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THE RELATIONSHIP BETWEEN BULK DENSITY AND THERMAL CONDUCTIVITY IN VARIOUS KOREAN WOODS

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ABSTRACT

The article deals with the effects of bulk density on thermal conductivity in specimens of 15 Korean woods *(Zelkova serrata, Pinus densiflora, Cornus controversa, Betula schmidtii, Betula platyphylla var. japonica, Ginkgo biloba L.*, *Cedrela sinensis A. Juss., Fraxinus mandshurica, Ulmus davidiana var. japonica, Prunus sargentii Rehder, Paulownia tomentosa (Thunb.) Steud., Larix kaempferi (Lamb.) Carrière, Robinia pseudoacacia, Kalopanax septemlobus and Tilia amurensis).*

The results of this study were compared with previous studies performed on wood specimens from China, India, and Turkey. Consistent with these previous studies, bulk density and thermal conductivity were positively correlated in Korean woods, and a simple regression model with a very high correlation of R^2 (94%) was obtained. Interestingly, we observed some variation between our simple regression models and those generated by previous researchers who had examined non-Korean woods.

KEYWORDS: Korean wood, bulk density, thermal conductivity, simple regression model.

INTRODUCTION

Countries around the world are considering how to reduce carbon emissions and respond to new climate pressures (Olivier et al. 2005). Particular attention has been paid to reducing the amount of carbon emitted by buildings (Jeong et al. 2012), which account for approximately 25% of total worldwide carbon emissions (Cho et al. 2019). Wood, as a sustainable resource, has re-emerged as an attractive building material, and demand for wood construction material is steadily increasing (Falk 2009). If new construction of buildings in Europe is planned to be wooden, carbon storage is equal to maximum 47% of European cement industry CO_2 emissions (Amiri et al. 2020).

Relaying on materials with low thermal conductivity is an excellent passive method of achieving energy efficiency (Seo et al. 2011). Wood is less thermally conductive than alternative building materials, which means that it functions as an outstanding thermal insulator (Agoudjil et al. 2011, Pásztory et al. 2020). However, Korean homes traditionally incorporate 'Ondol' heating systems into their floors (Yeo et al. 2003). Unlike other building materials, the flooring materials necessitated by this heating system must be highly thermally conductive for buildings to be heated efficiently (Seo et al. 2011). Kwon and Jeon (1999) surveyed apartment residents living in Seoul, Korea, to identify their preferences for living room flooring material. The results were heavily tilted in favor of wood flooring: 1.1% for tile, 2.9% for stone, 4.0% for carpet, 1.8% for cardboard, 19.4% for synthetic resin, and 70.9% for wood. The strong bias towards wood flooring was attributed to its hypo-allergenic health benefits and ergonomic texture.

Wood has the lowest thermal conductivity, and performed poorest at efficiently transferring heat energy, among all of the floor materials surveyed (Park and Jo 2020). A number of methods have been developed in an attempt to improve wood's thermal conductivity; thermo-mechanical densification (Pelit et al. 2014), impregnation of nano-chemicals (Seo et al. 2014, Taghiyari et al. 2020), altering the adhesives used for plywood floors (Aydin et al. 2014), adhesion between heterogeneous materials with low thermal conductivity (Park and Jo 2020), etc.

Wood is mostly comprised of cellulose, hemicellulose, and lignin. The ratio of these materials remains fairly consistent across species, with the result that the density of most woods is similar (Côté and Kollmann 1984). The bulk density of a wood and its porosity are inversely proportional (Jang and Kang 2019). As a result, the bulk density of a wood is closely related to its thermal conductivity (Gu and Zink-Sharp 2007). Vasubsbu et al. (2015) investigated the relationship between bulk density and thermal conductivity in 20 Indian woods. Wood that had a low bulk density had a high porosity, which resulted in low thermal conductivity. They determined that this relationship was positively liner. Çavuş et al. (2019) also investigated this relationship using 31 species of Turkish wood, concluding that oak had the lowest thermal conductivity (0.090 $W \cdot m^{-1}K^{-1}$) while Canadian poplar had the highest (0.197 $W \cdot m^{-1}K^{-1}$), and reporting a linear proportional relationship between thermal conductivity and bulk density.

Yu et al. (2011) investigated the connection between the moisture content of five types of hardwood and softwood routinely used in China, their thermal conductivity, and their bulk density, ultimately determining that thermal conductivity increased along with bulk density, temperature, and moisture content. A linear equation based on these factors was proposed.

As results of previous studies, the correlation between bulk density and thermal conductivity was investigated for wood produced in various countries. In Korea, Seo et al. (2016) analyzed changes in thermal conductivity as a function of moisture content in 56 types of domestic Korean wood species. However, to date there have been no investigations into the relationship between thermal conductivity and bulk density in Korean woods.

According to the Korean Forest Service's (KFS) 2019 'Statistical Yearbook of Forestry', domestic timber's self-sufficiency rate is gradually increasing from 11.9% in 2009 to 15.2% in 2018 due to the increase in production volume according to the policy of usage domestic wood (KFS 2019). This suggests that domestic wood will remain a popular flooring material for the foreseeable future. In this paper, we investigate how the bulk density of wood alters its thermal conductivity, information that is essential to the continued production of this vital building material.

MATERIAL AND METHODS

Material

As shown in Fig. 1, fifteen domestic wood specimens (1.75 × 10 × 15 cm) were provided by Chungnam National University in Korea (general and scientific names are listed in Tab. 1. Bulk density was measured and porosity was calculated using Eq. 1 below, with the assumption that each wood's true density was 1.5 $g \cdot cm^{-3}$ (Jang et al. 2020). 15 specimens were maintained in an air-dried state and their average moisture content was approximately 11%.

$$\Phi(\%) = \left(1 - \frac{\rho_{true}}{\rho_{bulk}}\right) \times 100 \quad (1)$$

where: Φ – porosity (%), ρ_{true} – true density ($g \cdot cm^{-3}$), ρ_{true} - bulk density ($g \cdot cm^{-3}$).

Fig. 1: Photograph of Korean wood specimens.

Tab. 1: Fifteen Korean wood specimens, representing 15 distinct species.

General name	Scientific name	Type
Sawleaf zelkova	*Zelkova serrata*	Hardwood
Korean red pine	*Pinus densiflora*	Softwood
Giant dogwood	*Cornus controversa*	Hardwood
Schmidt birch	*Betula schmidtii*	Hardwood
White birch	*Betula platyphylla var. japonica*	Hardwood
Maidenhair tree	*Ginkgo biloba L.*	Hardwood
Chinese cedrela	*Cedrela sinensis A. Juss.*	Hardwood
Manchurian ash	*Fraxinus mandshurica*	Hardwood
Japanese Elm	*Ulmus davidiana var. japonica*	Hardwood
Sargent cherry	*Prunus sargentii Rehder*	Hardwood
Paulovnia	*Paulownia tomentosa (Thunb.) Steud.*	Hardwood

Japanese larch	*Larix kaempferi (Lamb.) Carrière*	Softwood
False acacia	*Robinia pseudoacacia*	Hardwood
Castor aralia	*Kalopanax septemlobus*	Hardwood
Lime tree	*Tilia amurensis*	Hardwood

Thermal conductivity analyses

Thermal conductivity can be determined by any of three methods: the steady state method, the transient line source method, and the laser flash method (Jeon et al. 2011). We elected to use the transient line source method (according to ISO 8894-1 and ISO 8894-2) and employed a quick thermal conductivity meter (model: QTM-500, Kyoto Electronics, Japan).

When a constant power is applied to the heater, the temperature of the wire rises exponentially. Where heat does not transfer easily, the application of heat to small samples results in a steepening slope of this straight line. In samples that have high thermal conductivity, the slope is reduced. The thermal conductivity of 15 samples can be represented by obtaining the slope of the rising temperature curve over time, using the following Eq. 2:

$$\lambda = Q \cdot \ln\left(\frac{t_2}{t_1}\right) / 4\pi(T2 - T1) \qquad (2)$$

where: λ - thermal conductivity of specimen ($W \cdot m^{-1}K^{-1}$), Q - heat capacity per unit length ($W \cdot m^{-1}$), t_1 and t_2 - test time (s), and T_1 and T_2 - temperature (K).

Statistical analyses

A simple regression analysis was conducted to determine the effect of bulk density on thermal conductivity. The simple regression model we employed relied on the following equation:

$$\text{Thermal condictivity} = \alpha_0 + \beta X + \varepsilon \qquad (3)$$

where: X - bulk density, α_0 - constant (intercept term), ε - residuals (error term).

Calculation were made performed by IBM SPSS statistics v26 software (IBM Corp., Armonk, NY, USA). We also compared the results of prior researchers to Indian (Vasubsbu et al. 2015), Chinese (Yu et al. 2011), and Turkish (Çavuş et al. 2019) woods those of this study.

RESULTS AND DISCUSSION

Tab. 2 presents the bulk density, porosity, and thermal conductivity of the 15 tested specimens. Among these species, paulovnia bulk density was the lowest at 0.22 $g \cdot cm^{-3}$, and its associated thermal conductivity was 0.0870 $W \cdot m^{-1}K^{-1}$. In comparing the bulk density with paulovnia species to other countries, the bulk density of *Paulownia elongata* from Hungary was 0.3 $g \cdot cm^{-3}$ (Koman et al. 2017), Turkey specie was 0.326 $g \cdot cm^{-3}$ (Kaygin et al. 2009), that of the Malaysian specie was 0.325 g·cm^{-3} (Ab Latib et al. 2020). It was found that the bulk density of Korean paulovnia shows lower than other species.

Schmidt birch, in contrast, had the highest bulk density at 1.00 g·cm^{-3}, with an associated thermal conductivity of 0.2476 W·m^{-1}K^{-1}. Porosity was determined to be precisely inversely proportional to bulk density, assuming (as we did) woods' true density remained constant at 1.5 g·cm^{-3}. In comparing the bulk density with birch species to other countries, the bulk density of birch (*Betula*) from Lithuania was 0.632 g·cm^{-3} (Bendikiene and Keturakis 2016), that of Poland specie (*Betula pendula Roth*) was 0.38 to 0.75 g·cm^{-3} (Jakubowski et al. 2020). It was found that the bulk density of Korean Schmidt birch shows higher than other species. This result means that the porosity of Korean birch will be lower than that of species in other countries.

As F = 219.641 ($P < 0.001$) this simple regression model (Tab. 3) is appropriate. R^2 is a correlation coefficient indicating the degree of linear relationship between two variables. As thermal conductivity and bulk density have a linear relationship, which has a high explanatory power of 94.4%. β (bulk density) is 0.205 ($P < 0.001$), a statistically significant result with respect to thermal conductivity. The positive (+) β indicates that thermal conductivity increased along with density. The Durbin-Watson statistic is a measure of whether one residual affects others. It may be any value from 0 to 4, though the closer it is to 2 the more independent the residuals are. Our experiment resulted in a Durbin Watson value of 2.15. Fig. 2 compares the results of our simple regression model with those obtained from previous studies of woods from China, India, and Turkey.

Tab. 2: Bulk density, porosity and thermal conductivity.

Sample	Mass (g)	Volume (cm^3)	Density (g.cm^{-3})	Porosity (%)	Thermal conductivity (W.m^{-1}K^{-1})
Sawleaf zelkova	180.50	262.5	0.69	54.16	0.2001
Korean red pine	129.53	262.5	0.49	67.10	0.1433
Giant dogwood	122.27	262.5	0.47	68.95	0.1271
Schmidt birch	263.18	262.5	1.00	33.16	0.2476
White birch	200.88	262.5	0.77	48.98	0.2017
Maidenhair tree	109.05	262.5	0.42	72.30	0.1423
Chinese cedrela	159.16	262.5	0.61	59.58	0.1524
Manchurian ash	139.89	262.5	0.53	64.47	0.1447
Japanese Elm	182.35	262.5	0.69	53.69	0.1927
Sargent cherry	173.31	262.5	0.66	55.98	0.1870
Paulovnia	58.99	262.5	0.22	85.02	0.0870
Japanese larch	150.00	262.5	0.57	61.90	0.1698
False acacia	209.71	262.5	0.80	46.74	0.1954
Castor aralia	191.27	262.5	0.73	51.42	0.1934
Lime tree	119.47	262.5	0.46	69.66	0.1361

Tab. 3: Regression analysis of bulk density and thermal conductivity.

Variables	Unstandardized coefficients		Standardized coefficients	t(p)	F(p)	R^2	Durbin-Watson
	B	SE	β				
(Intercept)	0.043	0.009		4.922**	219.641**	0.944	2.15
Bulk density	0.205	0.014	0.972	14.82**			

Note: ** P < 0.001

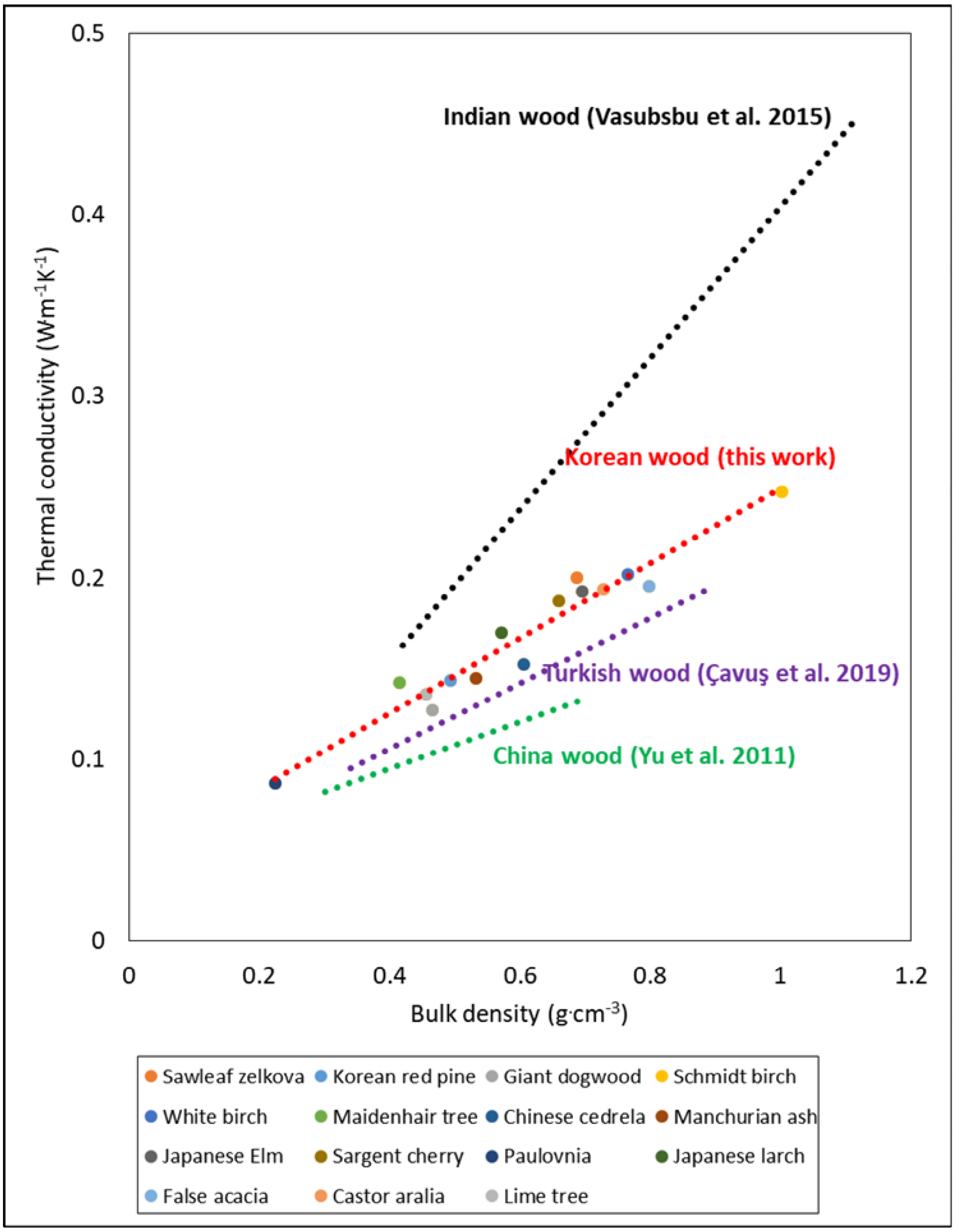

Fig. 2: The relationship between bulk density and thermal conductivity (red dotted line- Korea, green- China, purple- Turkey, black- India).

Consistent with previous studies, a relationship of positive proportionality between bulk density and thermal conductivity was confirmed across all tested woods. Our results also confirmed that there is some variation in the coefficients produced by the simple regression model across countries.

CONCLUSIONS

In this study, the bulk density and thermal conductivity of 15 Korean wood species were investigated. Among these species, paulovnia was the lowest bulk density (0.22 $g \cdot cm^{-3}$), and its thermal conductivity was 0.087 $W \cdot m^{-1}K^{-1}$. In contrast, Schmidt birch's bulk density was highest at 1.00 $g \cdot cm^{-3}$ and its thermal conductivity was 0.2476 $W \cdot m^{-1}K^{-1}$.

Our testing of 15 Korean wood species to determine the relationship between bulk density and thermal conductivity uncovered that the coefficient produced by the simple regression model varies across countries. Wood density, porosity, and thermal conductivity were correlated, which are important factors when making wood products. We anticipate that this study will assist producers is selecting appropriate woods for use as indoor flooring materials.

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