Data Article

Experimental data for thermal conductivity and dielectric properties of wood and wood-based materials

Noreen Saeed

School of Architecture, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

A R T I C L E   I N F O

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A B S T R A C T

Empirical data and methods of measurements for the research article “Experimental correlation of thermal conductivity with dielectric properties of wood and wood-based construction materials: Possibilities for rapid in-situ building energy evaluation” by Saeed et al. [1] is presented. The data offers an insight into the possible correlation between thermal conductivity and dielectric properties of wood and wood-based materials. There is independent data on thermal conductivity and dielectric properties of wood in the literature. However, data correlating the two properties is scarce, making our dataset unique. Data on the dielectric properties, thermal conductivity, density, and moisture content of 30 solid wood and 17 wood-based materials is presented. Wood-based materials include plywood, OSB, chipboard, and MDF. Measurements were made on 50 mm x 25 mm samples, typically 25 mm thick. The thermal conductivity was measured using the steady state method with a heat flow meter apparatus. Dielectric properties were measured using an unshielded system of two electrodes with an LCR meter at 10 kHz and 100 kHz frequencies at room temperature. All measurements were made in the transverse direction for solid woods and perpendicular to the face of the boards for wood-based materials.

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E-mail address: nsaeed@alumni.cmu.edu

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Specifications Table

| Subject                  | Materials Science (General) |
|--------------------------|-----------------------------|
| Specific subject area    | Correlation of thermal conductivity with dielectric properties of wood and wood-based materials |
| Type of data             | Tables                      |
| How data were acquired   | Thermal conductivity was measured using the steady state method with heat flow meter apparatus. A one-dimensional temperature gradient was created across the sample. Heat flux and temperature measurements were made using a heat flux sensor (PHFS-01 by Fluxteq) and thermocouples (PerfectPrime). Relative dielectric constant was calculated based on capacitance from an unshielded, two-electrode system. Samples coated with conductive paint were measured using an LCR meter (DE 5000 by DER EE) for capacitance and dissipation factor at 10 kHz and 100 kHz. |
| Data format              | Raw                         |
| Parameters for data collection | Measurements were made in the transverse direction for solid wood. All wood-based materials were measured perpendicular to the face of the board. All dielectric measurements were made at room temperature of 20–25 °C at 10 kHz and 100 kHz frequencies. The density range of the samples was 300–1300 kg/m3. The moisture content was between 5.9% and 8.9% with one exception. |
| Description of data collection | Data was collected through a series of experimental investigations. |
| Data source location     | Institution: Carnegie Mellon University |
|                         | City/Town/Region: Pittsburgh, PA |
|                         | Country: USA                 |
| Data accessibility       | Repository name: Mendeley Data |
|                         | Data identification number: 10.17632/jjr24sijxhvs.1 |
|                         | Direct URL to data: https://data.mendeley.com/datasets/jjr24sijxhvs/1 |
| Related research article | Authors’ names: Noreen Saeed, Jonathan A. Malen, Maysamreza Chamanzar, Ramesh Krishnamurti |
|                         | Title: Experimental correlation of thermal conductivity with dielectric properties of wood and wood-based materials: Possibilities for rapid in-situ building energy evaluation |
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Value of the Data

- Measuring thermal conductivity is time-consuming and delicate. This data provides an insight into the correlation of thermal conductivity and dielectric material properties for wood and wood-based materials. The intent is to enable scientists to predict thermal conductivity from dielectric properties rather than measuring.
- A researcher studying alternate methods for estimating thermal conductivity will benefit from this dataset. This could include material scientists who study material interrelationships or environmentalists looking for easier ways of evaluating building energy efficiency by inferring its thermal transmittance properties.
- Data correlating the two material properties is scarce and the relationship has not been systematically studied. By showing the possible correlation between thermal conductivity and dielectric properties, this dataset provides a springing board for new research and investigation.
• In the future, this data may prompt the development of new instrumentation to infer thermal conductivity based on dielectric properties for specific materials under specific environmental conditions.

1. Data Description

This dataset contains the measured properties of 30 solid wood blocks and 17 wood-based materials (OSB, plywood, chipboard, and MDF). The unique identifier number of each sample, material type, measured moisture content, density in oven-dry form, density on moist weight basis, dissipation factor at 10 kHz and 100 kHz, relative dielectric constant at 10 kHz and 100 kHz, and thermal conductivity are listed in the dataset. The measured thermal conductivity, its measurement temperature and a thermal conductivity value with a temperature correction applied to it are also given. With respect to the corrected thermal conductivity, the applied temperature correction factor, and applied unit for temperature correction have also been included. Calculated relative dielectric constant at 100 kHz and calculated $\alpha$ values have been provided as well. Details relating to the data are listed in Table 1. This table comprises the column names as given in the data CSV file, the unit of measurement, and a brief description of the data in each column.

Table 1
List of column names, units of measurement and descriptions of data provided in dataset.

| Column Name       | Units     | Description                                                                 |
|-------------------|-----------|------------------------------------------------------------------------------|
| ID                | –         | Unique Identification number of the sample                                   |
| Name              | –         | Name / type of material                                                     |
| MC                | %         | Moisture content                                                            |
| OD density        | kg/m³     | Oven dry density                                                            |
| Density           | kg/m³     | Density on moist weight basis                                               |
| Df10k             | –         | Dissipation Factor 10 kHz                                                   |
| Df100k            | –         | Dissipation Factor 100 kHz                                                  |
| Dk10k             | –         | Relative Dielectric Constant 10 kHz                                         |
| Dk100k            | –         | Relative Dielectric Constant 100 kHz                                        |
| THC_M             | W/m.K     | Thermal Conductivity as measured                                            |
| THC_C             | W/m.K     | Thermal Conductivity with correction for temperature at 25 °C               |
| Avg temp          | °C        | Average measurement temperature for thermal conductivity                    |
| Correction factor | –         | Correction factor for converting measured thermal conductivity at a higher temperature to thermal conductivity at 25 °C |
| Correction factor unit | –      | Unit for the temperature correction factor                                  |
| Calculated $\alpha$ | –       | Interpolated value of $\alpha$. This variable depends on frequency of measurement and moisture content of wood samples. More information about its calculation is given in Section 2.3 |
| Calculated_Dk_100kHz | –     | Expected value of the dielectric constant at 100 kHz. These values are calculated using Torgovnikov’s equation for predicting relative dielectric constant as described in Section 2.3 |

2. Experimental Design, Materials and Methods

2.1. Thermal Conductivity

Thermal conductivity was measured using the steady-state method by using a heat flow meter apparatus. Samples were cut into block shapes of 50 mm x 25 mm with a typical thickness of 25 mm. The weight and dimensions of each sample were recorded against its unique ID. Two, 12 mm deep holes were drilled into each sample to house the thermocouples. Heat flux sensor PHFS-01 by Fluxteq was used for measuring the heat flux per square meter. This sensor was
calibrated using NIST tracible materials by the manufacturer and is sold with a certificate of calibration. The heat flux was monitored using a multimeter (Aneng AN8008), while the thermocouple readings were observed using a temperature reader by PerfectPrime TC-41.

A temperature gradient was created across the sample by placing it between a heater and Peltier cooling plates. The cooling plates were placed on a heat sink, which was in turn cooled by a fan. The entire assembly (minus the fan and heat sink) was wrapped in several layers of insulation to minimize edge losses. An equation that relates heat flux to temperature difference in a solid plane was used to calculate thermal conductivity as:

$$q_x = \lambda \frac{\Delta T}{x}$$  \hspace{1cm} (1)

where \(q_x\) is the heat flux in W/m², \(\Delta T\) is the temperature difference between the two points along the temperature gradient inside the sample in °C, \(x\) is the distance between the two thermocouples in meters and \(\lambda\) refers to thermal conductivity in W/m.K.

Measurements were recorded at ten-minute intervals. The condition for establishing steady state was that a new measurement should not deviate from the average of the previous five readings by more than half percent. This rule is compliant with ASTM C518 [2] for steady state measurement of thermal transmission properties. The measurement time for this work averaged 2.5 hours per sample.

The measurement temperature was between 32 °C and 43 °C and is tabulated in our linked data CSV file. A temperature correction was applied to find the equivalent thermal conductivity at 25 °C. The corrections presented by Lewis [3] and Steinhagen [4] were used as quoted by TenWolde et al [5]. There are different corrections for wood, chipboard, plywood, MDF, and OSB and are given in the linked dataset.

2.2. Dielectric Properties

Dielectric properties were measured using an unshielded, two-electrode system. The samples were covered on two sides with copper conductive paint 843WB by MG Chemicals, which has an advertised resistivity of 5.3 \(\times\) 10\(^{-4}\) Ω·cm. These worked as the electrodes. The wires were fixed using a conductive silver epoxy by Atom Adhesives. These samples were sized 50 mm x 25 mm with a typical distance between the plates of 25 mm. The capacitance and dissipation factor readings from an LCR meter (DE 5000 by DER EE) were recorded at 10 kHz and 100 kHz.

Since the relative dielectric constant was measured from capacitance using an unshielded system, a correction for edge capacitance had to be applied. The formulas presented by Scott and Curtis [6] for rectangular electrodes of size equal to samples were used for this work. Although ASTM D150 [7] contains formulas for edge correction for several configurations of electrodes, it does not contain information for rectangular electrodes. The formulas presented by Scott and Curtis that were used to calculate the relative dielectric constant are given below:

$$C_e + C_g = \left(1.113 \frac{l}{(4\pi^2)}\right) \left\{ 1 + \ln \left[ 1 + \frac{\pi w}{d} + \ln \left(1 + \frac{\pi w}{d}\right)\right] \right\}$$

$$\left(1.113 \frac{w}{(4\pi^2)}\right) \left\{ 1 + \ln \left[ 1 + \frac{\pi l}{d} + \ln \left(1 + \frac{\pi l}{d}\right)\right] \right\} \mu\mu F$$ \hspace{1cm} (2)

$$C_n = 1.113 \frac{l w}{(4\pi^2)} \mu\mu F$$ \hspace{1cm} (3)

$$k = \frac{(C - C_e)}{C_n}$$ \hspace{1cm} (4)

Where \(C_e\) is edge capacitance, \(C_n\) is normal capacitance, \(C\) is measured capacitance, \(k\) is the relative dielectric constant, \(w, l\) refers to the dimensions of the electrode in cm and \(d\) is the
distance between the two plates in cm. As no formula exists for separating $C_e$ and $C_g$, Scott and Curtis [6] rate the method of using rectangular electrodes inferior to using circular electrodes and estimate an error up to 2.3% in measurements.

The average measured capacitance was 2.7 pF. The following precautions were taken to minimize measurement errors:

- Wires were kept as short as possible.
- All samples were fitted with the same gage, quality, and size of wires.
- The LCR Meter was calibrated using open and short method specified by the manufacturer before the measurements.
- Material under test was kept clear of other objects to avoid their field of capacitance. Special care was taken to remove any electronic gadgets from the surroundings which might interfere with the readings.
- To avoid interference, wires were arranged so as not cross each other.
- As many items as possible were measured in a single cycle. This ensured that environmental conditions like temperature, humidity, etc. acted on all the samples in a similar way
- During measurement, the surface that the sample rests on can influence the reading. A surface with a very small capacitance was chosen for this work.

2.3. Calculation of Expected Relative Dielectric Constant at 100 kHz

Torgovnikov [8] gives the equation for estimating dielectric constant of moist wood (adjusted to SI Units) using the following equation:

$$ \epsilon_r = 1000 \alpha \rho + 1 \quad (5) $$

where $\epsilon_r$ is the relative dielectric constant measured in the transverse direction in the oven-dry density range of 300 kg/m$^3$ to 800 kg/m$^3$, for moisture levels between 5% and 30%. $\alpha$ is a constant dependent on frequency and moisture content. The estimated error for calculating the dielectric constant of solid wood using this equation is listed by Torgovnikov as ±20%.

Torgovnikov identifies the value of $\alpha$ for various frequencies (including 100 kHz) at moisture levels of 5%, 10%, 15%, 20%, 25% and 30%. Any intermediate values of moisture content need to be interpolated. Using curve fitting, we estimated $\alpha$ at 100 kHz for our data using the following equation:

$$ \alpha = 0.0404 x^2 - 0.3319 x + 4.69 \quad (6) $$

where $x$ refers to moisture content as a percent. Our calculated values of $\alpha$ for wood samples along with the resulting values of the expected dielectric constant at 100 kHz are given in the linked dataset.

2.4. Density and Moisture Content

Samples were oven dried in a forced-convection oven at 104 °C for about 24 hours. The oven drying process continued until no significant change in weight was found at two-hour intervals. This method is compliant with ASTM’s standard test method for direct moisture content measurement of wood and wood-based materials D4442 [9]. The formula used to measure moisture content was:

$$ MC\% = \frac{M - M_{dry}}{M_{dry}} \times 100 \quad (7) $$

where $MC$ is moisture content%, $M$ is the original weight of the sample, and $M_{dry}$ is its oven-dry weight.
Density was measured by recording the sample weight and dimensions. The formula used was:

$$D = \frac{M}{V}$$  \hspace{1cm} (8)

where $D$ is density, $M$ is mass and $V$ is volume.

2.5. Error propagation

Uncertainty was calculated for each sample measurement. It was calculated based on the formula for uncertainty as a function of several variables given in Taylor [10]. Suppose $x, \ldots, z$ are measured variables, and their uncertainties $\delta x, \ldots, \delta z$ are independent and random. If the measured variables are used to compute a function $q(x, \ldots, z)$ then the uncertainty in $q$ is given as:

$$\delta q = \sqrt{\left(\frac{dq}{dx}\delta x\right)^2 + \ldots + \left(\frac{dq}{dz}\delta z\right)^2}$$  \hspace{1cm} (9)

The rate of the error for each variable was assumed according to the specifications of the instrument manufacturer, and in some cases was determined through repeated measurements.

2.6. Uncertainty for Thermal Conductivity

The uncertainty for temperature was taken as 1 °C, for distance measurement 0.4 mm, for heat flux 5% of heat flux and for voltage reader for heat flux as 0.5% of voltage + 3 μV. The calculated uncertainty for thermal conductivity measurement ranged between 7% and 11%.

2.7. Uncertainty for Relative Dielectric Constant

The uncertainty for measured capacitance was taken as 2% of capacitance + 0.05 μμF as indicated on the instrument. Measurement uncertainty for each side of the sample was taken as 0.4 mm and was determined through repeated experiments. Uncertainty of the method itself (2.3%) was also accounted for in the overall uncertainty. The uncertainty of this measurement ranged between 5% and 12%.

2.8. Other Sources of Error

Sources of errors other than the ones due to instruments are described in this section. One source of error may be from the use of a different piece of wood for measuring thermal conductivity and a different one for measuring dielectric properties. While the two wood samples were cut from the same block, the natural variation in grain can result in dissimilarities in the properties of the two samples. This might have resulted in some discrepancy in the results. The second source of error may be due to the hygroscopic properties of wood that can cause moisture content to change with changes in relative humidity of the surrounding environment. The measurements were carried out over a few months, so weather changes may have caused changes in the moisture levels of samples that went undocumented.
Ethics Statement

The author declares that the material presented in this paper is the author’s original work, is not being considered for publication or has been published elsewhere except for an academic thesis associated with a University degree.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

Data Availability

Data for: Experimental data for thermal conductivity and dielectric properties of wood and wood-based materials (Original data) (Mendeley Data).

CRediT Author Statement

Noreen Saeed: Investigation, Writing – original draft, Data curation.

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References

[1] N. Saeed, J.A. Malen, M. Chamanzar, R. Krishnamurti, Experimental correlation of thermal conductivity with dielectric properties of wood and wood-based materials: possibilities for rapid in-situ building energy evaluation, J. Build. Eng. 50 (2022) 104178, doi: 10.1016/j.jobe.2022.104178.
[2] ASTM C518-17, Standard Test Method For Steady-State Thermal Transmission Properties By Means of the Heat Flow Meter Apparatus, ASTM International, 2017, doi:10.1520/C0518-17.
[3] W.C. Lewis, Thermal Conductivity of Wood Base Fiber and Particle Panel Materials, USDA Forest Service, Forest Products Laboratory, 1967.
[4] H.P. Steinhagen, Thermal Conductive Properties of Wood, Green or Dry, From -40° to +100 °C: A Literature Review, USDA Forest Service, Forest Products Laboratory, 1977.
[5] A. TenWelde, J.D. McNatt, L. Krahn, Thermal Properties of Wood and Wood Panel Products for use in Buildings, USDA, Forest Products Laboratory, 1988.
[6] A.H. Scott, H.L. Curtis, Edge correction in the determination of dielectric constant, J. Res. Natl. Bur. Stand. 22 (1939) 747, doi:10.6028/jres.022.008.
[7] ASTM D150-18, Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation, ASTM International, 2018, doi:10.1520/D0150-18.
[8] G.I. Torgovnikov, Dielectric Properties of Wood and Wood-Based Materials, Springer Berlin Heidelberg, 1993, doi:10.1007/978-3-642-77453-9.
[9] ASTM D4442-16 Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials, ASTM International, 2016, doi:10.1520/D4442-16.
[10] J.R. Taylor, An Introduction to Error analysis: the Study of Uncertainties in Physical Measurements, 2nd ed, University Science Books, 1997.