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Study of the Energy Efficiency of Buildings under Tropical Climate with a View to Sustainable Development: Choice of Material Adapted to the Protection of the Environment

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Abstract**—**In the context of sustainable development and climate change, 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 occupants due to thermal discomfort in buildings. One can find a wide variety of efficient solutions but with high costs. In developing countries, especially tropical countries, we need to appreciate a technology with a very limited cost that is affordable for everyone, energy efficient and protects the environment. Biosourced insulation is a product based on plant fibers, animal products or products from recyclable paper or clothing. Their development meets the objectives of maintaining biodiversity, reducing waste and protecting the environment. In tropical or hot countries, the aim is to protect the building from solar thermal radiation, a source of discomfort. The aim of this work is in line with the logic of energy control and environmental protection, the approach is to make the occupants of buildings comfortable, reduce their carbon dioxide emissions (CO_2) and decrease their energy consumption (energy efficiency). We have chosen to study the thermo-physical properties of banana leaves and sawdust, especially their thermal conductivities, direct measurements were made using the flash method and the hot plate method. We also measured the heat flow on both sides of each sample by the hot box method. The results from these different experiences show that these materials are very efficient used as insulation. We have also conducted a building thermal simulation using banana leaves as one of the materials under Design Builder software. Air-conditioning load as well as CO_2 release was used as performance indicator. When the air-conditioned building cell is protected on the roof by banana leaves and integrated into the walls with solar protection of the glazing, it saves up to 64.3% of energy and avoids 57% of CO_2 emissions.

Keywords**—**Plant fibers, tropical climates, sustainable development, waste reduction.

I. INTRODUCTION

IN the context of sustainable development and climate change, the adaptation of buildings to the current climate context, particularly in humid tropical climates, is a necessary condition if we want to improve the thermal environment of the occupants in the habitat. The building sector consumes about 40% of the world's energy and accounts for about 1/3 of the world's greenhouse gas emissions [1]-[4]. The circular economy, one of the axes of which is based on the protection of the environment, also takes into account waste management. Its objective is to produce goods and services by limiting the consumption and waste of raw materials and renewable energy sources. The use of insulation of vegetable origin in the building sector allows us to apply the circular economy by recovering biodegradable waste. In hot climates, it is necessary to fight against solar gains to obtain thermal comfort conditions in buildings, avoiding the use of active cold production devices [5]. The roof is the most exposed surface, 60% of the thermal load of a building comes from this surface, stopping solar radiation before it reaches the wall, limiting energy absorption and energy transfer are measures to be adopted in order to reduce the energy input through the roof [5], [6]. As a result, thermal insulation plays an important role in determining the thermal and energy performance of a building [7]. Energy efficiency in buildings and thermal insulation of building envelopes is a very important area of research and has undergone great development in recent years [8], [9]. In summer the trajectory of the sun is the highest in the northern hemisphere. The received solar radiation is the strongest of the year. The higher the height of the sun, the greater the solar radiation received by the earth. During the hottest months the demand for energy for air conditioning increases, insulation of the roof and walls seems to be necessary to lower this consumption. In this case, the use of bio-based insulation materials is a necessary, perhaps even sufficient condition to reduce the external heat input to the internal comfort of the building. The thermal performance of an insulator is mainly characterized by its thermal conductivity. The thermal conductivity of insulation material is greatly affected by their operating temperature and moisture content, yet limited information is available [7]. In this work we will present a study carried out on the thermal performance of banana leaves where its thermal properties will also be presented. Finally, we will end our study by simulating banana leaves used as solar protection for roofs and walls.

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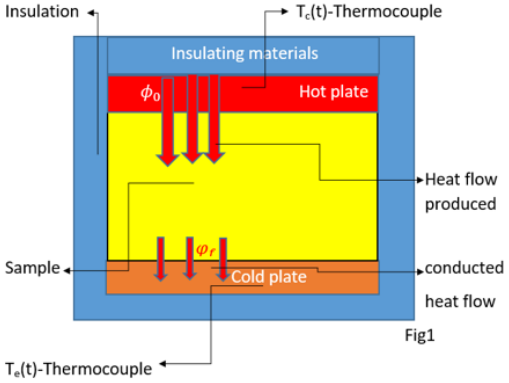

Fig. 1 Diagram of the hot plate method, $T_{e(t)}$-temperature of the cold plate, $T_{C(t)}$-temperature of the hot plate

II. METHODOLOGY

The study of energy efficiency takes into account the thermal conductivity of insulating materials. We proceeded by consulting the work carried out, mainly the different methods used to determine the thermal conductivity of the samples. Several methods were used such as the DICO method used by [10], the hot plate method (MPH) by [11]-[18] and finally the flash method used by [19]-[22], to name but a few. In the framework of our study, we have chosen the hot plate and flash methods because of their degree of reliability, moreover they have been highlighted in many works.

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 [17]. The sample is placed between a cold plate and a hot plate whose experimental device is shown in Fig. 1, in the stationary state the static calculations assume the use of Fourrier's law. 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 [17], [19].

The Flash Method [22] in its operating principle 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 may be added that this is a unidirectional method which consists of subjecting or absorbing a pulsed heat flow of short duration by one face of the sample and recording the evolution of the temperature during this same time interval at one or more points on the opposite face of the sample [21], [17]. The schematic diagram of the experimental set-up is shown in Fig. 2.

Figs. 4-7 were plotted using the R software.

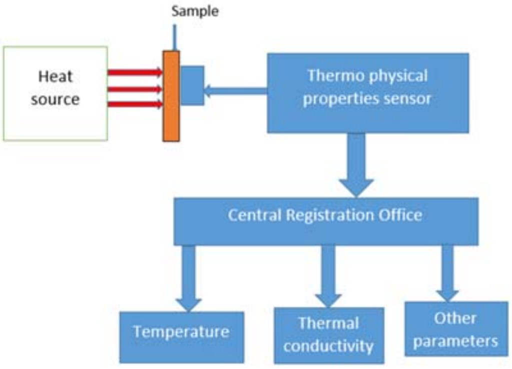

Fig. 2 Diagram of the flash method

III. THERMAL PERFORMANCE TEST OF BANANA LEAVES AND SAWDUST: HOT BOX EXPERIMENT

The thermal performance of banana leaves and sawdust was carried out inside a hot box (Fig. 1) where each sample of dimension 20 cm x 20 cm of thickness 15 cm is placed between two heat flows sensors each integrating a T-type thermocouple thus measuring the temperature and the heat flow on each face of the sample. The heat flow sensor on the upper side is placed in contact with two heating plates with respective electrical resistances of 19.7 Ohms and 19.3 Ohms. The box of internal dimensions 33 cm x 33 cm x 33 cm is insulated with a layer of polystyrene 6 cm thick on each side. The device is powered by an electric generator of adjustable voltage 45 Volt, the current intensity was close to 1 Ampere, but the voltage was fixed at 10 volts. The sensors were connected to a CR5000 datalogger (Campbell Scientific) linked to a computer that records the data using LoggerNet software. The banana sample was heated for 8 hours and the sawdust sample for 6 hours.

The temperature on the unheated side of each sample was measured and calculated using the Yves-Jannot equation

$$T(x,t) - T_i = \frac{\phi_0}{\lambda S}\sqrt{\left(\frac{4at}{\pi}\right)}\, exp\left(-\frac{x^2}{4at}\right) - \frac{\phi_0}{\lambda S} xerfc\left(\frac{x}{\sqrt{4at}}\right) \quad (1)$$

This equation translates the temperature evolution inside the sample at a distance x from the hot plate. S- Surface of the hot plate in square meter. ϕ_0- Heat flux dissipated in the hot plate in Watts. λ- Thermal conductivity of the sample in $Wm^{-1}K^{-1}$. $a -$ Thermal diffusivity of the sample. $t -$Experiment duration in seconds. T_i $-$Initial temperature in the sample or cold plate at the start of the experiment. $T(x,t) = T_e$(t) which represents the temperature of the cold plate on the other side of the sample.

IV. SIMULATION

We also looked at work on thermal simulation of buildings in order to take a look at simulation tools, parameters and their methods. Among the software listed in the literature for dynamic thermal simulation are: Design Builder, Comfie-Pleiade, Climawin, ArchiWIZARD, TrnSys Sumulation Studio [23], [24]. ISOLAB [25], CODYBA [8], TRNSYS [8], EQUER [26].

In the BESTEST method [27] for the International Energy

Agency (IEA) Building Energy Simulation Test and Diagnostic Method for Heating, Ventilation and Air Conditioning Equipment Models (HVAC BESTESTEST), the following software is used in the case study: CODYRUN (Reunion), ENERGYPLUS (USA), TRNSYS (Germany), HOT3000 (Canada) to name a few. We chose the DesignBuilder software for this work because it first uses the ENERGYPLUS calculation engine, then it takes into account all types of climate, particularly the humid tropical climate.

Dynamic Thermal Simulation (DTS) allows to model the thermal behavior of a building over time. It aims to rigorously study the impact of savings actions on comfort conditions, as well as on the energy needs and consumption of the site under study.

A. Presentation of the Studied Cell

We carried out simulations on a building cell on the interface of the thermal simulation software (Fig. 4) whose dimensions are 4 m x 4 m x 3 m, with a usable surface area of 16 m^2 using the Port au Prince weather file. Different thicknesses of banana leaf were tested on the roof in order to verify its influence on the thermal load of the cell as well as the air conditioning and CO$_2$ emission. The roof is made of 16 cm thick poured concrete, the walls of concrete block 20 cm + 2 cm plaster and the floor of poured concrete 16 cm. The cell is air-conditioned for all the sequences described in Table I.

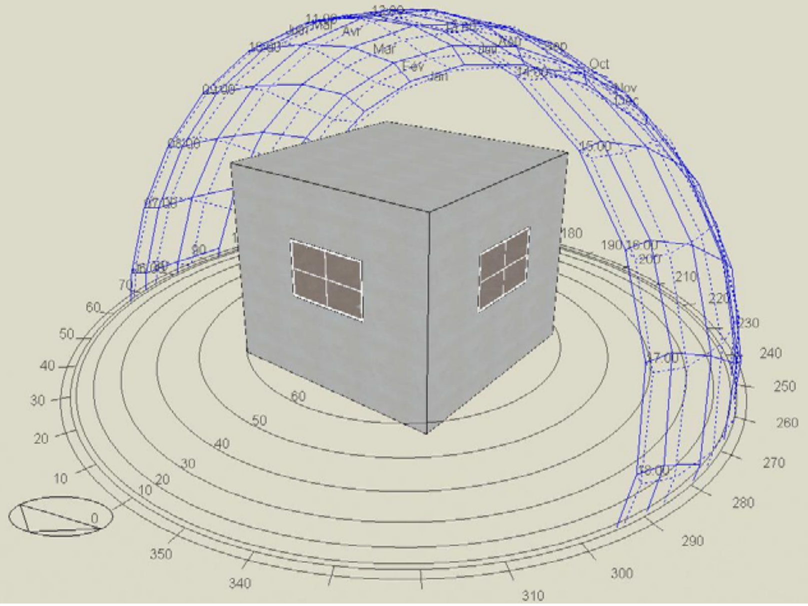

Fig. 3 Diagrams of the building cell studied with the sun's path

TABLE I
SIMULATION DESCRIPTION OF VARIANTS

1	Non-Insulated roof
2	Roof + 10 cm of banana leaf
3	Roof + 15 cm of banana leaf
4	Roof + 20 cm of banana leaf
5	Roof + 20 cm of banana leaf
6	Roof + 20 cm of banana leaf + 10 cm integrated to the wall
7	Roof + 20 cm of banana leaf + 10 cm integrated to the wall+ mask on widow

Simulations were carried out with the data from the experiments, namely the hot plate and the flash method. Table II gives the thermo physical properties of the banana leaves used, i.e., average thermal conductivity of 0.038 Wm^{-1}K^{-1}, specific heat 1556 JKg^{-1}K^{-1}, density 70 Kg/m^3. These data have been integrated in the insulation file of the thermal simulation software Design Builder.

V. RESULT

A. Result of the Study Conducted on the Thermal Performance of Banana Leaves and Sawdust

Through our hot box experiment we measured the temperature of the hot plate located on the upper side of the sample as well as that located on the other side (cold plate) of the sample. Using the data collected we also calculated the temperature on the other side by applying the equation of Yves-Jannot's theoretical model with a relative uncertainty of 1.6% on the result (see Fig. 1). Te(t) is the temperature of the cold plate or in the sample at a thickness "e" of the hot plate.

The heat flux produced by the hot plate placed on the upper of banana leaf was measured with a relative uncertainty of 0.293% or 4.723 Wm^{-2}. Hence the average heat flux of the hot plate (1612.369 ± 4.723 Wm^{-2}).

The heat flux conducted by the sample of banana leaf measured on the cold plate or on the other side of the sample with a relative uncertainty of 1.06% or 0.63 Wm^{-2}. The expression of the average heat flux is then written 59.34 ± 0.63 Wm^{-2}.

The thermal flux produced by the hot plate placed on the upper face of the sawdust sample measured with a relative uncertainty of 0.33% or 7.11 Wm^{-2} is written as 2134.93 ± 7.11 Wm^{-2}. The one conducted by the sample measured on the cold plate placed under its lower face with a relative uncertainty of

2.3%, i.e., 0.87 Wm^{-2} is written as 38.14 ± 0.87 Wm^{-2}.

The considerable difference between the heat flow produced by the hot plate and that measured on the other side of the sample shows that banana leaves and sawdust are very efficient from a thermal point of view. They have a high capacity to store heat, then the low evolution of its thermal conductivity as a function of temperature proves its good insulating capacity.

Fig. 4 shows the evolution of the temperature measured on both sides of the banana leaf sample which was influenced by the heat produced by the hot plate. We can notice that it was able to resist by slowly conducting the heat it received because the difference in temperature on its two faces is considerable. Moreover, after about 8 hours of heating we observe a slight progression of the measured temperature, that is to say Te(t) on the unheated side of the sample, that is to say on the cold plate. The temperature calculated using (1) is in agreement with the experimental temperature. These considerations allow us to deduce that the banana sample was able to store heat in large quantities, which gives it the grade of a good thermal insulator.

Fig. 5 is the evolution of the thermal conductivity from two methods, we see that the red curve is more stable, it corresponds to the hot plate method, this stability can be interpreted because the sample was well compacted, this supposes that there was no significant air pocket residing in it. The black curve obtained by the flash method undergoes fluctuations due to the presence of air pockets inside the sample, the observed peak corresponding to a thermal jump undergone by the sample, we can interpret it as the sudden encounter of heat with a layer of air that causes a sudden release of intense heat leading to an increase in thermal effusivity.

The thermal effusivity characterizes the ability of a material to change temperature when it receives a thermal energy input. It uses the heat capacity and thermal conductivity (λ) of the material for its calculation:

$$E = \sqrt{\rho \lambda Cp} \text{ expressed in a W S}^{1/2}\text{ m}^{-2}\text{ K}^{-1} \qquad (2)$$

λ in Wm^{-1}K^{-1}, Cp is the specific heat of the material in JKg^{-1}K^{-1}, ρ is the density of the material in Kgm^{-3}.

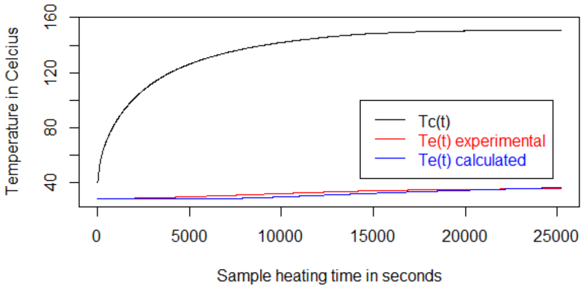

Fig. 4 Temperature evolution of a 15 cm thick banana leaf sample heated for more than 7 hours, hot plate experiment. Tc(t)-temperature hot plate, Te(t) experimental: temperature measured on the cold plate located under the sample at 15 cm from the hot plate, Te(t) calculated- temperature calculated on the cold plate at 15 cm from the hot plate

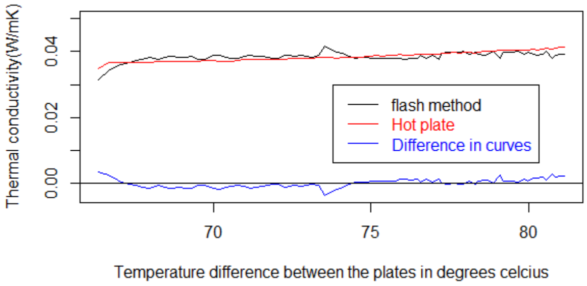

Fig. 5 Thermal conductivity evolution of a sample of sawdust following two methods, the black curve obtained using the Flash method. The curve in red is obtained using a hot plate which provides heat to the sample in a hot box

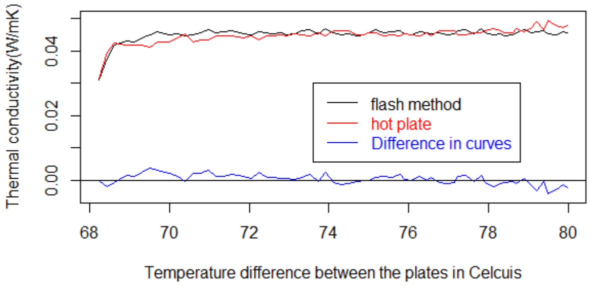

Fig. 6 Thermal conductivity evolution of a sample of banana leaf following two methods, the black curve obtained using the Flash method. The curve in red is obtained using a hot plate which provides heat to the sample in a hot box

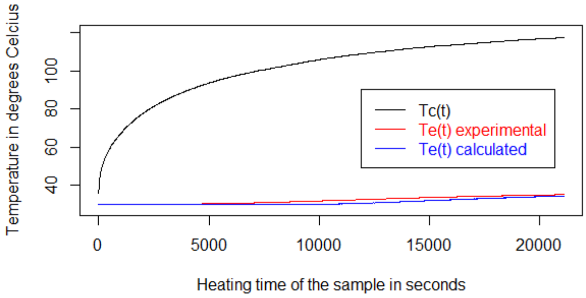

Fig. 7 Temperature evolution of a 15 cm thick sawdust sample heated for more than 6 hours, hot plate experiment. Tc(t)-temperature hot plate, Te(t) experimental: temperature measured on the cold plate located under the sample at 15 cm from the hot plate, Te(t) calculated- temperature calculated on the cold plate at 15 cm from the hot plate

The thermal effusivity measured by the Flash method for both samples are 64.34 ± 1.74 W S$^{1/2}$ m^{-2} K^{-1} for banana leaves and 93.99 ± 2.87 W S$^{1/2}$ m^{-2} K^{-1} for sawdust.

The specific heat of banana leaves was calculated using (2).

Fig. 6 represents the evolution of the conductivity of a sawdust sample. This measurement has been validated by two methods; the small differences observed on the curve are related to random phenomena.

Fig. 7 represents the evolution of the temperature of a sawdust sample placed between the hot and the cold plate in a box. The sample was heated for 6 hours, the considerable difference in temperature between the heated and unheated sides of the sample proves its good thermal performance.

TABLE II
THERMO PHYSICAL PROPERTIES OF BANANA LEAF

	Measuring range	Average value
Thermal conductivity ($Wm^{-1}K^{-1}$)	0,031 to 0.042	0,038
Specific heat ($JKg^{-1}K^{-1}$)	387 to 1915	1556
Density (Kgm^{-3})	70 to 134	-

B. Result of the Study Carried out on the Thermal Simulation of Banana Leaves Used as Solar Protection for the Roof

Fig. 8 represents the evolution of the air conditioner's power consumption, which is the annual air conditioning load. For the non-insulated roof (0 cm), i.e., without solar protection, the highest monthly distribution is observed, when it is protected with 10 cm of banana leaf, a significant decrease in the energy consumed for air-conditioning is observed. When the roof is insulated with 10 cm of banana leaf, an annual energy saving of 589,644 KWh is recorded compared to the case of the non-insulated roof. For a thickness of 15 cm a load of 605.1 KWh is avoided, for 20 cm 609.921 KWh is saved, a reduction of 36.5% and 610.139 KWh for 25 cm. Beyond 15 cm there is not a significant difference in energy saving, we can say that there is a small progression in energy saving. Above 30 cm, there is a regression in the energy saving of air-conditioning, that means when you put too much banana leaf on the roof the energy saving stops increasing, so you get a reversal of the situation. The proof is that between 10 cm and 15 cm the difference in energy saved is 15.457 KWh while between 15 cm and 20 cm the difference is 4.82 KWh, so 15 cm of roof thickness would be the right choice. Moreover, between 20 cm and 25 cm there is only a gap of 0.218 KWh, which means that it is not advantageous to insulate the roof with a 25 cm thickness. Finally, between 25 cm and 30 cm of roof insulation we obtain a negative cooling energy difference of -0,751 Kwh, which represents a loss of energy saving and means that the air conditioner consumes much more energy to cool the building cell for 30 cm of insulation, in other words to maintain the comfort of the cell. This means that 30 cm of insulation should consume less cooling energy than 25 cm, while the opposite was observed.

Continuing the study with 20 cm of banana leaf on the roof and 10 cm integrated into the wall, we see a greater increase in the avoided air conditioning consumption of 689,845 KWh, or a saving of 41.2%. By adding cap-type solar protections on the windows, we obtain a considerable decrease in air conditioning load, which represents an energy saving of about 1074.21 KWh, a saving of 64,3%.

Fig. 9 is the evolution of the carbon dioxide (CO_2) released for energy consumption in the building cell. According to the results shown on the graph the insulation of the roof with banana leaves avoids a significant emission of CO_2. For a thickness of 15 cm, 20 cm and 25 cm the regression of the CO_2 emission is not too significant, i.e., the values are close. The more the thermal load decreases the smaller the quantity of greenhouse gases released. We have the lowest CO_2 emission for the situation where the roof is insulated with an integration of banana leaves on the wall as well as the solar protection of the windows.

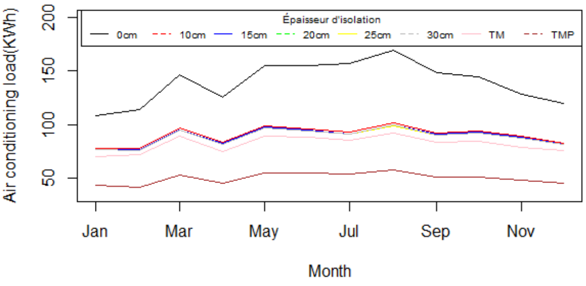

Fig. 8 Evolution of the air conditioning load for different thicknesses of banana leaf on the roof. The abbreviations TM correspond to 20 cm in the roof and 10 cm integrated in the wall, TMP- corresponds to 20 cm in the roof and 10 cm integrated in the wall including solar protection of the windows

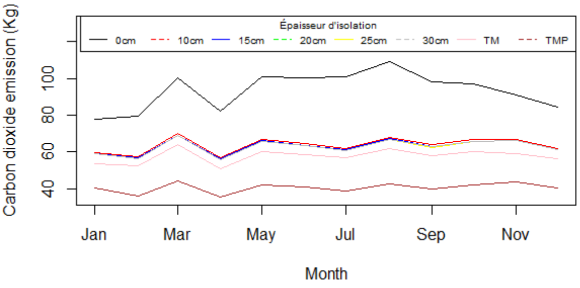

Fig. 9 Evolution of CO_2 emissions for different thicknesses of banana leaf

VI. CONCLUSION

The materials of vegetable origin see their viable evolution in the building sector, its applications could respond to the policy of circular economy as well as environmental protection and energy efficiency. They contribute to the reduction and recovery of biodegradable waste. The results of the thermo physical properties and the thermal performance test of banana leaves show its good insulating properties. DTS by protecting the roof and walls against solar radiation with different thicknesses of banana leaf imply a significant reduction in the air conditioning load and also leads to a reduction in the carbon dioxide released for the building's electricity consumption. According to the results of the simulation, 10 cm and 15 cm thicknesses are better in terms of air-conditioning energy savings, 15 cm being the right choice.

The thermo-physical properties of the banana leaves and sawdust samples, especially the thermal conductivity, were measured, but only the banana leaves were simulated. The banana leaves of thermal conductivity 0.038 $Wm^{-1}K^{-1}$ insulate better than the sawdust whose thermal conductivity is and 0.045 $Wm^{-1}K^{-1}$ and are classified as insulators.

The thermal conductivity of banana leaves as well as its specific heat 1556 $JKg^{-1}K^{-1}$ were integrated inside the Design Builder software in order to carry out the thermal simulations on a building cell with glazed windows having a 16 cm thick concrete roof with 20 cm concrete brick walls with 2 cm of plaster. The simulations were performed with the thermal

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conductivity of the banana leaves validated by the flash method and that of the hot plate. The banana leaves were chosen to perform the simulation because it is more insulating than sawdust because it has a lower thermal conductivity. The insulation of the roof with 20 cm of banana leaf causes a reduction annual of 36.5% of the air conditioning load and 33% of the CO_2 emission, a reduction of 41.2% of the air conditioning load and 38% of the CO_2 emission by integrating 10 cm to the walls, and finally a reduction of 64.3% of the air conditioning load and 57% of the CO_2 emission by adding solar protections to the windows. These different insulation strategies on the roof and walls lead to a progressive reduction of the air-conditioning load and CO_2 emissions. The temperature difference (Fig. 4 and 7) observed between the hot and cold plate proves the thermal performance of the banana and sawdust sheets, the same is true for the thermal flux.

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