International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:15, No:7, 2021

Study of the Thermal Performance of Bio-Sourced Materials Used as Thermal Insulation in Buildings under Humid Tropical Climate

Guarry Montrose, Ted Soubdhan

Abstract**—**In the fight against climate change, the energy consuming building sector must also be taken into account to solve this problem. In this case thermal insulation of buildings using bio-based materials is an interesting solution. Therefore, the thermal performance of some materials of this type has been studied. The advantages of these natural materials of plant origin are multiple, biodegradable, low economic cost, renewable and readily available. The use of biobased materials is widespread in the building sector in order to replace conventional insulation materials with natural materials. Vegetable fibers are very important because they have good thermal behaviour and good insulating properties. The aim of using bio-sourced materials is in line with the logic of energy control and environmental protection, the approach is to make the inhabitants of the houses comfortable and reduce their energy consumption (energy efficiency). In this research we will present the results of studies carried out on the thermal conductivity of banana leaves, latan leaves, vetivers fibers, palm kernel fibers, sargassum, coconut leaves, sawdust and bulk sugarcane leaves. The study on thermal conductivity was carried out in two ways, on the one hand using the flash method, and on the other hand a so-called hot box experiment was carried out. We will discuss and highlight a number of influential factors such as moisture and air pockets present in the samples on the thermophysical properties of these materials, in particular thermal conductivity. Finally, the result of a thermal performance test of banana leaves on a roof in Haiti will also be presented in this work.

Keywords—Buildings, insulating properties, natural materials of plant origin, thermal performance.

I. INTRODUCTION

IN the current context, humans have noticed a rise in global temperature linked to anthropogenic activities caused in particular by industrialized countries. These countries are sacrificing the planet with their CO_2 emissions and the consequences are already being felt by the occupants of the houses several decades ago. Today the problem is still relevant, to help solve it 195 countries ratified on December 12, 2015 the Paris Agreement on Climate Change which is the first universal climate agreement called the United Nations Framework Convention on Climate Change (COP21) that recommends countries to contribute to a 2 °C reduction in global temperature. An increased pressure from environmental activist, preservation of natural resources, and attended stringency of laws passed by developing countries leads to the invention and development of natural materials with focus on renewable raw materials [1]. This is because natural fibres are biodegradable, cheap, lightweight and abundant when compared to synthetic fibres [2]. Sustainable development is a key element for the growth of developing countries, in terms of construction the circular economy and energy efficiency are in line with the policy of environmental protection. The adaptation of buildings to the climatic context in hot climates is a necessity if we want to improve living conditions in housing and reduce the risks to the health and productivity of the occupants due to thermal discomfort in buildings and free evolution in particular [3]. Awareness of the depletion of energy resources, the increase in the price of fossil fuels and climate change have led to an interest in controlling energy consumption in general and energy-related consumption in buildings in particular [3]. The building sector consumes about 40% of the world's energy and accounts for about 1/3 of the world's greenhouse gas emissions [3]-[6]. Therefore, there is a great necessity to develop innovative solutions for building elements to minimize heat transfer through the fabric to its surrounding [7]. The building sector, which emits 20% of carbon dioxide (CO_2) for its energy consumption, must also be taken into account to overcome this problem. In this case, the use of bio-based materials for the thermal insulation of buildings is a necessary condition to reduce energy consumption as well as the emission of greenhouse gases, in particular CO_2. In tropical or hot countries, it is a question of protecting the building from solar thermal radiation, source of discomfort, the roof is the most exposed surface, 60% of the thermal load of a building comes from this surface [5], [8]. Therefore, the implementation of thermal insulation using bio-based materials as solar protection for the roof and walls should improve comfort in the absence of air conditioning or reduce energy consumption when the building is air-conditioned. The use of natural fibres is expanding in the building industry to replace conventional insulation materials with natural materials [9]. Bio-based insulation is a product made from plant fibres, animal products or recyclable paper or clothing [10]. Their development meets the objectives of maintaining biodiversity, reducing waste and protecting the environment, set by the Grenelle 1 and 2 laws [10]. Moreover, we have observed that insulating materials of plant origin present many disadvantages such as a strong variability of the

G. Montrose is a PhD student at the Department of Physics, Laboratory of Research in Geosciences and Energy (LARGE), University of the West Indies, Pointe à Pitre, France (corresponding author, phone +590690187901, e-mail: Guarry.Montrose@etu.univ-ag.fr).

thermo-physical properties for the same species depending on the thermal state of the sample. The effectiveness of thermal insulation is dependent on its thermal conductivity and its ability to maintain its thermal characteristics over on extended period of time [11]. The thermal conductivity of insulation material is greatly affected by their operating temperature and moisture content, yet limited information is available [11]. Proof of the thermal performance of an insulating material is either by determining its thermal conductivity or by evaluating the temperature difference between the two faces of the sample. The aim of using bio-based materials in this article is in line with the logic of energy control and environmental protection, the approach is to make the inhabitants of the houses comfortable and reduce their energy consumption (energy efficiency) as well as the emission of carbon dioxide.

In the body of this work, we will present a study conducted on the thermal conductivity of several samples of bulk plant materials using two methods. We will also present the heat fluxes measured on both sides of the samples. An in-depth analysis to show that they respect the conditions for a body to be insulating. Finally, the results of an experiment on the thermal performance of banana leaves placed on the roof of the Ecole Normale Supérieure (ENS) in Haiti.

II. Methodology

A. Review of the Literature

This work is devoted to the measurement of the thermo-physical properties of materials of plant origin, we have put a lot of effort into research. To achieve our goal, we took a look at the literature in order to consult the work already done, especially the methods used to determine thermal conductivity. In this order of idea several methods [12]-[18] have already been developed in the laboratory to calculate the thermo-physical parameters of these materials such as: Hot Plane, Guarded Hot Plate, Hot Box, Flux-Meter, Flash, Hot Wire, Flux-Meter Plate and Thermal Flow Meter Hot Plate, Hot Ribbon, Tri-Layer and Hot Disc. The methods used in our measurement campaigns are the guarded hot plate and flash.

1. Hot Plate Method

In stationary regime the Hot Plate Method (MPH) is very widely used by authors to evaluate the thermal conductivity of insulating materials in buildings. Among these works consulted in the literature are [19]-[24].

Saleh and Al-Ajlan measured the thermal properties of insulation materials including thermal conductivity and thermal diffusivity using the kept MPH. They also explained in their literature review that Abdelrahman et al. and Al-Hammad et al. proceeded in the same way in Saudi Arabia [14].

In the most influential work, the operating principle of MPH is based on the establishment of a temperature gradient over a known thickness of a sample in order to control the heat flow from one side to the other [14]. The sample is placed between a cold plate and a hot plate whose experimental setup is shown in Fig. 1, in the stationary state the static calculations assume the use of Fourrier's law (1). The MPH has been developed for the measurement of low thermal conductivity. This method requires a long handling time and the variation of humidity over time also leads to erroneous results. Errors can be related to the fact that the temperature gradient must be large and the duration of the experiment must be long, not to mention the contact resistance between the thermocouples and the sample [13], [14].

$$\lambda = \frac{e\phi_0}{S(T_{C(t)} - T_{e(t)})} \qquad (1)$$

$\frac{\phi_0}{S}$ –Flow density conducted by the sample in (Wm^{-2}); $T_{C(t)} - T_{e(t)}$ –Temperature difference between the two faces of the sample in Celsius; e - Thickness of the sample in meters.

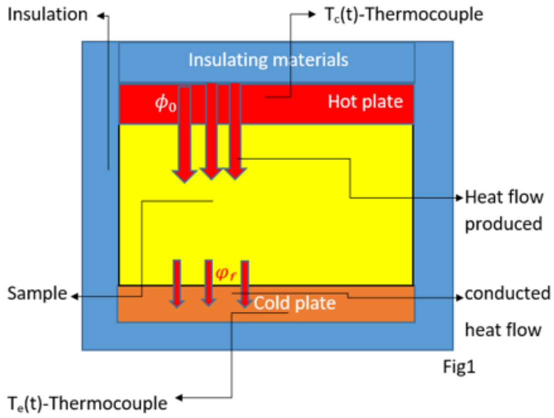

Fig. 1 Diagram of the MPH, $T_{e(t)}$-temperature of the cold plate, $T_{C(t)}$-temperature of the hot plate

2. Flash Method

In the literature, the Flash method (FM) is widely discussed, it has been proposed by Parker et al. and can be considered among the best known and most widely used methods to measure the thermal conductivity of insulating materials [13]. FM is a fast and simple measurement method, but it has the disadvantage that the measurements are performed at the surface layer. Among the works that have highlighted this method are [13], [12], [25], and [26].

Pierre Meukam measured the thermal conductivity and diffusivity of materials using the FM[13].

The FM [26] in its principle of operation consists in subjecting a system to a short thermal perturbation and observing the temperature response. The system studied can be a sample with a parallel face subjected to a thermal pulse on one of these faces, the temperature evolution being recorded on the opposite face. It can be added that this is a unidirectional method which consists in subjecting or making one face of the sample absorb a pulsed heat flow of short duration and to record the evolution of the temperature during this same time interval at one or more points on the opposite face of the sample [18], [13]. The schematic diagram of the experimental set-up is shown in Fig. 2.

Figs. 6-12 were plotted using the R software.

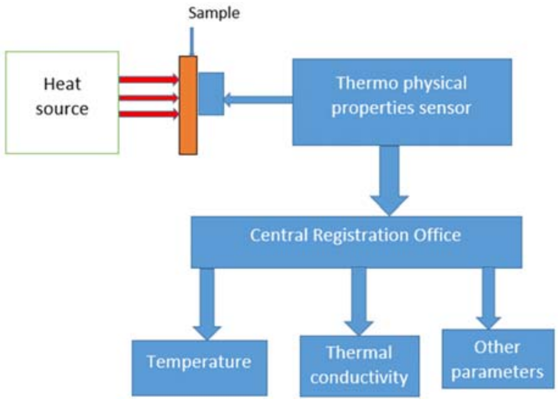

Fig. 2 Diagram of the FM

B. Experimental Device

We proceeded by the determination of the thermo physical parameters in particular the thermal conductivity on the one hand by means of a heating plate where the propagation of heat at the level of the sample is done practically without movement, it is the method hot plate kept, and it is called static. On the other hand, by means of a heat source where the sample undergoes a thermal disturbance, it supposes that the heat pulse is instantaneous and crosses the sample in a short time, it is the FM, and it is called dynamic.

1. Conductivity Measurement of Samples: MPH Kept

The test is carried out in a box with internal dimensions 33 x 33 x 33 cm, insulated with a 6 cm thick layer of polystyrene on each side to reduce heat loss from the inside to the outside. A layer of vegetable leaf (20 cm x 20 cm) 15 cm thick is placed in the box between two heat flow sensors which allowed us to record the heat flow emitted by two hot plates in contact with the flow sensor at the top of the sample and the one transmitted by the banana leaves to the heat flow sensor located under the sample. The device is powered by a generator with a maximum adjustable electrical voltage of 45 volts, the intensity of the current has been set at 1 Ampere, and the voltage is 10 Volts. The heat flow sensors each integrating a T-type thermometer records at each measurement the temperature on either side of the sample are shown in the following figure (Fig. 3). A thermal flow sensor of dimension 20 cm x 20 cm of sensitivity 307 $\mu V/(Wm^{-2})$ is put in contact with the two heating plates whose respective resistances are 19.3 Ohms and 19.7 Ohms, the other sensor of dimension 10 cm x 10 cm has a sensitivity of 56 $\mu V/(Wm^{-2})$.

2. Conductivity Measurement of Samples: FM

A heat pulse was sent on one side of the sample, then its behaviour on the other side is studied using the C-THERM TCI instrument which automatically records temperature, thermal conductivity, thermal effusivity and other parameters. The instrument takes one minute to perform each measurement. Through this method we tested samples with a thickness of 25 mm.

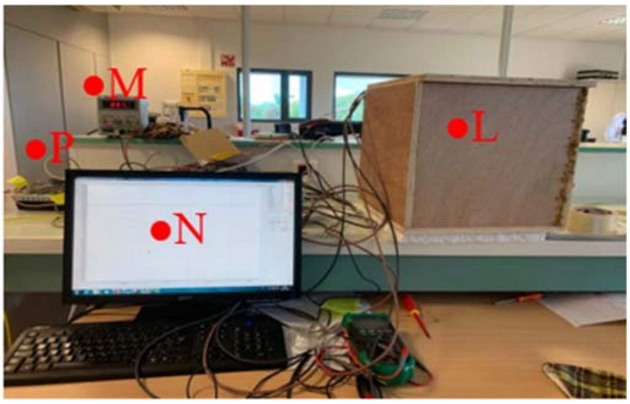

Fig. 3 Photograph of the hot box experimental device in the laboratory. M: electric generator of adjustable voltage which supplies the measuring station. P: Measuring station on which the sensors are connected (CR5000), clearly identified on Fig. 5. L: hot box in which the sample is placed between the sensors. N: Computer on which the measuring station is connected to record the data

3. Thermal Performance Test of Banana Leaves: Roof Experiment at the Master ENS Building

The work was carried out on a roof of more than 20 m^2 of surface divided into two parts, half of which was covered with a 20 cm layer of banana leaf (Fig. 4). The important difference in temperature between the uncovered (Tsenc) and straw-covered (Tsec) external surface shows that bio-source materials, in particular banana leaves, are good thermal insulators, depending on the day and time of day. The experimental procedure is as follows.

Fig. 4 Photograph of the roof in Haiti where the experiment was carried out, one part covered (D) with banana leaves and the other part not covered (E). The roof was subjected to the influence of solar radiation in order to test the thermal performance of banana leaves. In fact, the temperature of the bare concrete and that of the covered concrete has been measured. Tsenc: outside surface temperature of bare concrete (E), i.e., not covered with banana leaves. Tsec: outside surface temperature of the concrete covered (D) with banana leaves, i.e., under the banana leaves

Sensors were installed to measure solar radiation and surface temperatures. The radiation sensor is type SP-Lite with a sensitivity of 71.8 Microvolts/($W.m^{-2}$), the temperature sensors are type K thermocouples. The sensors have been connected to the CR5000 data logger; the data recording has been done using the Logger Net software with a time step of 15 minutes (Fig. 5). The temperature sensors were installed in order to measure the temperatures of the outside surface roof covered (Tsec) and not covered (Tsenc) of banana leaf as well as the temperatures of the inside surface roof covered (Tsic) and not covered (Tsinc).

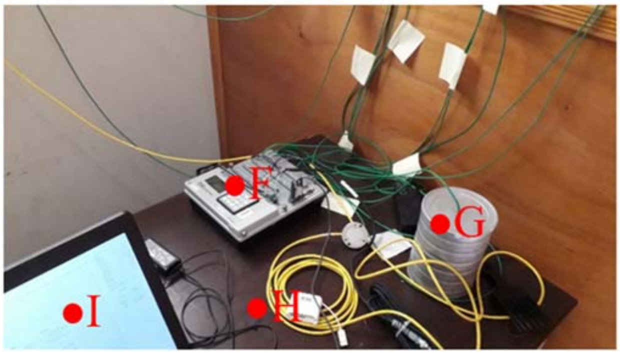

Fig. 5 Photograph of the experimental device in Haiti for roof measurements: F: Central measuring station (CR5000) where all sensors are connected; the green cables are thermocouples of type K allowing to measure the temperature. H: sensor to measure the sunshine (yellow cable). G: Cylinder in which a thermocouple is integrated to measure the dry air temperature. I: Computer connected to the central measuring station to record the data

III. Influence of Humidity and Air Pockets on Sample Conductivity.

According to Abdou et al. [11], the value of thermal conductivity can be strongly reduced by the presence of moisture in insulation materials. The thermal conductivity of insulation materials is strongly influenced by their operating temperature and moisture content, but there is limited information available on the performance of insulation materials under real climatic conditions. The impact of operating temperature and moisture content on the thermal conductivity of insulation varies with the type of insulation depending on the composition, properties and internal structure of the materials used, which determine the heat transfer modes and moisture storage capacity of the material. Therefore, we conducted a measurement campaign to study the influence of humidity on the thermal conductivity of the samples involved in this work. The presence of air pockets was also taken into account in our study. When we put the sample in contact with the C-therm TCI and gradually heat it, we noticed that the conductivity varies. This change comes from the fact that the material is humid and contains air, when it receives the heat flow its temperature increases, the air warms up and the humidity decreases. Once the air is expelled despite the increase in temperature under the influence of the heat flow, the thermal conductivity tends to stabilize around a certain constant value. The flow of heat imposed on the sample by the hair dryer exerts pressure on the sample surface, first of all it starts the evacuation of air molecules, water if present, and moisture in the material, which eventually disappears with the rise in temperature.

IV. Result and Discussion

Table I gives the results of the measurements carried out on the thermal conductivity of several biosourced samples. The measurement ranges obtained by the FM are validated by those of the hot guarded plate. The slight differences observed may be related to random phenomena. However, we remain critical of these results because for the same species there is a very large variability taking into account climatic conditions. The measurement of thermal conductivity depends on the thermal state of the sample at the time of the experiment. The results obtained are comparable to the thermal conductivities of classical insulation materials and are in agreement with the studies carried out on materials of plant origin existing in the literature [27]-[33], of course they are not of the same species as the samples we tested. In our guarded hot plate experiment, the banana leaves were heated for 8 hours, the steady state is reached at 151 °c, we found after calculation 0.115695 $Wm^{-1}K^{-1}$ for the thermal conductivity of the banana leaves. The latter result of the thermal conductivity (0.115695 $Wm^{-1}K^{-1}$) corresponding to the steady state of the hot box is in good agreement with that found for banana fibers in the literature [9]. It should be noted in the case of thermal insulation of buildings, bio-based materials will never be subjected to this temperature (151 °C), and they will be subjected to the temperature of the ambient environment in which we evolve, i.e., the temperature of the external environment. In this case, the banana leaves used as insulation or solar protection on the roof of a house would be exposed to the outside temperature of the environment in which we live. Therefore, the measuring ranges of the hot plate compared with the FM listed in Table I are allowed and meet the conditions for a body to be insulating. Dujardin [9] had not done any experiments to find the thermal conductivity of banana leaves, he reported that no data were available on the conductivity of banana leaves in the literature. To find this value he made an adjustment to the experimental thermal conductivity data using a first-order model. There is work in the literature on banana fibers associated with polymer matrix to form composite materials [9], [2], in our study we tested the pure banana sheet, that is to say (i.e.) it was not associated with any material.

Tables II and III give the results of the thermal performance test of plant material samples at the hot box level. A considerable difference is observed between the evolution of the heat flow recorded by the heat flow sensor in contact with the hot plate placed on the upper face of each of the samples and the evolution of that of the cold plate placed on the other face of the samples. At the same time, we also observed a big difference between the temperature evolutions on the two plates. These differences prove the capacity of the materials of vegetable origin to store heat, we also observed that the cold plate takes about an hour to detect the heat emitted by the hot plate. We can say that these biosourced materials conduct a small fraction of the heat they receive. Table IV gives the relative uncertainty on the different heat flux and temperature measurements.

The thermal conductivity from the hot box experiment was calculated from the moment the cold plate detects the heat flow from the hot plate using (1). Thermal conductivities were measured with a relative uncertainty of 0.017% for the FM and 0.025% for the MPH.

Figs. 6 and 7 are the thermal conductivity graphs of the banana and latan samples tested dry and then wet.

TABLE I
THERMAL CONDUCTIVITY OF BIO-SOURCED SAMPLES

	FM	Hot Box Method
Sample	Measuring range: Thermal conductivity ($Wm^{-1}K^{-1}$)	
Banana Leaf	[0,032 ; 0,042]	[0,036 ; 0,043]
Coconut Leaf	[0,034 ; 0,041]	[0,036 ; 0,043]
Sargassum	[0,031 ; 0,041]	[0,030 ; 0,042]
Latan Leaf	[0,036 ; 0,044]	[0,031 ; 0,039]
Palm kernel stain	[0,036 ; 0,045]	[0,030 ; 0,040]
Vetiver Fiber	[0,038 ; 0,043]	[0,033 ; 0,041]
Sugar Cane Leaf	[0,036 ; 0,044]	[0,031 ; 0,042]
Sawdust	[0,031 ; 0,047]	[0,031 ; 0,050]

TABLE II
HEAT FLOW MEASURED ON BOTH SIDES OF THE SAMPLES

	Hot plate	Cold plate
Sample	Measuring range: Thermal flux in W/m2	
Banana Leaf	[1032 ; 1701]	[6,96 ; 90,10]
Coconut Leaf	[1552 ; 2533]	[0,29 ; 25,98]
Sargassum	[1122 ; 2533]	[0,29 ; 39,19]
Latan Leaf	[1185 ; 2412]	[0,29 ; 28,37]
Palm kernel stain	[628 ; 2335]	[0,59 ; 49,57]
Vetiver Fiber	[1244 ; 2288]	[2,28 ; 39,72]
Sugar Cane Leaf	[1226 ; 2264]	[0,29 ; 34,64]
Sawdust	[1244 ; 2252]	[0,29 ; 51,96]

TABLE III
TEMPERATURE MEASURED ON BOTH SIDES OF THE SAMPLES

	Hot plate	Cold plate
Sample	Measuring range: Temperature	
Banana Leaf	[40 ; 151]	[28,61 ; 35,70]
Coconut Leaf	[37 ; 110]	[30,00 ; 34,22]
Sargassum	[35 ; 119]	[31,34 ; 33,43]
Latan Leaf	[37 ; 114,8]	[32,00 ; 36,52]
Palm kernel stain	[36 ; 108,7]	[31,77 ; 37,15]
Vetiver Fiber	[48 ; 115,5]	[30,00 ; 36,26]
Sugar Cane Leaf	[46 ; 119,6]	[30,71 ; 35,23]
Sawdust	[36 ; 117,4]	[29,84 ; 35,10]

TABLE IV
UNCERTAINTIES ON HEAT FLUX AND TEMPERATURE MEASUREMENTS

Sample	Uccertainty on Flow in %		Uncertainty on Temperature in %
	Hot plate	Cold plate	Cold plate
Banana leaf	0,293	1,06	1,6
Coconut leaf	0,361	1,6	1,8
Sargassum	0,23	0,94	1,1
Latan leaf	0,121	1,6	1,8
Palm kernel stain	0,406	1,11	1,3
Vetiver fiber	0,554	1,04	1,26
Sugar cane leaf	0,503	1,15	1,4
Sawdust	0,333	2,3	2,5

The conductivity of wet samples varies according to the nature of the material. In the case of banana leaves (Fig. 6) between 30 and 40 °C, the wet sample curves are above the dry one, this is due to an increase in the thermal effusivity of the material at the time of thermal contact between the heat source and the wet sample which causes a sudden release of heat due to the presence of water. When thermal equilibrium is reached above 40 °C, the wet sample curve becomes below the dry sample.

The curve of the wet latan leaves (Fig. 7) remains below that of the dry sample, the fluctuations observed are due to the presence of layers of humid air which causes an instantaneous restitution and absorption of heat.

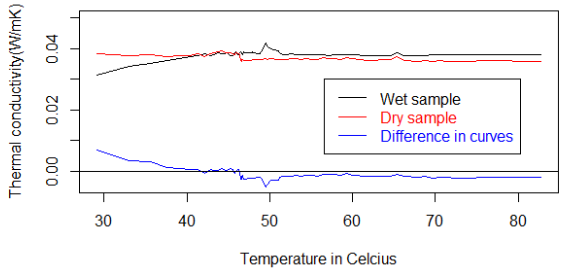

Fig. 6 Thermal conductivity graph of a dry and wet banana leaf sample by the FM

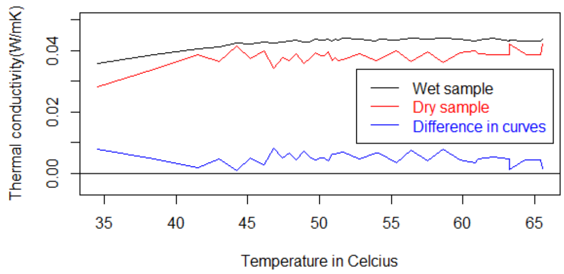

Fig. 7 Thermal conductivity graph of a sample of dry and wet latan sheet

The results of the experiment carried out on the ENS roof show the performance of banana leaves as solar protection for the roof. On the graphs of surface temperatures (Figs. 10 and 11), it can be seen that between the surface temperature covered and not covered with foil a maximum temperature difference of 20 °C at 14 h, this proves the capacity of banana leaves to store heat. The difference remains significant from 8 am to 7 pm, but during the night there is a significant reduction in the difference between the surface temperature of the concrete covered and not covered with banana leaves due to the fact that the concrete weakly restores to the inner surface the heat it has stored, at the same time the outer surface of the concrete absorbs the cold from the outside environment. The temperature of the covered surface becomes higher than the temperature of the uncovered surface, this implies that the banana leaves insulate the roof against the cold. We carried out the study over several days, but we choose to present the results of two of the most remarkable days, September 1 and 4, 2019.

Fig. 9 represents the evolution of the sunshine recorded in Haiti on September 4, 2019. The speed of this curve means that there was for this day passage of cloudy layer of great thickness instantaneously during the day since observing the curve around 12:00 PM we see a sharp drop in solar radiation from 1096 W/m^2 to 230 W/m^2 and this fluctuation persists until about 17:00 on September 4, 2019. We interpret this situation as an intermittent overcast sky. Similarly, Fig. 12 gives the sunshine measured as of September 01, 2019, we see a continuous progression of radiation from 6 h to 12 h that can result in a clear sky situation. At about 14 h we observe a sudden drop of the sunshine below 200 W/m^2, due to the displacement of a large instantaneous cloud mass over the area, then the situation returns to normal. A slight decrease is also noticed around 4 pm. It should be noted that there is a big difference between the evolutions of the sunshine for the two days, for September 4th there was relevant cloud mass moving intermittently from 11am until after 5pm while for September 1st, this disturbance occurred only for two moments 14h and 16h.

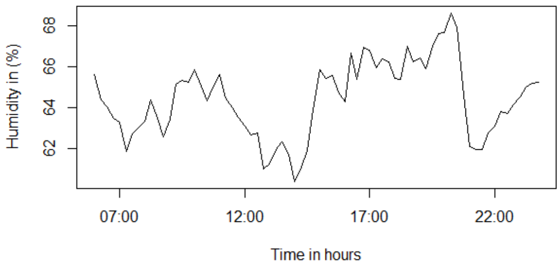

Fig. 8 Relative humidity measured on September 4, 2019 from 6am to 11:45pm

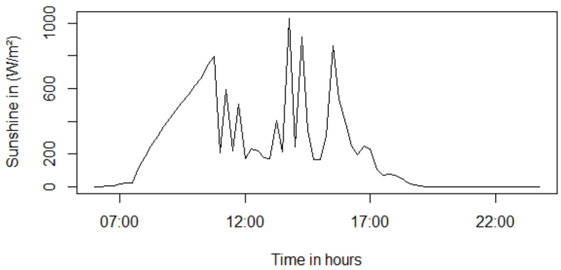

Fig. 9 Sunshine evolution for September 4, 2019 in Haiti

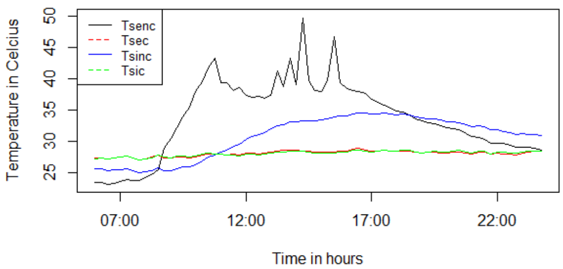

Fig. 10 Surface temperature evolution of exterior roof covered (Tsec) and not covered (Tsenc) with banana leaf, interior surface covered (Tsic) and not covered (Tsinc) on September 4, 2019 from 6 am to 11:45 pm

V. Conclusion

Vegetable fibres are expanding in the building sector, studies show that they are very promising to combat the energy-consuming aspect of the building. The low recorded thermal conductivity values prove their capacity to store heat and justify their good thermal performance. We can also say that they offer a high thermal resistance to the passage of heat by referring to the distance between the heat flows measured on both sides of the samples. Their thermo physical properties, in particular the thermal conductivity, change according to the humidity as well as the air pockets since they are porous materials. The thermal state of the sample at the time of measurement is important because the climate plays a role. The difference observed between the external surface temperatures of the roof covered and not covered with banana leaf from the experiment in Haiti, a maximum difference of 20 °C, shows that these materials are very interesting and encourages its use as solar protection due to its good insulating properties.

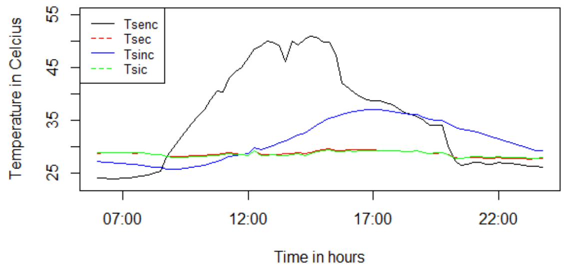

Fig. 11 Temperature evolution of the surface temperature of the inside roof covered and not covered with banana leaf and outside covered and not covered at the Master's room (ENS) in Haiti on 1 September from 6am to 11:45pm

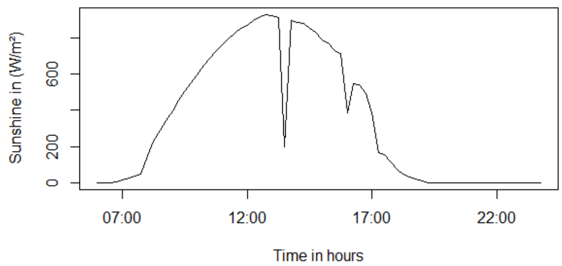

Fig. 12 Sunshine evolution for September 1st

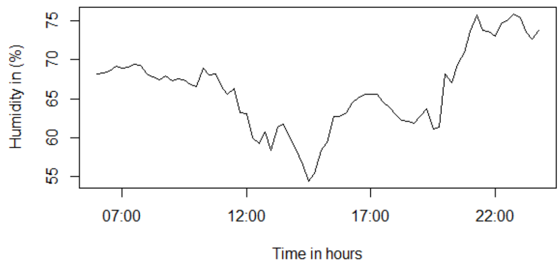

Fig. 13 Evolution of the relative humidity for September 1, 2019

References

[1] N. Amir, K. Abidin, et F. Shiri, « Effects of Fibre Configuration on Mechanical Properties of Banana Fibre/PP/MAPP Natural Fibre Reinforced Polymer Composite », *Procedia Eng.*, vol. 184, p. 573-580, déc. 2017, doi: 10.1016/j.proeng.2017.04.140.

[2] N. Amir, K. Abidin, et F. Shiri, « Effects of Fibre Configuration on Mechanical Properties of Banana Fibre/PP/MAPP Natural Fibre Reinforced Polymer Composite », *Procedia Eng.*, vol. 184, p. 573-580, déc. 2017, doi: 10.1016/j.proeng.2017.04.140.

[3] M. Kaboré, « Enjeux de la simulation pour l'étude des performances énergétiques des bâtiments en Afrique sub-saharienne », phdthesis,

Institut international d'ingénierie de l'eau et de l'environnement, 2015.
[4] A. Aslani, A. Bakhtiar, et H. Akbarzadeh, « Energy-Efficiency Technologies in the Building Envelope: Life Cycle and Adaptation Assessment », *J. Build. Eng.*, vol. 21, sept. 2018, doi: 10.1016/j.jobe.2018.09.014.
[5] T. Soubdhan, « Building solar protection under tropical climate: an experimental study of roof insulation; Protection solaire des batiments en climat tropical humide: etude experimentale de l'isolation en toiture », déc. 2003, Consulté le: févr. 05, 2021. (En ligne). Disponible sur: https://www.osti.gov/etdeweb/biblio/20520201.
[6] M. Zafaranchi, « Simulation and Analysis of Passive Parameters of Building in eQuest: A Case Study in Istanbul, Turkey », *Int. J. Energy Environ. Eng.*, vol. 14, nº 10, p. 253-259, sept. 2020.
[7] E. Cuce, C.-H. Young, et S. B. Riffat, « Thermal performance investigation of heat insulation solar glass: A comparative experimental study », *Energy Build.*, vol. 86, p. 595-600, janv. 2015, doi: 10.1016/j.enbuild.2014.10.063.
[8] F. Miranville, « Contribution à l'Etude des Parois Complexes en Physique du Bâtiment : Modélisation, Expérimentation et Validation Expérimentale de Complexes de Toitures incluant des Produits Minces Réfléchissants en climat tropical humide », Theses, Université de la Réunion, 2002.
[9] N. Dujardin, « Un Materiau Biosource de Choix : Les Fibres naturelles. Caractérisations et Applications », in *25èmes Journées Scientifiques de l'Environnement - L'économie verte en question*, Créteil, France, févr. 2014, vol. JSE-2014, nº 01, Consulté le: févr. 03, 2021. (En ligne). Disponible sur: https://hal.archives-ouvertes.fr/hal-00978360.
[10] « Guide_des_materiaux_ isolants », p. 32.
[11] A. Abdou et I. Budaiwi, « The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content », *Constr. Build. Mater.*, vol. 43, p. 533-544, juin 2013, doi: 10.1016/j.conbuildmat.2013.02.058.
[12] C. Lorrette, « Outils de caractérisation thermophysique et modèles numériques pour les composites thermostructuraux à haute température », p. 243.
[13] P. Meukam, « Valorisation des Briques de Terre Stabilisees en Vue de L'isolation Thermique de Batiments », p. 157.
[14] S. A. Al-Ajlan, « Measurements of thermal properties of insulation materials by using transient plane source technique », *Appl. Therm. Eng.*, vol. 26, nº 17, p. 2184-2191, déc. 2006, doi: 10.1016/j.applthermaleng.2006.04.006.
[15] Khaled Chaffar, « Thermographie Active Appliquee a la Caracterisation in Situ de Parois de Batiment.
[16] I. Traoré, « Transferts de chaleur et de masse dans les parois des bâtiments à ossature bois », p. 236.
[17] B. Samba, « Etude du champ thermique dans une plaque : Application à la mesure de la conductivité thermique des matériaux », p. 116.
[18] M. Aghahadi, « Etude expérimentale et modélisation physique des transferts couplés chaleur-humidité dans un isolant bio-sourcé. », p. 156.
[19] S. Dubois et F. Lebeau, « Design, construction and validation of a guarded hot plate apparatus for thermal conductivity measurement of high thickness crop-based specimens », *Mater. Struct.*, vol. 48, janv. 2013, doi: 10.1617/s11527-013-0192-4.
[20] F. Asdrubali, F. D'Alessandro, et S. Schiavoni, « A review of unconventional sustainable building insulation materials », *Sustain. Mater. Technol.*, vol. 4, juin 2015, doi: 10.1016/j.susmat.2015.05.002.
[21] G. Promis, « Hygrothermal performance of a straw bale building: In situ and laboratory investigations », oct. 2015. doi: 10.13140/RG.2.1.5115.9763.
[22] T. Ashour, H. Georg, et W. Wu, « Performance of straw bale wall: A case of study », *Lancet*, vol. 43, p. 1960-1967, août 2011, doi: 10.1016/j.enbuild.2011.04.001.
[23] J. Wihan, « Humidity in straw bale walls and its effect on the decomposition of straw », p. 271.
[24] A. Louis, A. Evrard, B. Biot, L. Courard, et F. Lebeau, « De l'expérimentation à la modélisation des propriétés hygrothermiques de parois isolées en paille », *undefined*, 2013. /paper/De-l%E2%80%99exp%C3%A9rimentation-%C3%A0-la-mod%C3%A9lisation-des-de-en-Louis-Evrard/cd79331f31f785d4b8600086cea14e50aa32369c (consulté le févr. 04, 2021).
[25] M. Aghahadi, « Etude expérimentale et modélisation physique des transferts couplés chaleur-humidité dans un isolant bio-sourcé. », p. 156.
[26] C. Gobbé, J. Gounot, et M. Bazin, « Mise en oeuvre de la méthode flash pour la mesure de diffusivité thermique sur des matériaux liquides ou fondus en fonction de la température. Application aux polymères », *Rev. Phys. Appl.*, vol. 24, nº 12, p. 1119-1128, 1989, doi: 10.1051/rphysap:0198900240120111900.
[27] Roberto Ricciua, Luigi A. Besalducha, Alessandra Galatiotob, Giuseppina Ciullab. Thermal characterization of insulating materials. Renewable and Sustainable Energy Reviews. Fevrier 2018 ; 82 : 1765-1773.
[28] L. Adityaa, TMI. Mahlia, B. Rismanchi , H.M. Ng , M.H. Hasane , HSC. Metselaar, Oki Murazaf, HB. Aditiya. A review on insulation materials for energy conservation in buildings. Renewable and Sustainable Energy Reviews. 2017, 73: 1352-1365.
[29] Francesco Asdrubali, Francesco D'Alessandro, Samuele Schiavoni. A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies. 2015; 4 :1-17
[30] Dr. Mohammad S. Al-Homoud. Performance characteristics and practical applications of common building thermal insulation materials. Building and Environment 40 (2005) 353–366
[31] Günther Kain. Design of Tree Bark Insulation Boards: Analysis of Material, Structure and Property Relationships. These de doctorat. Technischen Universität München : 2017
[32] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali. Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews. 62: (2016) 988-1011.
[33] A.M. Papadopoulos. State of the art in thermal insulation materials and aims for future developments. Energy and Buildings 37 (2005) 77–86.