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Comparison between the thermal properties of cement composites using infrared thermal images

P.F.P. Ferraz[1,*], R.F. Mendes[2], G.A.S. Ferraz[1], F.A. Damasceno[2], I.M.A. Silva[2], L.E.V.S.B. Vaz[2], L.M. Mendes[3], D. Cecchin[4] and J.O. Castro[2]

[1]Federal University of Lavras, Department of Agricultural Engineering, Campus Universitário, PO Box 3037, Lavras, Minas Gerais, Brazil
[2]Federal University of Lavras, Department of Engineering, Campus Universitário, PO Box 3037, Lavras, Minas Gerais, Brazil
[3]Federal University of Lavras, Department of Forest Sciences, Campus Universitário, PO Box 3037, Lavras, Minas Gerais, Brazil
[4]Federal University Fluminense, Department of Agricultural Engineering and Environment, Campus Praia Vermelha, São Domingos, Niterói, Rio de Janeiro, Brazil
[*]Correspondence: patricia.ponciano@ufla.br

Abstract. The use of agribusiness residual lignocellulosic fibres can be a good alternative in the development of lignocellulosic composites. The current work aimed to investigate the thermal performance of cement-based composites with lignocellulosic materials: Eucalyptus, sugarcane bagasse, coconut fibre in comparison with commercial gypsum board to be used as internal partitions of the building using infrared thermal images. Three repetitions for each kind of lignocellulosic material were made, and three commercial gypsum boards were used. In the production of the 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 calculations were performed for a nominal panel density of 1,200 kg m^{-3}. The thermal analysis was performed in a chamber composed of MDP (Medium-Density Particleboard) and with an internal layer of rock wool and the heat source (thermal resistance). For the superficial temperature measurement, a FLIR E75 camera was used to capture the infrared images. When the internal temperature of the chamber stabilized at 50 °C, an infrared thermal image was collected from each side of the composite. Thermal properties were analysed: thermal conductivity, resistivity, resistance, and transmittance. Based on the results, sugar cane cement composites were characterized by higher values of thermal conductivity. Related to thermal resistivity, thermal resistance, and thermal transmittance, only the coconut panel presented similar behaviour to the commercial gypsum board. Thus, cement composite using coconut can be a potential alternative that might solve energy and environmental concerns simultaneously.

Key words: conductivity; thermal cameras; thermal transmittance, thermal analyses, alternative building material.

INTRODUCTION

According to Rheinheimer et al. (2017), heating and cooling system of U.S. buildings are responsible for 37% of the country's energy consumption. Similarly, in the

European Union (E.U.) buildings, 43% of the E.U.'s energy is used for air heating or cooling. According to the same authors in tropical and subtropical countries, the energy used only for air conditioning in buildings is approximately 50% of the country's energy consumption, and another 20% is consumed for ventilation. Bambi et al. (2019b) stated that rural areas are facing different challenges, and according to Barbari et al. (2014a), in these areas, especially in less economically developed countries, it is complicated to access to data on building materials, to design the buildings properly. The outcome is the realization of structures wrongly dimensioned or, in some cases, the abandonment of natural materials in favour of more expensive materials but with inferior thermal characteristics and higher environmental impact (Barbari et al., 2014b). Therefore, it is mandatory to look for solutions for alternative natural materials that can reduce the thermal conductivity of the building envelope.

Agricultural lignocellulosic materials on cement-based panels can be considered as alternatives building materials because they allow a better thermal behaviour of the composite since they offer more significant potential for insulation (Teixeira et al., 2018). The materials used for the build construction may allow good thermal insulation, so climatic variations less influence their internal environment. The use of lignocellulosic material residue in cement composites is seen as a good option for new fibre cement formulations (Cevallos & Olivito et al., 2015). Besides, according to Conti et al. (2017), many studies have been focused on the use of natural materials in buildings, since these materials present high sustainability. Fibre-cements manufactured with lignocellulose fibres have been commercially obtained thanks to technological advances in the raw materials, in the optimization of the production processes with rationalized energy consumption, and lower investment costs (Ardanuy et al., 2015, Wei & Meyer, 2015; Fonseca et al., 2019).

Residuals lignocellulose fibres occupy a special place in the development of fibre-reinforced cement and concrete, because of the abundance and availability of natural and waste fibres in many parts of the world. Besides, these materials can also lead directly to energy savings, conservation of a country's scarce resources, and reduction in environmental pollution (Sudin & Swamy, 2006). These natural fibres have already been considered as potential alternatives, given their ecological friendliness and ready availability in fibrous form and also, since they can be extracted from plant leaves at low cost, in the most of cases (Silva et al., 2008). Currently, cement panels with lignocellulosic fibres are applied in the manufacturing of roofing tiles, corrugated and flat sheets, sealing panels (walls) and other construction materials, mainly nonstructural thin boards (Fonseca et al., 2019). Although several works have been done on the mechanical properties of the composite containing lignocellulosic materials, few papers have been previously reported on the thermal analyzes. Therefore, the development of composite building materials with low thermal conductivity will be an interesting alternative that might solve energy and environmental concerns simultaneously (Benazzouk et al., 2008).

Infrared cameras can be used to evaluate the thermal properties of the lignocellulosic cement composites. The thermal cameras measure the amount of invisible heat energy emitted by surfaces and convert them into surface temperature, producing thermal images (Nascimento et al., 2011). This methodology had already been used in different scientific areas such as medicine (Raja et al., 2017), animal welfare (Castro et al., 2019), building materials analyses (Meola et al., 2015; Gholizadeh, 2016;

Zhang et al., 2016; Bambi et al., 2019a) and others. Infrared thermography is a safe, nondestructive, and low-cost technique that allows analyzing the thermal information obtained from a sample.

The current work aimed to investigate the thermal performance of three cement-based composites properly reinforced with lignocellulosic materials (Eucalyptus, sugar cane and coconut fibre) and commercial gypsum board to be used as in internal partitions of the building using infrared thermal images.

MATERIALS AND METHODS

The experiment was carried out at the Federal University of Lavras (UFLA), Lavras, Brazil. For the production of panels, the following lignocellulosic materials were used: Eucalyptus (*Eucalyptus grandis*), sugarcane bagasse (*Saccharum officinarum*), coconut fibre (*Cocos nucifera*) and commercial gypsum board.

A *Eucalyptus grandis* wood tree was obtained from local experimental cultivation at Federal University of Lavras – UFLA. Sugar cane (*Saccharum officinarum*) was obtained in a commercial cachaça distillery in Lavras – Minas Gerais state, Brazil. The coconut fibre (*Cocos nucifera*) is derived from local floriculture in Lavras – Minas Gerais state, Brazil. Moreover, three commercial gypsum boards were bought at specialized stores in the city.

Initially, the Eucalyptus wood was cut into short logs and passed through a laminator for delaminating. Sugar cane and coconut fibres were processed in a hammer-mill. The materials were dried in stoves until 12% of humidity. The particulate materials were sieved through a set of two superposed sieves with 0.50 mm (top) and 0.42 mm (bottom) particle sizes for fine contents (lower than 0.42 mm) removal.

Lignocellulosic cement panels were produced using the Eucalyptus, sugar cane and coconut. Three repetitions for each kind of lignocellulosic material were made. Furthermore, three commercial gypsum board ($CaSO. 2H_2O$) which satisfies the criteria of ASTM Methods C-36 (2004) with 15 mm of thickness were bought. Totalizing four treatments and three repetitions.

For the calculations of the components of each panel (lignocellulosic material, cement, water, and $CaCl_2$), 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 1,200 kg m^{-3}.

In order to produce each panel, components were weighed and then mixed in a concrete mixer for eight minutes. The total mass of components for three panels equivalent to each treatment (at the same time) was mixed. After mixing, the mass of each panel was separated, weighed, and randomly distributed in aluminum moulds of 480×480×150 mm. The moulding and stapling were carried out in a cold process for 24 hours, and then panels were kept in a climatic room at a temperature of 20 ± 2 °C and 65 ± 3% relative humidity to ensure uniform drying for 21 days.

To measurement of the thickness (mm) of each panel, it was used a calliper in 4 points in each sample. The dimensional size and weight measured were used to calculate the thickness and density of the composites. Density (kg m^{-3}) was calculated by the relationship between the panel mass (Kg) and the panel size (m³). All of these analyses were developed based on the ASTM standard method (ASTM D1037, 2016) and Deutsches Institut fur Normung – DIN (1982) standards.

The thermal analysis was performed in a chamber composed of MDP (Medium-Density Particleboard) and with an internal layer of rock wool. The lower part of the chamber contains the heat source (thermal resistance) connected to a thermostat that maintained the temperature at 50.0 °C. The system had two thermocouples: the resistance temperature controller and the ambient temperature. The thermocouple signals were digitized in real-time with a data acquisition board (cDAQ-9174, National Instruments, Austin, TX, USA) equipped with an analogue input module (NI 9211, National Instruments).

For the temperature measurement, a FLIR E75 camera, with 320 × 240 resolution and 0.03 °C thermal sensitivity, emissivity factor, $\varepsilon = 0.95$ was used to capture the infrared images. The measurements were done with a distance of 1.50 m between the sample and the camera.

When the internal temperature of the chamber stabilized at 50 °C (Bambi et al., 2019), an infrared thermal image was collected from each side of the panel. Initially, it was collected an image of the external side of the panel and then an image of the inner side of the panel that is the side in contact with the heat source. Three replicates were made per treatment (Eucalyptus, sugar cane, coconut, and gypsum board). The infrared thermography was used to measure the temperature of the panels using the FLIR Researcher IR software to obtain the mean temperature of the area.

Theory and modeling

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 (Gandia et al., 2019):

$$\lambda = \frac{P\,d}{\Delta T} \tag{1}$$

where λ – thermal conductivity in W m^{-1} K^{-1}; P – radiation of the resistance (836.45 W m^{-2}); d is the thickness of the sample panel in m; ΔT – difference between internal and external panels temperature (K).

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 inhomogeneous 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). The ISO 6946 (2017) describes a method for calculating the thermal resistance and thermal transmittance of building elements based on the electrical analogy. According to Evangelisti et al. (2015), the thermal resistance is accordingly calculated using the following equations:

$$R = \frac{d}{\lambda} \tag{2}$$

$$U = \frac{1}{R} \tag{3}$$

where R – thermal resistance (m^2 K W^{-1}); d – 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

In order to evaluate the measurements of the thermal properties of the cement composites with lignocellulosic materials, the results were compared with the commercial gypsum board. Gypsum board is a widely used building material that can be used for indoor applications (Butakova & Gorbunov, 2016). Gypsum boards are considered a material with good properties in terms of heat insulation, comply with the standards for fire safety and provide a pleasant room climate (De Korte, 2015; Butakova & Gorbunov, 2016; Schug et al., 2017).

During the thermal analysis, the ambient temperature was kept in 22 °C (± 1.2).

Fig. 1 shows the surface temperature distribution of the cement composites with lignocellulosic materials from external size measured by infrared thermography. Also, it shows the temperature distribution from the internal side (in contact with the heat resource). The colour scale is based on the variation of the surface temperature.

The thermal performance results of the evaluated panels are shown in Table 1. Thermal properties were analyzed, evaluating thermal conductivity, thermal resistivity, thermal resistance, and thermal transmittance. Overall performance depends on material type, thickness, and mass density of the material (Gandia et al., 2019).

The commercial gypsum board presented lower values of thickness and density in comparison with the other composites evaluated. According to Costes et al. (2017), the highest thermal performances are obtained with the lowest densities' materials. Moreover, the same occurred in this study, the gypsum board and the coconut cement composite presented the lower values of thickness and density. Consequently, they showed better thermal performance.

Table 1. Thermal properties of the evaluated panels

Material	Thickness (mm)	Density (kg m^{-3})	Thermal conductivity (W m^{-1}K^{-1})	Thermal Resistivity (K W^{-1})	Thermal Resistance (m^2 K W^{-1})	Thermal Transmittance (W m^{-2}K^{-1})
Eucalyptus	17 ^{b} ± 0.667	1,182.1 ^{c} ± 68.471	0.050 ^{a} ± 0.002	20.103 ^{b} ± 0.624	0.344 ^{b} ± 0.003	2.903 ^{a} ± 0.024
Sugar cane	17 ^{b} ± 0.845	1,172.1^{c} ± 82.297	0.058 ^{b} ± 0.003	17.295 ^{a} ± 0.899	0.345 ^{b} ± 0.003	2.900 ^{a} ± 0.027
Coconut	16 ^{ab} ± 0.269	984.3 ^{b} ± 82.010	0.047 ^{a} ± 0.001)	20.028 ^{bc} ± 1.672	0.333 ^{a} ± 0.000	3.007 ^{b} ± 0.002
Commercial gypsum board	15 a ± 0.030	1,608.0 ^{a} ± 30.000	0.045 ^{a} ± 0.000)	21.991 ^{c} ± 0.096)	0.330 ^{a} ± 0.001	3.032 ^{b} ± 0.013

Average followed by the same lowercase letter in the columns did not differ statistically by the Tukey test at 5% significance; *Values in parentheses are standard deviation.

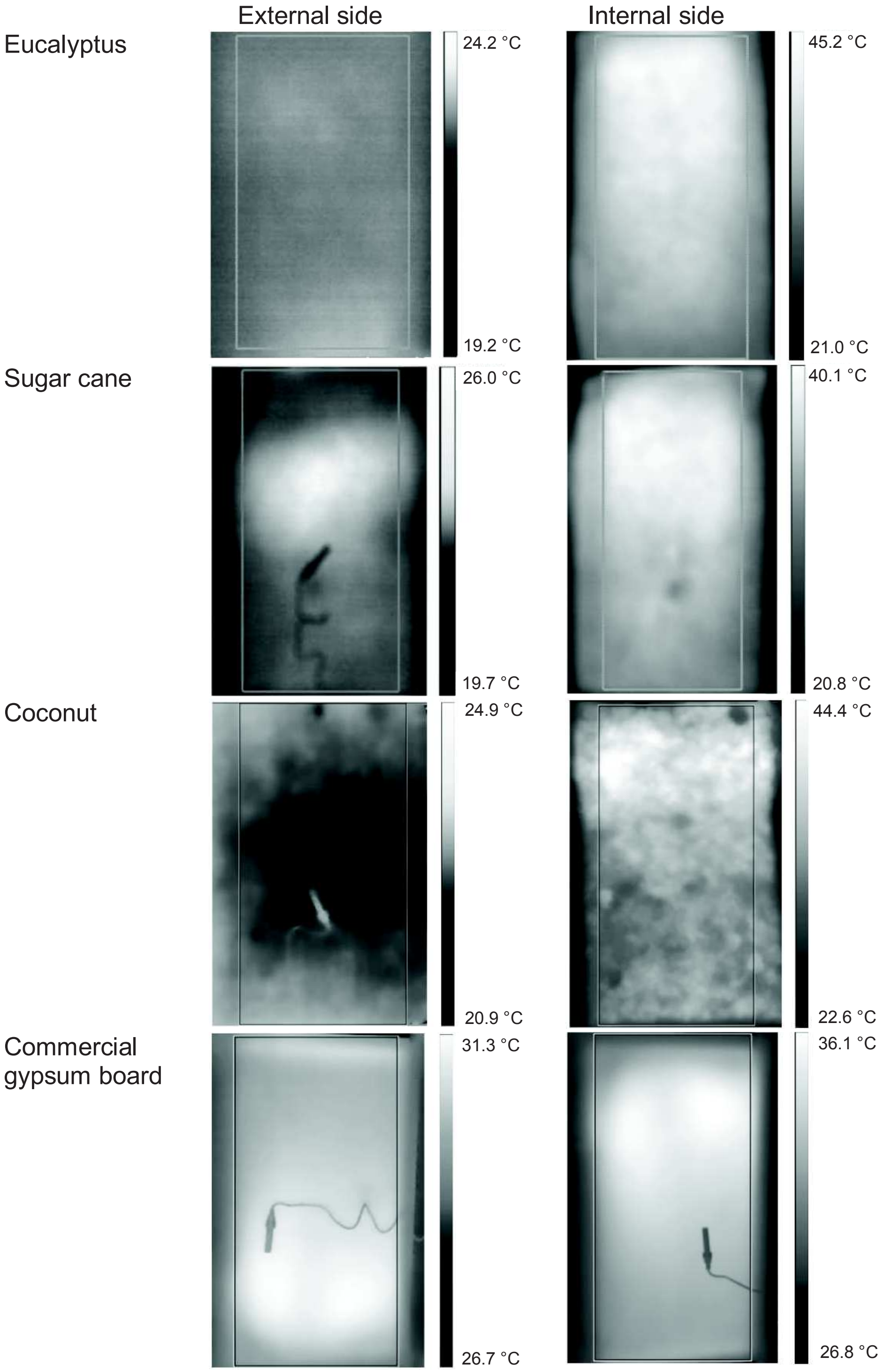

Figure 1. Infrared thermal images form external and internal sides of the panels based on the colour scale.

The highest density values of the composites were obtained for cement panels reinforced with Eucalyptus and sugar cane. It can be associated with the cement penetration into the permeable pores from the gaps and lumens found in the particles (Savastano et al., 2009).

Thermal conductivity is one of the most influencing factors on the performance of a building element (Schiavoni et al., 2016). It is evidenced in Table 1 that sugar cane cement composites panels were characterized by higher values of thermal conductivity. The commercial gypsum board, coconut, and Eucalyptus cement composite had similar thermal conductivity. Nevertheless, related to thermal resistivity, thermal resistance, and thermal transmittance, only the coconut panel presented the same behaviour to the commercial gypsum board. Higher thermal resistance values are obtained with lower thermal conductivity values.

According to Korjenic et al. (2011), the new approaches to energy efficient design are not only moving in the direction of lower thermal transmittance value to achieve lower energy consumption, but also the development and use of natural and local building materials.

Based on the thermal properties of the cement composites with lignocellulosic materials is possible to associate energy and environmental issues. The energy consumption required to heat or cool an environment is relatively higher in buildings with fewer insulation materials (Gandia et al., 2019). Therefore, based on the thermal analyses, a building constructed with coconut fibre might present energy expenditure to maintain thermal comfort similar to the commercial material widely used in the market (gypsum board). Besides, other advantage of the use of coconut fibre is that it is an extremely natural and ecological product (Bambi et al., 2018).

CONCLUSIONS

It was possible to investigate the thermal performance of the three cement-based composites properly reinforced with lignocellulosic materials (Eucalyptus, sugar cane and coconut fibre) and a commercial gypsum board using infrared thermal images.

According to the results of the current work, coconut presented the best thermal performance of the three cement-based composites properly reinforced with lignocellulosic materials evaluated (Eucalyptus, sugar cane and coconut fibre).

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