Agronomy Research **17**(S1), 923–934, 2019
https://doi.org/10.15159/AR.19.130

Measure of thermal transmittance of two different infill wall built with bamboo cultivated in Tuscany

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Abstract. Bamboo is used in different scenarios of application, its physical and mechanical characteristics guarantee a high flexibility of use especially in the buildings constructions. The experience gained in civil constructions demonstrates that bamboo can be considered a sustainable material able to replace wood in many constructive elements with structural functions. The applications of bamboo aimed at carrying out structural functions are thoroughly studied. For this reason the present research focuses on the thermal insulation performance. To ensure an approach focused on the sustainability of potential exploitation, the research examined only local material coming from three bamboo fields located in the Tuscany region (Italy). The material harvested and suitably treated was utilized for the realization of two different kind of wall, undergone later to experimental tests in compliance with the ISO 9869 standard for the calculation of the transmittance values. The measure of transmittance enabled to know the characteristics of thermal conduction of bamboo walls. The first wall was made of cut throw longitudinal axis bamboo culms; the second one was made of cut throw longitudinal axis bamboo culms coated in internal face with a sustainable mortar. The test was carried out using insulating thermal box with internal temperature under control.
The calculation of the transmittance in place was compared with the images captured by thermal camera. Thermal imagine allowed to highlight the behaviour of the material subjected to a thermal stress induced by the experimental test.

Key words: bamboo, thermal transmittance, thermal conductivity, sustainable building material.

INTRODUCTION

Europe has spearheaded global efforts to fight climate change, has been a driving force in developing renewables, and leads the world in energy-efficiency solutions for industry, transport, buildings. In order to build a major step in implementing the energy-efficiency-first principle for Europe, the main strategy consists the decarbonisation of the EU's stock in some sector such as building industry (EU, 2018). In addition, the transport system poses enormous potential to cut carbon dioxide emissions, but to do so it requires smart solutions and the approach of zero-km is cornerstone to reach these goals.

The growing human population on our planet in combination with an increase of consumption per capita is putting more and more pressure on global resources, which results in materials depletion, ecosystem deterioration and human health problems (Vogtländer et al., 2010).

The introduction of the concept of 'sustainability' in the building sector gradually led to the production of insulation products made of natural or recycled material. Some of them are already present in the market while others are still at an early stage of production or study. The actual sustainability of the considered insulation materials is linked to their availability. They should be used preferably where they are harvested, produced or manufactured (Asdrubali et al., 2015a).

In order to achieve this sustainable goal it is important to export this result also in developing countries. In rural areas, especially in less economically developed countries (LEDCs), it is very difficult to access to data on building materials, to properly design the buildings (Barbari et al., 2014a; Barbari et al., 2014b).

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 such as wood, raw earth, straw and other natural resources that can be regenerated, like bamboo.

The low thermal conductivity and fibrous character of the majority of organic materials contribute to a significant improvement of the thermal-insulation properties after incorporation in the structure of the exterior building envelope (Korjenic et al., 2011).

A great advantage of the insulation based on natural fibres is not only a low value of thermal conductivity but also the natural character of input fibres. Another advantage is that it is a renewable material, which does not place any significant strain on the environment (Zach et al., 2013).

The culm of the bamboo plant is used in rural and civil buildings in various parts of the world and is recognised as a material suitable for meeting various construction needs. Bamboo can be a valid alternative to classical wood construction material. Bamboos encompass 1,250 species within 75 genera, most of which are relatively fast-growing, attaining stand maturity within five years (Scurlock et al., 2000). The morphological, physical and mechanical characteristics make it a resistant and easily workable material. Bamboo is exploited according to the local culture and traditions, however its use as a building material with structural functions is restricted by local regulations that often undermine its effective use.

This work does not represent a survey on the mechanical characteristics of bamboo for which there is already substantial scientific literature, instead, it focuses on the study of the behaviour of bamboo as a material to be used in the building sector, favouring the function of thermal insulation in the creation of infill walls.

This research, after having identified a construction technique that is easy to perform, compares the thermal performances of two types of infill walls. In order to respect the sustainability criteria, the experimental tests have analysed bamboo coming from bamboo plantations found in the Tuscany Region, in the hope of being able to exploit this local material. The bamboo harvested has undergone a preservation treatment without intervening on the fibre structure. In order to take into consideration also the aesthetic aspect of the wall, a constructive system has been adopted that is able to preserve the natural appearance of the bamboo.

MATERIALS AND METHODS

Material

The chemical composition of bamboo is similar to that of hardwood, but it is characterised by the presence of alkaline layers. The mechanical strength is conferred by the presence of silica and cellulose, which perform a reinforcement function in the plant structure like that of steel inside reinforced concrete.

The thermal performance of raw bamboo and engineered bamboo composites materials was also investigated (Wang et al., 2018). All these studies demonstrated that:

- the thermal conductivity of bamboo increases with increase in density (Kiran et al., 2012),
- the specific heat capacity of raw bamboo increases with the temperature (Huang et al., 2016),
- the thermal conductivity and thermal diffusivity of raw bamboo is not constant along the radial direction (Huang et al., 2014).

Given the advantages compared to wood, it should be emphasised that one of the limits of bamboo concerns its natural durability which, compared to wood, may be more vulnerable to deterioration due to the absence of protective chemical elements, in addition to the presence of a hollow section that favours the colonisation of different pathogens capable of deteriorating the structure of the bamboo. To ensure greater durability it is essential to treat bamboo culms with preservatives and the effectiveness of these treatments depends above all on the penetration of the chemical products into the fabric of the culm. The outer part of the culms, moreover, which contains a high percentage of silica, forms a barrier for both insects and preservatives; the inner part is covered by a thin waxy layer, which is also waterproof.

The first phase of the research work identified 3 production sites located in the Tuscany region. These three bamboo plantations cultivate the same species, *Phyllostachys viridiglaucescens*, which is very rustic and able to adapt to the Tuscan territory. Three farms with a different aerial of cultivation in terms of altimetry and field slope were selected.

The samplings were carried out in October 2016 (Farm A), November 2016 (Farm C) and finally in February 2017 (Farm B) (Table 1).

Table 1. Description of sampling Tuscany farms

Farm	A	B	C
Coordinate (WGS84)	N 43.685131 E 11.205717	N 43.635049 E 11.172538	N 43.934574° E 10.266368°
Area (ha)	0.3	0,19	1
Ground level (a.s.l.)	205	121	35
Slope (%)	15	0	1

The culms taken from the plants were selected respecting the dimensional requirement to collect material with a diameter of about 7 cm at a height of 150 cm, the dimensional deviations have considered a tolerance of 1 cm.

All the material collected was free from pathologies, consequently the culms were subjected to a treatment with a 10% solution of borax ($Na_2B_4O_7 \cdot 10H_2O$) and boric acid (H_3BO_3) in a 1:1 ratio. The treatment of bamboo is not compatible with appropriate environment sustainability, but treatment agents are usable for several cycles. This treatment lasted 20 days and was necessary to eliminate the starch present in the stem (Mitch et al., 2009).

The culm of the plant can be divided into three sections that differ one from the other in the diameter and thickness of the stem. The apical section and the basal section are characterised by a morphological deformity that does not make them suitable for the selected construction technique. In fact, it is well-known that in the basal section there is a greater wall thickness (Fig. 1) and a slightly lesser external diameter than the central part.

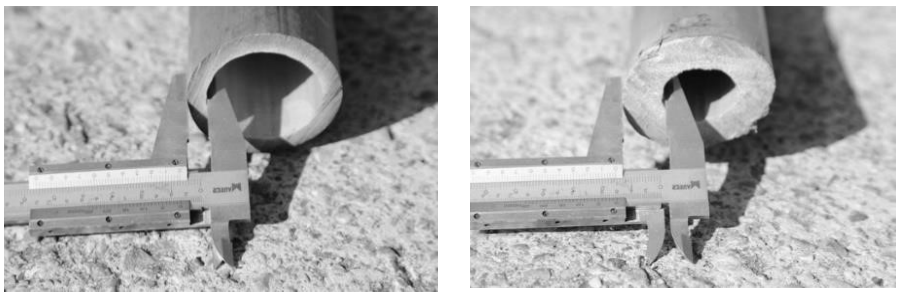

Figure 1. Wall thickness bamboo.

In order to obtain a homogeneous material, the culms were divided into three parts: a basal section of about 50–100 cm, a central section of 400–500 cm and an apical section of about 150–200 cm. At the end of the treatment period the culms were left to dry until achieving the characteristic brownish colour.

The construction technique chosen for the construction of the infill wall is similar to the one commonly adopted for the construction of bamboo roofs. This choice was based on two criteria. The first criterion is not altering the bamboo's natural condition to make it a construction material suitable for use in compliance with Design for Deconstruction (DfD). This is a concept in building science, which has the potential to improve the management of construction waste and thus contributes reducing the environmental impact of a building (Leso et al., 2018). The second criterion is adopting a construction technique capable of preserving the aesthetic features.

The selected and dried culms were cut along their longitudinal axis. This type of cut produced two elements from each individual culm characterised by a natural morphological deformity due to the nature of the plant. The half culms had their nodal diaphragms removed in order to allow for the coupling in the concave part as illustrated in Fig. 2.

Figure 2. Technique construction of bamboo roofs.

The second phase of the research identified the system for detecting the thermal performance. The thermal resistance measurements were made according to the guidelines of the UNI EN 1934:2000 and ISO 9869:1994 standards; the UNI EN 1934 standard thermal performance of buildings. Determination of thermal resistance by means of the hot chamber method with a thermal flow meter does not univocally specify the experimental apparatus to be used, leaving room for the operator to make any changes deemed necessary from time to time (Buratti & Moretti, 2008). For this purpose a metering chamber was constructed, adopting the design criteria indicated by Conti et al. (2017). The Metering chamber was equipped with heaters and ventilation systems in order to produce high temperatures. The internal dimensions of the chamber were 178 cm in length by 112 in width and 40 cm in height.

The metering chamber consisted of a central body, a removable rear wall and a specimen wrapper on the front. The connections between the walls were glued and assembled with a labyrinth shape, in order to avoid heat leakage. The specimen wrapper, designed to contain the specimen, protruded from the front wall. The heating system was installed inside the metering chamber and contained inside a box that acts as an infrared radiation trap which prevented the infrared radiation from directly hitting the specimen or the metering chamber walls. The internal box had an inlet and an outlet for proper air ventilation in order to transfer the heat outside the box and inside the metering chamber. The walls of the metering chamber and the specimen wrapper were made of polystyrene panels (BASF Styrodur) with a nominal thickness of 50 mm. The panels were coupled by means of vinyl adhesive along the entire contact surface to form a 100 mm nominal thickness wall. Polystyrene BASF Styrodur 50 mm thick panels have a 28 kg m^{-3} density. The Thermal Conductivity (λ) declared by the manufacturer is $\lambda = 0.034$ $Wm^{-1}k^{1}$ (at the mean temperature of 10 °C, for panels with a 20–70 mm thickness).

The experimental wall was configured as a separating element between the metering chamber and the external environment (room with a controlled temperature). The wall was created directly on the front of the chamber using 7 bamboo culms from the longitudinal cut of which we obtained 14 medium bamboo culms with a width of between 6.5 cm and 7.5 cm, and an average thickness of 0.5 cm. At the end of the execution the wall had the following dimensions: width 111.9 cm, height 39.9 cm and average thickness 6 cm. In Fig. 3 it is possible to see external face and inner face of the sample wall covered with bio plaster. In the external face two contact probes PT 100 were applied, in the inner face a heat flow plate and one contact probe PT 100 were placed.

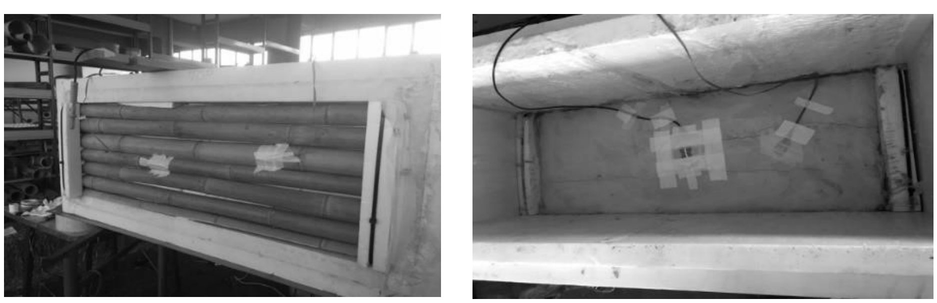

Figure 3. Experimental wall**.**

A thermal insulation paste was applied between the edge of the outside of the bamboo wall and the inner edge of the chamber in order to create a frame capable of preventing any heat loss. For the applicability of the method a temperature gradient was respected between the hot room and the environment that exceeded 20 °C.

Instrumentation

Currently, there are two common measurement techniques to evaluate the thermal resistance in existing buildings: direct measurement of the heat-flux, non-destructive method (Zarr, 2001; Cabeza et al., 2010), or direct survey of the fabric layers with direct measure of their thickness, destructive method (Asdrubali et al., 2014b). The non-destructive method requires the use of a heat flow meter that has to be operated according to the standard ISO 9869:1994.

Adopting the design criteria indicated by Evangelisti et al., (2015), the samples were previously monitored with thermographic surveys in order to asses the correct application of the sensors.

A preliminary thermographic analysis was carried out with the support of a FLIR TAU2 thermal imaging camera, which was used to capture the images of the two tests in order to highlight the critical points of the wall. The study of the images captured with thermal camera was conducted with the TermoViewer software.

The instrumental detection system for the survey was a Babuc A/M datalogger to which 3 contact temperature probes and a thermal flow meter probe were connected. On the inside wall of the sample a contact temperature probe BSR 124 and a BSR 240 heat flow plate were installed while the two other contact probes BSR 124 (PT100) were applied on the external wall (Table 2).

Table 2. Probe parameters

	Probe BSR 124	Probe BSR 240
Measuring Range	-50–70 °C	-50–50 Wm^{-2}
Accuracy	0.15°C	
Sensitive element	Pt100 DIN-IEC (EN6075)	Thermopile
Mechanics	Phosphorous Bronze flat probe	
Response time	10 s	
Cable	PVC flat (-15–75 °C)	
Operative temperature		-30–70 °C
Sensitivity (nominal)		0.050 mV $W^{-1}m^{-2}$
Resistance (nominal)		2 Ω
Temperature dependence		< 0.1% $°C^{-1}$

The internal temperature of the metering chamber was taken up to a temperature of about 50 °C and after a stabilisation period of 48 hours, the datalogger started recording the values of thermal flux and the temperature. The stabilisation period was monitored with PT 100 temperature probes placed inside the chamber and externally near the outer wall surface. The datalogger recorded the internal and external surface temperature of the wall and the flux-thermal value with a recording interval of 10 minutes. In order to compare the two types of wall, two tests were conducted, each of which had a duration of 210 hours equivalent to 1,260 measurements.

The values recorded by the datalogger were revised using InfoFlux developed by ANIT (National Association of Thermal and Acoustic Insulation) software which allows for calculating the thermal conductance, from which the transmittance value is derived. The experimental tests were performed so as not to have any significant thermal variations. This assumption allowed us to choose the progressive average method as the calculation method.

Once the opaque wall's stratigraphy and material properties are known, the U-value can be determined by the following equations:

$$R_{tot} = R_{si} + \sum_i \frac{d_i}{\lambda_i} + R_{se} \tag{1}$$

$$U_{design} = \frac{1}{R_{tot}} \tag{2}$$

where, U_{design} represents the thermal transmittance value evaluated by the calculation method (W $m^{-2}K^{-1}$); d_i the thickness of the i-th layer (m); λ_i its thermal conductivity (W $m^{-1}K^{-1}$); R_{tot} the total wall thermal resistance (m^2K W^{-1}); and R_{si} and R_{se} the interior and exterior surface resistances (K), respectively.

It is important to underline that the calculation method cannot be applied when the thickness and conductivity of each wall layer are not known (Choi & Jin Ko, 2017).

The progressive average method assumes that the U-value can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference, with the average being taken over a sufficiently long period of time that allows a good estimation of equivalent steady-state behaviour (Fokaides & Kalogirou, 2011; Simões et al., 2014). An estimate of the U_{PAM} Progressive Average Method can be obtained as:

$$U_{PAM} = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{i,j} - T_{e,j})} \tag{3}$$

where, U_{PAM} represents the thermal transmittance value evaluated by the progressive average method (W $m^{-2}K^{-1}$); n the number of measurement data; q_{ij} the density of heat flow rate (W $m^{-2}K^{-1}$); and $T_{i,j}$ and $T_{e,j}$ the interior and exterior ambient temperatures (m^2K W^{-1}), respectively (Choi & Jin Ko, 2017).

The first test was conducted by examining the wall without plaster; the second experimental test entailed the application of a bio plaster on the inner face of the previously analysed wall. Two sheets of untreated natural jute were applied to promote the sealing of the mortar and the overall thickness of the coating was 1.5 cm. Biocalce® Intonaco Kerakoll mortar was used to make the plaster, the test was carried out after respecting the drying times of mortar.

The calculations of the thermal performance took into account the provisions of the ISO 9869 standard that describes the heat flowmeter method for the measurement of measuring the thermal transmission properties (thermal resistance and thermal conductance from surface to surface, total thermal resistance and transmittance from environment to environment) of building components, primarily consisting of opaque layers perpendicular to the heat flow and having no significant lateral heat flow.

RESULTS AND DISCUSSION

The resulting graphs are collected in Fig. 4. They illustrate the behaviour of the wall during the conducting of experimental Test no. 1 which refers to the measurement of the average flow, average internal and external temperature and average conductance of the bamboo wall without plaster, and test no. 2. which refers to the same bamboo wall tested previously, but instead covered with plaster. Table 3 gives a summary of the results of the thermal analysis carried out by means of the progressive averages method.

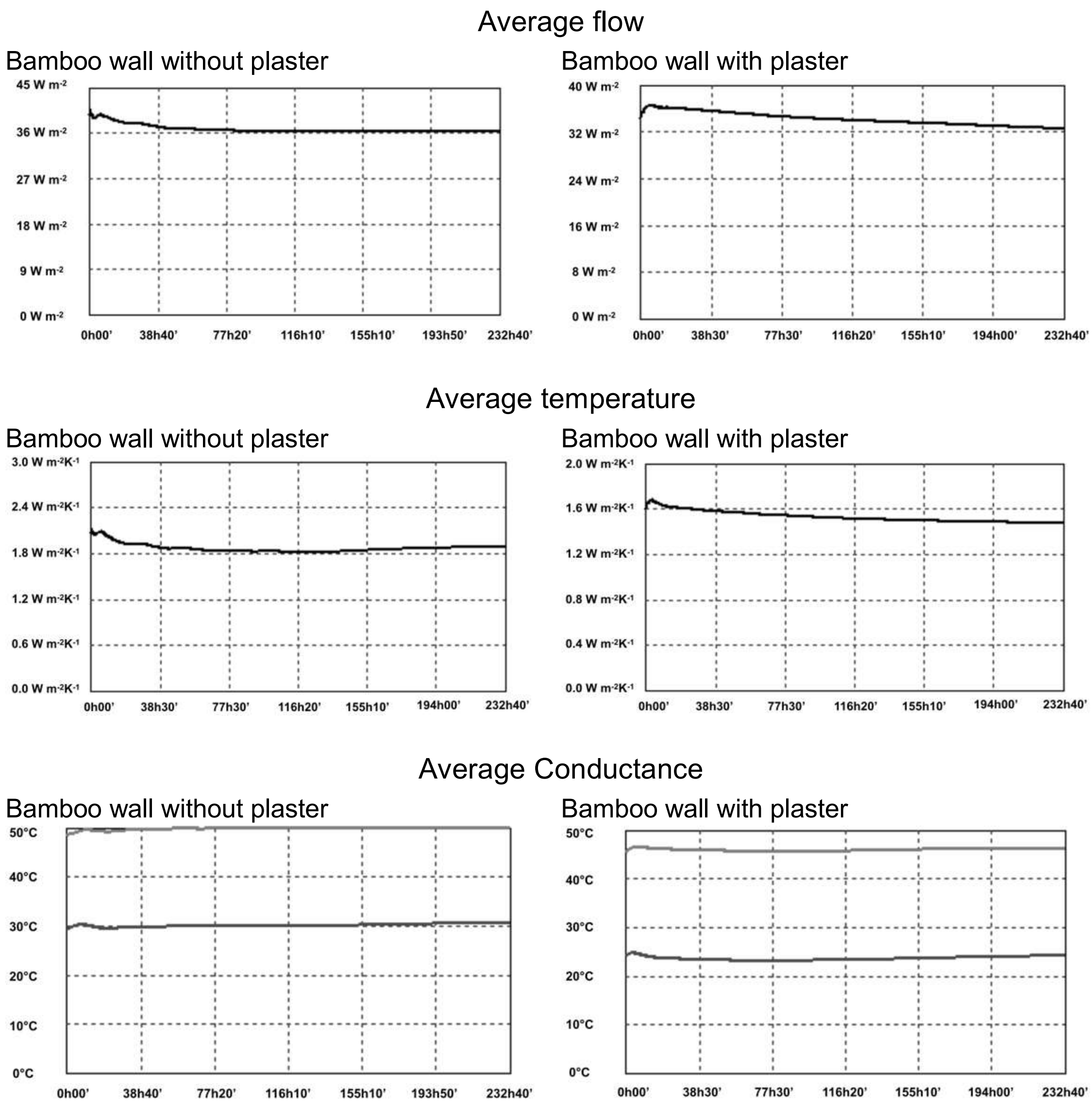

Figure 4. Resulting graphs test no. 1 without plaster, test no. 2 with plaster.

The comparison of the results obtained highlights the result in terms of different thermal insulation capacity between the two wall models tested. The plaster-coated wall recorded a better thermal insulation performance than the wall built with bamboo alone.

Experimental heat flux densities demonstrate that the heat transfer has been higher in the bamboo wall without plaster. More precisely, the heat transfer has been higher by a value of 0.4177 W $m^{-2}K^{-1}$ for conductance and 0.2528 W $m^{-2}K^{-1}$ for transmittance in the wall not covered.

The transmittance values of the bamboo wall covered with plaster was 1.178 W $m^{-2}K^{-1}$. This value does not deviate from the values of other natural materials such as clay wall thickness 6 cm, with U-value 1.56 W $m^{-2}K^{-1}$ (Goodhew & Griffiths, 2005), or light straw clay, that is a mixture of straw and clay, thickness 12 cm, with U-value 0.55 W $m^{-2}K^{-1}$ (Holzhueter & Itonaga, 2016). The thermal performances of bamboo are different from other natural materials such as straw. Shea et al. (2013) in a test for prefabricated straw bale panel measured a thermal transmittance of 0.190 ± 0.015 W $m^{-2}K^{-1}$.

Table 3. Results test no. 1 without plaster, test no. 2 with plaster

Test	1	2	
Measurements	1,260	1,260	Nr
Time step	10	10	min
Thermal flow	36.3912	32.5338	W m^{-2}
Inner wall temperature	49.8261	46.2919	°C
Outer wall temperature	30.5866	24.2171	°C
Conductance	1.8915	1.4738	W $m^{-2}K^{-1}$
Transmittance	1.4313	1.1785	W $m^{-2}K^{-1}$

Thermal resistance measurements can be wrong if structural abnormalities are found in the measuring points. For this reason, a preliminary thermographic analysis is required (Evangelisti et al., 2015).

The analysis made it possible to carry out a thermal mapping of the wall that allowed measuring the surface temperature through the pixels of the captured image. The images recorded in the two tests are illustrated in Fig. 5, the image on the left refers to test no. 1 and the one on the right to test no. 2.

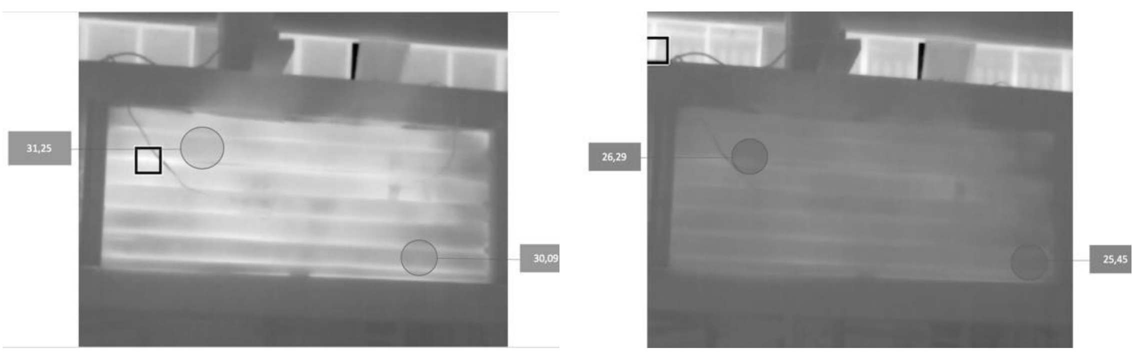

Figure 5. Thermal images of tested wall.

The chromium plating of the two images shown above also appears to be very different. On the whole, they show that the temperature of test no. 1 is higher than that of test no. 2, thus confirming a poorer insulating capacity. At the same time highlighting the presence of some heat dispersion point in the sample wall, it is possible to provide some information to detect the correct position of the probe in the wall.

CONCLUSIONS

Bamboo is a natural material which, due to its morphological characteristics can be used not only in constructions as a structural element, but that it can also have an insulating function as emerged from the tests carried out. Due to its easy of use and processing it can be configured as a material suitable for deconstruction, in addition to which the pronounced rusticity and speed of growth of bamboo allows its cultivation in numerous production areas.

The collection of the experimental material for the samples of bamboo wall, harvested in the same area of cultivation, did not reveal advantages or disadvantages due to altimetric variations between 0 to 205 a.s.l. and slopes of the cultivation fields between 0% and 15%. The culms collected were uniform for morphological, dimensional and sanitary conditions.

Like all natural materials, the performance linked to the insulating capacity of bamboo is influenced by several factors. Although in our study the coupling with a bio plaster (Biocalce®) was examined, the use of other natural materials is not excluded, such as raw earth.

Thermal images permitted to assess the correct application of the sensors and to give an empiric evaluation of thermal performance of the samples.

Moreover, with thermal images the critical points that favour heat dispersion were easily identifiable. These points can be recognised in the coupling lines between one culm and the next. As conclusion, heat dispersion was not due to the nature of the bamboo, but to the construction technique adopted.

Taking into account that the thermal performance of the wall with the plaster improved and considering a different construction technique able to limit heat dispersions, it is possible to hypothesize a further improvement in term of thermal performance of the insulating walls manufactured with bamboo.

Thanks to the speed of bamboo growth and marked adaptability to cultivation in different pedoclimatic scenarios, bamboo is configured as a material with a high potential for exploitation. Having this material at zero km encourages the diffusion and use even at non-industrial levels, promoting the creation of short supply chains and the reduction of the use of synthetic insulating materials, without doing away with technically and aesthetically appreciable solutions.

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