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Thermal analysis of cement panels with lignocellulosic materials for building

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Abstract. The use of lignocellulosic material residue in cement composites can be considered as a good option because they allow good thermal behaviour. This paper aimed to compare three kinds of cement panels reinforced with different lignocellulosic materials (Coffee husk, Coconut shell, and Banana pseudostem) based on their thermal properties. To produce each panel, the methodology suggested by Souza (1994) was used. Six replicates of each lignocellulosic panel with dimensions of 7.0×7.5 were evaluated. The thermal analysis was performed in a chamber composed of MDP (medium density particleboard). The chamber contained the heat source (incandescent lamp) connected to a thermostat that maintained the temperature at 48.0 °C. The porosity and thickness of the panels and the thermal behaviour of each sample panel (thermal conductivity, resistivity, resistance, and transmittance) and the difference in temperature of both sides of the panel were evaluated. The temperature difference to stabilization was obtained after a sampling time of 200 minutes, with 1,000 readings of 12 s each. Although all the panels were submitted under the same temperature, the inner and external superficial temperatures of the coffee husk panels reached smaller values. Besides, coconut and banana pseudostem panels presented the best results of thermal transmittance and thermal resistance. Thus, coconut shell panels present the best thermal performance, which means that this panel might be an attractive alternative building material, in terms of heat insulation for indoor applications.

Key words: conductivity, thermal cameras, thermal transmittance, alternative building material, coffee husk, coconut shell, and banana pseudostem.

INTRODUCTION

Many studies have focused on the use of natural materials in buildings since these materials present high sustainability (Conti et al., 2017), they are relatively abundant and inexpensive (Castro et al., 2019). The engineering design of rural and civil buildings must take the availability of the local materials into account, encouraging wherever possible the use of natural materials that can be regenerated (Bambi et al., 2019). Nowadays, industries are focusing more and more attention on lignocellulosic based natural fibres as reinforcement for composites (Das & Chakraborty, 2006). The use of lignocellulosic material residues to produce cement composites used in building constructions is considered as a good option for new lignocellulosic cement formulations. Agricultural lignocellulosic material cement-based panels can be considered as alternative building materials because they allow a better thermal behaviour of the composite since they offer more significant potential for insulation (Teixeira et al., 2018).

Cement-bonded particleboards/panels are products manufactured from a mixture of Portland cement, chemical additives, and particles generated from lignocellulosic materials (Mendes et al., 2017). Increasing research are ongoing to develop environmentally friendly, sustainable and reusable composite materials (Alao et al., 2019). According to César et al. (2017), the basic principle of panel production is that most of the lignocellulosic materials may be used for panel production. Besides, these panels produced with raw materials present the following advantages: good fire resistance, good thermal and acoustic insulation, good resistance to fungus and insects attack, and they can be considered as good materials to work (Iwariki & Prata, 2007).

According to Barbari et al. (2014a) in less economically developed countries, it is challenging to access data on building materials to design the buildings properly. The outcome is the abandonment of natural materials in favour of more expensive materials but with inferior thermal characteristics and higher environmental impact (Barbari et al., 2014b). The concern with the energetic efficiency of the constructions has considerably increased in the last years considering that the majority of energy consumed comes from the residential buildings, with a predominance of heating and cooling systems. It culminated with an effective increase in the adoption of air conditioners (Doukas et al., 2006; Castro et al., 2019). Therefore, it is mandatory to look for solutions for alternative natural materials that can reduce the thermal conductivity of the building and improve thermal comfort. According to Topol et al. (2019), thermal comfort can be defined as the state of mind, which expresses satisfaction with the thermal environment, and it is an important aspect of the building design process.

This paper aimed to compare three kinds of cement composites panels reinforced with the following residues agricultural lignocellulosic materials: Coffee husk, Coconut shell, and Banana pseudostem based on their thermal properties.

MATERIAL AND METHODS

The experiment was carried out on the Federal University of Lavras (UFLA), Lavras, Brazil. Three different kinds of lignocellulosic composites were produced using: coconut shell (*Cocos nucifera*), coffee husk (*Coffea arabica*), banana pseudostem (*Musa acuminate*). Lignocellulosic materials were processed in a hammer-mill. The material particles were selected through a sieve and the fraction retained between 20 (0.841 mm) and 40 (0.420 mm) mesh was used to produce the composites.

For the calculations of the components of each panel (lignocellulosic material, cement, water, and $CaCl_2$, as an accelerator), the methodology suggested by Souza (1994) was used to determine the equivalent mass of components. In the production of panels, the following parameters were applied: material and cement ratio, 1:2.75; water and cement ratio, 1:2.5; hydration water rate of 0.25; additive, 4% (based on cement mass); the percentage of losses, 6%. The calculations were performed for a nominal panel density of 1.2 g cm^{-3}.

The mixture of the components was produced in a mixer, and the particulate materials were gradually added in order to obtain a homogeneous mixture. After mixing, the mass of each panel was properly separated, weighed, and randomly distributed in aluminum moulds of 480×480×150 mm. The moulding and stapling was carried out in a cold process for 24 hours, and then the panels were kept in a climatic room at a temperature of 20 ± 2 °C and 65 ± 3% relative humidity to ensure uniform drying for 28 days.

The determination of the density of the composites was performed according to NBR 11936 (NBR 1977). The density was calculated by dividing the mass (measured in analytical balance) by the volume calculated (base area multiplied by height, measured by calliper ruler). Porosity was determined following procedures described in the ASTM C 948 standard.

To determine the thermal properties of the lignocellulosic panels, a thermal chamber composed of MDP (medium density particleboard) of sugar cane bagasse (Fig. 1, A) was used. The chamber has two layers of coatings, styrofoam, and a thermal blanket, to isolate the external medium (Fig. 1, B). The lower part contains the heat source (incandescent lamp) connected to a thermostat that maintained the temperature at 48.0 °C. The system had four thermocouples: the lamp temperature controller, the ambient temperature, the temperature before entering the sample, and the temperature after exiting the sample, according to the methodology proposed by Gandia et al. (2019). The system was connected to an Arduino microcontroller that was programmed to collect and storage the collected data at every 5 seconds. To validate the system, the heat output was verified with an infrared sensor camera, Fluke TI55FT20/54/7.5, with an accuracy of ± 0.05 °C.

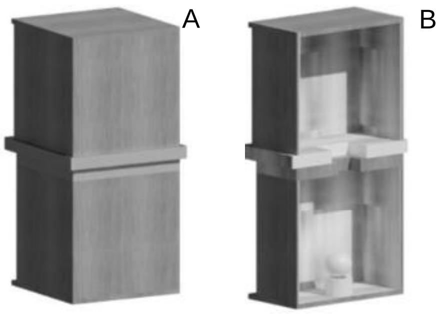

Figure 1. Schematic draw of the external side of the thermal chamber (A) and the internal side of the thermal chamber (B).

The thermal properties of the lignocellulosic panels were evaluated in six replicates of each lignocellulosic panel with dimensions of 7.0×7.5 cm at the 28 days age. The samples were assayed alone, and the material was exposed at temperature, around 48 °C. The heating rate was 1 °C min^{-1}. and the test cycle for each treatment was approximately 3.33 hours (200 minutes) with 1,000 readings of 12 seconds each.

The ISO 6946 (2017) and Evangelisti et al. (2015) describe a method for calculating the thermal resistance and thermal transmittance of building elements based on the electrical analogy. The equations below were used to calculate the thermal conductivity (Eq. 1), thermal resistance (Eq. 2), thermal transmittance (Eq. 3).

Thermal conductivity is the heat flow that passes through a unit area of a 1 m thick homogeneous material due to a temperature gradient equal to1 K (Schiavoni et al., 2016). The thermal conductivity was calculated using the following equation:

$$\lambda = \frac{P\,t}{\Delta T} \quad (1)$$

where λ – thermal conductivity in W m^{-1}K^{-1}; P – radiation of the heat source; t is the thickness of the sample panel in m; ΔT – difference between internal and external panels temperature (K).

The radiation of the heat source was determined by a solar radiation meter, Instrutherm model MES-100. Five samples were measured, and the mean value was 843.15 Wm^{-2}.

Thermal properties are expressed by thermal transmittance (ISO 6946, 2017), or U-value, which is the heat flow that passes through a unit area of a complex component or in homogeneous material due to a temperature gradient equal to 1 K (Schiavoni et al., 2016). The inverse of thermal transmittance is the thermal resistance, or R-value (Schiavoni et al., 2016).

According to Evangelisti et al. (2015), the thermal resistance is accordingly calculated using the following equations:

$$R = \frac{t}{\lambda} \quad (2)$$

$$U = \frac{1}{R} \quad (3)$$

where R – thermal resistance (m^2 K W^{-1}); t – thickness of the panel (m); λ – thermal conductivity (W m^{-1}K^{-1}); U – thermal transmittance value evaluated by the calculation method (W m^{-2}K^{-1}).

The data analysis of this study was evaluated in a randomized design. The results were submitted to analysis of variance (ANOVA) and Tukey test, both at a 5% significance level.

RESULTS AND DISCUSSION

According to Guillou et al. (2018), thermophysical properties are not as often reported, although they are essential for thermal applications of the composite and for modelling thermal behaviour. In this study, the thermophysical properties were calculated, and the results are shown in Table 1.

Thermal conductivity is the intrinsic property of a material that relates its ability to conduct heat and an indicator for determining if the sample can be used as a heat insulator (Vidil et al., 2016). This property is a function of several internal and external variables such as e.g. moisture, temperature, density, porosity, chemical and mineralogical composition and phase composition etc. (Muizniece et al., 2015; Têbl & Kic, 2016; Sair et al., 2019). The panel which presented the smallest thermal conductivity in this study was the coconut shell panel (0.0321 W m^{-1} K^{-1}). For thermal comfort, this low value is even more favourable, considering that buildings constructed with materials with lower thermal conductivity values imply milder temperatures inside the environments (Castro et al., 2019). Samples with lower thermal conductivity have better thermo-barrier properties (Hakkarainen et al., 2005). This low conductivity value can be explained by the lower density of the sample (0.984 g cm^{-3}). Usually, the lower the density is, the lower thermal conductivity is. Indeed, the lighter the boards, the more voids and the porous they contain, and the lower their thermal conductivity (Vidil et al., 2016).

Table 1. Thermophysical properties of the evaluated lignocellulosic panels

Material	t (mm)	Porosity (%)	Density (g cm^{-3})	λ (W $m^{-1}K^{-1}$)	U (W $m^{-2}K^{-1}$)	R (m^2 K W^{-1})
Coffee husk	16 [b] ± 0.6	52.5 [b] ± 9.7	1.267 [a] ± 79.757	0.0325 [b] ± 0.000	2.027 [a] ± 0.017	0.493 [b] ± 0.004
Coconut shell	16 [b] ± 0.3	62.8 [b] ± 2.7	0.984 [c] ± 82.010	0.0321 [c] ± 0.000	2.005 [b] ± 0.010	0.499 [a] ± 0.002
Banana pseudostem	17 [a] ± 0.8	87.5 [a] ± 2.7	1.003 [b] ± 22.055	0.0340 [a] ± 0.000	1.988 [b] ± 0.007	0.503 [a] ± 0.002
P value	0.000	0.0015	0.0024	0.0000	0.0002	0.0002
CV (%)	0.000	9.53	6.31	0.59	0.60	0.6

t – thickness of the panel (mm); λ – thermal conductivity (W $m^{-1}K^{-1}$); U – thermal transmittance value evaluated by the calculation method (W $m^{-2}K^{-1}$); R – thermal resistance (m^2 K W^{-1}).

Averages followed by the same letter in the line present statistical equality by the Tukey test at 5% significance. *The values in parentheses are standard deviation.

According to Wang (1988), a particleboard can be used as insulating components of building materials since its thermal conductivity is lower than 0.25 W $m^{-1}K^{-1}$. BS EN 13986 recommends thermal conductivities of 0.07 and 0.12 W $m^{-1}K^{-1}$ for panels with apparent densities of 0.300 and 0.500 g cm^{-3},respectively. So, the panels presented in this study do not meet the thermal conductivity requirement. Nevertheless, on the other hand, the produced coconut shell panel that presented the best conductivity value showed better values than the coconut husk panel described by Panyakaew & Fotios, (2011), who found values of 0.046 and 0.068 W m^{-1} K^{-1}.

Thermal transmittance (U) is an essential measure of heat loss through the material (Damdelen, 2019). According to Sánchez-Palencia et al. (2019), the thermal transmittance denotes how effective a building element is at preventing heat from transmitting through it. The U-value of the building material is the major factor in the determination of the steady-state heat losses and gains (UNI EN ISO 6946, 2008). It is also important to state that the thickness of the lignocellulosic panels is also a significant concept in U-value. There is a relationship between density, thickness, thermal conductivity, and U-value. When the density and thickness get more significant, the thermal conductivity and U-value increase (Demirboğa, 2003; Damdelen, 2019). However, all of the evaluated panels have similar thicknesses in this research, around 16 mm. Based on the evaluated panels, coconut shell and banana pseudostem presented similar U.

To evaluate a building's thermal comfort for occupants, the thermal resistance (R) is an important factor in defining the total energy consumption of heating and cooling systems (Desogus et al., 2011). With higher R-values, insulating effectiveness is more significant. The R-value depends on the type of insulation, including the material, thickness, and density (Peng & Wu, 2008). According to Table 1, coconut shell and banana pseudostem presented the highest R-values, which indicates that those materials present higher resistance to the heat-flux.

After analyzing the thermophysical properties of the evaluated lignocellulosic panels, an additional study has been carried out to analyze the heat flows exchanged between the internal (on contact with the heat source) and external (without contact with the heat source) panels surface. Surface temperatures and heat-flux rate through the test panels are shown in Fig. 2 and Table 2.

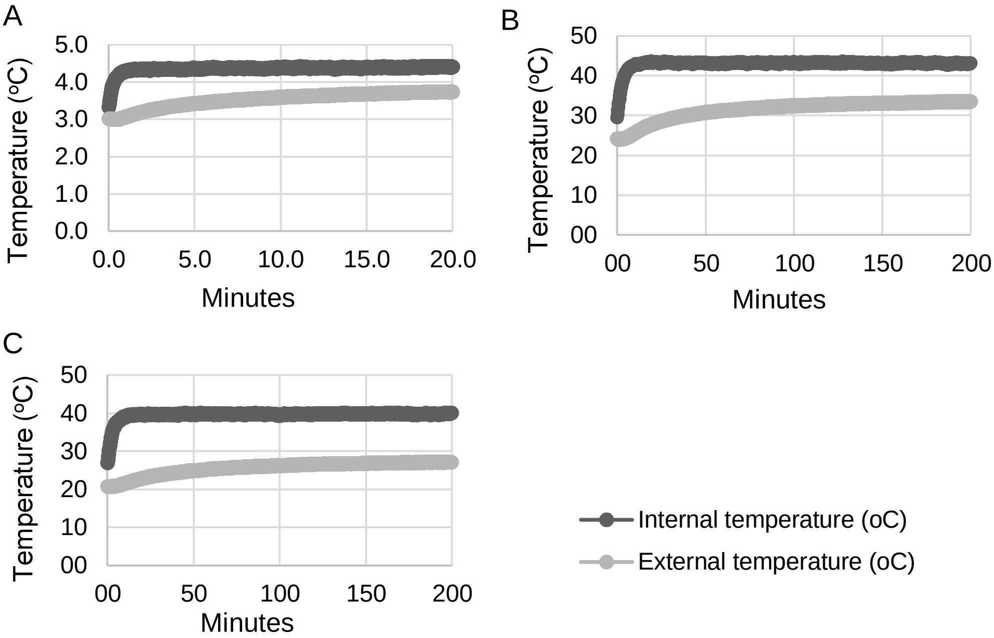

Figure 2. Internal and external temperature surface of the lignocellulosic panels (A) Coffee husk, (B) coconut shell, (C) banana pseudostem during 200 minutes of heat.

It is possible to observe that despite all the lignocellulosic materials being subjected to the same heat-flux, there was a difference in the internal and external temperature surface of the evaluated panels. Coffee husk presented the smallest difference between the external and internal temperature surfaces. According to Table 1, R-value of coffee husk was the smallest, which means the coffee husk panel presented a smaller resistance to the heat-flux.

On the other hand, Fig. 2 and Table 2 indicate that coconut shell and banana pseudostem presented no

Table 2. Difference between the internal and external temperature surface of the lignocellulosic panels (A) Coffee husk, (B) coconut shell, (C) banana pseudostem during 200 minutes of heat

Material	$T_{int} - T_{ext}$ (°C)	$T_{int} - T_{ext}$ (K)
Coffee husk	8.09^{b}	281.24^{b}
	± 2.36	± 2.360
Coconut shell	11.14^{a}	284.29^{a}
	± 1.37	± 1.367
Banana pseudostem	13.59^{a}	286.74^{a}
	± 1.08	± 1.076
P value	0.0002	0.0002
CV (%)	15.47	0.6

Tint – panel internal surface temperature. Text – panel external surface temperature. Averages followed by the same letter in the line present statistical equality by the Tukey test at a 5% significance.
*The values in parentheses are standard deviation.

statistical difference, and they presented the highest difference surface temperature and highest R-value (Table 2). The R-value is a measure of how well an envelope resists the heat-flow (Desogus et al., 2011). Based on these results, it is possible to affirm that Table 2 and Fig. 2 confirm the results of Table 1.

Fig. 3 allows us to compare the results presented by the difference between the internal and external superficial temperature of the panels. It is possible to notice that the surface temperature difference, in the three evaluated panels, becomes stable after a period. It is known that only some of the heat on the one side surface of building envelopes can be transferred into the building and arrive on the inside surface because of the thermal resistance of the building materials. The heat of one surface of building envelopes is not immediately transferred to the inside due to the thermal storage capacity of the building material (Peng & Wu, 2008). The results prove that all evaluated lignocellulosic composites can become an alternative biological building material because they offer significant potential thermal property (Teixeira et al., 2018). It is possible to conclude that it is very important to study the thermal dynamic properties of the lignocellulosic panels in order to optimize the choice of the envelope materials for maximizing the thermal comfort and energy performance leading to energy consumption.

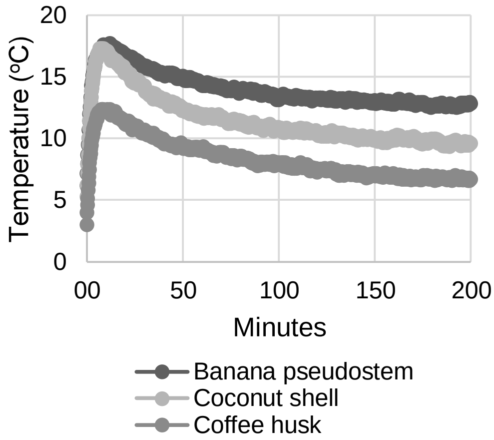

Figure 3. Difference of internal (in contact with the heat source) and external (without contact with the heat source) temperature surface of the evaluated lignocellulosic panels.

CONCLUSION

It was possible to investigate the thermal performance of the three cement-based composites properly reinforced with lignocellulosic materials (coffee husk, coconut shell, banana pseudostem) with satisfactory results.

According to the results of the current work, the coconut shell panel presented the best thermal conductivity (0.0321 W m^{-1} K^{-1}).

Besides, coconut and banana pseudostem panels presented the best results of thermal transmittance and thermal resistance. It indicates that coconut panel can be considered an alternative biological building material because they offer significant thermal properties.

The thermophysical properties evaluated can be considered useful tools for the study of the thermal behaviour of the lignocellulosic panels to be used in building constructions.

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