West Indian Journal of Engineering Vol. 28, No. 1, (July 2005) Technical Paper
(Manohar, Kochhar, Ramlakhan & Halder) 61-68

Thermal Conductivity Measurement of Wood by means of a Water-activated, Guarded-Hot-Plate Apparatus

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A water-activated, steady state Guarded-Hot-Plate apparatus was designed and built in accordance with ASTM C 518. The lateral temperature variation of the constant temperature plates over the metered area were within ±0.1°C of the set temperature. Heat flux across a polystyrene reference material was measured with an ORNL calibrated, rigid heat flux transducer. Calibration results were within 4% of the heat flow meter data for the reference material. Thermal conductivity (λ) measurements across to the wood grains were conducted on 11 species of commercially-used Trinidad wood. Specimens were conditioned at 29°C. Thermal conductivity tests were conducted at a mean temperature of 31°C with a 20° ΔT tensile strength tests were conducted in accordance with ASTM D143, a standard displacement method was used to measure density and a standard oven drying to constant weight method was used to measure moisture content. Specimens were graded as low density (< 600 kg/m³), medium density (601 kg/m³ to 900 kg/m³), and high density (> 900 kg/m³) wood. Results indicated a general linear trend of increase λ with density. However, material with a density difference within 50 kg/m³ may not follow the general trend as factors such as grain structure, fibrous content and biological composition may influence λ. There were no trends or relationships between tensile strength and density or tensile strength and λ.

Keywords: Thermal conductivity, Guarded-hot-plate, tensile strength, wood.

1. Introduction

Steady improvement of social and economic conditions in most Caribbean countries has brought about a steady increase in the consumption of timber over the past decade. The Caribbean region has substantial reserves of forest that can be economically-harvested to supply the needs of the region. However, most of the timber, treated and untreated, consumed by the furniture and construction industries are imported from North America, Canada or Brazil. This reality is a direct consequence of very little information being available on the properties of most verities of Caribbean timber. Trinidad and Tobago has a typical, tropical climate with a year-round average of 33°C maximum and 22°C minimum temperature. The use of uninsulated timber alone for wall construction in low-cost housing is quite common. Roofs are generally constructed with corrugated, galvanised sheets and a wooden drop-ceiling with no insulation. Knowledge of the thermal and strength properties of local timber will play a major role in influencing the choice of material.

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Pertinent discussion will be published in January, 2006 West Indian Journal of Engineering if received by November, 2005.

2. Constant Temperature Plate Design

A water-activated, steady state guarded-hot plate apparatus was designed to meet ASTM 518 specifications [1]. Two constant temperature plates 900 mm x 900 mm were constructed using 6 mm-thick aluminum sheet as the flat-plate surface and 9.5 mm-diameter copper tubes attached on the reverse side to form the heating element. The guard heating section was from another bank of tubes around the inner, heating section as shown in **Figure 1**. The heating coils were formed from two inter-woven spirals towards the centre of the plate. The coils started with an outer diameter of 584 mm and were joined at the plate centre. This arrangement resulted in water flowing spirally in alternate channels towards the plate centre and then outwards in alternate channels from the centre. Flow in adjacent channels was in opposite directions.

The guard area heating coils were also formed from two interlocking spirals starting with an outer diameter of 889 mm to touch the inner coils of diameter 584 mm, forming a 152 mm guard ring. A 203 mm x 203 mm ORNL calibrated, heat flux transducer was embedded in the surface of the cold plate.

3. Test Apparatus

The main heating for the hot water was done by a standard 200 1 commercial water heater. The main cooling for the cold water was done by a small refrigeration unit with a 746 W (1 hp) compressor. After initial heat-up and cool-down, the hot and cold water temperatures were maintained using a 680 W bi-directional, temperature controller. This unit had a finite temperature resolution of 0.1°C, a control temperature resolution of 0.1°C, a control temperature range of -20°C to 100°C and control stability of ± 0.05 °C. The temperatures of both hot and cold fluid were monitored and controlled automatically via a computer interface from the bi-directional, temperature controllers.

The design water flow rate of 0.345 kg/s in the coils was determined using a design temperature difference of 0.1°C between the inlet and outlet water temperature through the coils, heat flux across a sample of thermal conductivity 0.76 W/m.K and a ΔT between plates of 40°C. The 1 hp circulating pump was sized from head loss calculations using the Darcy-Weisbach equation [2].

$$h_L = f \, \frac{L}{D} \frac{v^2}{2g} \qquad \text{........(1)}$$

4. Instrumentation

Sixteen strategically-located, calibrated, K-type thermocouple were embedded on each plate surface to monitor the plate surface temperature and determine ΔT across the specimen. A 40-channel Data Worker Data Logger with quick-in data response was used to

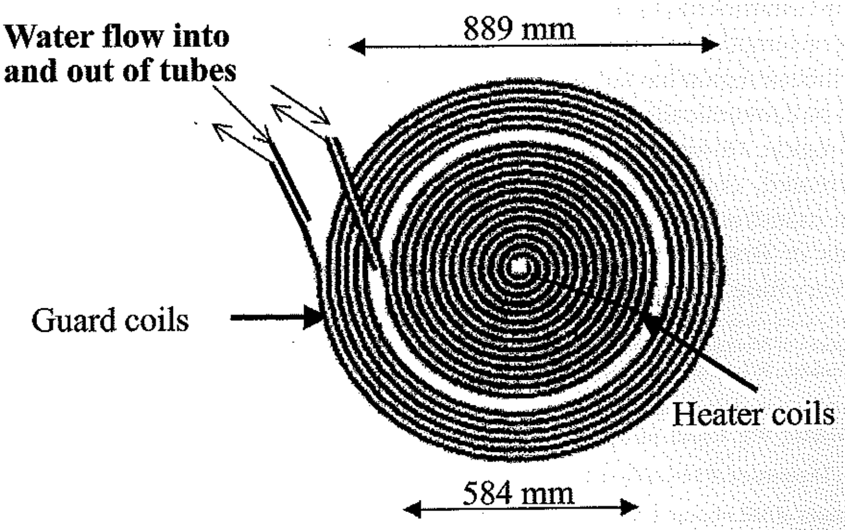

FIGURE 1: *Heating/Cooling Coil Arrangement on Constant Temperature Plates*

monitor the thermocouples. The point temperatures were tracked on a computer via the data logger multi-function computer interface. The data logger was manufacturer-calibrated with a temperature stability of ± 0.01°C and a voltage stability of $\pm 10\ \mu V$.

The variation of heat flux with output voltage of the ORNL calibrated heat flux transducer was governed by the equation

$$q''(Btu/h.ft^2) = C \times V(millivolt) \qquad \text{........(2)}$$

where $$C = 3.5128 \frac{(Btu/h.ft^2)}{mV} \qquad \text{........(3)}$$

5. Calibration

Calibration of the test apparatus was conducted using a 300 mm x 300 mm x 38.1 mm slab of commercially-available polystyrene as the reference material. The λ for the polystyrene reference material was determined in a heat-flow meter apparatus built by LaserComp [3]. This heat-flow meter was built and operated in accordance with ASTM C 518 [1] and was designed to provide λ measurements with an accuracy of ±1% with ±0.2% repeatability and ±0.5% reproducibility. Tests at mean temperatures between 10°C and 45°C at intervals of 5° with a temperature difference of 20°C between the hot and cold plates were conducted. Equation (4) is the result of a least-square-fit to the heat-flow meter data.

$$\lambda_{ref.} = 0.36058 \times 10^{-1} + 0.16404 \times 10^{-3} \bar{T} \qquad \text{........(4)}$$

Four calibration tests were conducted for the water-activated, cold plate, hot plate apparatus. Heat flux was determined from the mV output of the heat flux transducer using Eq. (2) with a conversion factor of 3.1546 [4] and λ was calculated from Eq. (5)

$$\lambda = \frac{q}{(\Delta T/\Delta x)}\ W/m.K \qquad \text{........(5)}$$

Table 1 shows a summary of the calibration test results. The calibration tests show that $\lambda_{cal.}$ results were within 4% of the $\lambda_{ref.}$ data.

6. Uncertainty

The experimentally determined λ was calculated from Eq. (5) in which λ is proportional to the ratio $\frac{q}{(\Delta T/\Delta x)}$. The value of q was determined from the voltage reading of the heat flux transducer. The specimen thickness was taken as the distance between the constant temperature plates. This was measured to the nearest ± 0.1 mm. The temperature difference between the constant temperature plates gave the ΔT value. These temperature readings were dependent on the thermocouple readings. From the theory of uncertainty analysis, the square of the uncertainty in the experimentally-determined λ is given by Eq. (6) [5].

$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 = \left(\frac{\Delta V}{V}\right)^2_{H.F.T.} +$$

TABLE 1: *Calibration Test Results*

Test #	Hot Plate Temp. (°C)	Cold Plate Temp. (°C)	Mean Temp. (°C)	ΔT (°C)	HFT Voltage (mV)	HFT Voltage (mV)	$\lambda_{cal.}$ (W/m.K)	$\lambda_{Ref.}$ (W/m.K)	% Deviation
1	52.70	20.60	38.15	32.1	3.187	3.187	32.1	32.1	3.187
2	41.80	25.70	33.75	16.1	1.550	1.550	16.1	16.1	1.550
3	52.80	24.50	38.65	28.3	2.737	2.737	28.3	28.3	2.737
4	62.70	37.60	50.15	25.1	2.589	2.589	25.1	25.1	2.589

$$\left(\frac{\Delta x}{x}\right)^2_{Thickness} + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2_{Thermocouple} \qquad \text{........(6)}$$

where $\left(\frac{\Delta\lambda}{\lambda}\right), \left(\frac{\Delta V}{V}\right), \left(\frac{\Delta x}{x}\right),$ *and* $\left(\frac{\Delta(\Delta T)}{\Delta T}\right)$ are the uncertainties in measured λ, heat flux transducer voltage, specimen thickness and thermocouple temperature. From the precision of the respective instruments, the uncertainty associated with the measured λ is

$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 = \pm\left(10 \text{ x } 10^{-6}\right)^2 \pm$$

$$\left(\frac{0.1}{50}\right)^2 \pm \left(\frac{0.005}{20}\right)^2 \qquad \text{........(7)}$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 = \pm 0.0000041$$

Hence, the uncertainty in measured λ is ± 0.002 W/m.K.

7. Test Specimens

Test specimens were prepared for 11 species of commercially-used Trinidad wood. The wood was first dried in the traditional way (stacked and exposed to the surrounding atmospheric conditions). Samples were then conditioned at 29°C under laboratory conditions to a mean moisture content of 14% wt. Teak samples were obtained from kiln dried wood. Five thermal conductivity specimens of size 300 mm x 300 mm were then machined for each species. Five samples each for moisture content and density tests were also prepared. Five specimens each for tensile tests were cut to shape and size in accordance with ASTM D 143 [6]. After preparation, all test specimens were allowed to acclimatise to laboratory conditions for 48 hrs before testing.

8. Experiments Conducted

For each species of wood, the following tests were conducted:-

(a) Thermal conductivity measurements across the wood grains were conducted with the water-activated, steady state Guarded-Hot-Plate apparatus.

(b) Wood density was determined using a standard displacement method [7].
A sinker was used to ensure quick and complete submersion of the specimens.

(c) A standard oven drying to constant weight method was used to determine the moisture content by weight. The specimens were dried at 70°C to avoid micro-structural changes.

(d) Tensile tests along the wood grains were conducted in accordance with ASTM D 143 specifications using a standard Monsanto Type W tensometer.

9. Test Results

For each species of wood, five tests were conducted to determine thermal conductivity, density, moisture content and tensile strength, respectively. The mean experimental value in each case was calculated and the results shown in **Table 2**. Comparative data, where available, are also given in **Table 2**. All thermal conductivity tests were conducted at a mean test temperature of 31°C with a ΔT of 20°C.

10. Published Wood Data

For comparison, published data of thermal conductivity, tensile strength and density for respective wood species are listed in **Tables 3** and **4**.

11. Discussion

The range of wood tested was graded into low, medium and high-density groups with range < 600 kg/m^3, 601 kg/m^3 to 900 kg/m^3 and > 900 kg/m^3, respectively.

TABLE 2: *Experimental Data for Trinidad Wood*

Experimental Results

Specimen Number	Local Name	Density (Av. Value) kg/m³	Moisture Content (Av. Value) wt. %	Thermal Conductivity (Av. Value) W/m.K	Thermal Conductivity (Av. Value) W/m.K
1	Mahoe	420	15	0.068	7.70
2	Matak	424	15	0.100	8.57
3	Cajuca	439	15	0.083	4.27
4	Crappo	650	13	0.163	8.08
5	Olivea	660	14	0.118	11.55
6	Teak (kiln dry)	673	6	0.137	12.65
CSIRO Report [8]		720	10	0.138	NA
7	Rubber	694	15	0.127	3.28
8	Pitch Pine (Caribbean	759	11	0.179	7.62
CSIRO Report [8]		656	15	0.138	NA
9	Serrette	773	12	0.175	11.59
10	Mora	1071	11	0.205	8.89
11	Balata	1107	11	0.207	6.60

TABLE 3: *ASHRAE Handbook Data [9], Mechanical Engineering Handbook Data [10]*

Mean test temperature - 29.3°C; Moisture content - 12 wt.%; Heat transfer across wood grain

Wood Name	Density Range Kg/m³ [9]	Thermal Conductivity Range W/m.K [9]	Tensile Strength (Average Value) MN/m² [10]
Southern Pine	570-659	0.144-0.161	6.21
Douglas Fir-Larch	536-581	0.137-0.145	7.79
Southern Cypress	502-514	0.130-0.132	13.10
Hem-Fir, Spruce Pine-Fir	392-502	0.107-0.130	7.31
Cedar	347-502	0.098-0.130	6.83
California Redwood	392-448	0.107-0.118	6.48
Oak	659-749	0.161-0.180	13.79
Birch	682-726	0.167-0.176	12.96
Maple	673-704	0.157-0.171	16.06
Ash	614-670	0.153-0.164	13.17

TABLE 4: *Reference [11] Data*

Mean test temperature - 27°C; Heat transfer across wood grain

Wood Name	Density (Mean) Kg/m^3	Moisture Content (Mean) wt. %	Thermal Conductivity (Mean) W/m.K
Cedar	340.2	10.58	0.0956
Spruce	387.5	9.17	0.0999
Cypress	400.8	8.94	0.1129
Pine	423.0	8.33	0.1102
Hemlock	461.8	7.29	0.1031
Douglas-Fir	477.4	12.86	0.1261
Southern Pine	548.9	10.39	0.1474
Elm	596.5	11.82	0.1605
Birch	638.2	9.75	0.1467
Maple	645.3	8.94	0.1759
Ash	628.4	12.03	0.1587
Oak	669.3	8.86	0.1723

A plot of thermal conductivity vs density from the experimental data shown in **Figure 2** indicated a general increase in thermal conductivity with increasing density. However, wood with density within close proximity of about 50 kg/m^3 did not necessarily follow the general trend. This deviation can be attributed to the influence of factors such as grain structure, fibrous content and biological composition on thermal conductivity.

The published data on **Tables 3** and **4** indicate similar trend of general increase in thermal conductivity with increasing density for the different species of wood. Similar observation of wood with density within close proximity of about 50 kg/m^3 that did not necessarily follow the general trend was seen.

Test results indicated no relationship between tensile strength and thermal conductivity or tensile strength and density (**Figure 3**). The published data on **Table 3** also indicates no general relationship between tensile strength and thermal conductivity or tensile strength and density. This factor is probably dependent mainly on fibre arrangement, fibre content and grain structure. However, individual consideration between the thermal conductivity and tensile strength data for the respective species of wood can provide useful information for the construction and furniture industry. For example, in furniture manufacture, Serrett with a high tensile strength would be an appropriate choice since the thermal conductivity consideration is not as significant.

Whereas, for wall-cladding Cajuca or Mahoe with a reasonable tensile strength and a low thermal conductivity would be a better suited material.

12. Conclusions

- In general, λ of wood increased with density.
- Wood with a density difference within 50 kg/m^3 may not show an increase in λ with density.
- There is no trend or relationship between tensile strength and density or tensile strength and λ.

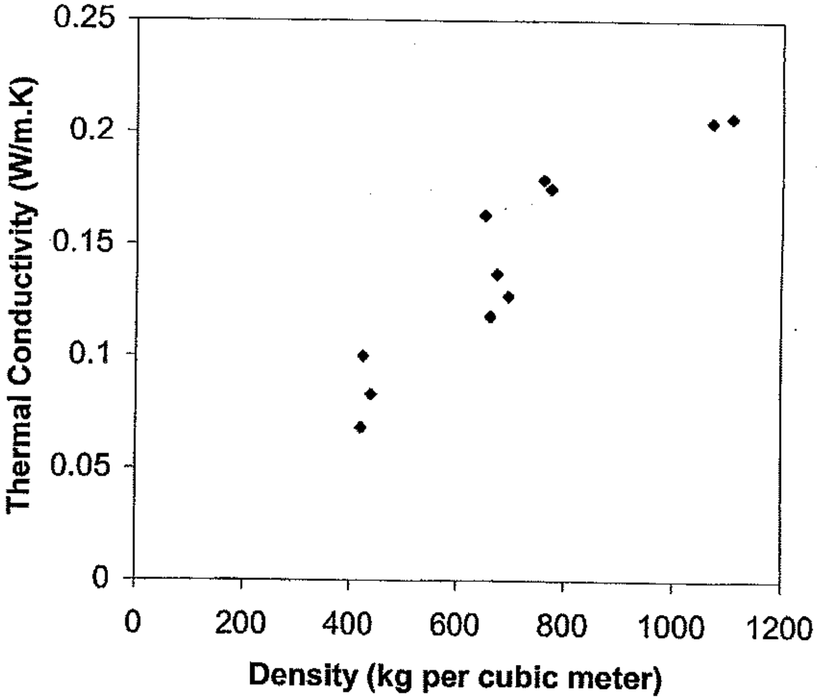

FIGURE 2: *Thermal Conductivity Variation with Density of Trinidad Wood*

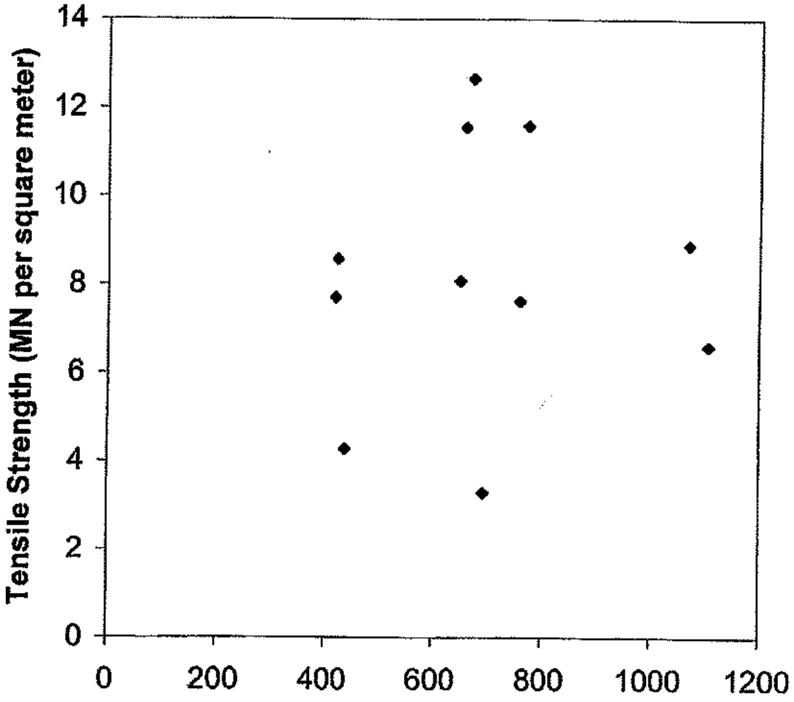

FIGURE 3: *Tensile Strength Variation with Density of Trinidad Wood*

13. References

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