Utilization of cork residues for high performance walls in green buildings

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Abstract: The building sector accounts for 40% of consumed primary energy, 20% of which is used to heat and cool indoor environments through HVAC systems. Though several intervention strategies are possible, the latest studies have highlighted that a conscious design of the building envelope was the most suitable solution to reduce environmental burdens. Actually, its components considerably affect the energy performances of buildings mitigating the effects caused by variable external environmental conditions and reducing expenditure by 50%-70%. Only in the last few years, research has been targeted to the development of innovative solutions to improve the energy performances of the building envelope by studying and using biocompatible natural insulating materials. Cork is one of the most popular natural materials used as insulators. It is obtained from the bark of the *Quercus suber* and only 25% of it, the high-quality cork, which is used to produce bottle stoppers, while the remaining 75% becomes waste material of the process. This paper proposes a multilayer agglomerated cork wall with two air cavities and a central OSB (oriented strand board) load-bearing structure that can be used as an external vertical partition in buildings located in Mediterranean climate areas. Specific graphs were developed to rapidly establish thermal insulation characteristics which also were taken into account ISO 13786 and the performances required from the building. The wall, which was composed of 6.5 cm-thick external layers of agglomerated cork, for a total thickness of 20 cm, had a periodic thermal transmittance value below 0.12 W $m^{-2}\cdot K^{-1}$. The same performances can be obtained using perforated brick walls, of at least 50 cm of length, insulated with no less than 5 cm of rock wool, for an overall weight per unit area over 20 times higher.

Keywords: agglomerated cork, agricultural residues, building energy, environmentally sustainable, heat capacity, thermal insulation, wall

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1 Introduction

Large amounts of waste materials of forestry and agricultural processes are still underutilized (Väisänen et al., 2016). Their most common utilization is the production of energy from biomass (Statuto et al., 2013; Valenti et al., 2016), even though this is a low-value energy source. An interesting alternative eco-friendly utilization of the organic residues from agricultural and forestry processes is to be found in the thermal insulation of buildings.

The building sector accounts for some 40% of consumed primary energy, 20% of which is used to heat and cool indoor environments through HVAC systems (Osterman et al., 2012; Pérez-Lombard et al., 2011).

During winter, the building envelope should minimize heat losses and transfer the stored heat when it is most needed, thus reducing the heating load (Porto et al., 2015). On the contrary, during summer, it should insulate from the external heat in the daylight hours and transfer the stored heat at night (Baratta and Venturi, 2008), so as to keep indoor temperature as constant as possible (Lavagna, 2010).

Only in the last few years, research has been targeted to the development of innovative solutions to improve the

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energy performances of the building envelope (Padovani et al., 2010; Schlanbusch, 2013) by studying and using biocompatible natural insulating materials (Barreca, 2012; Barreca and Fichera, 2013; Susca et al., 2011). Such natural materials are produced through energy-efficient processes; restrict the emissions of volatile compounds, which are harmful in indoor environments; are easily recycled; and are obtained from agricultural and forest industry waste and residues, which limits costs and environmental pollution.

Cork is one of the most popular natural materials used as insulators (Silva et al., 2005). It is obtained from the bark of the *Quercus suber* and only 25% of it, i.e. the high quality cork, is used to produce bottle stoppers, while the remaining 75% becomes waste material of the process (Colagrande, 1996). In general, it is estimated that 68000-85000 tons of underutilized cork residues are produced, out of a world annual production of 340000 tons (Modica et al., 2016; Valenti et al., 2016).

Owing to the physical characteristics of cork, e.g. low density, low rigidity, good sound absorption, water resistance, energy storage capacity and low thermal conductivity, its residues are used in the building sector as elements of cementitious mortars in order to improve energy performances and reduce the weight and fragility of plaster (Proto et al., 2017; Prusty et al., 2016).

Manufacturers of thermal insulators for the building sector use cork granulate in the form of agglomerate and conglomerate. In addition, cork can be easily recycled and, therefore, allows reducing the environmental impact of its lifecycle. For cork granulate to be widely used in green building, it is fundamental to study and find out the best solutions to obtain high performance components.

This paper proposes a multilayer agglomerated cork wall with two air cavities and a central OSB load-bearing structure that can be used as an external vertical partition in buildings located in Mediterranean climate areas.

The thermophysical values of the agglomerated cork boards used to make the wall were calculated by means of a specifically developed simplified instrumental measurement method. Particularly, measurements were taken on samples of agglomerated cork boards of different quality, gradation and density. Specific graphs were developed to rapidly establish thermal insulation characteristics also taking into account ISO 13786:2007 and the performances required from the building (Barreca et al., 2014) .

2 Materials and methods

2.1 Thermophysical characteristics of samples

Owing to its morphology, cork is a material (Vilela et al., 2013) particularly suitable to thermal insulation, since it is made up of closed hexagonal cells with a layered structure, which significantly reduces its density. The cell walls contain a thin central layer rich in lignin; thick secondary walls composed of alternate layers of suberin and wax; and a thin tertiary wall of polysaccharides. The presence of air in the cells increases the thermal resistance of the material and their peculiar closed shape enables to rapidly dissipate sound waves keeping them inside.

Cork granules, which result from a grinding process, can be aggregated again through heating processes (or by means of high-frequency ultrasounds) that soften suberin and lignin and allow the granules to bond together.

In this study, six types of agglomerated cork boards, commonly used for the thermal insulation of building envelopes, were tested to find the cork granulate whose characteristics could provide a board with the best thermal insulation parameters. The agglomerated cork boards were produced by means of an industrial method for compression and heating. The diameters of the cork granules and the pressure value were different for each board. A sample was taken from each board in Figure 1. The physical and geometric characteristics of the samples were shown in Table 1.

A size analysis by mechanical sieving test was carried out for each sample following the measurement procedures stated in ISO 2030:1990 and using a sieve sequence with apertures complying with ISO/R 40/3 (ISO 565:1990). The analysis showed that the samples of type A, B, and C were made up of agglomerated cork with sieve size ranging between 0.5 and 1 mm; while the samples of type D and E were characterized by an agglomerate with sieve size between 2 and 4 mm. Finally, sample F was composed of a granule agglomerate with sieve size between 4 and 8 mm (Figure 2).

Figure 1 Cork samples

Table 1 Average values of the physical and geometric characteristics of the samples examined

Type	Dimensions, cm			Surface, m^2	Board density, $kg \cdot m^{-3}$
	Length	Width	Thickness		
A	43	48.4	1.38	0.208	369.35
B	42.8	48.5	1.1	0.208	375.95
C	43	48.4	2.9	0.208	389.71
D	43.5	48.9	2.1	0.213	145.85
E	43.3	48.7	2.9	0.211	157.02
F	43.2	48.5	1.95	0.21	73.83

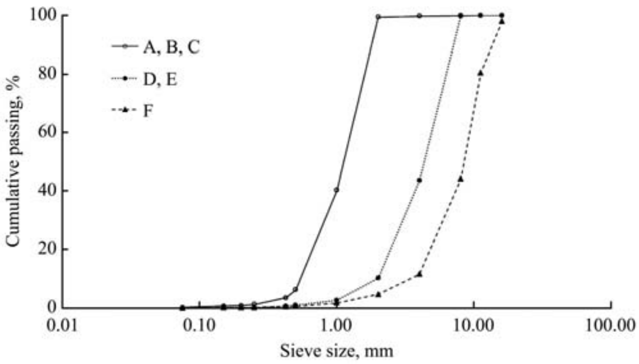

Figure 2 Grading curve of the three types of agglomerated cork

The thermal conductivity and heat capacity of the samples were measured by means of a specifically developed experimental method that makes use of a portable testing apparatus which is able to generate and measure a unidirectional heat flow passing through the sample to analyse. The testing apparatus in Figure 3 consists in a portable cold box that creates a temperature-controlled environment (cold room) located inside a wider and warmer environment having a temperature of about 10 K. These conditions generated a heat flow rate over 5 $W \cdot m^{-2}$ between the two faces of the board.

In compliance with ISO 9869:2014, thermophysical quantities were measured through the heat flow meter method.

The surface temperatures and heat flow rates on each face of the sample (hot and cold surfaces) were measured by means of four contact thermometers, with Pt100 1/3 DIN B thermistors, and of a thermopile heat flow meter, with sensitivity 50 $\mu V \cdot W^{-1} \cdot m^{-2}$. The values of the measured thermophysical quantities were obtained by averaging the instantaneous values taken every 60 s over a time interval of 300 s.

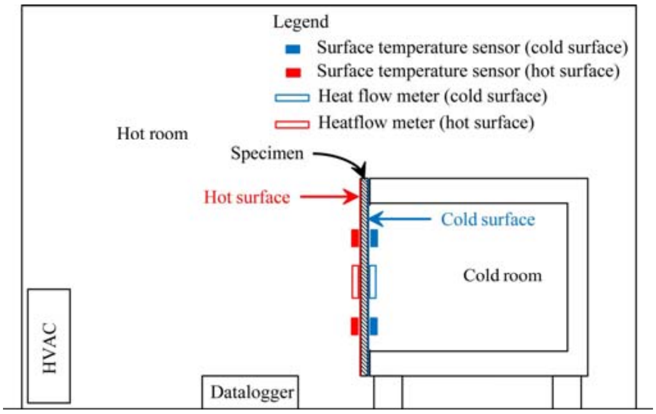

Figure 3 Test method diagram

In order to simulate dynamic conditions close to real thermal transients in the hot room, four-hour heat cycles, with a two-hour heating phase and a two-hour cooling phase, were reproduced through a simple timed convection heating system.

Heat flow meters enabled to calculate the heat which was stored and then transferred by the samples. During heating phases, the heat flow meter was placed on the hot surface to measure higher heat flow values than the one located on the cold surface. Such different flows may be due to the stored heat. On the contrary, during the cooling phase, a higher heat flow value was recorded on the cold surface. The difference between the two flows enabled to calculate the transferred heat. Heat variations depended on the heat capacity of the sample. The simplified calculation model took into account a continuous, uniform, isotropic body with physical characteristics independent from time, heat flow direction, temperature and heat transfer mechanism. It was assumed that the heat flow passing through the element was unidimensional and that it had a direction perpendicular to the passage surface. Moreover, exchanges by convection and radiation were considered negligible.

Throughout measurements, the samples underwent alternated heating and cooling phases, during which they stored heat (heating phases) and then transferred it (cooling phases).

The duration of the test was divided into *n* time intervals; heat and temperature variations were measured for each *i-nth* interval; and instantaneous heat capacity was calculated through (1).

The final heat capacity, which best represented the thermophysical performance of the sample, was calculated by applying the progressive average method, which compensated for possible measurement errors (Barreca and Fichera, 2016):

$$\bar{C} = \frac{\sum_{i=1}^{n} |\Delta Q_i|}{\sum_{i=1}^{n} |\Delta T_i|} \quad (1)$$

Since samples had a limited thickness, their internal temperature was approximated to be the average value between the temperatures measured on the hot surface and those measured on the cold surface.

If a linear temperature and heat flow variation over time is assumed, the following is obtained for each *i-nth* interval (Figure 4):

$$\Delta T_i = T_{fin,i} - T_{in,i} \quad (2)$$

$$\Delta Q_i = [(q_{h_{in,i}} + q_{h_{fin,i}}) - (q_{c_{in,i}} + q_{c_{fin,i}})](t_{fin,i} - t_{in,i}) A \cdot 0.5 \quad (3)$$

The measured values shown in Figure 5 enabled to apply ISO 9869:2014 to calculate thermal conductivity (Table 2).

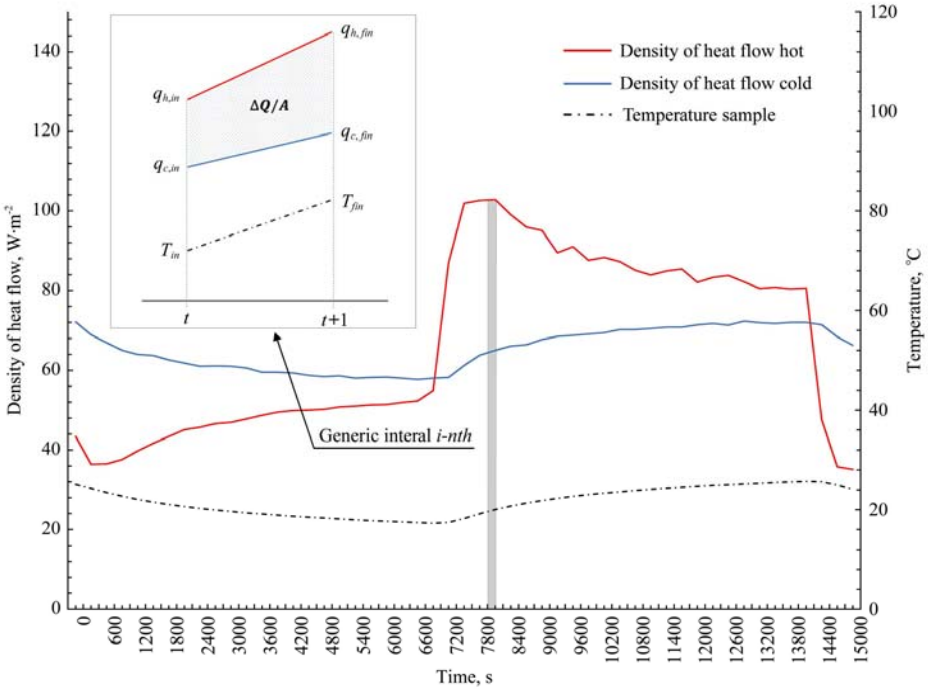

Figure 4 Heat and temperature variation at time interval *i-th*

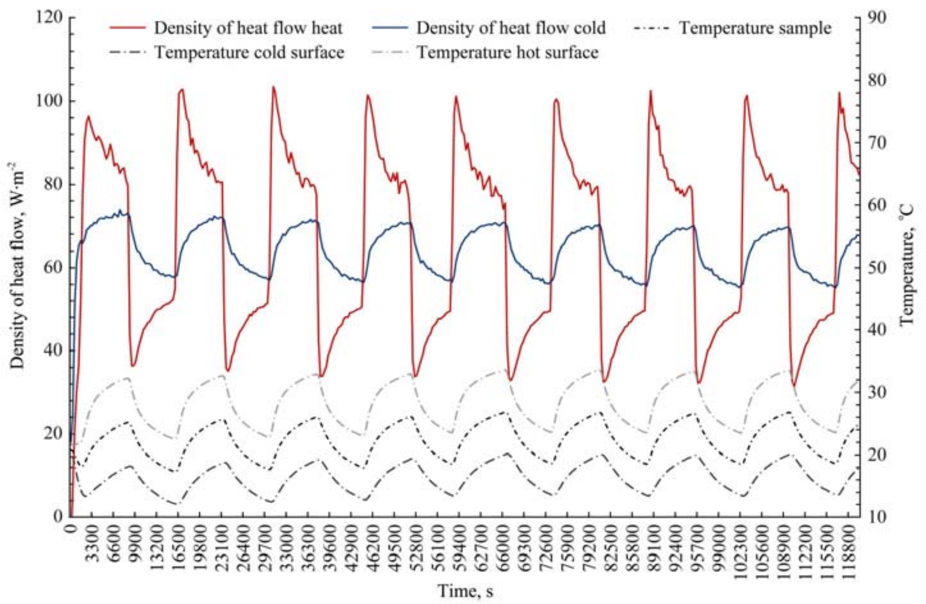

Figure 5 Density of heat flow rate/time profile

Table 2 Thermophysical values of the samples

Type	Thickness, cm	Average density, kg·m^{-3}	Heat capacity, kJ ·K^{-1}	Thermal conductivity, W ·m^{-1} ·K^{-1}	Thermal diffusivity, m^2 ·s^{-1}
A	1.38	369.35	3.03	0.076	0.0726
B	1.10	375.95	2.46	0.083	0.0770
C	2.90	389.71	4.64	0.081	0.1051
D	2.10	145.85	2.49	0.053	0.0938
E	2.90	157.02	3.11	0.051	0.1061
F	1.95	109.80	2.45	0.044	0.0775

2.2 Comparison of the results obtained through the RC_e method

The heat capacity values calculated by applying the method proposed above were compared to those calculated through the software LORD v3.21 (Gutschker, 2008) using the RC_e model described in Figure 6.

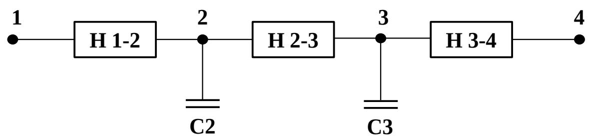

Figure 6 RC_e model diagram

Two model configurations (configuration A and B), both based on the Output Error Method (OEM) system but on different control parameters, were considered. As to configuration A, control parameters were the temperature measured on the hot surface at node 1 and the heat flow recorded on the cold surface at node 4. As for model B, control parameters were the surface temperature of the cold surface at node 4 and the surface heat flow on the hot surface at node 1. The weight of both parameters was 50%. The values calculated for both configurations were compared to those calculated with the proposed simplified model (Table 3).

Table 3 Comparison of the values of specific heat capacity and conductance calculated with the Proposed Simplified Model and with LORD 3.21

	Simplified Model Proposed		Model A		Model B	
	Capacity, kJ·K^{-1}	Conductance, W·m^{-2}·K^{-1}	Capacity, kJ·K^{-1}	Conductance, W·m^{-2}·K^{-1}	Capacity, kJ·K^{-1}	Conductance, W·m^{-2}·K^{-1}
A	3.03	5.51	2.85	5.40	2.94	5.58
B	2.46	7.52	2.31	7.18	2.39	7.40
C	4.65	2.79	4.70	2.71	4.66	2.64
D	2.50	2.52	2.37	2.54	2.19	2.49
E	3.11	1.76	2.69	1.74	2.63	1.74
F	2.45	2.27	2.29	2.25	2.50	2.33

The comparison of the results obtained from both models showed very little difference between the values from the proposed simplified model and those from the software LORD v3.21. A difference of slightly over 15% was recorded only for sample E, which demonstrated that the proposed model was reliable (Table 3).

Conductance values highlighted that the samples characterized by low density had lower conductivity and, therefore, higher insulating capacity. As a matter of fact, sample F, which was toasted and had a density of 109.80 kg·m^{-3}, showed a conductivity value of 0.044 W·m^{-1}·K^{-1}. On the contrary, samples B and C, which had a density of some 380 kg·m^{-3}, were characterized by a conductivity value of about 0.081 W·m^{-1}·K^{-1}. In fact, in close-cell materials, the lower the density, the higher the number of voids. Furthermore, when cork is toasted, cell walls stretch, thus increasing their volume and improving the insulating characteristics of the material.

Higher heat capacity values were found for samples with higher density, while lower heat capacity values were recorded for those with lower conductivity. The values of the thermal parameters obtained for cork boards were higher than those of other unconventional insulation materials used in sustainable building, e.g., straw bales, which have a density of 60 kg·m^{-3} and a conductivity value of 0.067 W·m^{-1}·K^{-1}, or recycled cotton boards, which have a thermal conductivity between 0.039 and 0.044 W·m^{-1}·K^{-1} but a density of 25-45 kg·m^{-3} (Asdrubali et al., 2015).

A fundamental parameter to insulate external walls in hot climate areas is thermal diffusivity (Bloem et al., 1993). This parameter represents the capacity of the thermal insulation to produce a time delay peak on the inside face of the walls. In hot climate areas, external partitions producing a time delay peak usually improve the internal microclimate conditions.

3 Results and discussions

Agglomerated cork boards are commonly bonded directly on external self-supporting walls. Though this is a valid solution in the energy-efficient retrofitting of existing buildings (Barbaresi et al., 2016), it is not economically and environmentally sustainable. Sustainable buildings and, above all, temporary buildings, increasingly require walls with a high level of thermal insulation that are made up of natural insulating material and can be rapidly manufactured. This paper proposes a multilayer agglomerated cork wall with two air cavities and an OSB load-bearing layer (Figure 7). This structure enables to exploit the breathability of the agglomerated cork boards and to let condensation or water vapour, which may form inside the environment, out. Moreover, the presence of cavities limits the heat transfer by solar radiation, since the faces of the wood agglomerate load-bearing board have a lower emissivity value than those of cork boards. Such characteristics make the wall particularly suitable to hot and wet climate areas.

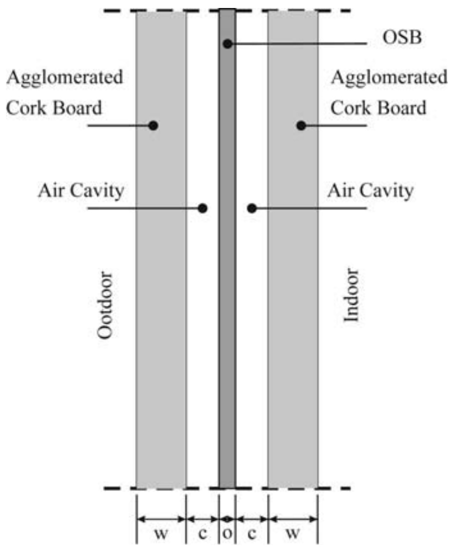

Figure 7 Outline of the multilayer agglomerated cork wall

The walls characterized by a low thermal diffusivity value allow obtaining a time delay peak of the external thermal stresses and, therefore, mitigating internal microclimate conditions. That is why the most suitable board to make the proposed wall is sample A. Though having one of the highest thermal conductivity values among the tested boards, that sample has the lowest thermal diffusivity value.

The dynamic thermal performances and characteristics of the wall were calculated by means of the method proposed by the ISO 13786:2007, considering a horizontal heat flow passing through the wall. In particular, this method takes into account the dynamic behaviour of building components undergoing a sinusoidal temporal temperature variation. The thermophysical characteristics of the layers of the wall are shown in Table 4.

Table 4 Thermophysical characteristics of the layers of the wall

	Agglomerated cork board	Air	OSB
Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$	0.076	0.047	0.150
Board density, $kg \cdot m^{-3}$	369.35	1	550.00
Specific heat, $kJ \cdot kg^{-1} \cdot K^{-1}$	2.69	1.00	2.70

The application of the calculation method to different configurations of layers showed a limited influence of the thickness of the air cavity on the variation in the overall transmittance of the wall.

Figure 8 shows that the transmittance of the wall decreases considerably at a thickness of the cavity of about two centimetres and then remains fairly constant. As a result, in the overall sizing of the wall, the thickness of the two air cavities was fixed at three centimetres, while the thickness of the OSB board was fixed at one centimetre, which was enough to assure its load-bearing function EN 300: 2006.

These values allowed calculating the periodic thermal transmittance, the internal areal heat capacity and the decrement factor.

Figures 8, 9 and 10 allow establishing the thickness of the agglomerated cork layers according to the thermal performances required from the building and to the local climate conditions. It should be taken into account that the best wall performances in hot climate areas are obtained for high internal areal heat capacity values and low decrement values. In order to assure comfortable indoor environments, walls should have periodic thermal transmittance values lower than 0.12 $W \cdot m^{-2} \cdot K^{-1}$ (Figure 9) (Barreca and Tirella, 2017), above all in areas where, in the months of maximum insolation, the monthly average value of irradiance on a horizontal surface is higher than or equal to 290 $W \cdot m^{-2}$ (Ozel, 2013).

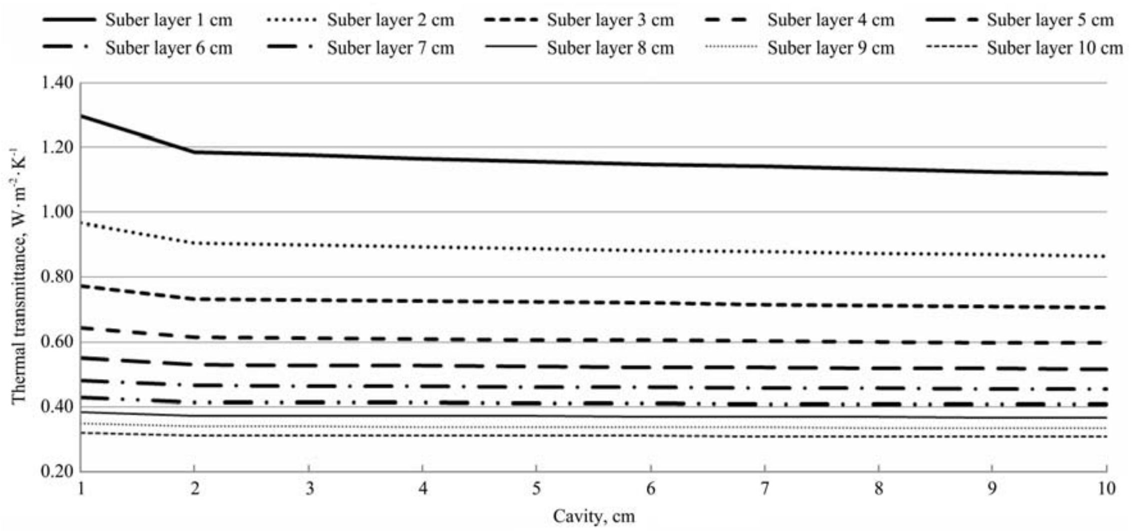

Figure 8 Variation in the thermal transmittance of the multilayer wall for different agglomerated cork layer thicknesses

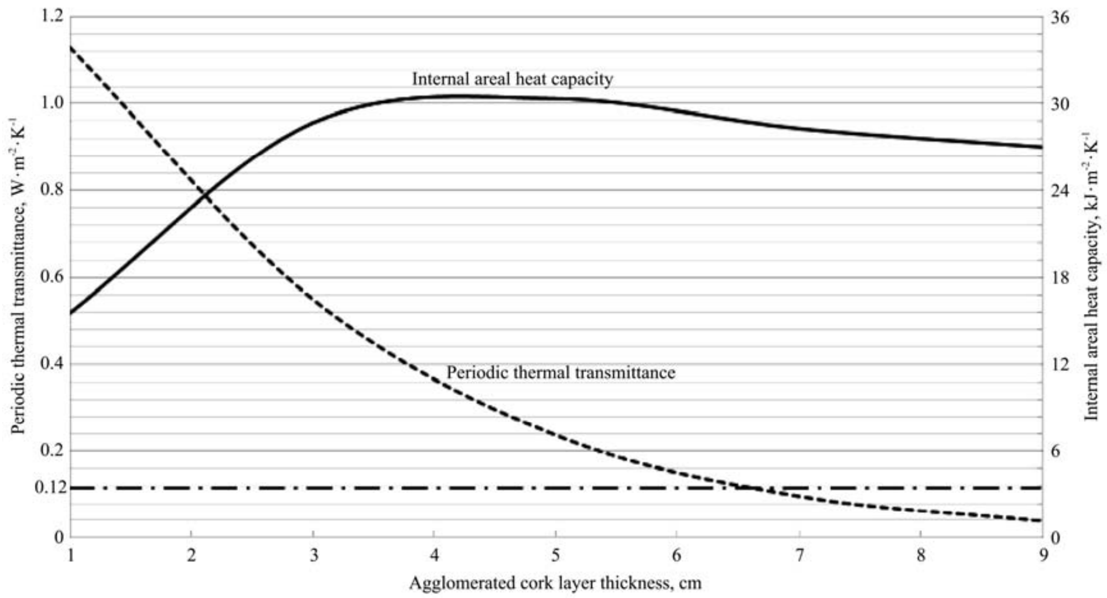

Figure 9 Variations in the periodic thermal transmittance and in the internal areal heat capacity for different agglomerated cork layer thicknesses and periodic thermal transmittance values to assure comfortable indoor environments

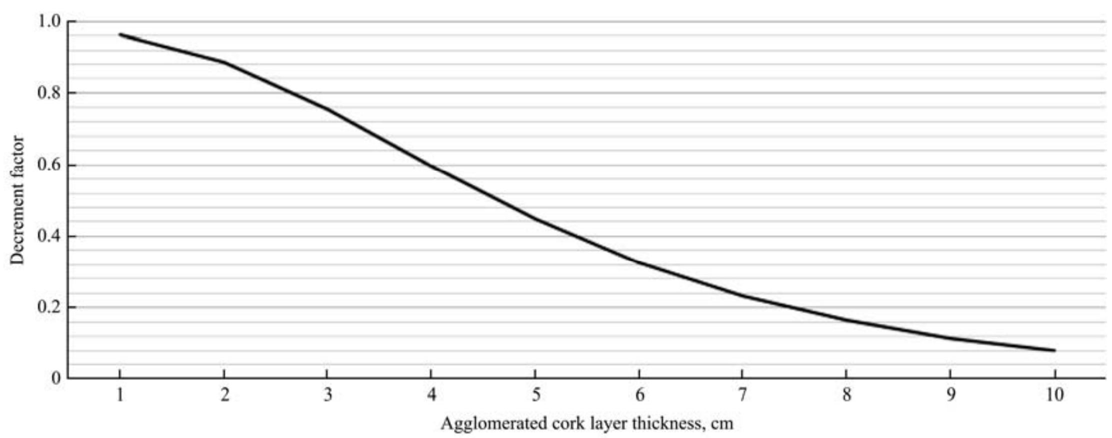

Figure 10 Variations in the decrement factor for different agglomerated cork layer thicknesses

4 Conclusions

This paper proposes a quick method to calculate the thermophysical characteristics, particularly thermal conductivity and heat capacity, of agglomerated cork boards. Such a method entails the use of a testing apparatus that could be easily transported to the place where natural materials are produced. The goal is to simplify the determination of the physical characteristics of the thermal performances of transient materials, which is the most suitable method to simulate the real-life behaviour of building elements, since steady-state analyses do not allow verifying the real thermal insulation behaviour of materials. Several studies on the determination of the thermal characteristics of materials make use of specifically developed tools to generate particular thermal conditions that can be applied to samples in order to analyse their behaviour in the presence of a thermal transient. Owing to their complex construction, such tools can be used exclusively in a laboratory and on small samples (Dubois and Lebeau, 2015).

The proposed model was applied to samples of agglomerated cork boards, obtained from forestry processes and characterized by different density, granulometry, and thickness. This material has excellent characteristics of thermal inertia that make it suitable to the thermal insulation of buildings in both summer and winter. Furthermore, it is biocompatible and soundproof.

Therefore, a multilayer double cavity wall is proposed.

The wall with 6.5 cm-thick external agglomerated cork layers and with a total thickness of 20 cm has a periodic thermal transmittance value lower than 0.12 $W \cdot m^{-2} \cdot K^{-1}$. The same performances can be obtained from perforated brick walls of at least 50 cm of length and insulated with no less than 5 cm of rock wool (Di Perna et al., 2011), for an overall weight per unit area over 20 times higher. Moreover, the developed graphs allow designing a wall with the most suitable performances in relation to its place of use. Thanks to its high performances in hot climate areas, to the high environmental sustainability of its materials, and to its low weight, which makes it easy to transport and install, such a wall is also suitable to the construction of temporary buildings in naturalistic and fragile areas, such as parks and natural reserves. Yet, it could be also used in civil construction adopting certain precautions in order to guarantee its durability over time.

Nomenclature

Symbol	Definition	Unit
A	Sample surface,	m^2
C	Heat capacity	$kJ \cdot K^{-1}$
Q	Heat energy	J
q	Density of heat flow	$W \cdot m^{-2}$
ϕ	Heat flow	W
T	Temperature	K
V	Volume	m^3
t	Time	s
m	Mass	kg
λ	Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
ρ	Board density	$kg \cdot m^{-3}$
Δ	Gradient	
c	Cold	
fin	Final	
h	Hot	
in	Initial	
n	n-nth interval	
x	Sample thickness	m

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