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Study of Thermal Properties of Some Selected Tropical Hard Wood Species

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Abstract: The uses of wood and wood-based materials in everyday life ranging from domestic to industrial purposes have called for renewed updating of the information and knowledge on various thermal properties of the materials at various stages and classifications. This paper investigates the thermal properties (specific heat capacity and thermal conductivity) of some selected tropical hard wood species using the method of mixtures and the Lee's Disk method respectively. The results show that the thermal conductivity of the selected wood species fall within the general range of 0.1-0.8 W/mK for tropical wood materials, with *Celtis mildraedii* having the least thermal conductivity of 0.08*W/*mk and *Strombosia glaucescens* the highest value of 0.392 W/mK. The specific heat capacity was highest for *Holorrhena floribunda* (1.97 J/g.K) and the lowest for *Pterygota macrocarpa* (1.01 J/g.K). These results can be used for testing the validity and efficiency of hard woods used for domestic and industrial applications.

Keywords: Wood Materials, Heat Capacity, Thermal Conductivity, Lee's Disk Method, Method of Mixture, Temperature and Time

1. Introduction

Wood is a porous biomaterial which contains small holes and spaces that influence the mechanism of heat transfer (thermal conductivity) and specific heat capacity [1]. Wood can be bound or free and appears in a solid or liquid state [2] [3]. It consists of an organic composite material which is made up of cellulosic fibers and lignin.

Wood has a long history of use both as a solid fuel and as a construction material. Owing to temperature variations, the crystalline structure of chains may be altered, resulting in permanent loss in strength and considerable changes in physical behaviour, including its ability to conduct heat [4].

Thermal properties of wood are needed in applications such as fuel conversion, building construction, and other areas of industry [5] [6]. Knowledge of the thermal properties of wood helps to understand and model heat transfer processes in wood and wood-based materials. For example, the energy design and evaluation of energy performance of wood-frame buildings partially rely on the thermal properties of wood and wood products [7].

Thermal conductivity is a measure of the rate of heat flow through one unit thickness of a material subject to a temperature gradient. Measurement of thermal conductivity of wood dates back several decades. The early experimental work was primarily performed using the steady-state, guarded hot plate method. Thereafter, transient techniques, such as the laser flash method [8], transient plane source technique [9], and transient hot wire method [10], were developed. The main factors that significantly affect thermal conductivity of wood are density, temperature and moisture content [11] [12].

Thermal conductivity is a critical attribute when offering energy conserving building products. This is due to the fact that wood has excellent heat insulation properties. Lower thermal conductivity values equate to greater heat insulating properties [13]. Wood exhibits low thermal conductivity (high heat-insulating capacity) compared with materials such as metals (aluminum 204.3W/mK, iron 72.7W/mK), marble (2.08 - 2.94W/mK), glass (0.96W/mK), and concrete (1.7W/mK) [11].

Thermal conductivity along the grain is significantly greater than across the grain. According to [14], the ratio of longitudinal versus radial conductivity is at 1.85 for mahogany air-dry. [15] determined a value of 2.05 for oven-dry pine at 20°C however, when the moisture content was 140 percent, the value was only 1.8.

[16] determined the average specific heat capacity of fiberboard as 1.427 kJ/kg°C and density of 0.232 g/cm^3 in a temperature range of 27°C to 100°C. Different sample preparations and use of different experimental methods provide explanation for the subtle differences in experimental results of average specific heat capacities [1]

A literature survey, however, reveals a very little of experimentaldata on thermal properties (thermal conductivity and heat capacity) of wood species grown in Ghana. The knowledge of thermal properties and other physical properties of the wood sample is very significant and paramount in the choice of wood samples that are suitable and thermally friendly for different building designs [17]. To promote the existing knowledge, this paper discusses thermal conductivity and heat capacity of thirteen (13) tropical hardwood species widely used in Ghana.

2. Materials and Methods

2.1. Description of Study Site

The wood samples were picked from the Pra-Anum forest reserve ((located between longitudes 1° 12' and 1° 15' W and latitude 6° 14' and 6° 20' N). The Pra-Anum forest reserve is underlain by three geological formations which are Lower Birim Rocks, Tarkwain System and Cape Coast Granite rocks. The prevalent soil series at the Pra-Anum Reserve is the Bekwai Series or the ferric acrisol (Bekwai Series). This soil is red, well drained, and sedentary in nature and found on summit and upper slopes where slope gradient lies between 3% and 12%. The soil profile consists of 15 cm to 45 cm of dark brown or dusky red, humous, porous, silty clay loam top soil which grades below into 60 cm to 150 cm of reddish brown or red, silty clay loam subsoil containing frequent quartz gravels and stones and ironstone concretions.

The study site is about 200 km^2 in extent and lies between Asante Ofoase in the Ashanti Region and Akyem Ofoase in the Eastern Region of Ghana. The site has an equatorial type of climate with mainly woodland vegetation while thicket is intermingled with tall hardwood species. The average temperature is 22°C and with annual rainfall value of 15.5 mm.

2.2. Sample Collection and Preparation

The samples were cut transversely from the mid-stem of the species. A total of 104 samples, four each from Morinda lucida, Khaya senegalersis, Blighia sopida, Sterculia rhinopetali, Pycnanthus angolensis, Brideli amicranthia, Celtis mildraedii, Daniellia ogeafaro, Chrysophylump perpalchrum, Holorrhena floribunda, Strombosia glaucescens, Albizia zygia, and Pterygota macrocarpa were collected.

The samples were made into discs of dimensions 10.0 cm diameter and 0.5 cm thickness for the determination of the thermal conductivities. For the determination of the heat capacities, the samples were re-worked into cubes of side 3 cm. In order to facilitate their easy handling during the experimental process small holes of 0.5 cm radius were bored from their midpoints. The samples were dried up at a room temperature of 28°C for a period of 180 days. During this time they were weighed continuously and their weights monitored until the rate of change in weight became less than 0.1% per day. They were then considered stable to changes in moisture content with time.

2.3. Laboratory Measurements

A total of 52 samples i.e. four (4) for each of the thirteen (13) tree species were used for the thermal conductivity measurements using Lee's Disk method. The specific heat capacities of the remaining fifty two (52) samples were determined using the method of mixtures.

2.3.1. Thermal Conductivity Measurements

Each sample was sandwiched between the brass disk and brass base of the Lee's apparatus and the brass base was fitted to steam chest. In order to keep the heat loss from the sides to a minimum, the sample was made in the form of a thin disk with a large cross sectional area compared to the area exposed at the edge. Steam was passed into the apparatus and the steady state temperatures T_1°C and T_2°C were recorded. The brass base and the samples were then removed and the brass disk was heated directly on the heating chamber until its temperature was 7°C higher than that recorded in the steady state. The heating chamber was removed to allow the brass disk to cool down by placing an insulator on it. The temperature readings were then taken at intervals of 30 s until the temperature fell to about 7°C below the steady state temperatures. The cooling-curve was plotted and the gradient was determined from the temperature data obtained. Using [18] equations, the rate of heat flow through the wooden disc H (J/s) was given by

$$H = \frac{kA(T_2 - T_1)}{x} = mc\left(\frac{dT}{dt}\right) \tag{1}$$

$$dT = \frac{kA\left(T_2 - T_1\right)}{mcx} \cdot dt \tag{2}$$

$$k = \frac{mcx}{A(T_2 - T_1)} \cdot S = \frac{mcx}{\pi d^2 \cdot T_2 - T_1} \cdot S \tag{3}$$

where S is the slope of the cooling ($^{dT}\!/_{dt}$) graph, m is the mass of the brass disk [kg], c is the specific heat capacity of the brass disk [J/Kg°C]; x is the thickness of each sample [m]; Ais the cross-sectional area of the sample [m^2]; (T_2-T_1) is the difference in the steady state temperature [°C], K is the thermal conductivity [W/mk].

For each wood species four (4) experiments were conducted and the average value of K determined

2.3.2. Error Estimation of K

Using (3)

$$\frac{\Delta K}{K}=\sqrt{\left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\frac{dT}{dt}}\right)^2+\left(2\frac{\Delta d}{d}\right)^2+\left(\frac{\Delta x}{x}\right)^2+\left(\frac{\Delta T_2+\Delta T_1}{T_2-T_1}\right)^2} \quad (4)$$

where: $\left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\frac{dT}{dt}}\right)^2$ is an error term from the slopes calculation, $\left(2\frac{\Delta d}{d}\right)^2$ is the error term from the diameter, $\left(\frac{\Delta x}{x}\right)^2$ is the error term for the thickness, $\left(\frac{\Delta T_2+\Delta T_1}{T_2-T_1}\right)^2$ is the error from the temperature reading, K is the thermal conductivity of the material and ΔK is the change in thermal conductivity of the material.

$$\frac{\Delta k}{k}=\sqrt{\left(\frac{S_1-S_2}{S_m}\right)^2+\left(2\frac{d-d_m}{d}\right)^2+\left(\frac{x-x_m}{x}\right)^2+\left(\frac{\Delta T_2+\Delta T_1}{T_2-T_1}\right)^2} \quad (5)$$

where: S_1 is the first slope of sample, S_2 is the second slope of sample, S_m is the mean slope of sample, x is the thickness of sample of sample, x_m is the mean thickness of sample, d is diameter of sample, d_m is the mean diameter of sample.

Ignoring the last term of (5) gives;

$$\frac{\Delta k}{k}=\sqrt{\left(\frac{S_1-S_2}{S_m}\right)^2+\left(2\frac{d-d_m}{d}\right)^2+\left(\frac{x-x_m}{x}\right)^2}$$

For example for Pterygota macrocarpa

$$\frac{\Delta k}{k}=\sqrt{\left(\frac{0.045-0.04}{0.0425}\right)^2+\left(2\frac{100-99.33}{100}\right)^2+\left(\frac{5-4.96}{5}\right)^2}$$

$$\frac{\Delta k}{k}=\sqrt{(0.1176)^2+(0.0134)^2+(0.008)^2}$$

$$\frac{\Delta k}{k}=\sqrt{0.013937}$$

$$\Delta k=k\times\sqrt{0.013937}$$

$$\Delta k=0.288\times\sqrt{0.013937}$$

$$\Delta k=0.034\ W/m.K$$

Thus, the error associated with K was of the order of 10^{-2}.

2.3.3. Specific Heat Capacity Measurements

A calorimeter of known specific heat capacity and mass was partially filled with a mass m_w of water at a temperature T_1 and then mounted in a suitable manner so that it is thermally insulated from the outside system. A mass m_{wd} of the wood sample which was in a form of a disc of unknown specific heat capacity c_{wd} was heated together with an iron of known specific heat capacity c_I to a higher temperature T_b in boiling water and then quickly transferred to the calorimeter. The pieces of Iron acted as a sinker. The temperature of the calorimeter and the water contained in the calorimeter quickly rose to a value T_2. It then slowly began to fall as heat was lost to the room. The cooling effect was allowed to be large in order to study it. The temperature readings were then taken at interval of 15 s until the temperature fell to 1°C below the steady state temperature of the water in the calorimeter.

The specific heat capacity of the various wood species were determined by

$$m_{wd}c_{wd}\left(T_B-T_{c2}\right)+m_Ic_I\left(T_B-T_{c2}\right)=m_wc_w\left(T_{c2}-T_w\right)+m_cc_c\left(T_{c2}-T_w\right) \quad (6)$$

From equation (4)

$$c_{wd}=\frac{m_wc_w\left(T_{c2}-T_w\right)+m_cc_c\left(T_{c2}-T_w\right)-m_Ic_I\left(T_B-T_{c2}\right)}{m_{wd}\left(T_B-T_{c2}\right)} \quad (7)$$

where: c_{wd} is the specific heat capacity of the wood species [J/g.K] m_I is the mass of the Iron [g];

m_{wd} is the mass [g] of the wood species; m_w is the mass of water [g]; m_c is the mass of the empty Calorimeter [g]; c_c is the specific heat capacity of empty Calorimeter [J/g.K]; c_w is the specific heat capacity of water (J/g.K); c_I is the specific heat capacity of Iron [J/g.K]; T_B is the final Temperature [K]; T_{c2} is the corrected Temperature [K]; T_w is the Temperature of the water [K]

Substituting mass of Iron (m_I) = 60g; mass of water (m_w) = 367g; mass of empty calorimeter (m_c) =235g; specific heat capacity of empty Calorimeter (c_c) = 0.45J/g.K; Specific heat capacity of water c_w = 4200J/g.K into equation (4) gives the specific heat capacity as:

$$c_{wd} = \frac{1685.89(T_{c2} - T_w) - 27(T_B - T_{c2})}{m_{wd}(T_B - T_{c2})}$$

Heat Capacity of wood

$$C_{wd} = (m_{wd})(c_{wd}) \quad (8)$$

2.3.4. Cooling Correction for Specific Heat Capacity (c)

The cooling correction was determined from Figure 1 by

$$Q = k\int_{t_2}^{t_3} (T - T_{room})\,dt \quad (9)$$

The right hand side of this equation is the area under the curve of $(T - T_{room})$ versus t, denoted by A_2. The left hand side (Q), the heat lost by cooling in the interval (t_3 - t_2), is proportional to ΔT_3. Thus we obtain $\Delta T_3 = k A_2$, where k is another constant. Similarly, the drop in temperature due to cooling in the time interval between $t = t_1$ and $t = t_2$, is given by $\Delta T_2 = k A_1$.

The final equation is then given as

$$\frac{\Delta T_2}{\Delta T_3} = \frac{A_1}{A_2} \quad (10)$$

The corrected temperature is given as

$$T_{c2} = \Delta T_2 + T_2 \quad (11)$$

Sterculia rhinopetali in figure 1, givesA_1 =480, A2=350.4, T_2 = 31.9°C,

$$\Delta T3 = 31.9 - 31.7 = 0.2°C$$

From equation 6, $\Delta T_2 = \frac{A_1}{A_2} \times \Delta T_3$

$$\Delta T_2 = \frac{480}{350.4} \times 0.2$$

$$\Delta T_2 = 0.27°C$$

Thus, the corrected temperature, T_{c2}= 0.27 + 31.9 = 32.2°C

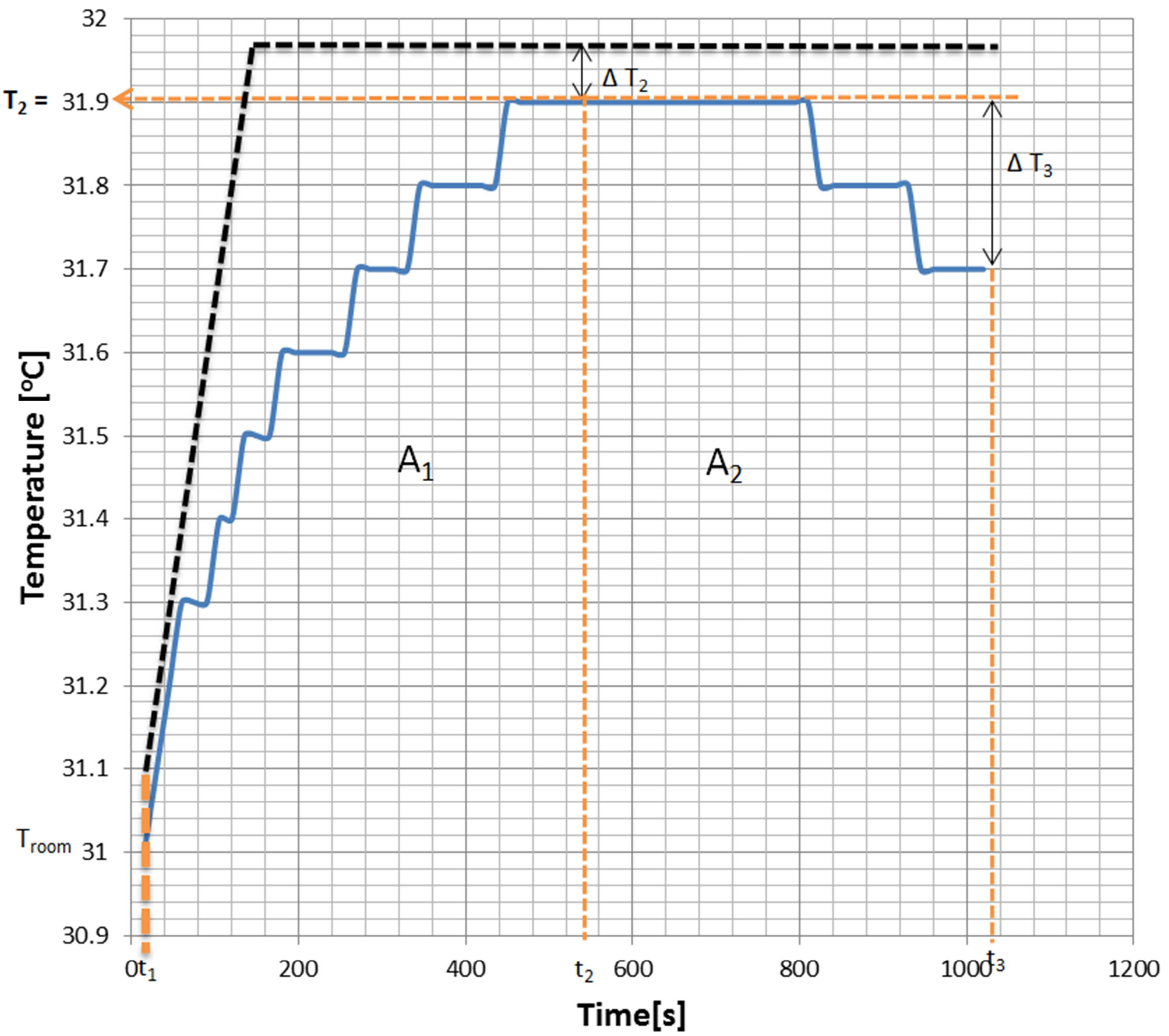

Figure 1. *Cooling Correction for Sterculia rhinopetali.*

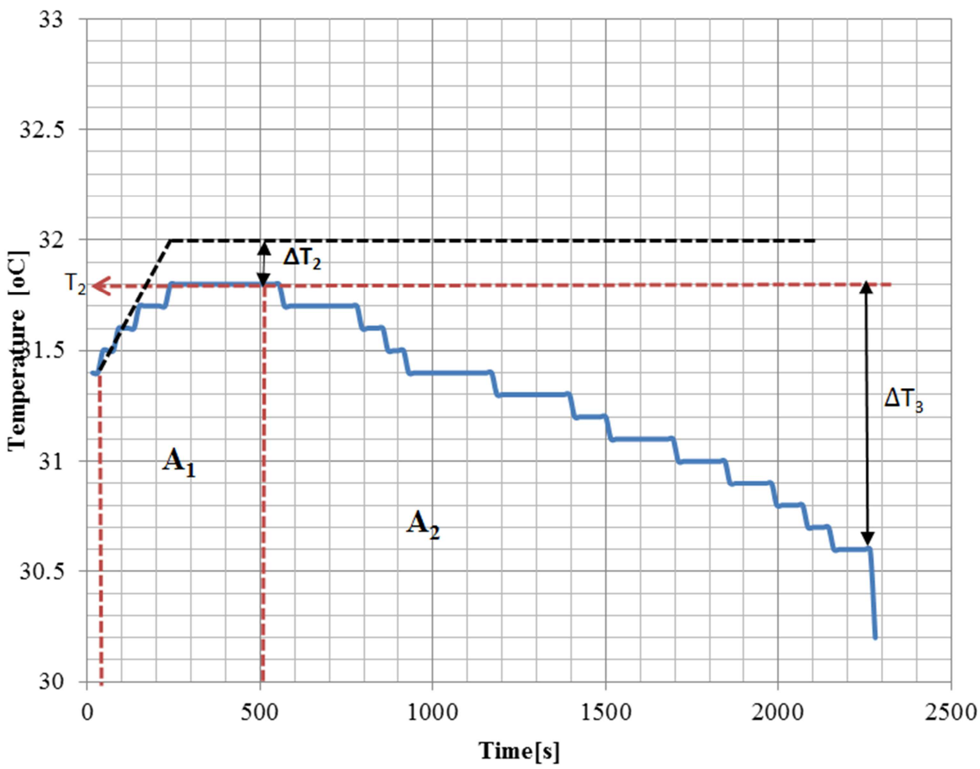

Figure 2. *Cooling correction for Morinda Lucida.*

Also, Morinda Lucida in Fig. 2, gives A_1= 592, A_2=2370, T_2 = 31.8°C,

$$\Delta T_3 = 31.8 - 30.6 = 1.2\ °C$$

But, $\Delta T_2 = \frac{A_1}{A_2} \times \Delta T_3$

$$\Delta T_2 = \frac{592}{2370} \times 1.2$$

$$\Delta T_2 = 0.3^{o}C$$

Thus, the corrected temperature, $T_{c2} = 0.3 + 31.8 = 32.1$

3. Results and Discussion

3.1. Thermal Conductivity

Table 1. *The thermal conductivities of the various wood species with their percentage change in error.*

Botanical names of the samples	Density 0f Samples [g/cm^3]	Thermal conductivity, K [W/m.K]	Error, Δk [%]
Sterculia rhinopetalia	0.49	0.201	2.48
Celtis mildraedii	0.56	0.080	1.59
Khaya senegalersis	0.47	0.212	2.90
Chrysophylum perpalchrum	0.43	0.178	1.57
Blighia sopida	0.49	0.278	0.90
Holorrhena floribunda	0.74	0.230	2.06
Daniellia ogeafaro	0.69	0.157	1.60
Pycnanthus angolensis	0.51	0.151	1.91
Morinda lucida	0.59	0.339	3.19
Strombosia glaucescens	0.60	0.392	1.71
Bridelia micranthia	0.43	0.359	1.07
Pterygota macrocarpa	0.72	0.288	4.63
Albizia zygia	0.40	0.388	3.60

The results of thermal conductivity of the thirteen (13) hardwoods are shown in Table 1. It was observed that Albizia zygia with a density of 0.40 g/cm^3 had the highest thermal conductivity value of 0.392 W/mK while Celtis mildraedii with a density 0.56 g/cm^3 had the least thermal conductivity value of 0.08W/mK. Thus, Celtis mildraedii was found to be most insulating. The range of thermal conductivity (k) values for the tropical wood species determined (0.08-0.392W/mk) in this paper were within the general range of conductivity (0.1-0.8 W/mK) [11] [19] [20] for wood materials. From literature the thermal conductivity of some metals and non-metals such as steel, iron, silver, granite and glass are respectively 43 W/mK, 80 W/mK, 430 W/mK, 4.0 W/mK, and 1.4 W/mK. The thermal conductivity of Albizia zygia (0.392 W/mK), highest for our tropical wood species is far less than Silver (430 W/mK) and glass (1.4 W/mK) which could be used for various applications.

Thermal conductivity is important in thermal insulation of buildings and related fields such as heat sink applications. It is a critical attribute when offering energy conserving building products because of the significant presence of wood and wood products in buildings. Lower thermal conductivity values equates to greater heat insulating properties [13]. Celtis mildraedii with the lowest thermal conductivity value out of allthe wood samples, possesses the best thermal insulating properties among the species which could be used as windows and doors of buildings etc. However, the higher the thermal conductivity value, the higher the overall heat transfer. Albizia zygia which was found to possess the highest thermal conductivity can be used in heat sink applications as a passive heat exchanger. It could also be used in cold and temperate regions where heaters are needed to stabilize room temperatures. Steady-state thermal conductivities are useful for comparisons among building materials for thermal efficiency. The temperature of the disc slab increases as the time increases up to stability for each disc. The equilibrium values of the samples are significant when a gradual decrease in the thermal conductivity results in corresponding increase in temperature with time. The rate at which thermal equilibrium was attained was found to be faster at the falling than for the increasing temperature. This effect could be attributed to the fact that initially, enough energy is required to break the bonds of the particles in the samples and on reaching their maximum excited positions and as the thermal energy reduces, the particles tend to return to their mean position.

The thermal conductivity of solid wood increases with density, [21]. However, this paper exhibits some inconsistencies in the thermal conductivity-density relationship for wood. For example, Albizia zygia *with* density of 0.40 g/cm^3 and thermal conductivity of 0.388W/m.K while Pterygota macrocarpa with density 0.72 g/cm^3 had thermal conductivity of 2.88W/m.K. Thus, it is seen that even though Pterygota macrocarpa has higher density than Albizia zygia the former has a higher thermal conductivity. This might be so because thermal conductivity does not depend on density alone but also on other factors such as the moisture content, temperature, extractive content and the number of checks and knots in the wood specie.

3.2. Heat Capacities

The results of the Specific heat capacities and the heat capacities of the various wood species are presented in Table 2. Holorrhena floribunda recorded the highest specific heat capacity value of 1.97J/g.K while Pterygota macrocarpa recoreded the lowest value of 1.01 J/g.K. The mean specific heat capacity of hardwood species is found to be 1.7 J/g.K [22]. However, it was observed that, Daniellia ogeafaro, Pterygota macrocarpa, Sterculia rhinopetalia, Celtis mildraedii, Bridelia micranthia, Stromboria glaucescens, Blighia sopida and Pycnanthus angolensis were below this value. Pterygota macrocarpa recorded the lowest value. Albizia zygia, Chrysophylum perpalchrum, Holorrhena floribunda, Morinda lucida and Khaya senegalersis were above the mean constant specific heat capacity; with Holorrhena floribunda recording the highest specific heat capacity value. The densities and the moisture content of the wood species vary, and this might be the reason for variations in heat capacities observed.

Specific heat determines the heat absorption capacity of a material for a given rise in temperature. Heat capacity is effective in improving building comfort in any place that experiences daily temperature fluctuations. The high specific heat capacity of Holorrhena floribunda, Albizia zygia, Chrysophylum perpalchrum, Morinda lucida and Khaya senegalersis will enable them to store heat and aid in the re-emission of energy back into the building, saving energy and reducing costs.

Wood is the most commonly used building material in the world. Mostly used as trusses on which roofs of houses are built, other alternatives as steel are too expensive for construction. The above listed wood species could serve as reasonable alternatives since they are relatively cheap and in large quantity. In hot climates the use of these wood species will help in stabilizing or normalizing the room temperature for an extended time.

Table 2. *The specific Heat capacities and Heat capacities of the wood species.*

Wood Samples	Specific Heat capacity c_{wd} [J/g.K]	Heat capacity c_{wd} [J/K]
Sterculia rhinopetalia	1.66	08.35
Celtis mildraedii	1.66	31.54
Khaya senegalersis	1.85	22.20
Chrysophylum perpalchrm	1.87	22.44
Blighia sopida	1.58	20.54
Holorrhena floribunda	1.97	25.61
Daniellia ogeafaro	1.41	11.28
Pycnanthus angolensis	1.32	18.48
Morinda lucida	1.87	18.70
Strombosia glaucescens	1.54	18.48
Bridelia micranthia	1.44	21.60
Pterygota macrocarpa	1.01	09.09
Albizia zygia	1.78	21.36

Figure 3 compares the heat capacities of the various wood species. The standard values are compared with the measured values by the formula: Heat Capacity of wood (C_{wd}) = (m_{wd}) × (c_{wd}) equation 8.

It can be inferred from the graph that the measured heat capacities compares favourably with the standard heat capacity. Wood species with widest difference between the standard and measured heat capacities was found in Pterygota macrocarpa with standard heat capacity of 15.3 J/K and measured heat capacity of 9.09J/K. This is followed by Pycnanthus angolensis with a standard heat capacity of 23.8 J/K and the measured heat capacity of 18.48 J/K. The remaining wood species were found to possess marginal standard - measured heat capacity differences. The results obtained show that the values for the heat capacities are not comparable to that of the thermal conductivities of the wood species. For example Holorrhena floribunda with thermal conductivity of 0.230 W/m.K has heat capacity of 25.61 J/g.K. This confirms from literature that heat capacities and thermal conductivities do not have have comparable values and are quite unrelated. One possible reason for this is the moisture redistribution in the specimens under changing thermal gradient [7].

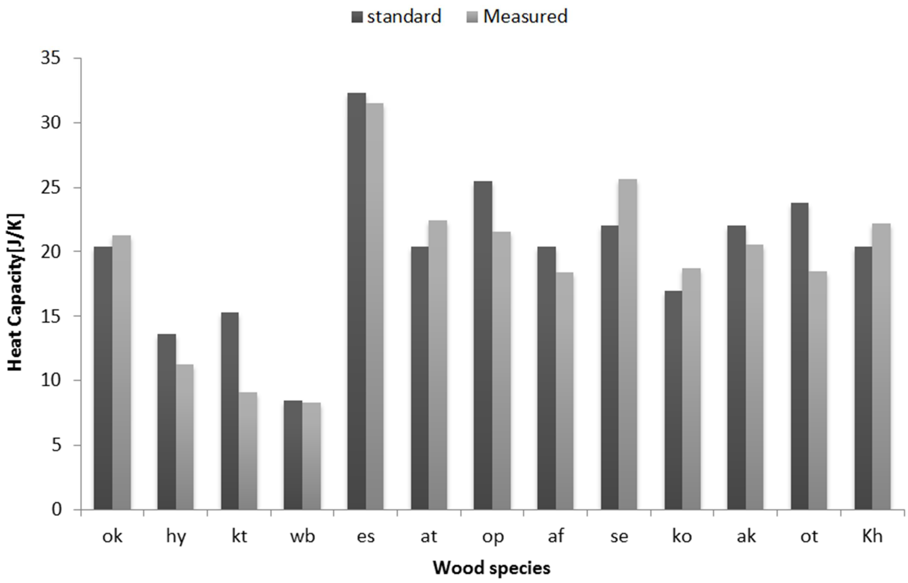

Figure 3. *A Plot of Measured and Standard Heat capacities against wood species.*

4. Conclusion

Thermal Conductivity and heat Capacity of thirteen (13) different tropical hardwood species were measured experimentally by using Lee disk method and method of mixture, respectively. From experimental results, Celtis mildraedii had the lowest thermal conductivity whilst Holorrhena floribunda had the highest Specific heat capacity. A high thermal resistivity favors the wood specie as an interior building insulating material for naturally cooled building design in Ghana and elsewhere. The results obtained in general, revealed that the wood materials in the study possess good thermal properties. The thermal conductivities values for the samples were found to conform to the general range of conductivity for wood materials. This would assist building engineers in the choice of construction materials to adopt for effective use. The thermal conductivity of common structural woods and wood-based materials is much less than the conductivity of metals with which wood is often mated in construction. Building materials have evolved over the years therefore there is the need for continuous updating of the information on their thermal properties.

The mean specific heat capacity of wood species of 1.7 J/g.K. is comparable to the specific heat capacities obtained in this paper. Wood species which showed the largest difference between the standard and measured heat capacities was found in Pterygota macrocarpa with standard heat capacity of 15.3 J/K and measured heat capacity of 9.09 J/K. This is followed by Pycnanthus angolensis with a standard heat capacity of 23.8J/K and the measured heat capacity of 18.48 J/K.

Heat capacity is effective in improving building comfort in any place that experiences daily temperature fluctuations. The high specific heat capacity of Holorrhena floribunda, Albizia zygia, Chrysophylum perpalchrum, Morinda lucida and Khaya senegalersis shall enable them to store heat energy and aid in the re-emission of energy back into the building, saving energy and reducing cost.

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Nomenclature

1. Albizia zygia=ok
2. Blighia sopida=ak
3. Bridelia micranthia= op
4. Celtis mildraedii=es
5. Chrysophylum perpalchrum=at
6. Daniellia ogeafaro=hy
7. Sterculia rhinopetalia=wb
8. Holorrhena floribunda=se
9. Morinda lucida= ko
10. Khaya senegalersis=kh
11. Pterygota macrocarpa=kt
12. Pycnanthus angolensis=ot
13. Stromboria glaucescens=af

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