Determination of Thermal Conductivity Properties in Some Wood Species Obtained from Turkey

Vedat Çavuş,[a,]* Sırrı Şahin,[b] Bruno Esteves,[c] and Ümit Ayata[d]

With the increased awareness of thermal insulation of buildings, the knowledge of thermal conductivity of non-structural materials applied for roughing, cladding or flooring has become more important. The objective of this study was to investigate the thermal conductivity of 31 different wood species originated from the region of Izmir in Turkey. Thermal conductivity of air dried boards was determined in accordance to ASTM 5334 standard which measures this property on the interior of wood rather than on the surface. Thermal conductivity varied from 0.090 to 0.197 W/mK. The highest thermal conductivity was obtained for oak and the lowest for Canadian poplar. A linear relation was obtained between wood density and thermal conductivity.

Keywords: Thermal Conductivity; Wood

*Contact information: a: Izmir Katip Celebi University, Faculty of Forestry, Forest Industry Engineering Department, Cigli/Izmir, Turkey; b: Department of Agricultural Buildings and Irrigation, Agriculture Faculty, Ataturk University, Erzurum, Turkey; c: Superior School of Technology, Polytechnic Institute of Viseu, Viseu, Portugal; d: Bayburt University, Faculty of Art and Design, Interior Architecture and Environmental Design, Bayburt, Turkey; *Corresponding author: vedatcavus@hotmail.com*

INTRODUCTION

The variations of exterior temperature between night and day and between summer and winter seasons make thermal conductivity (TC) of wood an important property when applied as cladding, roughing, or flooring in building construction. Moreover, with the increase in energy costs, consumers are becoming more aware of the importance of a good thermal insulation of the materials used in construction. It follows that the knowledge of the thermal conductivity of the most commonly used wood species is vital.

With respect to wood, the TC is highly dependent on wood density and moisture but also on the direction of the measurements, on the kind and amount of extractives or other chemical substances, on the relative density and proportion of earlywood/latewood, and also on wood defects (MacLean 1941). Generally, higher density leads to higher TC, and good linear correlations have been reported before (Narayanamurti and Ranganathan 1941; Gu and Zink-Sharp 2007; Yu *et al.* 2011; Vay *et al.* 2015). For instance Pelit *et al.* (2014) densified fir wood and concluded that after densification the TC had increased by about 50%. Moreover, Yapici *et al.* (2011), who determined the thermal conductivity of several species, obtained higher thermal conductivities for more dense woods, with the highest TC achieved for oak (0.8 g/cm^3), followed by fir (0.45 g/cm^3), beech (0.6 g/cm^3), chestnut (0.52 g/cm^3), and Scots pine (0.47 g/cm^3).

Water is a good heat conductor, and therefore higher amounts of water in wood increase the thermal conductivity. According to some authors (MacLean 1941; Vay *et al.* 2015) below the fiber saturation point there is a linear correlation between moisture in wood and thermal conductivity.

The direction of the measurements is also important for thermal conductivity, which is generally higher in the axial direction (Samuel *et al.* 2012). This is due to the orientation of the molecular chains within the cell wall (Suleiman *et al.* 1999). According to Kotlarewski *et al.* (2014) the rate of heat flow in the axial direction is two and a half times greater than the rate through the other directions. Although cellulose microfibrils have different orientations, the majority are aligned with the longitudinal axis. Vay *et al.* (2015), supported by different studies (Griffiths and Kaye 1923; Rowley 1933; Bučar and Straže 2008), stated that the thermal conductivity is about 2 to 3 times higher in the longitudinal direction than in the radial or tangential directions. Although smaller, there is also a difference between radial and tangential directions. Thermal conductivity in the radial direction is about 5% to 10% higher than in tangential direction (Griffiths and Kaye 1923; Faouel *et al.* 2012). Some studies show that hardwoods that have a high amount of rays usually have higher thermal conductivity, since rays serve as paths for the heat transport, making radial thermal conductivity higher than tangential (Rowley 1933; Vay *et al.* 2015).

Wood porosity is also an important factor because air is a poor thermal conductor compared to wood material. Therefore porous woods have lower thermal conductivity. For example, Vasubsbu *et al.* (2015) tested the thermal conductivity of several Indian trees and observed that the lowest TC were obtained for the most porous woods. The curry tree presented almost 73% porosity and had the lowest TC, around 1.47 x 10^{-4} cal/(s·cm ºC).

EXPERIMENTAL

Materials

Boards of 31 different species commonly used in Turkey were used in this study. The species were: walnut (*Juglans regia*), maun (*Swietenia mahagoni*), black locust (*Robinia pseudoacacia* L.), chestnut (*Castanea sativa* Mill.), oak (*Quercus petraea* Liebl.), apple (*Malus domestica*), eucalyptus (*E. camaldulensis* Dehnh.), avocado (*Persea americana*), fig (*Ficus carica*), European larch (*Larix decidua*), Monterey cypress (*Cupressus macrocarpa*), black pine (*Pinus nigra*), fir (*Abies bornmuelleriana*), beey (*Morus* Sp.), cedar (*Cedrus libani*), Scots pine (*Pinus sylvestris* L.), red pine (*Pinus brutia* Ten.), ash (*Fraxinus excelsior*), Mediterranean cypress (*Cupressus sempervirens*), lime (*Tilia cordata*), juniper (*Juniperus communis* L.), plum (*Prunus domestica*), olive (*Olea europaea*), iroko (*Chlorophora excelsa*), hornbeam (*Carpinus betulus* L.), peach (*Prunus persica*), Canadian poplar (*Populus canadensis*), black poplar (*Populus nigra*), Russian olive (*Elaeagnus angustifolia*), plane (*Platanus orientalis* L.), and white oak (*Quercus alba*). The wood samples came from various lumber sales sites, in Izmir City, Turkey. The samples were air dried until an initial moisture content of around 12% (ISO 554, 1976).

After the drying period 5 samples with dimensions 5 cm x 5 cm x 15 cm (radial x tangential x longitudinal) were cut from each board. The density of all the samples was determined at 12% moisture content by weighing and measuring the dimensions of the samples with a calliper.

Thermal Conductivity Measurement

Thermal conductivity measurements were made with a THERM 2227–2, ALHBORN thermal conductivity meter (Fig. 1) in accordance with ASTM 5334-08. Although this method is more suitable for isotropic materials, it has already been used by Kotlarewski *et al.* (2014) to determine the TC of balsa wood. In order to make the measurements, a 14 cm long hole was drilled in each sample along longitudinal direction. After introducing the still pin in the hole, three measurements were made for each sample. The device is done measuring when a balance of 30 to 36 °C degrees is obtained, which takes 10 min.

Fig. 1. Thermal conductivity measurement (Model THERM 2227–2, ALHBORN)

Statistical Analysis

A statistical analysis was made by using SPSS 17 Software (Sun Microsystems Inc., Santa Clara, CA, USA). For thermal conductivity (W/mK) the average value of fifteen replicates was recorded.

RESULTS AND DISCUSSION

Table 1 presents the results of the variance analysis of thermal conductivity made on the 31 different wood species. Results show that the wood species had a significant effect on thermal conductivity, which makes the selection of wood species important when wood is applied to building construction.

Table 1. Thermal Conductivity Variance Analysis

Source	Sum of Squares	df	Mean Square	F	Sig.
Wood species	0.357	30	0.012	123.042	0.000*
Error	0.042	434	0.000		
Total	9.523	465			

Table 2 presents the thermal conductivities of the 31 species measured in this work. The lowest thermal conductivity was obtained for Canadian poplar (0.090 W/mK), followed by Monterey cypress (0.093 W/mK), black poplar (0.109 W/mK), and fir (0.11 W/mK). The highest was for oak (0.197 W/mK) followed by olive (0.195 W/mK), Mediterranean cypress (0.195 W/mK), and plum (0.179 W/mK). The lowest density was obtained for Canadian poplar (0.340 g/cm^3), Monterey cypress (0.405 g/cm^3), and fir (0.410 g/cm^3), and the highest density was olive (0.894 g/cm^3), followed by oak (0.841

g/cm^3) and plum (0.799 g/cm^3). There wasn't much information available about thermal conductivity of the species studied; however some authors reported comparable thermal conductivities for some of them. For example Kol and Sefil (2011) reported a thermal conductivity of 0.1297 W/mK and 0.1362 W/mK in tangential and radial directions for fir (*Abies bornmülleriana* Mattf.), which is a little higher than the value obtained here (0.110 W/mK); nevertheless the samples in the cited study had 0.457 g/cm^3 density, which was also higher than the samples of the present study (0.410 g/cm^3). However, Dündar *et al.* (2012) presented a thermal conductivity of 0.111 W/mK, which is almost the same as the value obtained here, for samples with 0.388 g/cm^3 density. Surprisingly, Yapici *et al.* (2011) reported a much higher thermal conductivity perpendicular to the grain for this fir (0.195 W/mK) with 0.450 g/cm^3 density. These authors also reported a thermal conductivity of 0.182 W/mK for Scots pine and 0.196 W/mK for chestnut, which were a little higher than the values obtained here of 0.132 W/mK and 0.114 W/mK.

Table 2. SPSS Analysis Results for Thermal Conductivity of the Studied Species and density

Wood species	**N**	***k* (W/mK)**	***HG***	***Sd***	**Mini-mum**	**Maxi-mum**	**Density g/cm^3**
Walnut (*Juglans regia*)	**15**	0.134	HI	0.012	0.104	0.152	0.636
Maun (*Swietenia mahagoni*)	**15**	0.152	DE	0.012	0.136	0.171	0.732
Black locust (*Robinia pseudoacacia* L.)	**15**	0.166	C	0.012	0.146	0.187	0.732
Chestnut (*Castanea sativa* Mill.)	**15**	0.114	KL	0.007	0.102	0.128	0.517
Oak (Quercus petreae L.)	**15**	0.197	A*	0.018	0.172	0.224	0.841
Apple (*Malus domestica*)	**15**	0.167	C	0.016	0.140	0.187	0.699
Eucalyptus (*E. camaldulensis* Dehnh.)	**15**	0.153	DE	0.011	0.134	0.178	0.611
Avocado (*Persea americana*)	**15**	0.120	JK	0.004	0.113	0.128	0.485
Fig (*Ficus carica*)	**15**	0.117	KL	0.003	0.110	0.120	0.628
European Larch (*Larix decidua*)	**15**	0.116	KL	0.008	0.100	0.126	0.535
Monterey cypress (*Cupressus macrocarpa*)	**15**	0.093	M	0.007	0.082	0.106	0.405
Black pine (*Pinus nigra*)	**15**	0.143	FG	0.009	0.127	0.157	0.552
Fir (*Abies bornmuelleriana*)	**15**	0.110	L	0.005	0.099	0.118	0.410
Berry (*Morus* Sp.)	**15**	0.155	DE	0.005	0.148	0.164	0.680
Cedar (*Cedrus libani*)	**15**	0.127	IJ	0.008	0.116	0.142	0.427
Scotch pine (*Pinus sylvestris* L.)	**15**	0.132	HI	0.008	0.118	0.145	0.504
Red pine (*Pinus brutia* Ten.)	**15**	0.129	I	0.006	0.120	0.139	0.514
Ash (*Fraxinus excelsior*)	**15**	0.157	D	0.009	0.144	0.168	0.722
Mediterranean cypress (*Cupressus sempervirens*)	**15**	0.195	A	0.011	0.174	0.216	0.641
Lime (*Tilia cordata*)	**15**	0.119	K	0.006	0.105	0.125	0.520
Juniper (*Juniperus communis* L.)	**15**	0.130	HI	0.005	0.120	0.138	0.424
Plum (*Prunus domestica*)	**15**	0.179	B	0.013	0.164	0.198	0.799
Olive (*Olea europaea*)	**15**	0.195	A	0.016	0.171	0.217	0.894*
Iroko (*Chlorophora excelsa*)	**15**	0.137	GH	0.009	0.123	0.154	0.619
Hornbeam (*Carpinus betulus* L.)	**15**	0.151	DE	0.012	0.133	0.174	0.686
Peach (*Prunus persica*)	**15**	0.155	DE	0.013	0.137	0.170	0.641
Canadian poplar (*Populus canadensis*)	**15**	0.090	M**	0.007	0.076	0.098	0.340**
Black poplar (*Populus nigra*)	**15**	0.109	L	0.012	0.086	0.127	0.411
Russian olive (*Elaeagnus angustifolia*)	**15**	0.121	JK	0.006	0.114	0.134	0.559
Plane (*Platanus orientalis* L.)	**15**	0.132	HI	0.006	0.121	0.140	0.537
White Oak (*Quercus alba*)	**15**	0.148	EF	0.007	0.137	0.156	0.603
HG: Homogeneity Group, N: Number of measurements, k: thermal conductivity mean, Sd: Standard Deviation, *: Highest value, **: Lowest value							

Figure 2 presents the relation between thermal conductivity and density of the tested woods. Results show that there was a clear linear relation between density and thermal conductivity, as stated before (MacLean 1941). A similar relation was reported by Mason *et al.* (2016) for several kinds of woods reported in literature. Nevertheless, there are some woods that present a higher thermal conductivity than expected in accordance to density. This is the case for Mediterranean cypress. This is probably due to the differences in anatomical features such as porosity or amount and kind of extractives, which are known to influence the thermal conductivity of wood (MacLean 1941; Vasubsbu *et al.* 2015).

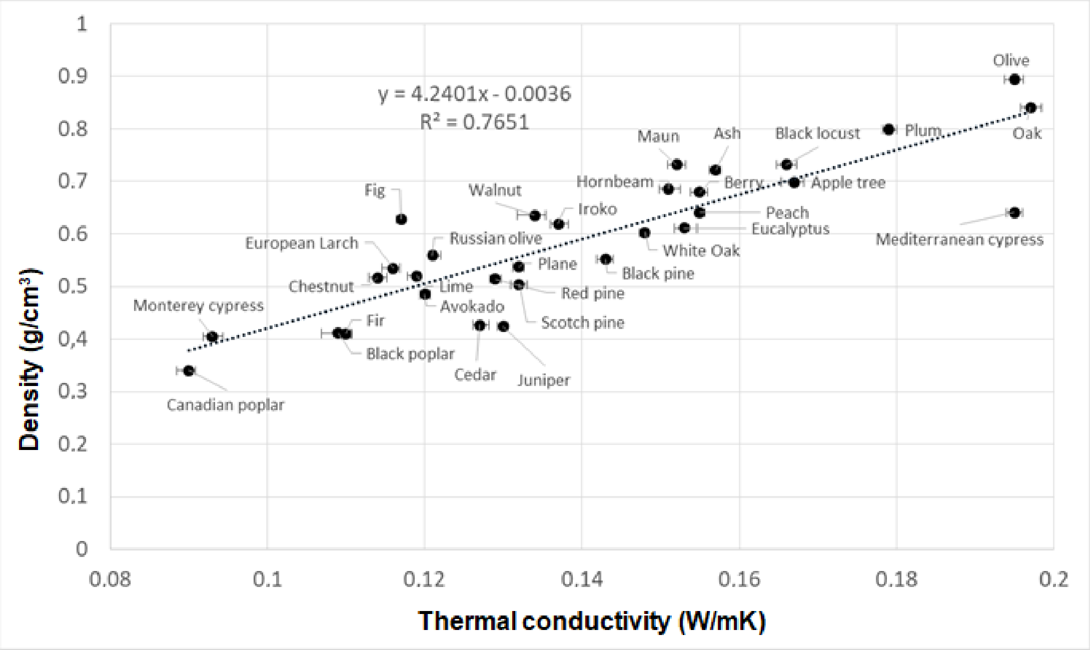

Fig. 2. Relation between thermal conductivity and density

Based on looking at thermal conductivity alone, species like fir or Canadian and black poplar would be the ideal choices for interior cladding, roughing, or flooring since they would have the best insulation performance. Although it is known that low density species are not suitable for flooring due to their low hardness, this property is not that important when used for example in roughing. On the other hand, for example oak, one of the most used species for flooring, has the highest thermal conductivity of this list, showing that it is not the best choice in terms of energy consumption.

CONCLUSIONS

Results show that wood species have a significant effect on thermal conductivity, establishing once more that it is important to select the right wood species for application to building construction. The highest thermal conductivity was obtained for oak (0.197 W/mK) and the lowest for Canadian poplar (0.090 W/mK). A linear relationship was achieved between thermal conductivity and density of wood. Results show that a more careful selection of wood species for non-structural applications can be made in order to decrease energetic consumption.

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