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Thermal response of some select wood samples for a passively cooled building design

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Abstract

Determination of thermal properties of some select wood samples for predicting temperature variation with thickness as determinant for selection of thermally suitable wood samples needed in passively cooled building design was undertaken. Results show that sample E, Iroko wood sample has among others, the best thermal insulation properties based on the highest and least values of thermal diffusivity[$91.60 \pm 0.04 m^2 s$] and thermal absorptivity [$1.993 \pm 0.111 m^{-1}$] respectively. For the frequently used wood samples in building design investigated, the thermal conductivity of all of them are compatibly suitable for thermal insulation according to prediction limits given by other researchers. Moreover, thermal mathematical modelings have been developed for the prediction of thermal response of the wood samples frequently used in building design and these equations thermally thrive on predicting the variation and suitability of the investigated samples at any given thickness and time of the day with solar radiations absorbed by wood samples used for roofing, making of ceiling panels, making of doors or any other padded building design.

Keywords: Thermal response, thermal properties, passively cooled building design and wood samples.

INTRODUCTION

Weather and climate determine the thermal states of any geographic region. The steady ambient temperature of any geographic region is therefore a function of the environmental prevalent temperature. The thermal state of a region reflects the thermal state of vegetation, land, water bodies, air and the building that we live in.

Nigeria which is located in an equatorial region has much of the sun's radiation (solar energy) and the region is relatively hot at night [1]. Solar energy, the only inexhaustible energy source, has varieties of applications. These include, heating of houses and water, generation of electric power, drying of food samples and so on [1]. With particular reference to heating of houses, it is obvious that some of the wood samples frequently used in building of houses be investigated experimentally in order to know the degree of their thermal states in terms of the conductivity, absorptivity, emissivity and diffusivity of heat. The determination of these thermal properties and the density of the wood samples will help to determine the thermal response of wood samples frequently used in building of houses.

The knowledge of thermal properties and other physical properties like density 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. Heat flow through any wood sample depends on their thermal properties which means that the variation in temperature with thickness of wood sample can be used to monitor the thermal conductivity or insulation of the wood sample in response to the incident solar energy [2]. This source-sink temperature variation with thickness at any given time of the day throughout the year is an important tool in the design of passively cooled building [3].

A passively cooled building is the one which is maintained comfortably cooled through natural means as opposed to the use of electrical or mechanical devices [4].It is obvious that the concept of thermal diffusivity is developed from the analysis of most of the heat transfer problems which are either to determine the temperature distribution within a system and the rate of heat transfer for specific operating conditions or prescribe the necessary configuration in order to accomplish a given heat transfer and thermal response to materials [1].

This work is necessary and complementary to the work done by [1] on the thermal response of different walling materials for self-cooling building design. According to the author, the design of passively cooled building demands the good selection of walling and roofing materials that will enhance a self-cooling of building in the tropical sub-region like Nigeria with high level of incident solar radiation. Using materials of thermally tolerated properties in the design of building, passively cooled building that is thermally friendly can be actualised.

Wood is a product of lumbering activities that exhibits thermal, electrical and mechanical properties. The sensitivity of wood to thermal properties like conductivity, diffusivity, absorptivity and emissivity reflects the thermal properties of wood. The electrical sensitivity of wood which is dependent on the moisture content of the wood reflects the electrical properties of wood. Again, those properties of wood samples relating to its resistance to deformation by applied forces signify the mechanical properties of wood. For the purpose of this study, thermal properties of wood sample will be particularly considered. Thermal conductivity increases with density, moisture content and temperature. Thermal conductivity of woods increases at about 0.25% per degree Celsius [5].

Although specific heat capacity C, is fairly constant for different wood samples, it increases with temperature and moisture content [6, 7]. For oven-dry wood sample, the specific heat capacity C_0 is given by equation (1):

$$C_0 = 0.266 + 0.001166t \qquad (1)$$

For wet wood sample at moisture content M, specific heat capacity is given as

$$C_m = \frac{C_a + (MCa/100)}{1 + (M/100)} \qquad (2)$$

Where t is a conversion factor in $JKg^{-1}K^{-1}$ and Ca is apparent specific heat capacity of the absorbed water which is usually higher than unity for pure water. Thermal diffusivity (λ) is the ratio of conductivity K, to the product of density ρ and specific heat capacity C or

$$\lambda = K/\rho c \qquad (3)$$

Thermal diffusivity decreases slightly with increasing wood density and moisture content and it is constant with temperature because of the compensating factor [5].

To actually predict temperature variation and thermal response of wood samples, thermal absorptivity is also considered for successful computation of the temperature predictive model.

Theory:

Amount of radiant energy absorbed or reflected depends on the materials colouration [8, 9]. The proportion of energy absorbed causes changes in temperature of the wood sample. Thermal radiation or radiant heat emitted by hot bodies is electromagnetic containing a wide range of wavelengths. This energy absorbed by the surface may be used in:

(i) Heating of air outside the wood sample
(ii) Increasing the surface temperature of wood materials
(iii) Heating the interior layer of the wood samples
(iv) Radiating heat from the wood sample to the surrounding space.

The solar radiation experienced in the interior space of a building is propagated through roofing sheets, wood and nails used in roofing and the wall [10]. Work done by [11], shows that the exact nature of heat transmission by the process of conduction depends on the bonding between molecules, such that those which are relatively rigidly bound, will pass more energy than those which are weakly bound. Radiation transport is temperature dependent. At higher temperature, radiation becomes significantly high, while convection can be neglected for small pore size [9]. It is also important to note that the temperature of porous material at any depth depends on the net amount of heat absorbed by the material (a factor of thermal conductivity), the heat energy required to bring about a given change in temperature of the material (thermal capacity) and the energy required for changes, such as evaporation which occur constantly at the surface. Hence, temperature variations with thickness of solid materials is a factor which depends on the thermal conductivity, specific heat capacity, density, thermal absoptivity and diffusivity of the material which determine whether or not the material can be used as a heat conductor or insulator. The heat flow in any solid material is governed by the following one -dimensional unsteady state heat conduction equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{K}\frac{\partial T}{\partial t} \quad (4)$$

For a semi-infinity homogeneous solid with constant thermal properties, equation (4) can be solved when the boundary condition at the material surface is known. The energy balance equation at the material surface is used as a boundary equation, which is expressed according to [12] as:

$$-K({\partial T}/{\partial x})_{x=0} = h(T_A - T_{x=0}) \quad (5)$$

where $T_A = T_{atm} + \alpha I - \varepsilon \Delta R)$ (6)

is known as the solar temperature; k = thermal conductivity of the material; T = temperature of the material; h = heat transfer coefficient at the surface of the material; T_{a+m} = atmospheric temperature; α = solar radiation absorptivity at the surface; I = intensivity of solar radiation; ε = long wave emissivity of the surface; and ΔR = difference between the incident long wave radiation and the radiation emitted from the surface. The general solution of the one dimensional heat conduction equation (assuming T is finite when x$\rightarrow \infty$) may be written as

$$T(x,t) = A_0 + \sum_{m=1}^{\infty} A_m \ \exp[\mathrm{i}(m\omega t + \delta_m x)] \quad (7)$$

where $\delta m = m^{1/2}\alpha(1-i)$; $\alpha = (\omega\rho c/2k)^{1/2}$, c = specific heat capacity of the material, ρ = density of the material and $\omega = {2\pi}/{period}$. Equation (7) gives the dependence of material temperature with thickness on the periodic variation of temperature of the surface. T_A can be expressed as Fourier series, thus:

$$T_A = a_0 + \sum_{m=1}^{\infty}[\ a_{m1}\cos(mwt) + a_{m2}\sin(m\omega t\ )\ ] \quad (8)$$

$$= a_0 + \sum_{m=1}^{\infty} a_m \exp[\ i(m\omega t - \delta m)\ ]$$

substituting for (T(x, t) in equation (7) and for T_A in (8) and considering the real part, we obtain (9) according to [13, 14]

$$T(x,t) = a + \sum_{m=1}^{\infty} B_m \exp(-m^{1/2}\alpha x)\cos(m\omega t - m^{1/2}\alpha x - \delta m - \beta m) \quad (9)$$

where $B_m = \delta m(1 + m^{1/2}\mu)^2 + m\mu^2)^{-1/2}$

$$\mu = k\alpha / h = (\ kw\rho c/2)^{1/2} / h$$
$$\beta_m = \tan^{-1}[\ m^{1/2}\mu / (1 + m^{1/2}\mu)\ ]$$

and a_0 represents the average daily material temperature. The daily temperature variation at different depths of the material is given by equation (9). With $\beta_m = 0$, $w = 2\pi/24hr$, $\beta_m = a_m$; the equation above is modified into the following convenient form in (10) according to [11]

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos[\omega(t - t_0) - \alpha x/\omega)] \quad (10)$$

where A_s = daily temperature amplitude at the surface of the wood sample, that is at x = 0;
t = time of the day in hours
t_0 = time of minimum temperature at the surface in hours
x = coordinate through the thickness of the wood sample,
α = thermal absorptivity
ω = angular velocity (365 days cycle)

T_m is calculated from the hourly surface temperature average T_{hss} (^oC) as

$$T_m = \sum_{m=1}^{24} T_{hs} / 24 \quad (11)$$

Thus, on 24 hours period, equation (10), takes the form in (12)

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos[\omega(2\pi/24)\ \{t - t_o\} - 12\alpha\, x/\pi\ \}\ ] \quad (12)$$

The measurement of the thermal conductivity k, density ρ and specific heat capacity c, of any material enables the determination of the value of the thermal diffusivity λ, for the material using the equation given by [15,16] in (13)

$$\lambda = k/pc \quad (13)$$

the thermal diffusivity , λ value is used in calculating thermal absorptivity, in(14), according to [9]

$$\alpha = [\omega/2\pi]^{1/2} \quad (14)$$

MATERIAL AND METHODS

In this study six wood samples of materials shown in table 1 collected at the Ewet Timber Market in Uyo Local Government Area of Akwa Ibom State, Southern Nigeria were used in this study. These samples were collected fresh and seasoned to dry completely of its moisture to a constant mass. They were labelled and shaped to the required sample specimens of 0.0605 ±

0.0005m and 1.47 ± 0.0005m as the diameter of the Lee's disc apparatus and thickness of the sample respectively.

Thermal conductivities were determined for each of the wood samples A,B,C,D,E and F using the steady state method. The Lee's disc apparatus was used [6]. The dry wood samples were used to avoid the problem of redistribution of water under the influence of temperature [17].

Table 1: presentation of wood sample and sample code

S/N	Wood sample	Code of wood sample
1	Archi	A
2	Obeche	B
3	Owen	C
4	Gmelina	D
5	Iroko	E
6	Mahogany	F

Table2: Summary of the statistics of the error-treated thermal properties of the select wood samples

Sample	Density(ρ) kgm^{-3} x 10^3	Specific heat capacity(c)$Jkg^{-1}K^{-1}$ x 10^3	Thermal conductivity(k) $Wm^{-1}k^{-1}$	Thermal resistivity (r) $W^{-1}mk$	Thermal diffusivity(λ) m^2s^{-1}x 10^{-7}	Thermal absorptivity (α) m^{-1}
A	0.781 ± 0.003	1.070 ± 0.002	0.101 ± 0.001	9.901 ± 0.002	1.21 ± 0.02	17.339 ± 0.178
B	1.821 ± 0.010	1.110 ± 0.004	0.112 ± 0.002	8.929 ± 0.003	55.41 ± 0.03	2.562 ± 0.225
C	0.684 ± 0.007	1.050 ± 0.004	0.061 ± 0.003	16.393 ± 0.004	84.93 ± 0.02	2.070 ± 0.091
D	0.392 ± 0.002	1.030 ± 0.001	0.092 ± 0.002	10.870 ± 0.001	2.28 ± 0.01	12.631 ± 0.03
E	1.081 ± 0.001	1.020 ± 0.003	0.101 ± 0.001	9.901 ± 0.004	91.60 ± 0.004	1.993 ± 0.111
F	1.110 ± 0.025	1.870 ± 0.027	0.103 ± 0.004	9.709 ± 0.003	50.00 ± 0.03	2.697 ± 0.181

The heat conduction across the sample, at the steady state temperature, equals the rate at which it is emitted from the exposed surface [9]. The specific heat capacity was determined for each sample by method of cooling correction described by [18], which takes care of any heat loss due to radiation. A copper-constantan thermocouple was used for temperature measurements.

Again, the bulk density was measured for each of the wood samples using the weighing displacement methods [9]. Thermal difusivity, λ, and absorptivity, α for each wood sample are calculated using equation (13) and (4) respectively. From the thermal conductivity, the thermal resistivity was also evaluated for each wood sample as shown in table 2.

Table 2 shows the experimental results of the error-treated mean thermal conductivity k, specific heat capacity c, density ρ, thermal diffusivity λ, and thermal resistivity for each of the wood samples frequently used in building design. From table 2, it can be observed that the thermal conductivity of the different wood samples lie between 0.061 to 0.112$wm^{-1}k^{-1}$. Clearly, it is suggestive of the fact that the rate of heat flow by conduction through the samples is very low. This is within the limit of conductivities of construction and heat insulating materials by [19] and [20] which according them lie between 0.023 and 2.9wm^{-1}k^{-1}. The range of bulk density for completely dry wood samples of materials is observed to be 392 to 1821kgm^{-3}. Specific heat capacity of the select wood samples in the table lies between 1020 and 1870Jkg^{-1}k^{-1}. Thermal absorptivity of the samples also lies between 1.993 and 17.339m^{-1}. Moreover, thermal diffusivity of the select wood samples lies between 1.21 x 10^{-7} and 91.60 x 10^{-7}m^{2}s^{-1} while the thermal resistivity lies between 8.929 to 16.393w^{-1}mk.

Figures 1 to 5 crystally show the graphic details of the variations of the various thermal properties of the select wood samples. In terms of specific heat capacity, fig. 1 shows high value for sample F(mahogany) while specimen E(Iroko) has the least. Again, fig. 2 shows high value of conductivity for sample B(Obeche) while sample C(Owen) has the least.

Thermal resistivity, a reciprocal of thermal conductivity shows the reverse picture of what is obtainable in terms of the high value and low values of thermal conductivity in fig. 3. For thermal diffusivity, sample E(Iroko) has a maximum peak while sample A(Archi) has the minimum peak according to fig. 4. In the same vein, thermal absorptivity is highest in sample A while sample C has the least.

Substituting the respective values of thermal absorptivity of different wood samples into equation (10), we have the following equations for predicting the sample temperature at any given thickness x, and time of the day t, for each wood sample, while the equation formed by substituting the mean absorptivity value of a particular wood with different samples of the same wood gives the general equation for the prediction the thermal response of the wood samples.
For sample A

$$T(x,t) = T_m - A_s \exp(-17.52x)\cos[0.262(t-t_0) - 17.52] \quad (14)$$

For sample B

$$T(x,t) = T_m - A_s \exp(-2.79x)\cos[0.262(t-t_0) - 2.79] \quad (15)$$

For sample C

$$T(x,t) = T_m - A_s \exp(-2.61x)\cos[0.262(t-t_0) - 2.61] \quad (16)$$

For sample D

$$T(x,t) = T_m - A_s \exp(-12.66x)\cos[0.262(t-t_0) - 12.67] \quad (17)$$

For sample E

$$T(x,t) = T_m - A_s \exp(-2.10x)\cos[0.262(t-t_0) - 2.11] \quad (18)$$

For sample F

$$T(x,t) = T_m - A_s \exp(-2.88x)\cos[0.262(t-t_0) - 2.88] \quad (19)$$

Equations (14) – (19) show the specific mathematical models for estimation of temperature variations with thickness, x for samples A, B, C, D, E, and F. The equations are unique and they act as mathematical caveat for predicting the best wood sample suitable for a passively cooled building design. Theoretically, substances with higher thermal diffusivities would record the least radiation absorptivities at any particular time t of the period. Consequently, it can be deduced that sample E(Iroko) with highest thermal diffusivity but lowest thermal absorptivity will record the lowest temperature and this is followed by sample C(Owen), Obeche and mahogamy in that order. However, Archi will record the highest temperature being the sample with the highest value of absoptivity and this is directly followed by Gmelina wood sample.

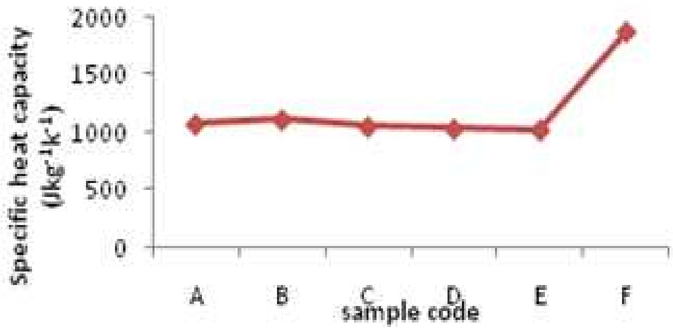

Fig. 1: A graph of Specific heat capacity against sample codes

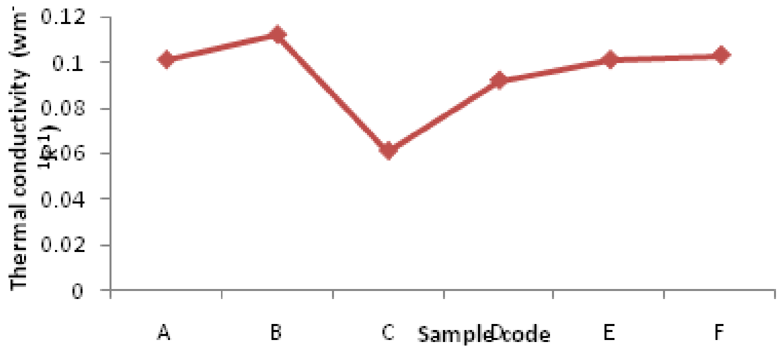

Fig. 2: A graph of thermal conductivity against sample codes

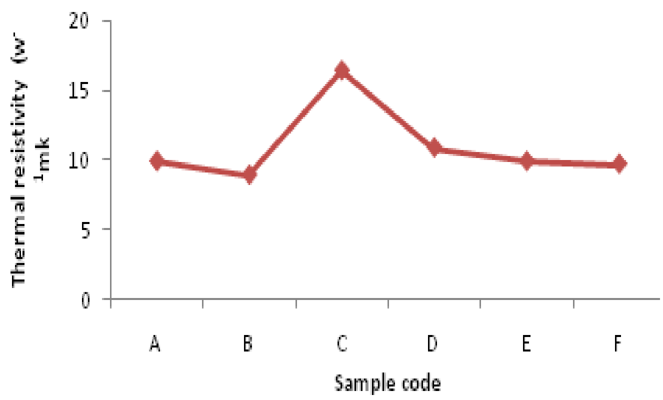

Fig. 3: A graph of thermal resisitivity against sample codes

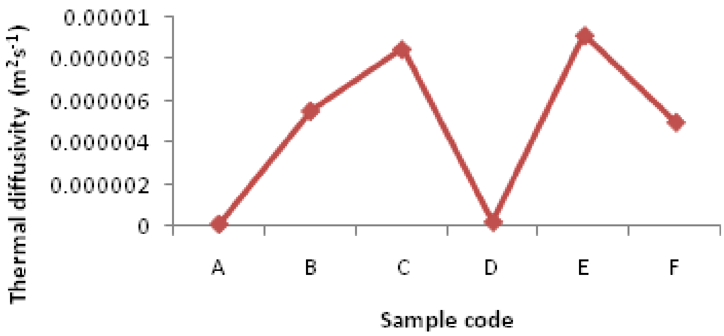

Fig. 4: A graph of thermal diffusitivity against sample codes

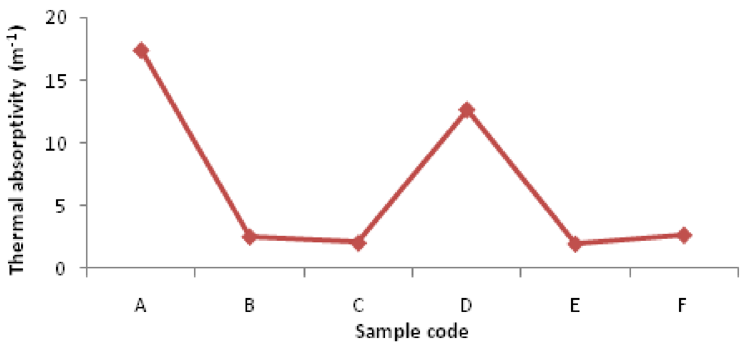

Fig. 5: A graph of thermal absorptivity against sample codes

CONCLUSION

The highest thermal diffusivity and lowest absorptivity of sample E (Iroko) seen in both table 2 and the relevant graph, give the bright -line distinction of the thermal suitability of the sample for design of passively cooled building when compared with other wood samples analyzed thermally in this work. Although sample E is the best sample for the design of passively cooled building, the low thermal conductivity observed in some of the samples investigated here signifies a high thermal resistivity, suggesting good thermal insulation of the select wood samples. Although sample E is experimentally deciphered to be the best thermal insulator for design of passively cooled building, sample B,C and F are also recommended for the design of thermally insulated building in the absence of sample E, mostly for use in ceiling panels, construction of doors and windows and other padded building design where thermal insulation is held at high esteem.

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