Characteristics of insulating panels realised from coconut palm fibres for low-temperature thermal insulation

Abstract: In recent years, there has been growing interest in issues relating to pollution and energy consumption, and the resulting regulations have led the construction sector to focus on thermal insulation. The application of bio-based insulation materials can help to minimise the environmental impact of buildings by reducing energy demand both during construction and over the lifetime of the building. Agroforestry biomass plays an interesting role, as its use can reduce greenhouse gas emissions. The aim of this work is to produce insulating panels from agroforestry by-products for low-temperature thermal insulation applications. The insulating panels in this study are produced from coconut palm fibres and their thermophysical properties are determined. They were produced using a human-motricity press and the temperature rise was controlled using the hot-tape method. Characteristics such as calorific value and modelling of temperature rise as a function of time to calculate thermal conductivity, thermal effusivity and diffusivity were determined. The calorific value varies from 3668.0 to 4135.0 and from 3742.0 to 4186.0 $cal.g^{-1}$ when the moisture content is 11.28 and 10.61%, respectively. The thermal conductivity, effusivity and thermal diffusivity are 0.4 $W.m^{-1}.K^{-1}$, 760.30 $J.m^{-2}.°C^{-1}.s^{-1/2}$ and $2.73.10^{-7}$ $m.s^{-1}$, respectively. In view of these results, coconut fibre represents a potential precursor to produce insulating panels.

Keywords: Eco-materials, insulation, environment, thermophysical properties

1. INTRODUCTION

Global warming because of greenhouse gas emissions is one of the most important environmental problems on which the international community is focusing its efforts. The same applies to the scientific community, which is resolutely committed to working towards sustainable development. In the construction industry, the development of innovative, environmentally-friendly materials is becoming increasingly important for achieving sustainable development objectives [1–3]. Energy efficiency in buildings is an important factor in helping to reduce greenhouse gas emissions. The building and construction sector accounts for 30 to 40% of global energy consumption [4]. In the building sector, a large proportion of energy is used for heating, cooling and air conditioning [4,5].

The scientific community and civil society are supported by the political and administrative authorities in their efforts to anticipate the technological and environmental challenges of achieving sustainable development objectives. Nowadays, the scientific community is focusing on research into the use of local materials, in particular biomass from agroforestry, as substitutes for fossil or synthetic materials, which are expensive to exploit and have an irreversible impact on the environment.

In the insulation production industry, there is a growing demand for scientific research into the development of new materials that comply with environmental protection regulations.

An insulating panel is a rigid or semi-rigid sheet-like material used for thermal or acoustic insulation. Many materials are available in the form of insulating panels. They can be grouped into 3 categories: Synthetic insulation, mineral wool, and ecological insulation. The latter are made from natural fibres of plant origin with satisfactory thermophysical properties. These include: vegetable fibres, sawdust [6], wood fibres [7], *etc.*

They are obtained using both wet and dry processes. The wet process has shown some limitations, for example, the fracture of the fibreboard obtained is linked to the breaking of the glue joint and not to the breaking of the wood fibre; it also requires a lot of water. Panels produced using the dry process, on the other hand, have better mechanical properties, and the equipment used to process them is developing rapidly. In the industrial production of dry process panels, the raw material is either lignocellulosic fibres or agglomerates of hardwood and/or softwood fibres.

Insulating panels are expensive, however, and are still confined to high added-value applications. If they are to be used more widely in the building sector, the total cost of the raw materials used in their manufacture will have to be reduced [8]. The materials commonly used are synthetic, such as polyurethane, polystyrene, polyvinyl chloride, fillers for fabrics and mineral fibres such as rock wool and glass fibre [9,10]. For example, lignocellulosic fibres from hemp [11], flax [11] sunflower and date palm have already been used as insulating materials [12].

The general objective of this study is to produce insulating panels from agricultural by-products from Benin for low-temperature thermal insulation applications. Specifically, the aim was to:

- ✓ produce insulating panels from coconut palm fibres with interesting thermophysical properties;
- ✓ determine the thermo-physical properties of coconut palm fibres.

Coconut trees are widespread in the coastal zone of Benin. They are most prevalent in the Mono and Atlantic departments. According to the data collected, there are around 35,756 and 33,503 coconut trees in Mono and Atlantique respectively. The same agricultural statistics study on the estimated availability of this species in Benin in 2021 identified around 82,631 coconut trees [10]. Materials derived from natural resources have great potential because they have a low density, a lower environmental impact and good thermal properties [11].

2. MATERIAL AND METHODS

2.1. *Materials*

The plant material is coconut palm fibre. These are very light fibres made up of lignins and cellulose, as shown in Figs. 1, 2 and 3 show, respectively, the starch used as a binder in this study and the human-powered press used for compacting to make the insulation boards.

Thermal characterisation was carried out using an experimental device built around a data acquisition unit, to which a set of heating resistors and thermocouples were connected. Data processing was carried out on a desktop microcomputer using the Excell spreadsheet program. An electronic balance was used at the start of the operation to ensure that the acceptable mass difference (0.5g) between the samples was respected.

The production equipment consists of mechanical presses manufactured in the workshop. The laboratory equipment consists of the following: apparatus (calorimetric bomb and others), solvent, reagents, and glassware for thermo-physical and chemical characterisation.

Fig. 1. Various images showing coconut palm fibres

Fig. 2. Starch

Fig. 3. Human-powered press

2.2. Methods

2.2.1. Techniques for realising test specimens

The process is based on a small, human-powered press developed in the workshop with the aim of obtaining experimental-sized coconut palm fibre specimens. The size obtained complies with the dimensions required by the standard that underpins the device for measuring the thermophysical quantities sought.

The approach adopted in preparing the test specimens is purely experimental. The methodology for determining thermophysical quantities is based on a reliable measurement and data processing protocol. It is therefore a source of guaranteed results.

2.2.2. Description of the experimental system

The experimental set-up is built around a data acquisition central, to which a heating resistor + thermocouple probe assembly is connected. This equipment is controlled by a desktop microcomputer. The device consists of: samples of raw material (1), heating resistor + thermocouple inserted between two samples of material (2), polystyrene (3 and, 5) and, mass (4) (Fig. 4).

During the test, the insulation boards were cut into two smaller sizes of approximately equal mass so that effusivity and diffusivity could be determined. An electronic balance is used for this purpose to ensure that the acceptable difference in mass (less than or equal to 0.5 g) between the samples is respected. The set-up is based on the principle of simultaneous measurement of conductivity and effusivity with the symmetrical 2D "hot ribbon".

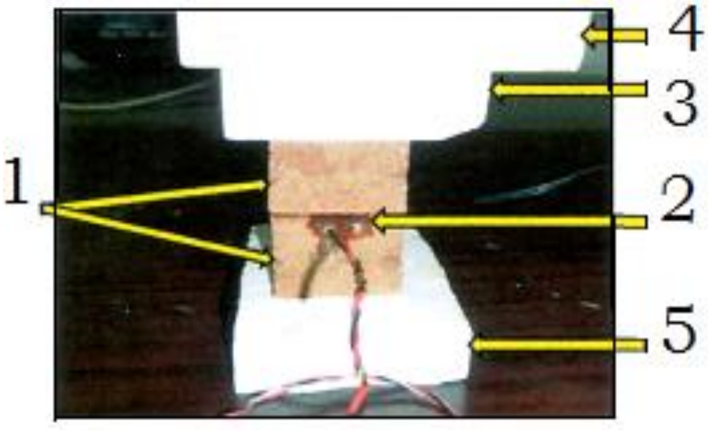

Fig. 4. Example of assembly for a hot tape measure (14).

Table 1. Characteristics of the ribbon

R	L	l	U
43.4 Ohms	5cm	1,5cm	6.3 V

2.2.3. Physicothermal characteristics

2.2.3.1. Measuring and determining calorific value

The measurement and determination of calorific values involves four (04) stages: commissioning of the calorimeter bomb, preparation of the samples, analysis, and calculation.

Commissioning

During commissioning, the instrument is switched on under oxygen pressure varying between 30 bar (435Psi) and 35 bar (507.5Psi). In the "Main menu", the "Calorimeter operation" mode is selected with the "Determination" operating mode chosen when "Standardisation" is displayed. Heating and pump" were set to "On" mode. The "Level Temp" temperature is approximately 25°c before starting the analysis.

Preparation and analysis

In the cup, 0.1 mg of the product and the additive is weighed. 5ml of demineralised water is added to the can body. The seal between the can body and the head support is moistened with demineralised water. 10 cm of wire is used to burn the sample. The two legs of the head support are connected using the wire, so a hole is made in each leg. A small loop with the wire pointing towards the product is made so that the drop formed when the current passes fall onto the material. The wire must not touch the material. The cup is placed on the head support, which is carefully positioned in the can in a vertical plane. The cup must be placed carefully so as not to spill the product, and it must be ensured that it does not get stuck in the body of the can before the head support is pushed in.

The oxygen inlet tube is connected above the calorimeter bomb. Oxygen was supplied via the "O_2 fill" mode on the touch screen, on which a 60-second countdown was displayed. The oxygen supply is then disconnected. The bucket is first filled with demineralised water via the bulb and placed in the calorimeter using a set of three coded pins. The calorimeter bomb is placed in the bucket in the central area provided for it, at the same time connecting the two electrodes to the calorimeter bomb in the two places provided for this purpose before closing it. The device is switched on and a number is assigned to the test. On the screen entitled "Weight", the mass was entered via the touch screen. Similarly, the mass of the additive was entered via the screen entitled "Additive". After running the test, the calorimeter cover is raised only if the analysis is complete.

Calculation of calorific values

Several empirical relationships are used to calculate the calorific value (C.V.) from the centesimal composition of certain constituents of the material. For solid and liquid materials, the following formula can be applied:

$$\boldsymbol{PCI_{Brut}(Cal.g^{-1}) = PCI_{Mesur\acute{e}} - (14 \times \%Soufre) - (54\%Hydrog\grave{e}ne)} \quad (1)$$

To calculate the dry calorific value, it is obtained from the moisture content, so the following relationship is used:

$$\boldsymbol{PCI_{Sec}(Cal.g^{-1}) = \frac{PCI_{Brut}(Cal.g^{-1})}{(100 - \%H_2O)} \times 100} \quad (2)$$

The 6100 calorimetric bomb is the equipment used to determine the gross calorific value of materials.

2.2.3.2. Hot-tape method [15]

Principe

The principle is based on the consideration of short time hot plane type behaviour at the centre of the probe and long-time hot wire type behaviour when the flux becomes assimilable to a radia flux (Fig.5). The ribbon will therefore take the same form as the hot plane, only its dimensions will differ.

The method has been put into practice by setting up a data acquisition and processing chain.

This is the symmetrical model using a pair of samples of the same type. It offers advantages in terms of implementation, as it allows measurements to be taken under variable conditions for sufficiently short periods of time for it to be assumed that the water content of the pairs of samples has remained constant.

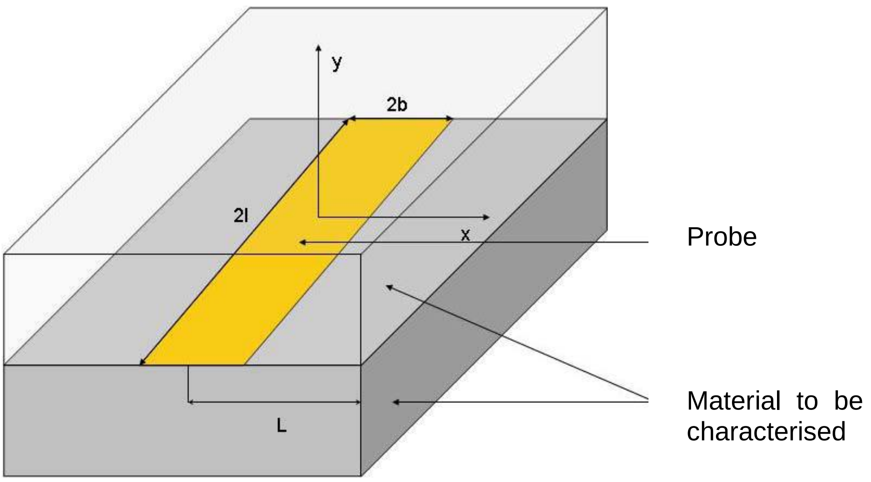

Fig. 5. Principle of the hot-tape method

Experimental protocol

The heating resistor and thermocouple are inserted between the two samples of material. The assembly is protected on either side by an insulator (polystyrene) and then stabilised or immobilised with a mass. When the resistor is energised, the computer displays the behaviour of the pair of materials when heated. The data acquisition chain made it possible to follow the evolution of the temperature as a function of time every second (dt=1second).

These data were used in an Excel spreadsheet to calculate the effusivity at short times (0 and 50s) and the thermal conductivity at long times (100 and 150s).

2.2.3.3. Calculating Effusivity and Conductivity

Determination of effusivity

The effusivity (E) is determined by plotting the function $\Delta\theta = f(\sqrt{t})$. It is determined based on the first fifty (50) successive measurements. The set of data considered is obtained using the best linear regression. The slope β of this curve is used to calculate the effusivity E, using relationship (1).

$$\boldsymbol{\beta} = \frac{2\varphi_0}{ES\sqrt{\pi}} \tag{3}$$

Table 2. Parameter values for effusivity E calculation

U (Volts)	R (Ohms)	L (cm)	l (cm)	$S = \mathrm{L} \times \mathrm{l}$ (m^2)	$\boldsymbol{\varphi}_0 = \frac{\mathrm{U}^2}{\mathrm{R}}$
6,3	43,4	5	1,5	0,00075	0,91451

Determination of thermal conductivity

The thermal conductivity (λ) is determined by plotting the function $\Delta\theta = \mathrm{f}(\ln t)$. It is determined between 100 and 150 seconds. The set of data considered is obtained using the best linear regression. The slope α of this curve can be used to calculate the effusivity E, using relationship (2).

$$\alpha = \frac{\varphi_0}{4\pi\lambda L} \tag{4}$$

This gives the thermal conductivity λ $(\mathrm{W.m^{-1}.K^{-1}})$. The various parameters involved in the relationship are shown in Table 3.

Table 3. Parameter values for conductivity calculation

U (Volts)	R (Ohms)	L (m)	$\varphi_0 = \frac{U^2}{R}$
6,3	43,4	0,05	0,91451

Determination of thermal diffusivity

Thermal diffusivity is a physical quantity that characterises the ability of a material to transfer heat (thermal energy) through it. It depends on the material's ability to conduct heat (thermal conductivity) and its ability to store heat (volumetric thermal capacity). The diffusivity of samples can indicate the material's ability to conduct and store thermal energy (1). It characterises the spread of heat within the material (in terms of speed). It is expressed in $m^2.s^{-1}$.

This parameter is directly contained in the simplified heat equation, where [13]:

$$\vartheta = \frac{\lambda}{\rho C_p} \quad (5)$$

ϑ: thermal diffusivity of the material in $m^2.s^{-1}$, λ: The thermal conductivity of the material in $W.m^{-1}.K^{-1}$, ρ: The density of the material in $kg.m^{-3}$ et C_p: mass heat capacity at constant pressure in $J.\ kg^{-1}.\ K^{-1}$.

3. RESULTS AND DISCUSSION

3.1. Presentation of baskets produced

The two main stages in making insulating panels are illustrated in Fig. 6. Starch was used as a binder for the fibres. Its main role is to reinforce adhesion. The insertion of the fibre block that will be pressed to obtain the insulating panels was also shown. The woven structure of the coconut palm fibres remained visible, as they had not been grounding.

Fig. 6. Main stages in the production of insulation panels

3.1.1. Composite specimen

After pressing and drying the samples, the insulation boards are removed and stored in boxes as shown in Fig. 7.

Fig. 7. Insulating panel sample with storage box

3.2. Monitoring the rise in temperature of material

Heat and mass transfer is one of the most widely studied physical phenomena [14]. Fig. 8 shows the curves visualising the rise in temperature of the insulation board sample as a function of time. These curves, displayed on the computer, represent the behaviour of the pair of materials when heated, linked to the gradual rise in temperature within the materials when the resistor is energised. They have a similar appearance to half of a parabola whose axis of symmetry is the horizontal line passing through the initial temperature. They can be subdivided into three (03) parts:

- ✓ between 0 and 50 seconds, the part with the fastest rise in temperature. This part of the curve is linearised to calculate the effusivity E;
- ✓ between 50 and 100 seconds, the part where we feel a tendency towards stabilisation. This is shown by a slight increase in the curve;
- ✓ the third part, between 100 and 150 seconds, shows a further increase in the speed of the temperature rise. This can be explained by the more ascending portions of the curves than in the previous section. It was used to calculate the thermal conductivity.

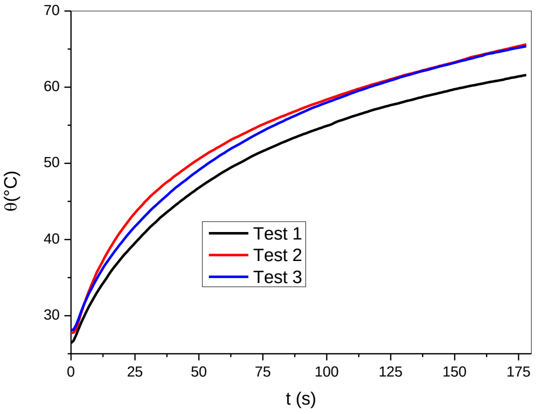

Fig. 8. Curves showing the rise in temperature in materials

3.3. Modelling of temperature rise curves in homogeneous and composite cow dung coating materials

Four intrinsic properties characterise a material from a thermal point of view: heat capacity, thermal conductivity, thermal diffusivity and thermal effusivity. They are determined in the course of this work to characterise the insulating panels produced.

3.3.1. Determination of calorific value

This property therefore reflects the material's ability to store energy and release heat. The results of determining the calorific value of the samples are obtained at two different moisture contents (10.68% and 11.28%).

Table 4 : Calorific values of the panels produced

Sample	**Calorific value (cal.g^{-1})**		**Moisture content (%)**
	Gross	**Dry**	
Coconut palm fiber	3668.0	4135.0	11.28
Coconut palm fiber	3742.0	4186.0	10.61

3.3.2. Calculation of effusivity of materials

Fig. 9 shows the linear regressions for the curves showing the temperature rise in the insulation boards for the calculation of effusivity. Table 4 shows the results for effusivity and coefficient of determination (R^2), which are 0.99879, 0.99613 and 0.99907, demonstrating good linear regression. Thus, these values very close to unity of the coefficients of the regression lines indicate that the effusivity values could be calculated from the equation of the lines.

Table 4 shows the effusivity of the three samples taken in this work. It is equal to 779.56, 743.33 and 758.00 $J.m^{-2}.°C^{-1}.s^{-1/2}$ with an average equal to 760.30 $J.m^{-2}.°C^{-1}.s^{-1/2}$. Effusivity describes how quickly a material absorbs heat. In other words, the higher the effusivity, the more energy the material absorbs without heating up quickly. The very high effusivity achieved indicates that the insulating panels manufactured can absorb high levels of energy without heating up quickly.

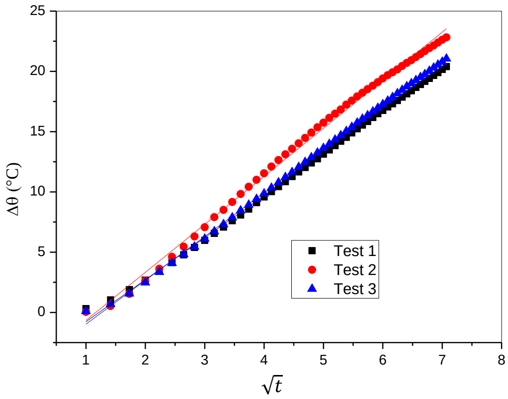

Fig. 8. Regression lines for temperature rise curves for calculating effusivity E.

Table 5 : Results of effusivity determination

Tests	Test 1	Test 2	Test 3
Determination coefficient (R^2)	0,99879	0,99613	0,99907
Effusivity E (J.m^{-2}.°C^{-1}.s$^{-1/2}$)	779.56	743.33	758.00
Average Effusivity (J.m^{-2}.°C^{-1}.s$^{-1/2}$)		760.30	

3.3.2. Calculating the thermal conductivity of materials

Fig. 10 shows the regression straight lines of the curves showing the increase in temperature of the materials over the time interval between 100 and 150 seconds.
Table 4 shows the results for thermal conductivity and coefficient of determination (R^2), which are 0.99929, 0.99994 et 0.99983, demonstrating good linear regression. Thus, these values very close to unity of the coefficients of the regression lines indicate that the thermal conductivity values could be calculated from the equation of the lines. ThisTable shows the thermal conductivity of the three tests. It is equal to 0.43, 0.39 et 0.38 W.m^{-1}.K^{-1} with an average equal to 0.40 W.m^{-1}.K^{-1}.

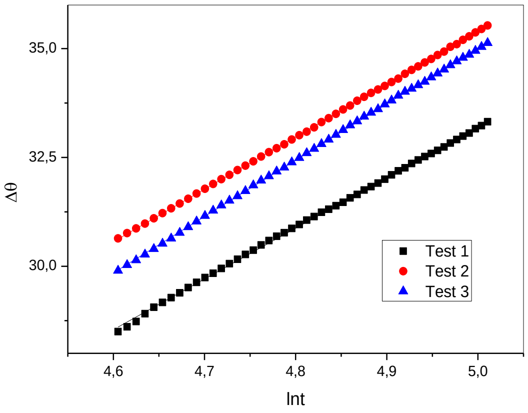

Fig. 9. Straight regression for temperature rise visualisation curves in materials for calculating conductivity λ

Table 6 : Results of conductivity determination

Tests	Test 1	Test 2	Test 3
Determination coefficient (R^2)	0.99929	0.99994	099983
Thermal conductivity λ $(\mathrm{W.m^{-1}.K^{-1}})$	0.43	0.39	0.38
Average conductivity λ (W.m^{-1}.K^{-1})		0.40	

The thermal conductivity of certain materials is shown in Table 6. From the results obtained, the insulating panels made from coconut palm fibres have a low thermal conductivity compared with certain materials including plaster (0.53 W.m^{-1}.K^{-1}), glass (0.53 W.m^{-1}.K^{-1}) and reinforced concrete (0.53 W.m^{-1}.K^{-1}). But they are good insulators, like wood, with thermal conductivities ranging from 0.15 - 0.4 .W.m^{-1}.K^{-1}. However, a material does not have good thermal insulation properties when its thermal conductivity is greater than or equal to 1.7 W.m^{-1}.K^{-1}.

It should be noted that the materials used have lower thermal conductivities than Wood Fiber Plates [TS EN 13168] (0.035 W.m^{-1}.K^{-1}), Wood Wool Slabs [TS EN13171] (0.065 W.m^{-1}.K^{-1}), Expanded Perlite [TS EN 14316-1] (0.06 W.m^{-1}.K^{-1}) and Expanded Cork [TS 304 EN 13170] (0.045 W.m^{-1}.K^{-1}) [17].

Table 7 : Thermal conductivity for certain materials

Materials	λ (W.m^{-1}.K^{-1})	Characteristics
Copper	400	Excellent thermal conductor
Soft Steel	40	Good thermal conductor
Glass	1.35	Reinforced concrete
Reinforced concrete	2.3	-
Gypsum	0.53	-
Brick	0.3	-
Wood	0.15 – 0.4	Good insulator
Glass wool	0.03 – 0.05	Excellent insulator
Air	0.026	-

3.3.1. Calculation of thermal diffusivity of materials

Table 4 shows the results for thermal diffusivity and coefficient of determination (R^2), which are 0.99187, 0.99446 et 0.9950, demonstrating good linear regression. Thus, these values very close to unity of the coefficients of the regression lines indicate that the thermal diffusivity values could be calculated from the equation of the lines. This Table shows the thermal diffusivity of the three tests. It is equal to 2.98.10^{-7}, 2.73.10^{-7} et 2.48.10^{-7} m^2.s^{-1} with an average equal to 2.73.10^{-7} m^2.s^{-1}.

Table 8 : Results of thermal diffusivity determination

Tests	Test 1	Test 2	Test 3
Determination coefficient (R^2)	0.99187	0.99446	0.9950
Diffusivity (m^2.s^{-1})	2.98.10^{-7}	2.73.10^{-7}	2.48.10^{-7}
Average diffusivity (m^2.s^{-1})		2.73.10^{-7}	

4. CONCLUSION

Coconut palm fibres could be transformed into insulating panels with proven insulating properties. Their thermophysical characteristics are a very important criterion in assessing their thermal performance. These parameters provide indications for a judicious choice of insulating materials with a view to reducing heat transfer. Given the results obtained for calorific value, thermal conductivity, effusivity and thermal diffusivity, it can be stated that coconut palm fibres are potential precursors for insulating panels. The calorific value varies from 3668.0 to 4135.0 and from 3742.0 to 4186.0 cal.g^{-1} when the moisture content is 11.28 and 10.61%, respectively. The thermal conductivity, effusivity and thermal diffusivity are 0.4 W.m^{-1}.K^{-1}, 760.30 J.m^{-2}.°C^{-1}.s$^{-1/2}$ and 2.73.10^{-7} m.s^{-1}, respectively. Based on the results obtained, the characteristics of the insulating panels in the present work could be improved to take them from a good insulator to an excellent one.

From an ecological point of view, the base material can make an effective contribution to limiting greenhouse gas emissions and protecting the environment.

COMPETING INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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