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Thermal Properties of Chipboard Panels Made of Sugar Cane Bagasse (*Saccharum officinarum* L)

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The sugar cane bagasse is the most abundant agricultural residue produced in Brazil. It can be used for the production of chipboard panels and as constructive components for several types of environments. The substitution of timber for the bagasse minimizes environmental impacts and contributes to the generation of a new product with lower density and lower thermal conductivity which can improve the thermal conditioning of buildings. This study aims at determining the heat flow through chipboard panels made of sugarcane bagasse and comparing these chipboard panels with similar ones made of *Pinus* and *Eucalyptus*. The results show that the heat flow during the heating of the panels is lower for the panels made of sugar cane bagasse and the heat accumulation promoted by this panel is greater than by others. Therefore this product may be suitable to be used as liners, between cavity walls, partition walls and more.

Keywords: *sugar cane bagasse, chipboard panel, environmental comfort, heat flow*

1. Introduction

The quality of the environment has a direct impact on quality of life and health. The thermal properties of materials composing the buildings should provide comfort to the environments however it usually does not happen.

Research on thermal performance of buildings are aimed at sub-coping structures[1-3]. It is important to study about construction elements that can promote thermal comfort between adjacent environments. The *"dry wall"* technology, which uses structured panels to divide environments, has been used by major construction companies to lower costs and delivery of housing units in time. However, these elements are usually devoid of treatments to minimize thermal discomfort that they cause in a country like Brazil, with such different climates and amplitude of thermal fluctuations. In a study evaluating the thermal comfort of ceramic flooring[4] the author emphasizes the importance of reducing the discomfort when in contact with cold floorings. For this, the possibility of reducing this discomfort by incorporating refractory raw material to ceramics has been studied.

The creation of efficient and environment friendly components for building, using alternative materials such as the sugarcane bagasse should be considered, since Brazil is the largest producer of sugar cane and the only country that has mastered the technology for the entire chain production with awell organized production[5]. In the 2010/2011 harvest, sugarcane production reached 570 million tons[6]. Each ton of sugarcane produces on average 259 kg of bagasse[7]. Nevertheless, Brazil still does not use the bagasse to produce chipboard panels on industrial scale. Countries such as China and the U.S. produce and market the chipboard panels made of sugar cane bagasse since 2001[8]. In India this occurs since 1950[9].

Materials derived from agricultural residues, in general, may be used in the manufacturing of chipboard panels, as they minimize environmental impact and are natural substitutes for wood for this purpose. These panels may be manufactured with any lignocellulosic material that presents chemical composition similar to wood. Studies have proven the panels produced in labs with sugar cane bagasse and biodegradable, renewable and non-pollutant agglutinant such as the polyurethane resin based in castor bean oil obtained mechanical properties values that are equivalent to the boards manufactured in industrial scales, based on wood particles, with density varying between 0,9 and 1,0 g/cm^3[10,11].

Battistelli et al.[12] studied sugar cane bagasse and the stem leaf fibers from bamboo as raw material to produce chipboards. The results showed satisfactory values regarding elasticity and rupture, according to the utilized standard. They also elucidated that the porosity of these boards may contribute to obtain thermal and acoustic comfort in the household, emerging as the new construction material for indoor sealing.

The use of chipboard panels, which in Brazil today is primarily intended for the furniture industry[13], can

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be extended and adequate to new comfort functions, considering the bagasse as raw material for the panel. Because of its low density and thermal conductivity, it is characterized as an insulating material and it can be used in the settlement of floorings, between cavity walls, as filling for raised flooring, partition walls and sub-copings, with the function of promoting the thermal inertia for environments needing it. Among the project strategies to achieve mechanisms of passive heating and cooling in a building are its shape and dimensions, orientation, size and number of openings and the materials used, which can have both the ability of thermal accumulation and insulation. This thermal capacity can be understood as a response or reaction of these materials to the application of heat. The heat flow expresses the behavior of these panels regarding this.

The aim of this study was to determine the heat flow of chipboard panels made of sugar cane bagasse and to compare them with similar panels made of *Pinus* and *Eucalyptus* in order to identify potential applications in improving the thermal conditioning of several types of environment.

2. Material and Methods

For this study, chipboard panels made of *Pinus* and *Eucalyptus* which are sold in Brazil, and the panels made of sugar cane bagasse which are marketed in China were used. These panels had their apparent density and humidity determined. Figure 1 illustrates the assembly sequence used in this experiment.Three cubic modules were built (Figure 1A), each module made from a different species that was studied,with dimensions of 600 mm for the edge and 15 mm thick. Five tops were manufactured for each module and the average of eachmeasurement was used to represent the behavior of each species. These cubic dimensions were proposed in order to obtain the most homogenous heat distribution in the center of the module. The gable with 600 mm was chosen so the model's final dimension was adequate to the necessary handling for the experiment, as moving the modules, changing the tops, installation and setting of sensors and instruments used through the essay. These modules were coated internally with 15 mm foam and with aluminized reflector blanket (consisting of five

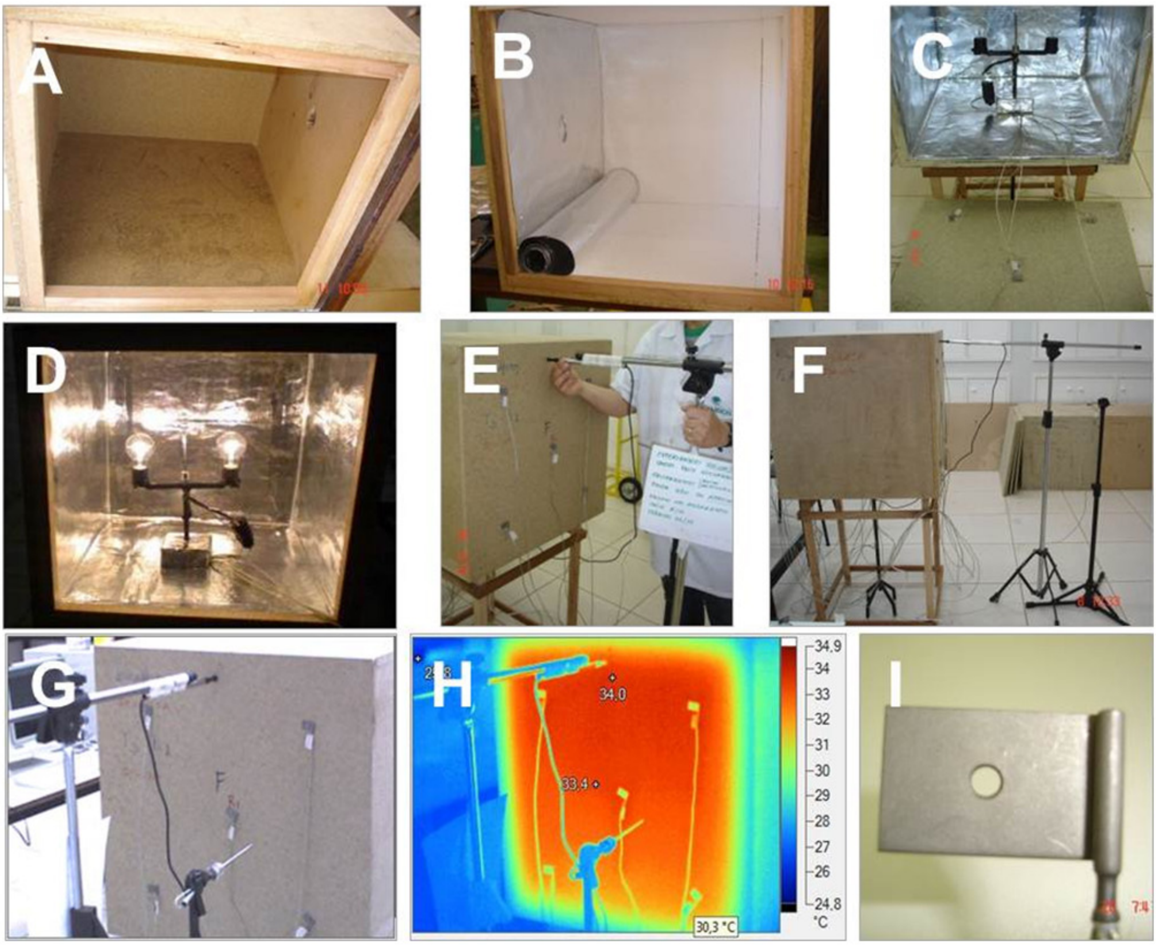

Figure 1. Assembly sequence of the experiment, in which: (A) module ready; (B) internal coating with foam and aluminized blanket; (C) device containing the heat source turned off and the sensor attachment on the inner face of the lid; (D) device containing the heat source turned on; (E) placement of sensors on the outside and hot wire thermo-anemometer; (F) final assembly of the experiment; (G and H) thermographic photo with color alarm deactivated and activated, espectively; (I) detail of the contact sensor type k with the attachment plate.

layers and reflection of approximately 90%), as shown in Figure 1B. Only the lids were not coated, as they received temperature sensors. A device containing two 25 W lamps was positioned in the central part of the internal module (Figures 1C and 1D), to act as the heat source inside.The setting of the heat source, as well as the use of sensors inside and outside the modules was based on the methodology used by Daré[1], and adapted to the specific objectives of this experiment.Contact sensors type K were installed (in detail in Figure 1I) on the internal (Figure 1C) and external (Figure 1E) faces of the lids, following the same position, with two sensors on top, one at the center of the panel and two at the bottom. Also environment sensors type K were placed inside (between the lamps, Figure 1C) and outside (Figure 1F) module. These sensors were connected to a *data logger* (by *Yokogawa*) that received the signals sent, converted and recorded temperatures, per minute, in °C. The assay time length, 180 minutes was determined to stabilize the temperature as 50 °C. A hot wire anemometer term (by *Extech Instruments*) was used to record the change of the air speed near the panel during the test, as shown in Figure 1F. The lids on the modules were photographed with a thermographic camera (by*Fluke*) to record the temperature distribution on the surface of the panels (Figures 1G and 1H).

The method used was the free fluid convection (air) confined to the system (control volume) composed by a module subject to the temperature gradient generated within the system. The objective was to determine the heat flow q" (W/m^2) passing through the panel by calculating the rate of heat transfer q (W) of the flat surface constituted by the lids of the panels. The model used was based on free convection, wherein the equations that describe the heat transfer originate from the principles of conservation of energy and thrust forces maintain keeping the flow. Relating the equations [14-16] known by Fourier's law and by Newton's equation of cooling, the equation that determines the rate of heat transfer q (W) was calculated, as shown below:

$$q = \rho \cdot c_p \cdot V \cdot \frac{\Delta T}{\Delta t} + \frac{T_{int} - T_{ext}}{\frac{e}{k \cdot A} + \frac{1}{h \cdot A}} \quad (1)$$

In which:

- Q: rate of heat transfer (W);
- ρ: air density (kg m^{-3});
- c_p: specific heat in the air (kJ kg^{-1} °C^{-1});
- V: control volume (m³);
- ΔT: temperature variation (°C);
- Δt: time variation (s);
- T_{int}: average internal temperature (°C);
- T_{ext}: average outdoor temperature (°C);
- e: thickness of the panel, equal to 0.015 m;
- *k*: thermal conductivity of the panel (W m^{-1} °K^{-1});
- A: heat transfer area of the plate (m^2);
- h: heat transfer coefficient by convection (W m^{-2} °k^{-1}).

The values of thermal conductivity *k* (W m^{-1} °K^{-1}) of the chipboard panels made of Pinus and Eucalyptus were obtained through the standard[17]; and the thermal conductivity of the panels made ofsugar cane bagasse was calculated through an assessment conducted at theLaboratório de Meios Porosos e Propriedades Termofísicas do Departamento de Engenharia Mecânica da Universidade Federal de Santa Catarina (Laboratory of Porous Means and Thermophysical Properties in the Department of Mechanical Engineering at the Federal University of Santa Catarina), in accordance to the standard ASTM C177-10 (2004)[18].

For the calculation of ρ, one can use the Equation 2[19].

$$\rho = \frac{1}{\left(\frac{R \cdot T}{P}\right) \cdot \left(\frac{1 + 1.6078 \cdot W}{1 + W}\right)} \quad (2)$$

In which:

- ρ: air density (kg m^{-3});
- R: gas constant (287.05 J kg^{-1} K^{-1})
- T: air temperature (K);
- P: atmospheric pressure (N / m^2);
- W: mixing ratio (kg kg^{-1}).

and W (kg kg^{-1}) can be expressed by Equation 3.

$$W = 0.62198 \cdot \frac{p_w}{P - p_w} \quad (3)$$

Where:

- p_w: vapor pressure (N m^{-2});
- By Equation 4 it is possible to determined p_w.

$$p_w = \phi \cdot p_{ws} \quad (4)$$

being

- ϕ: relative humidity of the air(decimal);
- P_{ws}: partial pressure of air saturation (N m^{-2}).

According to Albright[19], p_{ws} can be determined, for air temperatures between 0and 200 °C, by Equation 5.

$$\ln(p_{ws}) = \frac{-5.8002206 \cdot 10^3}{T} + 1.3914993 - 48.640239 \cdot 10^{-3} + 41.764768 \cdot 10^{-6} \cdot T^2 - 14.452093 \cdot 10^{-9} \cdot T^3 + 6.5459673 \cdot \ln(T) \quad (5)$$

The specific air heat (c_p) can be calculated by Equation 6, for the air temperatures ranging from 250 ≤ T ≤ 2000K, with an error of 0.25%[16].

$$c_p = 1.03409 - 0.2848870 \times 10^{-3} . T + 0.7816818 \times 10^{-6} . T^2 - 0.4970786 \times 10^{-9} . T^3 + 0,1077024 \times 10^{-12} . T^4 \quad (6)$$

The coefficient of heat transfer by convection (h) can be determined by Equation 7.

$$h = \frac{\overline{Nu_L} \cdot K}{L} \quad (7)$$

being

- $\overline{Nu_L}$: Nussel number (dimensionless);
- L: plate length (m).

For free convection, $\overline{Nu_L}$ can be determined by the expression 8[19]**.**

$$\overline{Nu_L} = \left\{ 0.825 + \frac{0.387 \cdot Ra_L^{1/6}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}} \right\}^2 \quad (8)$$

Where:

- Ra_L: Rayleigh number (dimensionless);
- Pr: Prandtl number (dimensionless).

The Rayleigh number can be calculated by Equation 9.

$$Ra_L = Gr_L \cdot \Pr = \frac{g.\beta \cdot (T_s - T_{ext}) \cdot L^3}{\nu \cdot \alpha} \quad (9)$$

Where:

- Ra_L: Rayleigh number (dimensionless);
- g: acceleration of gravity (9.81 m s^{-2});
- L: length of linear flow - vertical ascending (m);
- Ts: average surface temperature (°C);
- T_{ext}: air temperature in the free stream conditions (°C);
- β = coefficient of volumetric expansion;
- α: thermal diffusivity (m^2 s^{-1});
- ν: kinematic viscosity (m^2 s^{-1}).

The coefficient of volumetric expansion β can be calculated by Equation 10.

$$\beta = \frac{1}{T_f} \quad (10)$$

- In which T_f: film temperature (K).

The film temperature T_f is used when the surface and fluid temperatures are very different, being the arithmetic mean between these two (Equation 11).

$$T_f = \frac{T_s + T_{ext}}{2} \quad (11)$$

The Prandtl number expresses the ratio between momentum diffusivity and mass diffusivity and is expressed according to Equation 12.

$$\Pr = \frac{c \cdot \mu}{k} \quad (12)$$

Where:

- μ: dynamic viscosity of air (N s m^{-2});
- k: thermal conductivity of air (W m^{-1} K^{-1}).

The thermal properties of air μ k can be determined by Equations 13 and 14, with errors of 1.25% and 0.28%, respectively. Equations 13 and 14 can be used in temperature ranges from 1050K ≤ T ≤ 250 and 250 ≤ T ≤ 600K, respectively.

$$\mu = -0.98601 + 9{,}80125 \times 10^{-3}\,T - 1.17635575 \times 10^{-4}\,T^2 + 1.2349703 \times 10^{-7}\,T^3 - 5.7971299 \times 10^{-11}\,T^4 \quad (13)$$

$$k = -\,2.27650 \times 10^{-3} + 1.2598485 \times 10^{-4}.T - 1.4815235 \times 10^{-7}\,T^2 + 1.73550646 \times 10^{-10}.\,T^3 - 1.066657 \times 10^{-13}.T^4 + 2.47663035 \times 10^{-17}.T^5 \quad (14)$$

The thermal property α, which measures the relation between the ability of the material to conduct heat and its ability to accumulate this energy can be calculated by Equation 15.

$$\alpha = \frac{k}{\rho \cdot c_p} \quad (15)$$

The kinematic viscosity ν can be calculated by Equation 16.

$$\nu = \mu : \rho \quad (16)$$

The results of heat flow q''(W/m²) were obtained by dividing the rate of heat transfer q (W) calculated for each species by the lid area of the respective modules.

3. Results and Discussion

3.1. *Physical characterization*

Table 1 presents the average apparent density and humidity of the panels with their respective statistical parameters for the three studied species.

The chipboard panels made of sugar cane bagasse showed lower apparent density and humidity than the panels made of other species. These differences between the panels were already expected, since each type of panel was produced by a separate company and the processing variables, different in this case, directly influence their properties.

3.2. *Thermal characterization*

In Figure 2, Graph A illustrates the behavior of the temperature over time for the panels of the three species. Graphs B, C and D show the temperatures recorded during the first thirty minutes of testing, relative to the placement of the sensors on the panel for the studied materials.

The theoretical modeling based on free convection has proven to be adequate in relation to the methodology used as this physical phenomenon has been observed in all tests. Sensors located on top of the panels (internal and external top), recorded temperatures higher than those on the bottom (internal and external bottom) demonstrating this phenomenon. The internal sensors registered a temperature higher than those on the outside, indicating that the panels offered resistance to the passage for heat. Graph A shows the average temperatures recorded by the internal sensors throughout the test. The variation between the average temperatures of the internal modules showed similar trend between themselves, but the values observed for the modulus of sugar cane bagasse were noticeably higher than the others. The temperature inside the module

Table 1. Average values of apparent density and humidity of the panels.

Species	*Density*			*Humidity*		
	Average	*CV %*	*Deviation*	*Average*	*CV %*	*Deviation*
Pinus	*0,645*	*1,432*	*0,009*	*8,88*	*2,589*	*0,229*
Eucalyptus	*0,636*	*1,190*	*0,007*	*9,69*	*0,783*	*0,075*
Sugar cane bagasse	*0,543*	*1,127*	*0,006*	*8,08*	*1,107*	*0,080*

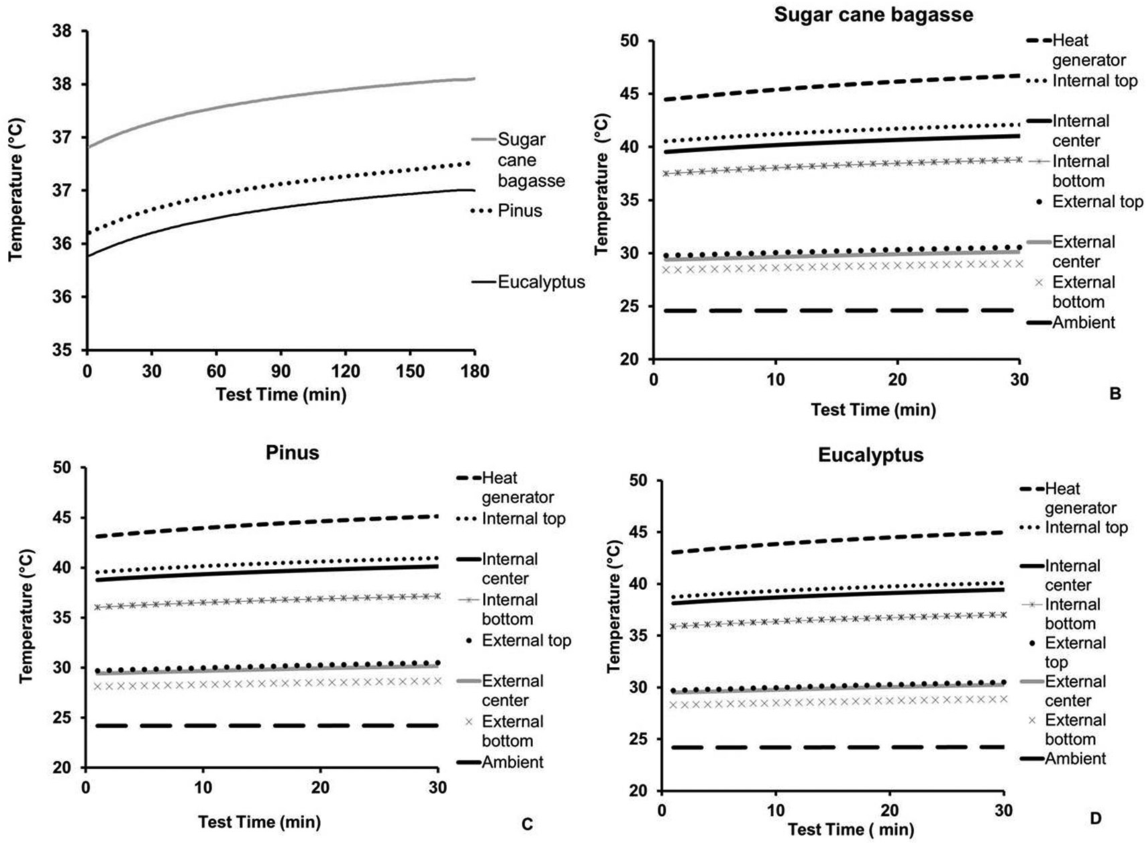

Figure 2. (A) behavior of the temperature throughout the test time for the three types of panel, behavior of the temperature in the first 30 minutes for the panel made of (B) sugar cane bagasse,(C) Pinus and (D) Eucalyptus.

of sugar cane bagasse remained higher throughout the test in comparison to other species. This behavior is consistent with their characteristic of low thermal conductivity, offering resistance to the passage of heat. The ability of this material to accumulate heat qualifies it as a good insulating material. In a study on thermal insulation by reflection[1], the author highlights the importance of these elements in the energy efficiency of urban and rural buildings and presents results of approximately 70% attenuationamong the roofs with sub-coping and the roofs without sub-coping. This is not a reflective material, but has high ability to accumulate heat. The use of a liner as a second barrier may reduce the transfer of heat into the building by up to 62% for a shelter with a single 6 mm Eucatex liner[20]. In a study on new concepts of materials for Brazilians poultry houses[21], the author indicates that to maintain the competitiveness of Brazilian poultry industry it would be necessary to adopt new architectural conceptions associated with more efficient thermal conditioning and responsive to different climatic and economic realities of each region. According to the author, the ideal liner must have both the ability to reflect incident heat as to isolate and internally retard its effects. For this, the use of liners or sub-copings with insulating materials may constitute an optimal protection against solar radiation. The panel made of sugar cane bagasse, absorbing heat during the day can at night, with the lowest temperature, dissipate this heat to the outside before they relay it to the inside. For environments with low thermal inertia, in cold climates, the usefulness of this type of panel has the opposite effect, maintaining the conditioning existing inside the environment, hindering in this case the output of heat. If the panel is not only used as a liner, but also as the coating between walls, it could minimize heat exchange between the building and the outside.

Although the capacity of the module made of sugar cane bagasse to accumulate heat is high and this value higher than others, their behavior in relation to heat flow was different during the assessment process. In Figure 3, the graphs E, F, G and H show the behavior of the species in relation to heat flow throughout the test and in each of the phases separately.

Graph E shows the behavior of the panels throughout the test. In graph F, it is possible to see that in the first thirty minute of the test, corresponding to the temperature from 0 to 42 °C, the panel made of sugar cane bagasse had a lower flow than the others. That is, up to this temperature, this panel showed insulating behavior, retaining more heat than dissipating it through the lid. As the power supplied to the modules made of the three species was the same, the module made of sugar cane bagasse took longer to be heated, therefore consuming more energy to reach 42 °C. Graph G shows that after thirty minutes of testing, such behavior has undergone inversion, with heat flow levels becoming higher in comparison to the panel made of *Eucalyptus*and very close to the one made of *Pinus*, until stabilization,

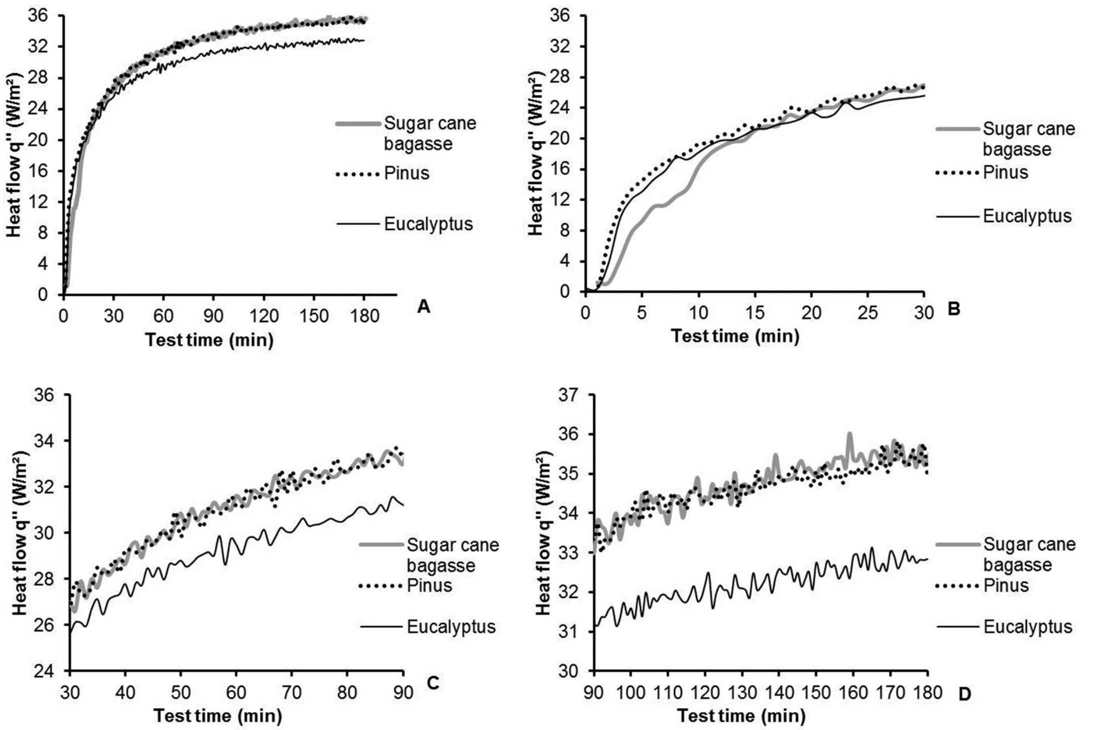

Figure 3. (A) behavior of the heat flow q "(W) throughout the test for the three types of panel, (B) behavior of the heat flow in the first 30 minutes of the test; (C) between 30 and 90 minutes of testing; (D) between 90 and 180 minutes of testing.

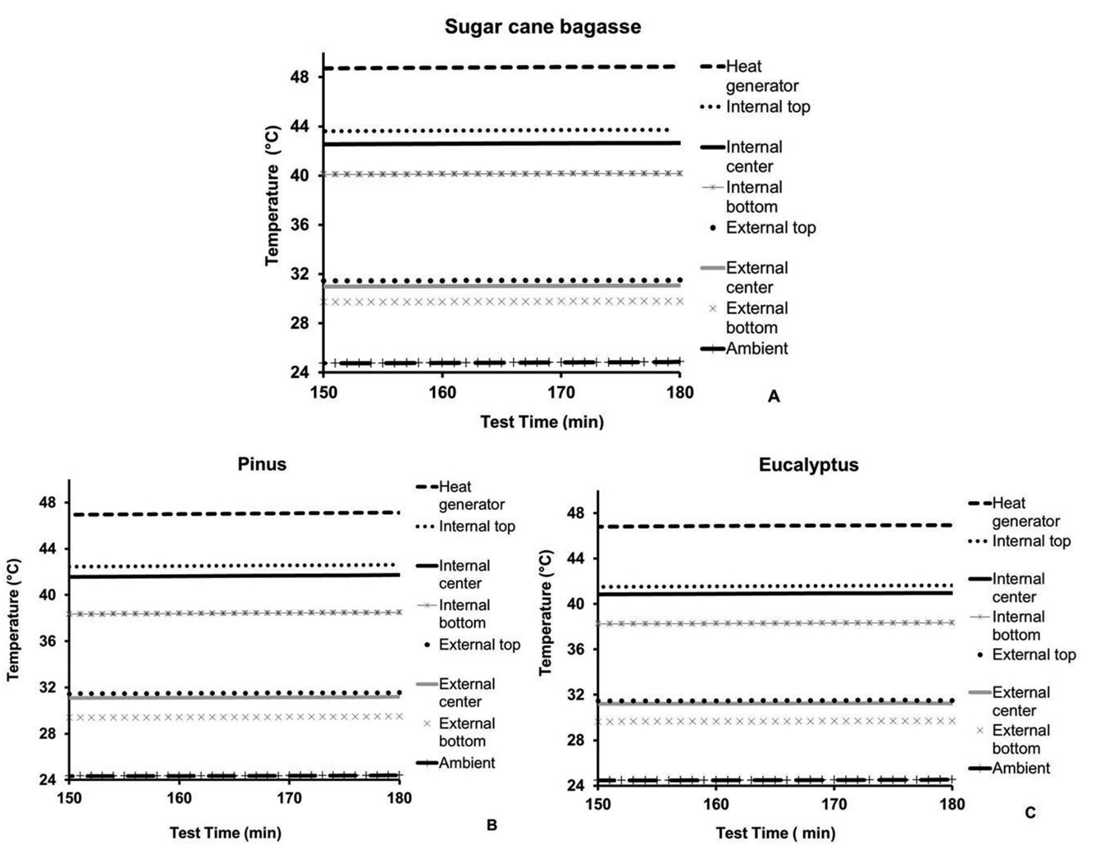

Figure 4. Temperature of the sensors within the last thirty minutes of testing for the species (A) sugar cane bagasse (B) *Pinus* and (C) *Eucalyptus*.

which is displayed on graph H. This demonstrates that the panel made of sugar cane bagasse has a temperature limit for its insulating behavior. It is important to highlight that throughout the test until temperature stabilization, at the 180th minute, there was no decrease in the amount of heat accumulated within the module made of sugar cane bagasse, even when it started to present a higher heat flow. Figure 4 illustrates the temperature stabilization of the sensors in all the collection positions within the last thirty minutes of testing for three species under study.

Graphs I, J and K show that in the last 30 minutes of testing, the stabilization temperature of the source of heat inside the module made of sugar cane bagasse was higher than the others, exceeding 48 °C, while the others did not reach this temperature. The graphs also show that the temperatures of the internal sensors recorded higher values for the panel made of sugar cane bagasse than for the other panels, while external sensors showed stabilization with similar values for the three species. As it was observed, there was reversal behavior of the heat flow from a certain temperature for the panel made of sugar cane bagasse, but there was no decrease in the heat quantity accumulated within the module, so it is possible to infer that the panel reverses part of this heat, demonstrating its ability to absorb heat. This retention capacity qualifies it as a good heat insulating material to be use in linings.

4. Conclusion

The panel made of sugar cane bagasse presented thermal behavior compatible with its characteristics of low density and thermal conductivity. In the thirty first minutes of testing, the panel made of sugar cane bagasse showed values of heat flow inferior than the other species, which have a higher density. The panel made of sugar cane bagasse has insulating behavior up to 42 °C. As for temperatures above this, the panel showed characteristics of retention of heat generated inside the module. Such elements qualify it as a good material to be used for linings, coatings and also as filling between dry-wall providing improved comfort in environments with low and with high thermal inertia.

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