding surface between the layers.

The multiple variance analyses applied on the data obtained from the thermal conductivity test is given in Table III. According to the variance analysis, the effects of adhesive type, grain orientation, wood species, and layer in LVL were statistically significant.

In this study, thermal conductivity value of oriental beech is higher than Scotch pine. Sova et al. stated that T_c increases proportionally with wood density, MC, and temperature.[23]

CONCLUSIONS

According to the interaction, the effect of types of adhesives and grain orientation on thermal conductivity in Scotch pine is given in Figure 1. For radially cut samples, the lowest result was obtained in UF

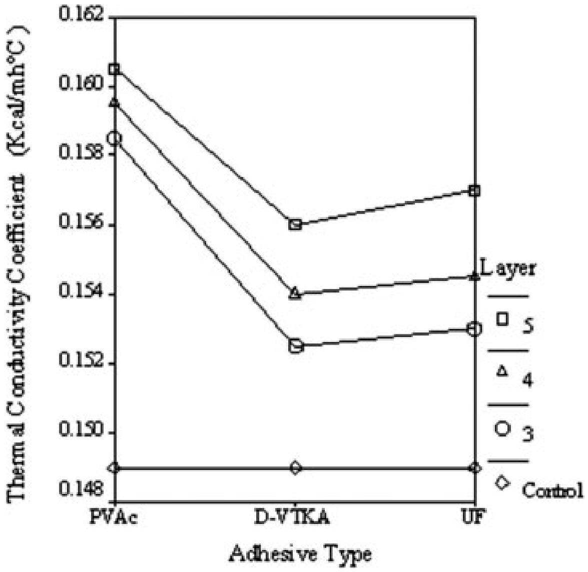

Figure 4 Effect of types of adhesives and layer in LVL on thermal conductivity in oriental beech.

adhesive and for tangentially cut samples, and the lowest result was obtained in polyurethane adhesive. In addition to this, PVAc gave the highest thermal conductivity in both grain orientations.

According to the interaction given in Figure 2, effect of types of adhesives and grain orientation on thermal conductivity in oriental beech. For radially cut samples, the lowest result was obtained in UF adhesive and in for tangentially cut samples, in polyurethane adhesive. In addition to this PVAc gave the highest thermal conductivity in both grain orientations.

According to the interaction given in Figures 1 and 2 between the adhesive types and grain orientation, oriental beech higher than Scotch pine result was obtained for both grain orientations. In addition to this, radially higher than tangentially gave thermal conductivity values.

Thermal conductivity in radial direction is at average 5–10% higher than the ones in tangential direction.[24]

According to the interaction, the effect of types of adhesives and layer on thermal conductivity in Scotch pine is given in Figure 3. For 3-layer LVL samples, the lowest result was obtained in polyurethane adhesive and in for 4- to 5-layer LVL samples, in UF adhesive. In addition to this PVAc gave the highest thermal conductivity in all (3-4-5) layer LVL.

According to the interaction, the effect of types of adhesives and layer on thermal conductivity in oriental beech is given in Figure 4. Polyurethane gave the lowest thermal conductivity in all (3-4-5) layer LVL. In addition to this, PVAc gave the highest thermal conductivity in all (3-4-5) layer LVL.

According to the interaction given in Figures 3 and 4 between the adhesive types and layer, oriental beech higher than Scotch pine result was obtained for all (3-4-5) layer LVL. In addition to this, the more the layer number gave, the more is the thermal conductivity value. But for 3–4 layer LVL in polyurethane and UF, lower than massive was obtained for thermal conductivity values.

Consequently, oriental beech wood cut radially and bonded with PVAc adhesive and five layers in LVL can be used as a material in construction where the thermal conductivity is required. Scotch pine wood cut tangentially and bonded with polyurethane adhesive and three layers in LVL can be used as a material in construction where the insulative is required.

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