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COMPARATIVE ANALYSIS OF ANISOTROPIC PROPERTIES OF SELECTED WOODS IN EASTERN NIGERIA

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Abstract This study investigates the anisotropic property of selected wood samples from rain forest zone (south eastern part) of Nigeria. The experimental investigations of five wood samples were done, distance between the probes in each was measured and documented and heating each from Parallel (longitudinal) and at right angle (Radial) to the grain direction of each wood sample was done. Melina sample has 1251kg/m^3 of density and 0.13w/mk^{-1} for thermal conductivity as the lowest along longitudinal grain direction and Agba sample has 1427kg/m^3 of density and 0.08w/mk^{-1} for thermal conductivity as the lowest for the radial grain direction. It is recommended that application of wood for any usage, grain direction should be considered especially where heat is eminent. Melina been the lowest along longitudinal with 0.13w/mk^{-1} is best suited for application along the said grain direction. And Agba having 0.08w/mk^{-1} best for application along radial grain direction.

Keynotes: Density, Thermal conductivity, radial, longitudinal grain directions and density, woods, Anisotropic Properties, comparative Analysis

1. Introduction

The conduction of heat through wood and wood based materials has been well understood since the time of Fourier. Wood is an anisotropic material, hence it ability to have different characteristic at different variables (Madhusudana et al 2015). The conduction of heat across Nigerian woods is less understood, especially since this phenomenon has received little attention until investigations to alternative building materials starts to develop as a result of high cost of concrete and iron based materials in Nigeria. Wood thermal conductivity depends on heat flow direction, on wood grain direction, on defects, on Density - moisture content and dried wood and on temperature (Maclean, 2009). This paper deals on the density of the dried wood and how it affects thermal conductivity of wood. Therefore, to get the thermal conductivity of a particular wood we have to consider the combination of the variances: the properties affecting thermal conductivity of wood (density), the theoretical models for examining the relationship of wood structure and the experimental rig and instrumentations to be used.

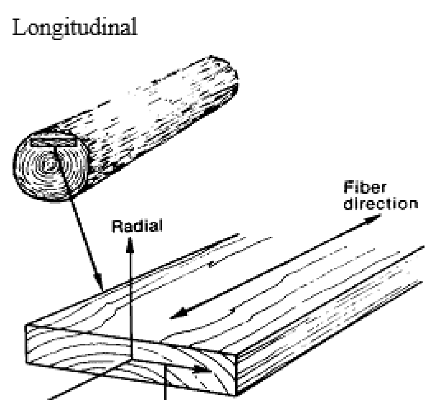

Fig. 1 Diagram showing the build-up of grain direction and growth rings of woods

Wood is an orthotropic and anisotropic material (Ojobor, 2010). Because of the orientation of the wood fibers and the manner in which a tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial, and tangential (Fig.1) The longitudinal axis is parallel to the fiber (grain) direction; the radial axis is perpendicular to the grain direction and normal to the growth rings.

From a generalized 3-dimensional unsteady state equation we drive Fourier steady state equation (Etuk et al, 2010); whenever temperature gradient exists in a body or a system, heat will flow from the higher temperature region to the lower temperature region at a rate proportional to the temperature gradient i.e.

$$\frac{q}{A} = \alpha \frac{\delta T}{\delta X} \qquad \textbf{(1)}$$

$$q = -KA\frac{\delta T}{\delta X} \qquad \textbf{(2)}$$

$$\text{At steady state } \frac{\delta T}{\delta X} = 0 \qquad \textbf{(3)}$$

At steady state and if there are heat sources into or heat-sink out of the body: -
Then;
Energy balance becomes;
Energy in + energy generated/lost = δu + energy out
Where δu = change in internal energy.
Thus:

$$Q = -KA\frac{\delta T}{\delta X} \qquad \textbf{(4)}$$

$$\text{Energy generated} \quad = qA\delta x \qquad \textbf{(5)}$$

$$\Delta U = \rho C v \delta T \delta X A dx \qquad \textbf{(6)}$$

$$\text{Energy out} = -KA\delta T\delta X)_{x+dx} \qquad \textbf{(7)}$$

$$= -A\frac{\{K\delta T}{\delta X} + \frac{\delta}{\delta X}(K\delta T/\delta X)_{dx\}}$$

$$\text{Thus, } q + \delta x(\frac{K\delta T}{\delta X}) = \rho C v \delta T \delta X \qquad \textbf{(8)}$$

$$\text{i.e } q + \frac{K\delta^2 T}{\delta X^2} = \rho C v \frac{\delta t}{\delta x}$$

For a 3- dimensional heat flow and with no internally generated heat:

$$\frac{K\delta^2 T}{\delta X^2} = \rho C v \frac{\delta T}{\delta X} \qquad \textbf{(9)}$$

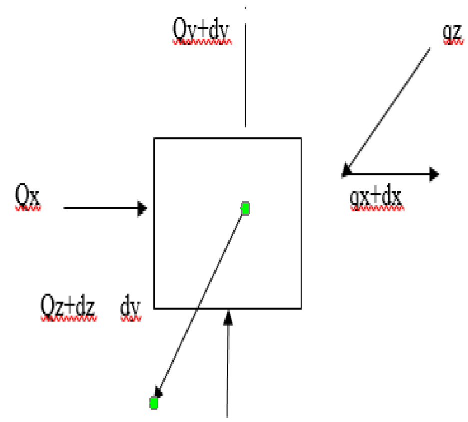

Fig. 2 Heat flow 3D analysis

Thus,for3D:

$$K\left(\frac{\delta^2 T}{\delta X^2} + \frac{\delta^2 t}{\delta y^2} + \frac{\delta^2 t}{\delta z^2}\right) = \rho C v \frac{\delta t}{dx} \qquad \textbf{(10)}$$

Or $\delta^2 T = \frac{\delta^2 T}{\delta X^2} + \frac{\delta^2 t}{\delta y^2} + \frac{\delta^2 t}{\delta z^2} + \frac{q}{k} = \frac{1}{\alpha \delta t/\delta x}$ this is the vertical divergence of temperature, with internal heat generation q.

Where $\alpha = \frac{k}{\rho c}$ = thermal diffusivity. Having generated this equation Fourier's steady state equation is chosen since our δt/δx =0, therefore the equation 9 after transformation becomes thus;

$$K = \frac{\Delta Q}{A\Delta t}\frac{x}{\Delta T} \qquad \textbf{(11)}$$

It is defined as the quantity of heat, Δ*Q*, in a time change transportation Δ*t* along material thickness *x*, going in a direction regular to a surface of area *A*, per unit area of A. Owing to a temperature difference Δ*T*, underneath the case of steady state conditions and heat transfer is only based on the temperature slope. Alternatively, it can be thought of as a flux of heat (energy per unit area per unit time) divided by a temperature gradient (temperature difference per unit length)

(Zi-Tao *et al*, 2011), conducted a study on the thermal conductivity for uniform density of wood cells. This study shows that when woods are not fully saturated by water; there is a significant increase in thermal conductivity as density increases. But when the cell lumen of wood is fully filled with free water: maximum moisture content of wood, the thermal conductivity decreases and density increases. Wood fully saturated with water, water dominates the thermal conductivity through the wood cell structures. Therefore, the higher the holes in the wood (lower density) the more water in the lumen and the higher the effect on the wood's thermal conductivity. (Antwi-Boasiako et al, 2018), in their work thermal conductivity, resistance and specific heat capacity of chemically-treated, widely-used timber for building envelope, still talked about the two major properties affecting the thermal conductivity of wood - density and moisture content. For better data in their experiment, they suggested that the percentage water content in a woods, should be over 15% test condition be maintained for a minimum period of 24 hours this is to ensure that any significant moisture rearrangement in the sample have ended. The exact measurement of thermal conductivity of moist wood and wood particles will not give essentially a better find for thermal conductivity indicator for woods. Wikipedia encyclopedia modified (Madhusudana et al., 2015), reviewed this contact conductance as it affects the thermal conductivity of solid bodies. The answer to the question of air density and lumen space and geometry in case of (Zi-Tao *et al*, 2011) to their work seemed answered.

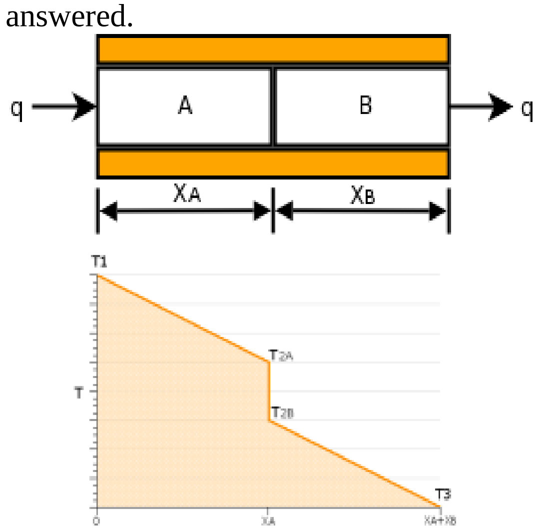

Fig. 3 Heat flow between two bodies in contact and the temperature distribution

Okoli et al, (2017) still took us to the theory we are working on; Fourier's law.

The heat flow between the two bodies is found by bringing in the energy conservation theory in the equation and expanding it to give us the thermal contact conductance of a solid body.

Heat flow between two bodies is found as;

$$q = \frac{T_1 - T_3}{\Delta x_A/(k_A A) + 1/(h_c A) + \Delta x_B/(k_B A)} \quad \textbf{(12)}$$

Where;

q = applied heat; A = area of the contacting area

$T_1 - T_3$ = the change in temperature comprising the contacting area.

K_A = thermal conductivity of body A and K_B = thermal conductivity of body B

X_A and X_B = the distances from the probe of bodies A and B

$1/h_c$ = the contact resistivity the inverse of contact conductance.

We observed that the heat flow is directly related to thermal conductivity of the bodies in contact, K_A and K_B, the contact area, A and the thermal resistance, 1/hc, which is the inverse of the thermal conductivity coefficient h_c (Antwi-Boasiako et al, 2018).

2. Materials and method

2.1 Design of Apparatus

In order to evaluate the thermal conductivity of Nigerian woods, through a triangular interface and pyramid volume, a known thermal conductivity apparatus was modified - lee disc was re-designed to obtain data over a temperature range of Nigerian wood samples and under some certain thermal conditions. The primary influence of the modified lee disc (as it was called after re-design) is that the materials are locally sourced. These materials are readily available at the common Nigerian markets and could withstand the experimental temperature range without giving way for the samples first. These materials are also in relatively wide use, somewhat easy to machine and weld. The dimensions of all the materials -- U-channel iron part A and B (460mmx 40mmx25mm) stand and u-channel iron part C-- (355mmx40mmx25mm) used as the base, flat iron bar part F – (204x38x5mm) used as the handle, M12 x 120mm long bolt and nut were used for fastening the handles. All these dimensions were determined after considering the constraints of available space for the selected wood samples, also the u-channel for the base was also dimensioned based on the total dimension of the electric iron and the sample material and the space to screw them together. There is an iron pipe of 127mmx 65mm diameter used to hold the electric iron and the wood sample as you tighten the handle of the apparatus. A work bench of 3120x6180x614mm was provided to create ergonomic and for the other instruments like thermocouple, ammeter and voltmeter to rest on it. Modified lee disc can also be used for other heat source shapes like circle for experiments- an added advantage. For rigidity welding was used to join the u-channels to each other while nut and bolt were used to fasten the apparatus to the laboratory table. Heat was supplied to the assembly by Q-link manufacturing company with a triangular shaped 210 x110mm electric iron of 1100w capacity, To avoid heat loss; the wood samples were cut in the same shape with the electric iron of triangular shape and coated with fiber glass heat insulator, with a little dimensional difference. The heat source is from mains of supposedly 240v.

$$P = IV \qquad \textbf{(13)}$$

Power (w) is equal to the applied heat Q.

The calculation of thermal conductivity of woods and other materials involves the use of some instruments to acquire some vital data needed for the calculation. Some of the instruments used are: Type K thermocouple was used. The range is -323k to 1573k with tolerance of ±0.75%. K- Type is described as 3.24x150mm metal sheath 100cm compensating wire. This gives us the temperature difference (dt) in the Fourier's law with a digital thermometer displaying the data.

Thermometer:

TES- 1303 digital thermometer for the thermocouple (probe) above was used. This temperature sensor followed NBS and IEC 584 temperature /voltage standard table for K-type thermocouple. Dimension of the temperature sensor includes; 135(L) x 72(W) x 31(H) mm and 235g weight with battery and has a display rate of approximately 2.5 times per second.

Ammeter

Analog AC ammeter of 0- 25amps measurement ranges was used to measure the current that is supplied to the heater. This gives us the, I value in equation 8 above.

Voltmeter

Also an analog AC voltmeter range of 0-500volts was used to measure the voltage coming to the heater. Again this gives us the value of V in equation 8.

Meter Rule

This was used to measure the distance of the two probes (thermocouples) and also helped in measuring the width and the height, for the calculation of the wood samples area A (m^2).

2.3 Sample Characterizations:

Mentioned earlier the five selected samples were chosen due to their availability in the market and their rampant usage in Nigeria. All the samples are of the same shape- triangular. Their dimensions vary with average value of ± 3mm. Melina, Mahogany, wall-nut; Inyi and Agba are the names of the wood samples used. Each of the specie has two samples of different grain direction from the applied heat: Longitudinal direction is measured 180^0 to the grain direction and radial direction is measured 90^0 to the grain direction. Five woods were further for the density and thermal conductivity analysis. Holes were drilled in the direction of the applied heat with different distances. Using the data calculated for density and thermal conductivity already for the sampled woods, Analysis was done with respect to the grain directions of the two samples. We are to determine what happens when density increases in longitudinal direct and also along the redial direction of the wood sample grain.

2.4 Thermal Conductivity

Fig. 4 shows the schematic diagram of the system labeled A-G

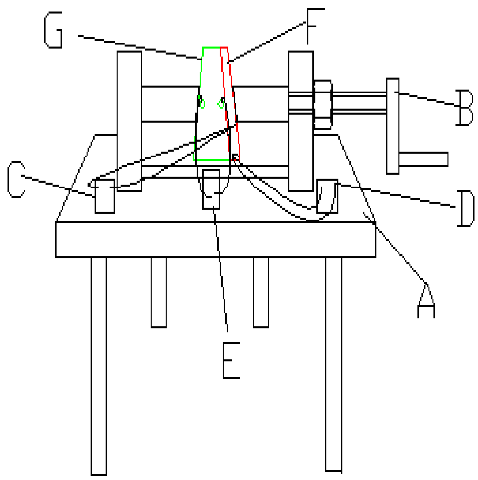

Fig. 4 Schematic Diagram of modified lee disc apparatus

KEYS

A – Laboratory Table, B – Modified Lee Disc Apparatus, C – Ammeter, D – Voltmeter, E – TES-1303 Digital Thermometer with Type-K Thermocouple, F – 1.5kw Power Source, ands G – Wood Sample

2.5 Steady State Testing

Before the heater element and the mains, an ammeter (in series) and a voltmeter (in parallel) were placed. For good contact with the probes and the wood samples a little oil was added in the holes. Voltage and the current were held steady. They were heated until the temperature of probe 1 and probe 2 became steady, while differences in the temperature were measured every 15minutes time interval. This means that the heat in to the surface every minute is the same to the heat out of the end surface of the wood sample every minute. We assumed that there is no heat loss since our dx is small. All conductivity measurements were taken while the specimens were at steady state. Steady state was ascertained by timing with a clock to know when the variation of the control parameters and the measured value does not exceed our specified drift tolerance range for fifteen minutes for this experiment. The selection of the heater settings is influenced by the maximum temperatures. The epoxy used to pot the thermocouples softens at elevated temperature (at least, until it is completely out-gassed), but since no strain was applied to the wire this was not taken into account to determine the over-temperature condition. The temperature used to determine if an over-temperature condition existed was 823k, ensuring that none of the components or instrumentation was damaged. Preliminary testing of the test facility revealed that maximum heater settings could be used without violating the over-temperature criteria. Therefore, all testing includes the maximum heater setting. But the rheostat in the electric heater was supposed to help us to regulate the heat applied, to avoid burning the wood.

Table 1 Experimental values taken from the rig and calculated values

Samples	Grain direction	(dx) Probe distance (m)	Area (A) M^2	Δt T1-T2 (K)	Density (ρ) g/m^3	Thermal conduc. K (W/MK^{-1})
Agba	Longitudinal 180^{0c}	0.072	0.013	330.4	1643	0.13
	Radial 90^{0c}	0.043	0.012	350.4	1427	0.08
Inyi	Longitudinal 180^{0c}	0.064	0.013	298	2911	0.14
	Radial 90^{0c}	0.062	0.012	340.8	3057	0.12
Melina	Longitudinal 180^{0c}	0.076	0.013	352.4	1251	0.13
	Radial 90^{0c}	0.066	0.012	365.3	1574	0.12
Mahogany	Longitudinal 180^{0c}	0.065	0.012	331.4	1917	0.13
	Radial 90^{0c}	0.058	0.013	347	1950	0.10
Tick (Wallnut)	Longitudinal 180^{0c}	0.063	0.013	330.9	2270	0.12
	Radial 90^{0c}	0.072	0.013	358.7	2280	0.12
Mean values		0.063	0.013	342.8	2028	0.13

During the test the mean values of 'I' and 'V' are 0.035amps and 230 respectively.

AREA; from the triangular shaped sample the area was calculated using area of a triangle

$$\frac{1}{2}xbxh \quad \textbf{(14)}$$

DENSITY; The weight of the wood samples were weighed with scale and the volume of a pyramid used in calculating the volume.

$$\frac{1}{3}xbxhxl \quad \textbf{(15)}$$

And the density is the mass per unit volume of the samples Kg/m^3

Table 2 calculated data for density and thermal conductivity for two grain directions

Longitudinal direction (180o to applied heat)		Radial direction (90o to applied heat)	
K (W/MK^{-1})	Density ρ (g/m^3)	K (W/MK^{-1})	Density ρ (g/m^3)
0.13	1643	0.08	1427
0.14	2911	0.12	3057
0.13	1251	0.10	1574
0.13	1917	0.11	1950
0.12	2270	0.12	2280

Density is one of the major properties of wood that influences its thermal conductivity. Like water, thermal contact conductance etc Density has effect in the choice of wood as an insulator. Density was calculated. The applied heat source from the mains is gotten from the electrical relations of equation 8. Therefore, the thermal conductivity is given by the same Fourier's law of equation 3. The equation was transposed to get the K which is what we are looking for, and we have thus;

$$K = qA\frac{\delta X}{\delta T} \qquad (16)$$

Where;
K is the thermal conductivity unknown (w/mk^{-1}) : q is the heat applied in watt (w)
dT is the temperature difference in Kevin (K); dx is the distance between the probes T1- T2 (M); A is the cross section area of the wood samples (m^2)$^{.}$ Calibration of the thermocouple was made using mercury in glass thermometer, after boiling water at 373k and getting an ice block.

3.0 Results and Discussion

3.1 Density and thermal conductivity along longitudinal and radial grain directions of wood

From table 2, above thermal conductivity was plotted against density as shown on the bar chart below. From the bar chart the wood samples are numbered as 1 for Agba, 2 for Inyi, 3 for Melina, 4 for mahogany and 5 for wall-nut. When density of the wood sample was 2911kg/m^3 the thermal conductivity was 0.14w/mk^{-1} the sample was Inyi and when it was 1251kg/m^3 the thermal conductivity was 0.12w/mk^{-1} the sample is Melina, along the same longitudinal grain direction. Also when the density was 3057kg/m^3 the thermal conductivity was 0.12w/mk^{-1} the sample is Inyi and again density was1427kg/m^3 the thermal conductivity was 0.08w/mk^{-1} the sample is Agba along the same radial grain direction.

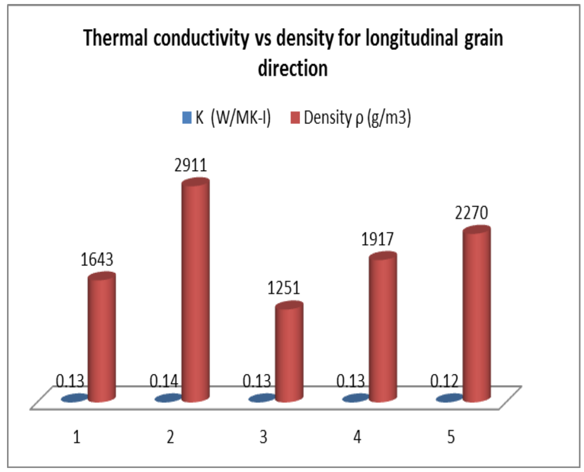

Fig. 5 Thermal conductivity vs density along longitudinal grain direction

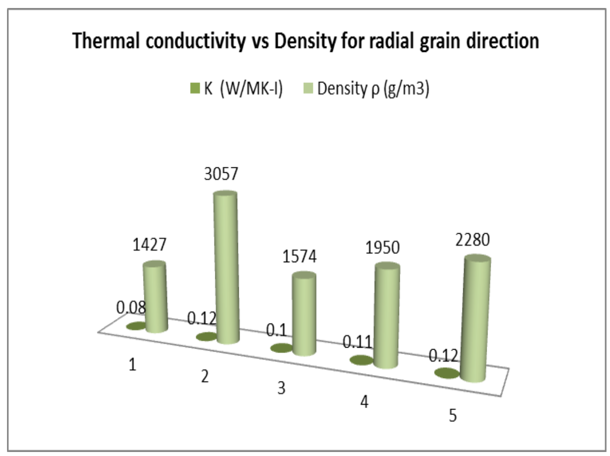

Fig. 6 Thermal conductivity vs density along radial grain direction

4 Conclusions

It was observed that grain direction plays an important role in the thermal conductivity of woods, while density remains a linear function in the determination of thermal conductivity of woods. This can be seen from the chart above that when the thermal conductivity is high the density is also high irrespective of the grain direction. To improve the insulating capacity of wood it is better to have the heat applied at the right angle (radial) Irrespective of the grain density.

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