Thermal Conductivity of Plantation Wood Species and Selected Tropical Hardwoods from the Philippines

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This study investigated the transverse thermal conductivity of low-density plantation wood species and tropical hardwoods from the Philippines using the guarded hot-plate method. Results showed that thermal conductivity of low density, plantation species and denser tropical hardwoods ranged from 0.128 to 0.188 W/mK and 0.161 to 0.300 W/mK, respectively. Thermal conductivity was directly influenced by both density and moisture content of wood. Transverse thermal conductivity increased by 0.73% and 1.79% per percent increase in MC from 0% to 21% MC for low density (<500 kg/m^3) and high density (>500 kg/m^3) wood, respectively. Linear regression models fitted for thermal conductivity and ovendry density indicated a strong fit. However, there was a poor to moderate relationship between thermal conductivity and MC. The results of the present study may be of interest in the conversion of woody biomass to bioenergy or to building designers looking for natural materials to improve energy performance and efficiency of wood structures where heat transfer and temperature control are a significant economic consideration.

DOI: 10.15376/biores.20.3.6877-6886

Keywords: Thermal conductivity; Energy efficiency; Sustainable building; Philippine woods; Fourier's law

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INTRODUCTION

Thermal conductivity of wood is the property that measures the "ease" or "difficulty" for the flow of heat energy when subjected to a temperature gradient. Wood is made up of cellulose, hemicellulose, and lignin interwoven into a complex composite of high and low molecular weight polymers. It has a long history of use as fuel and building construction material. Understanding the thermal properties of wood and wood composites is essential in various applications such as fuel conversion (Ragland *et al*. 1991; Thunman and Leckner 2002), insulation (Rice and Shepard 2004; Kawasaki and Kawai 2006), and building construction (Kamke and Zylkowski 1989; Czajkowski *et al*. 2016). Thermal conductivity plays an important role in the design of structures in which heat transfer and temperature control are a significant economic consideration (Olek *et al*. 2003). The steady state heat conduction according to Fourier's Law is when the heat flux is proportional to the magnitude of the temperature gradient (Siau 1984). Accordingly, thermal conductivity can be expressed as,

$$k = \frac{q \, \mathrm{d}x}{A \, \mathrm{d}T} \tag{1}$$

where q is the heat flux (W/m^2), A is the cross-sectional area perpendicular to flow (m^2), dx is the specimen thickness (m), dT the temperature gradient between surfaces (K), and k is thermal conductivity (W/mK). Wood is a complex and heterogeneous material with thermal conductivity varying both between and within species. Other factors affecting thermal conductivity of wood include density (Yu *et al*. 2011), moisture content (TenWood *et al*. 1988), temperature (Harada *et al*. 1998; Suleiman *et al*. 1999), grain direction (Vay *et al*. 2015; Flity *et al*. 2024), porosity, anisotropic nature (Bucar and Straze 2008; Hu *et al*. 2023), and chemical composition (Suleiman *et al*. 1999), among others.

The most established method for high precision thermal conductivity measurement of wood is the guarded hot-plate (GHP) method (Hu *et al*. 2023; Ebert and Vidi 2024). The wood specimen is placed under a high temperature heat source for a sufficient length of time to achieve a uniform temperature gradient (steady state) throughout the sample. The rate of heat flow is obtained based on the electric input to the heating element and thermal conductivity calculated based on Eq. 1. Other methods such as the laser flash (Harada *et al*. 1998), transient plane source technique (Suleiman *et al*. 1999), and transient hot wire method (Kol 2009) were also developed. The present study reports on the thermal conductivity of wood using the GHP method from fast-growing industrial plantation species and from selected Philippine tropical hardwoods. These wood species are commonly used for general construction and often exported to North America and Europe. Thermal conductivities of wood species grown from Southeast Asia are often lacking or not available. Results from this study could potentially be useful for modelling heat transfer processes or in the design of energy efficient and sustainable buildings using components or members of these wood species.

MATERIALS AND METHODS

Wood Specimens

Twelve (12) Philippine wood species (10 to 15 years old) from fast-growing plantation and tropical hardwoods were selected from the stock of the Forest Products Research and Development Institute, Department of Science and Technology (Table 1). These species were chosen because of their common use or to cover a wide range of densities. Five discs (50 mm ×10 mm; diameter × thickness) with no signs of decay, cracks, checks, or knots were cut and surfaced from each species (Fig. 1). All specimens were then placed in a conditioning chamber (Memmert HCP105) where temperature and relative humidity were adjusted to achieve target equilibrium moisture contents (MC) of 21% followed by 12% (dry basis). Lastly, specimens were placed in an oven set at 105 °C until constant weight (ovendry) was achieved. Specimen weight and volume were determined at each level of MC, from which wood densities were calculated using (ASTM D2395-14).

Fig. 1. Plantation species and tropical hardwoods from the Philippines used in thermal conductivity measurements

Table 1. Philippine Plantations Tree Species and Tropical Woods Used in GHP Thermal Conductivity Measurements

Family	Common Name	Scientific Name	Density (kg m^{-3})*	Species code	Parts used
Plantation Species Meliaceae	Bagalunga	*Melia dubia* Cav.	430	BG	Sapwood
Myrtaceae	Bagras	*Eucalyptus deglupta* Blume	540	BA	Sapwood
Verbenaceae	Gmelina	*Gmelina arborea* Roxb.	430	GM	Sapwood
Meliaceae	Mahogany	*Swietenia macrophylla* King	510	MH	Sapwood
Fabaceae	Mangium	*Acacia mangium* Willd.	520	MN	Sapwood
Tropical Hardwoods Anacardiaceae	Amugis	*Koordersiodendron pinnatum* (Blco.) Merr.	713	AM	Heartwood
Apocynaceae	Batino	*Alstonia macrophylla* Wall	620	BT	Heartwood
Ebenaceae	Kamagong, ebony	*Diospyros discolor* Willd.	937	KM	Heartwood
Fabaceae	Narra	*Pterocarpus indicus*	546	NR	Heartwood
Lamiaceae	Teak	*Tectona grandis*.	550	TK	Heartwood
Dipterocarpaceae	White Lauan	*Shorea contorta* S. Vidal	480	WL	Heartwood
Dipterocarpaceae	Yakal	*Shorea astylosa* Foxw.	828	YK	Heartwood

* CAB International Compendium. www.cabi.org/isc

Thermal Conductivity Measurement

A single-specimen guarded hot plate apparatus calibrated using brass plates was used to measure the thermal conductivity of all wood specimens following ISO 8302 (1991) method with some modifications. A wood specimen of uniform thickness (50 mm x 10 mm) was placed in thermal contact between heated (323 K) and cold (303 K) metal discs (50 mm), resulting in a uniform temperature gradient after about 20 to 30 min across the transverse grain direction of the specimen (Fig. 2). To minimize lateral heat loss and erroneous heat flux reading, a cylindrical layer of cellular insulation (Styrofoam 20 mm) was wrapped around both hot and cold discs and the wood specimen (Fig. 1). The apparatus was enclosed in a glass chamber to prevent convective losses or gains from the surrounding air. The setup ensured that the heat flow was perpendicular to the specimen surface with no lateral parasitic heat loss. The temperatures of the hot and cold discs were recorded using thermocouples (Type K) attach to a data logger. The rate of heat flow was recorded based on the electric input to the heating element of the hot disc. All measurements were performed under steady-state conditions and thermal conductivity calculated according to Eq. 1. Thermal conductivity was measured for all wood specimens at 21%, 12%, and 0% MC values. Five replicate wood specimens were used for each measurement. A linear regression model was fitted between thermal conductivity and density using Statgraphics Centurion 19 (2023) software to determine the influence of wood density on thermal conductivity.

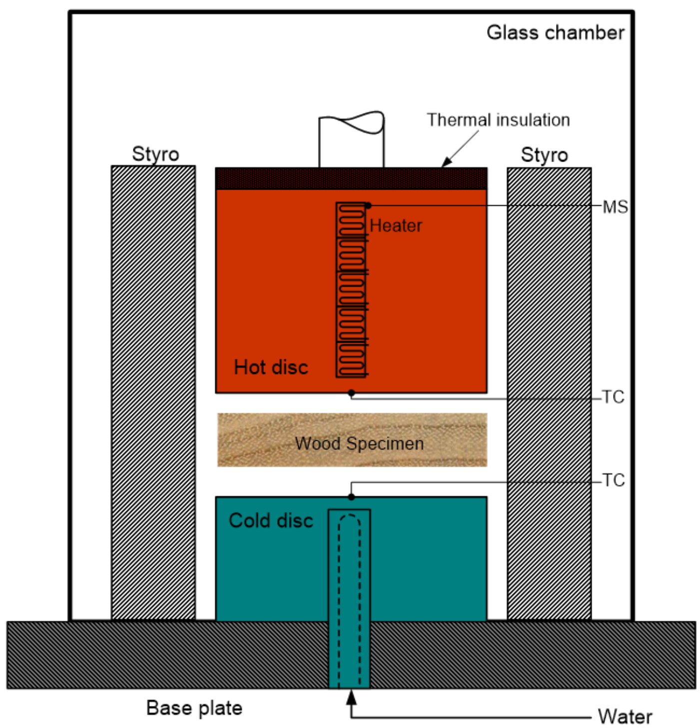

Fig. 2. Schematic diagram of the guarded hot-disc apparatus used to measure thermal conductivity of Philippine plantation wood species and selected tropical hardwoods. (TC: surface thermocouple; and MS: metering section heater).

RESULTS AND DISCUSSION

The results from transverse thermal conductivity measurements of Philippine plantation species and tropical woods using the GHP method are shown in Table 2. The GHP method is commonly used for high precision thermal conductivity measurements on porous and non-porous solid materials based on the direct application of Fourier's law (Hu *et al*. 2023; Ebert and Vidi 2024). It is an absolute method requiring no calibration measurements. The GHP method was originally developed for electrical insulation, but many researchers have used this technique to measure thermal conductivity of wood (Bucar *et al*. 2008; Sonderegger *et al*. 2011; Vololonirina *et al*. 2014; Vay *et al*. 2015). The measurement, however, requires a relatively large sample and a long time to reach steady-state heat flow. Thermal conductivity measurements in this study were performed with wood MC values at 0%, 12%, and 21% to determine effect of MC on thermal conductivity. These results showed that there was a 0.73% and 1.79% increase in transverse thermal conductivity per percent increase in MC from oven-dry to 21% MC for species with density <500 kg/m^3 (plantation species) and >500 kg/m^3 (hardwoods), respectively (Table 2). A similar range of increase (1% to 2%) was reported by Cammerer and Achtziger (1984) with increasing MC for several wood species from Europe. A linear regression model was fitted to explain the variation in transverse thermal conductivity with MC for wood species used in this study (Figs. 3 and 4). In general, there was a significant statistical relationship between thermal conductivity and MC of wood (P-values < 0.001). However, the coefficient of determinations (R^2) indicated poor to moderate relationship between the variables (Table 3). This could be due to various factors including the natural variability of wood, error in measurements, and moisture redistribution during thermal conductivity measurement, among others. TenWolde *et al*. (1988) reported that measurements using moist samples cause moisture redistribution resulting in transient heat flow. During redistribution the conductivity was reportedly larger than the steady state conductivity (TenWolde *et al*. 1988). The increase in thermal conductivity may be due to the presence of more water, which is more conductive than fibril and air, as the moisture level increases (Yu *et al*. 2011). Maeda *et al*. (2021) explained the increase in terms of the "Dufour effect" *i.e.*, increased energy flux due to the occurrence of a mass concentration gradient (Dufour 1872). In any case, caution must be taken in the use of these relationships, as the mechanism of how MC affects thermal conductivity is still largely unclear.

The density of tropical hardwood varies widely from very light such as balsa (*Ochroma* sp.) to the very heavy ironwood (*Xanthostemon* sp.). Wood density is a fundamental property that plays an important role in wood utilization. It serves as an index of wood strength, influences dimensional stability, workability, machinability and gluability of wood. Density also affects the ability of wood to conduct heat energy. Low density wood has better insulating properties (lower thermal conductivity), while higher density transfers heat more readily. The difference in density between tropical hardwoods and low-density plantation species used in this study is shown in Table 2. Measurements of ovendry thermal conductivity using GHP method resulted in 0.128 to 0.188 W/mK and 0.161 to 0.300 W/mK for low-density, plantation species and denser hardwoods, respectively. Low-density species have lower thermal conductivity due to the presence of large proportion of voids (air space) in its structure relative to the solid wood substance. The trapped air pockets act as barriers to heat flow, making the material a good insulator. High-density wood has less air space and a greater volume of solid wood substance resulting in higher thermal conductivity (Yu *et al.* 2011; Vay *et al.* 2015; Cavus *et al.* 2019). The increase in thermal conductivity with density is consistent with that reported by Yu *et al.* (2011) using several softwood and hardwood species from China.

Analysis of variance (ANOVA) showed a significant relationship (P-value < 0.05) between the thermal conductivity and ovendry density of wood species used in this study (Fig. 5). A linear regression model fitted to describe said relationship is shown below:

$$\text{Thermal conductivity (W/mK)} = 0.067 + 0.00079 \times \text{Density (kg/m}^3\text{)} \qquad (1)$$

The R^2 and correlation coefficient were 66.01% and 0.812, respectively, indicating a moderately strong relationship between the variables. Regression models can potentially be used as a powerful tools to predict thermal conductivity of other wood species with known ovendry density and their suitability for specific applications. Further work will be done in the future to cover other wood species from the Philippines and to include other factors such as temperature, flow directions, etc. to improve the accuracy of the model.

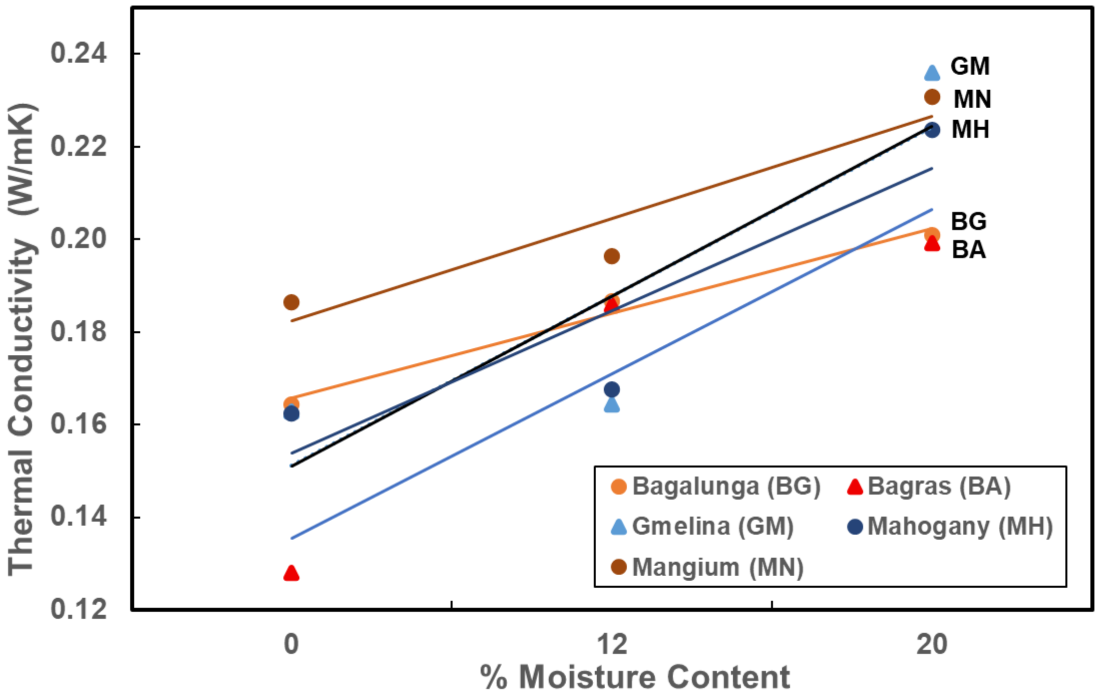

Fig. 3. Transverse thermal conductivity of plantation species from the Philippines with varying moisture content. Each point is the average of five replicate wood specimen.

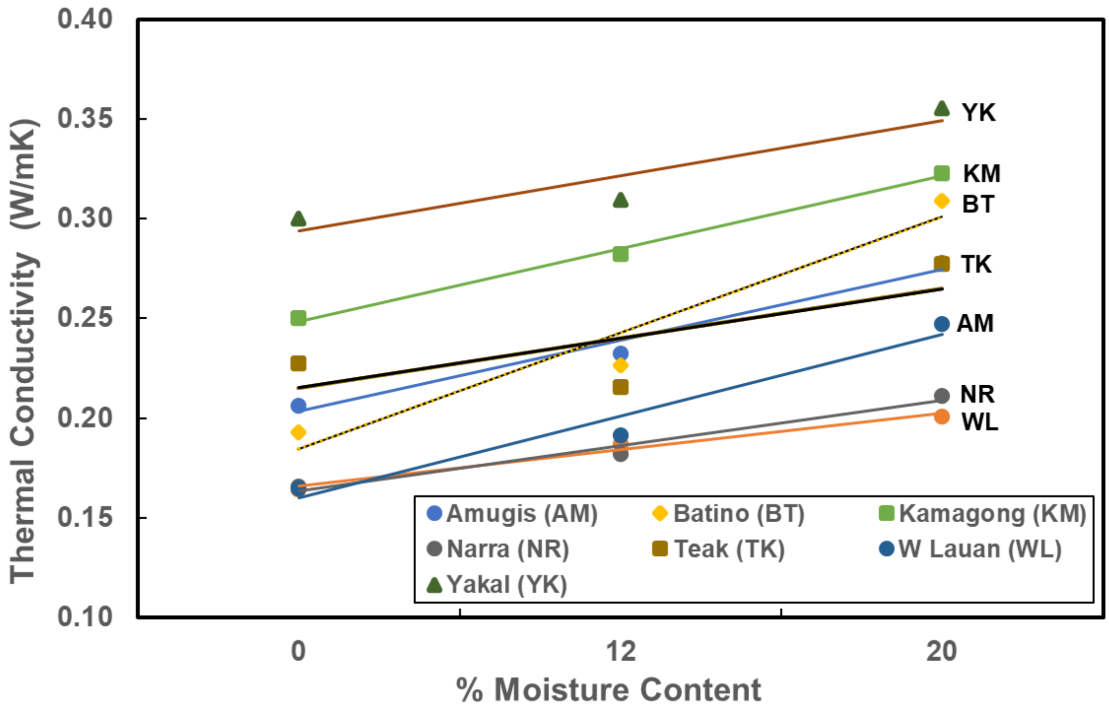

Fig. 4. Transverse thermal conductivity of tropical hardwoods from the Philippines with varying moisture content. Each point is the average of five replicate wood specimen.

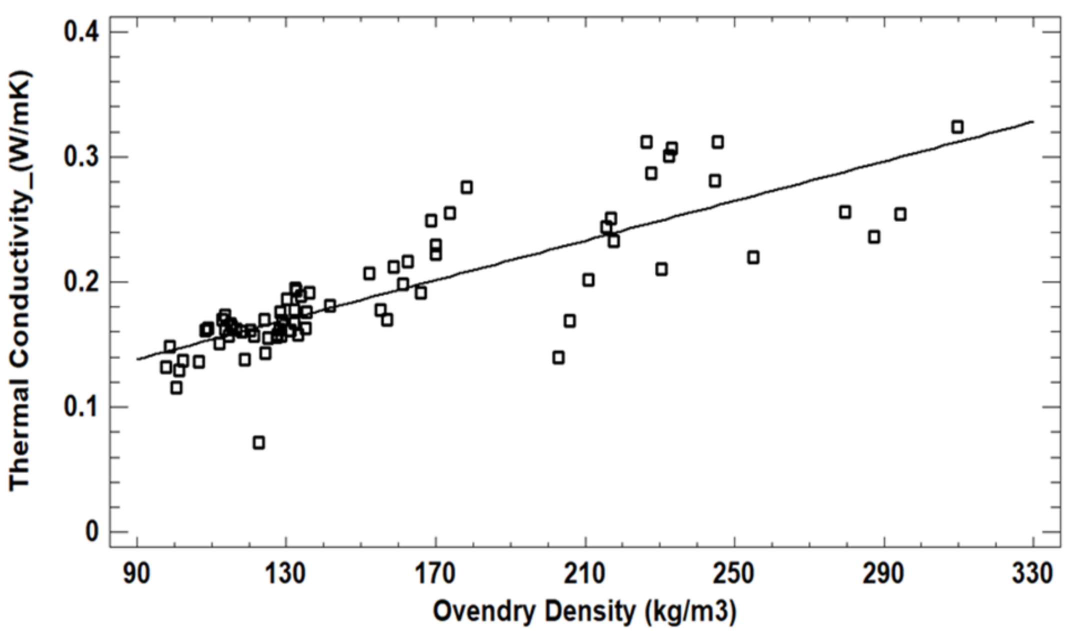

Fig. 5. Relationship between transverse thermal conductivity and oven-dry density of plantation species and tropical hardwoods from the Philippines

Table 2. Transverse Thermal Conductivity of Plantation Species and Tropical Hardwoods from the Philippines with Varying Moisture Content

Wood Species	Thermal Conductivity* (W/mK)			Linear Regression Model**	R^2 (%)	*P*-value of model
	0%	12%	21%			
Plantation Species						
Bagalunga (*M. dubia)*	0.164	0.187	0.201	y = 0.164 + 0.0018 x	57.55	0.001
Bagras (*E. deglupta)*	0.128	0.186	0.200	y = 0.132 + 0.0036 x	61.44	0.003
Gmelina (*G. arborea)*	0.163	0.164	0.240	y = 0.151 + 0.0033 x	62.78	0.001
Mahogany (*S. macrophylla)*	0.167	0.170	0.220	y = 0.154x + 0.0028 x	64.98	0.001
Mangium (*A. mangium)*	0.188	0.202	0.230	y = 0.182 + 0.0020 x	61.73	0.001
Tropical Hardwoods						
Amugis (*K. pinnatum)*	0.206	0.233	0.278	y = 0.202 + 0.0033 x	47.61	0.002
Batino (*A. macrophylla)*	0.193	0.226	0.310	y = 0.183 + 0.0054 x	76.49	0.001
Kamagong (*D. discolor)*	0.250	0.282	0.320	y = 0.247 + 0.0034 x	32.50	0.014
Narra (*P. indicus*)	0.161	0.177	0.210	y = 0.628 + 0.0021 x	58.56	0.002
Teak (*T. grandis)*	0.241	0.223	0.290	y = 0.216 + 0.0022 x	16.62	0.003
White Lauan (*S. contorta)*	0.146	0.180	0.240	y = 0.159 + 0.0038 x	54.58	0.001
Yakal (*S. astylosa)*	0.300	0.310	0.360	y = 0.269 + 0.0028 x	15.84	0.001

*Each value is the average of 5 replicate wood specimens ** y = thermal conductivity (W/mK), x= % moisture content

CONCLUSIONS

1. The study investigated the transverse thermal conductivity of low-density plantation wood species and selected tropical hardwoods from the Philippines using the guarded hot-plate method.
2. Results showed that ovendry thermal conductivity of low-density, plantation species and denser tropical hardwoods was about 0.128 to 0.188 W/mK and 0.161 to 0.300 W/mK, respectively. Transverse thermal conductivities increased by 0.73% and 1.79% per percent increase in MC from 0% to 21% MC for wood species with density <500 kg/m^3 (plantation species) and >500 kg/m^3 (hardwoods), respectively.
3. Thermal conductivity was directly influenced and appeared to be positively correlated to both density and moisture content of wood. Linear regression models for thermal conductivity and MC of wood indicated a poor to moderate relationship between the variables. Oven-dry density and thermal conductivity resulted in a relatively strong fit.
4. The results may be of interest in energy conversion of woody biomass-or to building designers looking for natural materials to improve energy performance of wood structures where heat transfer and temperature control are a significant economic consideration.

ACKNOWLEDGMENTS

The authors wish to thank the DOST-Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD) for providing partial funding support for this project (Project No. 1213133, 2014); to the DOST-Forest Products Research and Development Institute for the use of their thermal conductivity apparatus; and to Mr. Jovito Elec and Engr. Sapin of the DOST-FPRDI for their assistance during the experiment and providing wood specimens for this study.

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Article submitted: May 8, 2025; Peer review completed: June 7, 2025; Revisions accepted: June 23, 2025; Published: June 26, 2025.
DOI: 10.15376/biores.20.3.6877-6886