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RESEARCH ARTICLE

THERMOPHYSICAL CHARACTERIZATION OF TROPICAL WOODS *PTEROCARPUS ERINACEUS (KOSSO)* AND *AFZELIA* FOR THEIR USE IN THERMAL INSULATION IN HABITAT

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ABSTRACT

Simultaneous transient measurements of thermal conductivity, thermal effusivity and thermal diffusivityin perpendicular direction to fibers of *pterocarpus erinaceus(kosso)* and *afzelia* woods were performed at room temperature (20 °C) with thermophysical characterization of building materials called hot strip based on different thicknesses of these two wood species, using samples of its last dried in vat at 105 °C. The fundamental advantages of this technique lie in the short duration (0 to 180 s) of manipulations ; the very low cost of the probe an estimation method based on a relatively simple modeling of the temperature in center of the probe and the ability to obtain two parameters from a single thermogram record. The main objective of this study is to consider the possibility of using these two species in the development of new insulating materials. The results obtained showed that thermal conductivity and thermal diffusivity of the two wood species increase with thickness. Thermal effusivity decreases from 493.99 $J.m^{-2}.K^{-1}.s^{-0,5}$ to 454.3 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 3 mm and 6 mm thick and then increases from 454.3 $J.m^{-2}.K^{-1}.s^{-0,5}$ to 478.40 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 6 mm and 15 mm thick for afzelia. The kosso thermal effusivity decreases from 424.58 $J.m^{-2}.K^{-1}.s^{-0,5}$ to 362.83 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 3 mm and 15 mm thick. Thermal conductivity of kosso is lower than that of afzelia between 3.6 mm and 15 mm. It was further noted that both species have thermophysical properties in accordance with the literature but that kosso wood is a good candidate for new insulating materials production.

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INTRODUCTION

The context ofclimate change and the need to move towards a more energy-efficient society give considerable weight to the development of wood industry, by ecological and renewable nature of this natural resource. Currently, civil engineering industry around the world is showing a growing interest in wood-based structures. The literature indicates that controlling the thermal and mechanical properties of wood-based materials would have many advantages, including low implementation costs and a positive impact on the environment (Nzieegui *and al*, 2017), which would also be beneficial applications such as fuel conversion, building construction and other areas of industry (Joly *and al*, 1980).

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The considerable development of housing market in Benin and, above all, the need to save energy, while ensuring thermal comfort in habitat, requires a better knowledge of the thermal characteristics of the walls to be carried out (Houngan, 2008). The use of climate-appropriate materials, such as wood, allows the building envelope, in addition to its insulating role, to regulate temperatures and indoor humidity itself (via wall inertia and the phenomenon of breathable walls). In addition, this helps to minimize the energy consumption ofbuilding (Raji, 2006; Nzieegui *and al*, 2017). Hygroscopic and ligno-cellulosic material, wood functions as a natural regulator of moisture in our homes. Its basic thermal characteristics such as thermal conductivity, thermal diffusivity and specific heat depend or do not depend on species, anatomical direction (Pozgaj *and al,* 1997), density (Niemz *and al*, 2010), humidity (Harada *and al*, 1998), temperature (Hrcka, 2010), mechanical load (Olek *and al*, 2003), etc. Despite this knowledge, some non-traditional factors influence the values of the thermal properties of wood. The purpose of this article is to describe the influence of the type of gasoline and the thickness of sample on the thermal properties of the wood species under consideration and to consider the possibility of their use in development of new materials insulating.

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MATERIALS TESTED

The materials characterized are tropical wood test tubes of parallelepiped geometry and length 5 cm, of width 3 cm and of varying thicknesses from (0.3 cm ; 0.6 cm and 1.5 cm). The thickness measurements were made with a micrometer at 0.001 %. These dimensions are chosen based on the basic assumptions of the hot strip method. To do this, we made three series of test tubes, the compositions of which are on the table1. Figure 1 show some samples of materials studied.

Table 1. Composition of the control samples

Species	Kosso			Afzelia		
Thickness (cm)	0.3	0.6	1.5	0.3	0.6	1.5
Mass (g)	4.50	7.30	16.10	5	8.80	18.50
Density(kg. m-3)	1000	811.11	715.55	1111.10	977.78	822.22
Moisture content (%)	12.5	15.87	14.18	19.05	15.79	14.20

Figure 1. Kosso (Ko) and afzélia specimens, (A)

HOT STRIP METHOD

Principle: The hot strip method consists of using a simple rectangular shaped electrical resistance on which is placed a thermocouple consisting of small diameter wires. Temperature measurement is carried out at center of the resistance, which avoids having to take into account thermal losses by electrical wires at one end of the resistance. The resistance is inserted between two samples of plane surfaces of material to be characterized. The dimensions of samples are such that the disturbance caused by the flow rung imposed on the probe does not reach any of their faces during the duration of the measurement (semi-infinite medium hypothesis). The length-to-width ratio of the resistance is chosen so that the heat transfer at center of the resistance can be considered dimensional for less than 180 s. The idea is to use the thermogram corresponding to the start of heating during the time when the heat transfer on center of probe remains unidimensional to estimate thermal effusivity by a warm plane model (Figure 2). A complete modelling of dimensional transfers in samples, combined with a parameter estimation method, allows the thermogram to be used between 100 s and 180 s to estimate thermal conductivity.

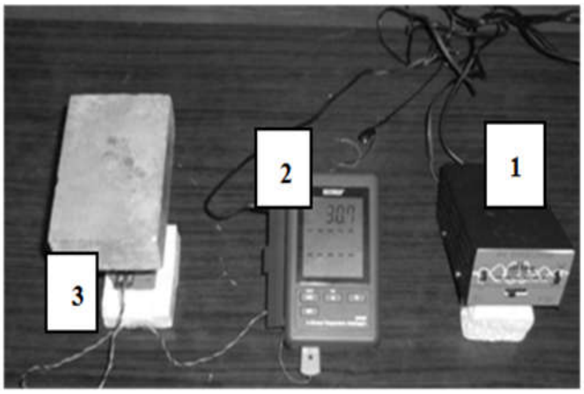

Figure 2. Hot strip experimental device used

(1-stabilized power supply, 2-acquisition central, 3-resistance inserted between 2 samples of material)

Hot strip modeling

Hot strip modeling: Figure 3 shows the diagram of a symmetrical hot strip model. The basic assumptions are (Jannot, 2008):

- **Medium:** Semi-infinite in both directions of heat propagation (sufficient thickness) ;
- **Transfer:** No heat transfer from one sample to another;
- **Initial Condition:** The initial temperature T_0 of samples is uniform ;
- **Transfer:** No heat transfer from one sample to another;

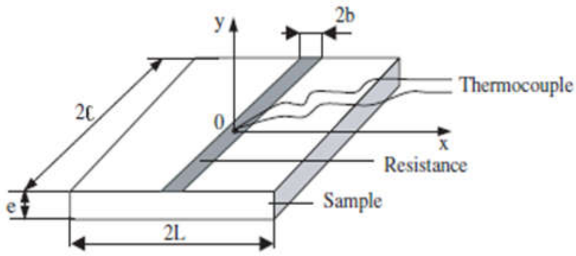

Figure 3. Hot strip symmetrical 2D model

Raising the temperature T (x, y, t) at a point of coordinates (x, y) of the strip satisfies equation (1) during the time when the transfer at this point remains bidirectional (infinite hot strip):

$$\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2} = \frac{1}{a}\frac{\partial T(x,y,t)}{\partial t} \quad (1)$$

With the following boundary conditions:

at $y = 0 : -\lambda S \frac{\partial T_s(x,y,t)}{\partial y} = -\varphi_0$, if $x < b$ (2)

and $-\lambda S \frac{\partial T_s(x,y,t)}{\partial y} = 0$, if $x > b$ (3)

at $x = 0 : -\lambda S \frac{\partial T_s(x,y,t)}{\partial x} = 0$, by symmetry (4)

at $x = L : T_s(L, y, t) = 0$, semi-infinite medium hypothesis in (ox) dirction (5)

at $y = e : T_s(x, e, t) = 0$, semi-infinite medium hypothesis (oy) direction (6)

Problem resolution: By successively applying a Laplace transform and then a finite Fourier transform in cosine between x = 0 and x = L and by inverse Fourier transformation we obtain:

$$\theta_s(0,0,p) = \frac{1}{L}\theta_{cs}(0,0,p) + \frac{2}{L}\sum_{n=1}^{\infty}\theta_{cs}(n,0,p) \quad (7)$$

Finally, by inverse transform of Laplace by the method of Stefhest, the temperature $T_s(0,0,t)$ can be calculated by:

$$T_s(0,0,t) = \frac{\ln 2}{t}\sum_{j=1}^{n_L} V_j\,\theta_s\left(0,0,j\frac{\ln(2)}{t}\right) \quad (8)$$

Parameters estimation: Figure 4 shows the three thermograms: hot strip, hot plane and hot wire. By comparison, we notice that the hot strip behaves like hot plane at short times (between 0 and 50 s) and as hot wire at long times (between 80 s and 180 s). The expected benefits of this method are a very low cost of the probe and an estimation method based on a relatively simple temperature modelling at center of the probe:

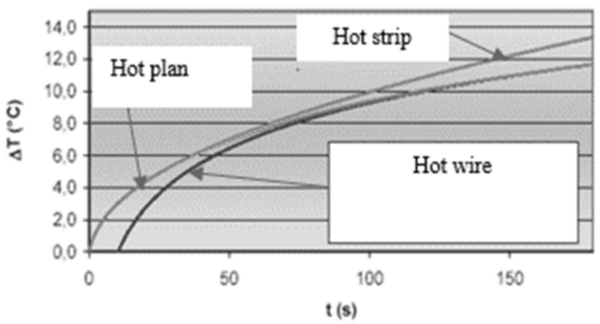

Figure 4. Comparison of Hot strip, Hot Plane and Hot Wire Models (Jannot, 2008)

- unidirectional during t_1 for thermal effusivity estimation (hot plane method) ;
- bidirectional between t_1 and t_2 for thermal conductivity estimation (hot wire method).

This study was carried out using a flat electric resistance MINKO HK913P of 43.5Ω and surface $(5 \times 1.5)\,cm^2$. A K type thermocouple consisting of 0.02 mm diameter wires was attached to one face of the resistance. A flow rung was applied to the resistance placed between two wood samples and the temperature of the thermocouple was recorded for 180 s with a time step of 1 s and a resolution of 0.1 °C. Three measurements were carried out on each sample. Thermal effusivity is estimated between 0 and 50 s by minimizing the quadratic gap between the experimental curve and the curve calculated by a hot plane 1D model.

Thermal conductivity is estimated between 80 s and 180 s by minimizing the quadratic gap between the experimental curve and the curve calculated by a 2D model.

The hot plane thermogram has for expression:

$$T_s(0,0,t) - T_s(0,0,0) = \frac{2\varphi_0}{ES\sqrt{\pi}}\sqrt{t} + \varphi_0\left[R_c - \frac{(mc)_s}{(ES)^2}\right] \quad (9)$$

The thermal effusivity is obtained by:

$$E = \frac{2\varphi_0}{\alpha S\sqrt{\pi}} \quad (10)$$

with α direction coefficient of regression line in function of $\sqrt{t}$data by the relation (9).

The hot wire thermogram has for expression :

$$T_s(0,0,t) - T_s(0,0,0) = \frac{\varphi_0}{4\pi\lambda L}\ln(t) + \varphi_0\left[R_c + \frac{\gamma}{4\pi\lambda L} - \frac{\ln\left(\frac{r_0}{\sqrt{a}}\right)}{2\pi\lambda L}\right] \quad (11)$$

The thermal conductivity is obtained by :

$$\lambda = \frac{\varphi_0}{4\pi\beta L} \quad (12)$$

with β the directing coefficient of the regression line as a function of ln (t) given by relation (11).

Thermal diffusivity is achieved by the relationship :

$$a = \left(\frac{\lambda}{E}\right)^2 \quad (13)$$

RESULTS

The thermal conductivity, thermal effusivity and thermal diffusivity of pterocarpus erinaceus and afzelia were measured in a transient regime using hot strip technique at room temperature 20 °C and normal pressure.

The values presented on the Figures (5, 6, 7) are the averages of three independent measurements taken in perpendicular direction to the fibers, on the same samples under the same conditions.

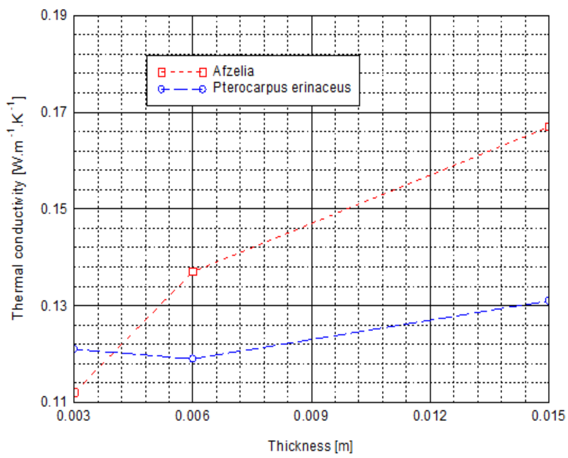

Figure 5. Variation of thermal conductivity of kosso and afzelia according to the thickness in anhydrous state

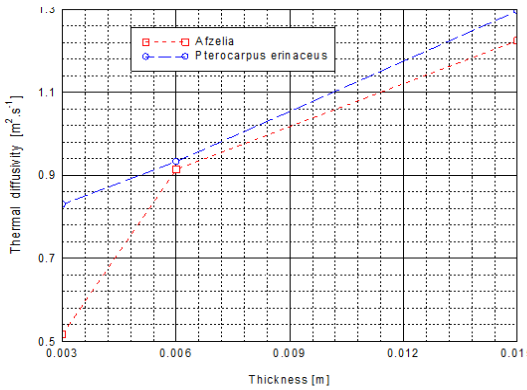

Figure 6. Variation of thermal diffusivity of kosso and afzélia according to the thickness in anhydrous state

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Species	Kosso			Afzelia		
Thickness (cm)	0.3	0.6	1.5	0.3	0.6	1.5
Mass (g)	4.50	7.30	16.10	5	8.80	18.50
Density(kg.m-3)	1000	811.11	715.55	1111.10	977.78	822.22
Moisture content (%)	12.5	15.87	14.18	19.05	15.79	14.20

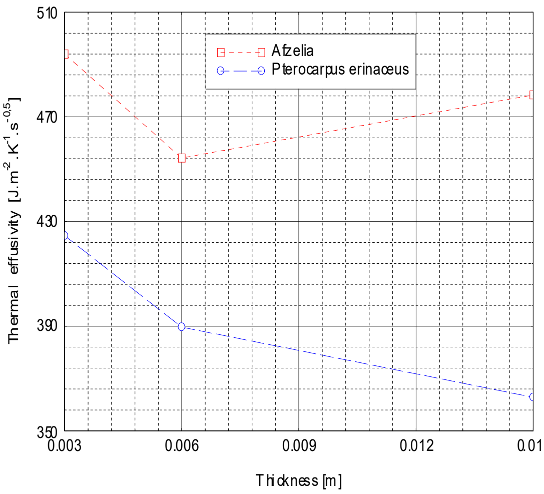

Figure 7. Variation of thermal effusivity of kosso and afzélia according to thickness in anhydrous state

DISCUSSION

The value of thermal conductivity; thermal diffusivity and thermal effusivity respectively vary between 0.112 $W.m^{-1}.K^{-1}$ and 0.167 $W.m^{-1}.K^{-1}$(Figure 5); $0.517.10^{-7}\ m^2.s^{-1}$and $1.296.10^{-7}\ m^2.s^{-1}$ (Figure 6) and 362.83 $J.m^{-2}.K^{-1}.s^{-0,5}$ and 493.99 $J.m^{-2}.K^{-1}.s^{-0,5}$ (Figure 7). These values are apparently low. The sometimes observed dispersion on distribution of experimental point can be explained by the fact that surface temperature measured by the samples during the experimental campaign was not always the same for each measurement. The method yielded different results for the three thicknesses. It is noted that the uncertainties obtained are, relatively small. Indeed, wood is a porous material with a cellular substance whose cavities (empty) fill air. Literally, porosity ranges from 0.5 to 0.8. The vacuums due to porosity serve as diffusion centers for phonons, and they absorb a fraction of the volume of thermal conductivity of the material leading to lower thermal conductivity. The presence of other thermal conduction obstacles in addition to voids such as cell rays and boundaries could also affect the conduction process.

However, conduction through the voids appears to be the dominant factor influencing thermal conduction in these types of wood samples. Figure 8 shows the variation in the thermal effusivity of kosso and afzelia wood depending on the thickness in the anhydra state. It shows that afzelia wood is more effusive than kosso wood; also that the thermal effusivity of kosso wood decreases 424.58 $J.m^{-2}.K^{-1}.s^{-0,5}$ to 362.83 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 0.3 cm and 1.5 cm thick while that of afzelia wood decreases 493.99 $J.m^{-2}.K^{-1}.s^{-0,5}$ at 454.3 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 0.3 cm and 0.6 cm thick and then increases 454.3 $J.m^{-2}.K^{-1}.s^{-0,5}$ at 478.40 $J.m^{-2}.K^{-1}.s^{-0,5}$ between 0.6 cm and 1.5 cm thick for afzelia wood. More significant differences in conductivity, effusvivity and thermal diffusion values are noted for the samples for different wood varieties.

This may be due to differences in the material's microstructure (porosity, tortuosity, etc.) or a different hydration state of the samples. In addition, the thermal diffusion of the samples increases with thickness.This could be related to the measurement status of our samples, as they were completely dry (open and bound water were released) since other authors such as Houngan (2008) and Djossou (2014) showed that the thermal diffusion of wood does not have a sense of variation fixed with the open water content. By way of comparison, the two characterized wood species have lower thermal effusivity values of 500 $J.m^{-2}.K^{-1}.s^{-0,5}$ which is in keeping with the literature which makes it clear that the thermal effusivity of the wood is on average 400 $J.m^{-2}.K^{-1}.s^{-0,5}$ (Harijaona, 2011). In addition, for example, Philippe Jodin published in the manual "Wood Engineering Material" the values of thermal conductivity of 0.1 to 0.2 $W.m^{-1}.K^{-1}$, wood measured in the direction perpendicular to the fibers, at 0 % water content (Arbolor, 1994). Sahin also published the value of the conductivity of Fraximus excelsior wood in the radial direction at 8 % water content at 20 °C, from five measurements and found an average of 0.140 $W.m^{-1}.K^{-1}$with a standard deviation of 0.005, measured with the hot wire method on 2 x 5 x 10 cm samples (Sahin, 2009). Thermal conductivity values of 0.12 $W.m^{-1}.K^{-1}$to 0.14 $W.m^{-1}.K^{-1}$, measured at 0 % water content, of the genus fraximus are also published in the Wood Manual in Chapter 3, which was written by the authors Simpson and Ten Wolde (Simpson, 1999). Its values are close to the values provided by our method of warm strip in transitional regime and are in line with the literature. From the analysis of Figures 6 and 7, we note that conductivity and thermal diffusion grow globally according to thickness. This result is consistent with those of Hrcka (2010), and Harijaona(2011) and confirms that the wood exhibits good thermal behaviour at low thickness. Many authors such as Quenard andal (1986), cited by Ngohe (1992) have observed the maximums for the thermal diffusivity of porous materials between 0 and 10 % water content. Our working condition (0 % water content) did not allow us to actually observe these maximum thermal diffusivity.

CONCLUSION

In this study, the thermal properties of pterocarpus erinaceus and afzelia wood species were measured in perpendicular to the fibers on 3 samples of direction each type of gasoline at different sizes, whose water content varies between 0 and 60 %. Efficiency and thermal conductivity in the direction perpendicular to the fibers were measured by the hot strip method, the advantages of which are: a very low cost of the probe and a very short operating time. In conclusion, we can remember the strong dependence of thermal properties of pterocarpus erinaceus and afzelia woods in terms of their thickness. It will therefore be difficult to consider only one average value of conductivity and thermal effusivity in the simulation of walls in these woods subject to variations in thicknesses. The results of this work also show that the type of wood species and their microstructures influence the thermophysical properties of wood. The two tropical wood species are a good, low-thickness thermal insulator. Kosso wood is a good candidate for new insulating materials because it has a relatively low thermal conductivity compared to afzelia wood. In perspective, a study of the influence of moisture, the effect of the porosity of the material and the effect of fiber orientation on the thermophysical properties of these species is necessary. Similarly, a study of the isotherms of desorptions is essential in order to know the hygro-thermal equilibrium states of its wood species under well-defined climatic conditions.

NOMENCLATURE

a: Thermal diffusivity, $m^2.s^{-1}$
E : Thermal effusivity, $J.K^{-1}.m^{-2}.s^{-0,5}$
l: Length, m
m: Mass, kg
R: Electrical Resistance, Ω
S: Surface, m²
T: Temperature, K
t: Time, s
w: Water content, %
x, y, z: Space variables, m

Greek letters

ρ : Density, $kg.m^{-3}$
λ: Thermal conductivity, $W.m^{-1}.K^{-1}$
θ_s: Laplace transform of probe temperature
φ: Heat flux, W
Indices / Exhibitors
s: Related to prob

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