THERMAL INSULATION PERFORMANCE ASSESSMENT OF AGGLOMERATED CORK BOARDS

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Abstract. For the last few years, the building industry has been focusing on research, on the construction of passive houses, and on the use of natural, local materials that are nontoxic, are recyclable, and can assure good thermal insulation. Cork is a natural material for which qualities have been known since ancient times and that fully meets sustainability requirements. High-quality cork is mainly used to produce bottle stoppers. Because of the manufacturing process, more than 75% of it becomes a waste product. Furthermore, a large amount of waste cork comes from industry, forest cleaning and pruning, and waste selection. This material is then recycled and triturated to obtain cork granulate. Producing cork granulate is a sustainable solution that recycles a waste product, substantially keeps the characteristics of the original material, and turns this waste product into a resource for manufacturing new products, such as insulating boards made up of cork agglomerate, which are increasingly used in the building sector. In this study, certain thermophysical parameters of six agglomerated cork boards were evaluated. Different constituent characteristics of the boards, such as grain size distribution, density, and thickness, were taken into account to evaluate how they would influence insulating performances. The tested agglomerated cork boards showed thermophysical characteristics similar to those of cork bark and even exhibited a higher diffusivity value than natural cork. Ultimately, it may be assumed that agglomerated cork boards are a suitable and sustainable solution particularly for the thermal insulation of buildings in hot climates and when a healthy environment is required.

Keywords: Cork agglomerate, insulation, *Quercus suber*, sustainability, thermal conductance.

INTRODUCTION

For the last few years, the building industry has been focusing on research, on the construction of passive houses, and on the use of natural, local materials that are nontoxic, are recyclable, and can assure good thermal insulation (Hoang et al 2009; Barreca 2012). Cork is a natural material for which qualities have been known since ancient times and that fully meets sustainability requirements. It is obtained from the bark of an oak, *Quercus suber*, that is widespread in Portugal, Spain, North Africa, and in a few areas of Italy. Its characteristics have long been known. In the 1st century, in his *Naturalis Historia,* Pliny the Elder recommended to use it for its good insulating capacities (Plinio 1985). In studies on plant anatomy, cork plays a crucial role because it was the first plant tissue to be examined under a microscope (Hooke 1664). It has a very homogeneous and compact parenchymatous tissue with a honeycomb-like structure (Pereira 1998). This peculiar structure and the suberization of its cell walls make the cells similar to watertight compartments, owing to the presence of a large amount of gas in the suberose cells. As a result, cork is also considerably light, very elastic, impermeable to liquids and gases, and thermally

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and sound insulated (Palma 1986). Finally, cork is strong and quite resistant to the enzymes secreted by parasites, because suberin is one of the most resistant organic substances. Although it is widely grown, the regeneration of its bark is slow; it takes more than 10 yr on average to regenerate after the first barking, which usually takes place 20-25 yr after the start of the plant. That is why cork, and especially first-class cork, is a valuable material. High-quality cork is mainly used to produce bottle stoppers and, during its manufacturing process, more than 75% of it becomes a waste product (Colagrande 1996). Also, a large amount of waste cork comes from industry, from forest cleaning and pruning, and from waste selection. This material is then recycled and triturated to obtain the so-called cork granulate. Cork granulate is commonly used in the building sector as bulk material in the air gaps of curtain walls. It is also added to plaster to produce thermal insulating boards (Cherki et al 2014) or mixed with asphalt (Pereira et al 2013) or with lightened mortar (de-Carvalho et al 2013). Because cork granulate is the result of a process that recycles waste cork into raw material for new products, it is considered sustainable (Rives et al 2012). Recently, insulating boards made of agglomerated cork have been introduced in the building sector (Gil 2015). They are offered in various versions depending on the binder used, gradation, and specific density (Gil 1996). In particular, because the type of binder used to make the boards influences their final mechanical and thermal behavior, various types of synthetic and natural binders were tested (urethane, melaminic, and phenolic resins) (Gil 2009). However, a special building method has been developed using the resin of cork (suberin) to bind the granules (Conde et al 1999). The method entails overheating granules (or using high-frequency ultrasonic waves) to soften the suberin and the lignin that make cork granules expand and bond together (ISO 1989). In this study, certain thermophysical parameters of six agglomerated cork boards were evaluated. Different constituent characteristics of the boards, such as grain size distribution, density, and thickness, were taken into account to evaluate how they would influence thermal insulating performances.

MATERIALS AND METHODS

The six analyzed boards are commonly sold on the Italian market to insulate walls and roofs. Five boards were made of blond cork, and one was made of brown cork (dark board) (Fig 1). Three 0.45- $\times$ 0.45-m samples were taken from each board to test gradation, board density, thermal conductivity, heat capacity, and thermal emissivity. To apply Fourier's law, which is essential to calculate the thermophysical properties of materials, agglomerated cork boards thicker than the average size of the basic elements of the material were considered (Bonacina et al 1984).

Size Analysis and Board Density

Boards were characterized by three different gradations. The manufacturer supplied a sample of about 1 kg of cork granulate for each gradation. A size analysis (ISO 1990) was performed through mechanical sieving by taking three 100-g samples from each bulk gradation (BL 1, BL 2, and BR) and using mesh apertures conforming to the series ISO/R 40/3 and a balance with precision of 0.1 g. The calculated average values allowed construction of the relative cumulative percentage retention curves (Fig 2).

Board density (ρ, kg/m^3) was measured by averaging the measurements taken on the three samples of each board according to ISO 2219 and dividing the mass (m, kg) of the samples by their volume (V, m^3):

$$\rho = \frac{m}{V} \quad (1)$$

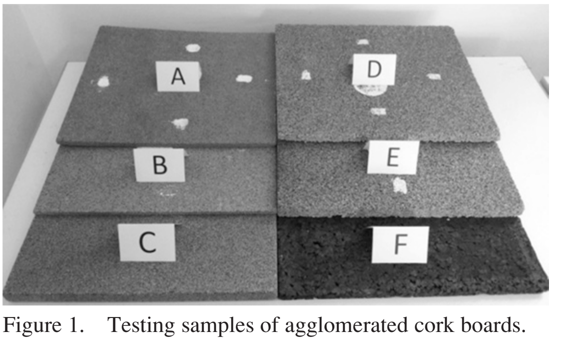

Figure 1. Testing samples of agglomerated cork boards.

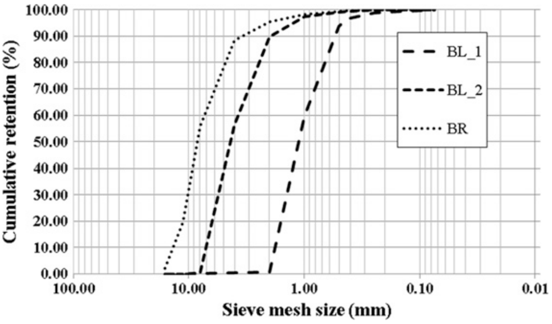

Figure 2. Cumulative retention curves for the three cork granulates. Semigranular scale.

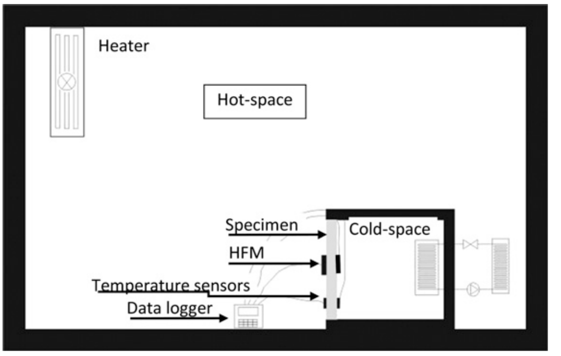

Figure 3. Testing apparatus used for the insulation analyses on the samples.

The length and width of the samples were measured at three locations using a steel rule with a resolution of 0.50 mm. The thickness was averaged from five measurements taken on a granite flat table with a precision caliper (0.10-mm resolution). The mass of the sample was measured using a balance with precision of 0.1 g and at constant temperature and environmental humidity (Table 1).

Thermal Conductance

A testing apparatus similar to one the authors used in a previous study (Fig 3) (Barreca and Fichera 2013) was used to implement the procedure described by ISO (1994) and to evaluate the thermophysical properties of the boards under conditions similar to those of their actual use, ie for the thermal insulation of walls in buildings located in hot climate areas (Matias et al 1997).

This simple and easily portable apparatus was composed of a cold insulated box in which internal temperature was kept between 26°C and 2°C by a refrigeration system. The board to test was fixed to a side of the box and the box was placed in a confined environment with temperatures of 20-40°C controlled by an automatic heating system that turned on at preset intervals to simulate the dynamic variations of external temperature in the hot season of the Mediterranean climate. Four surface temperature sensors and a heat flowmeter (HFM) were attached at the center of the inner and outer faces of each sample to continuously measure the heat flow passing in both directions. With a view to limiting mutual interferences, sensors were placed in a symmetrical but offset position.

All the sensors of temperature, surface heat flow, and air temperature and humidity of the environment inside and outside the cold box were networked by data loggers, which acquired and stored the values taken at 300-s intervals. A thermal infrared (IR) camera allowed verification of homogeneity of sample surface temperatures, as well as possible heat losses or hidden sources of thermal radiation. After 72 h of measurements and after checking certain conditions imposed by ISO (1994), such as a constant difference in temperature between the hot and cold spaces greater

Table 1. Physical properties of investigated samples.

Sample	Type of cork granulate	Thickness (m) 10^{-3}	Weight (kg)	Volume (m^3) 10^{-6}	Board density (kg/m)	Mean cork diameter (m) 10^{-3}
A	BL1	13.81	1.06	2872.06	369.35 ± 0.01	0.80
B	BL1	11.02	0.86	2283.38	375.95 ± 0.02	0.80
C	BL1	29.03	2.35	6035.48	389.71 ± 0.01	0.80
D	BL2	21.10	0.65	4467.02	145.85 ± 0.01	3.02
E	BL2	29.04	0.96	6115.26	157.02 ± 0.01	3.02
F	BR	19.50	0.53	4845.79	108.70 ± 0.01	6.67

than 10°C and a heat flow > 5 W/m^2, instantaneous conductance was calculated by means of Eq 1.

$$\Lambda_t = \frac{q(t)}{T_h(t) - T_c(t)} \tag{2}$$

where: Λ_t is the conductance at time t (W/m/K); $q(t)$ is the instantaneous density of heat flow rate at time t (W/m); $T_h(t)$, $T_C(t)$ is the instantaneous temperature at time t on the internal and external surface of the sample at time t (K).

The final conductance value was obtained by applying the progressive average method to Eq 2 throughout the testing period on more than 1000 measurements of temperature and heat flow density taken on the surfaces of the sample.

The progressive average of the values enabled the limiting of the influence of the system transient periods and of the peak heat values caused by possible anomalies of the system.

Heat Capacity

Specific heat capacity is a thermophysical parameter particularly significant for insulating materials because, together with density and thermal conductivity, it enables calculation of the thermal diffusivity of the material, which is the rate at which the internal temperature changes when exposed to a temperature difference across the material. Also, it allows calculating the phase lag of the thermal wave or phonon, a phenomenon extremely useful to mitigate temperature changes inside buildings in hot climate areas.

Because of the limited thickness of the samples, their heat capacity was measured through a simplified procedure by applying the transient method (Wakili et al 2003) to the apparatus previously described. The temperature variation inside the confined environment, which occurred at regular 120-min intervals, led to a cyclic, transient heat transfer. The variable heat difference between the confined environment and the inside of the cold box originated a variable heat flow that passed through the tested sample and was measured when entering and exiting it by means of the two HFM placed on both faces. The following can be derived from the general conduction equation in finite terms:

$$\Delta Q = \rho V c \, \Delta T / \Delta t \tag{3}$$

where: ΔQ is the shift heat flow (W); c is the specific heat capacity (J/kg/K); ΔT is the temperature shift (K); Δt is the time shift (s)

As a result, referring to the time interval, which corresponds to the turn on/off cycle of the heating system outside the cold box, and assuming a linear temperature variation inside the sample, the following was obtained from Eq 3:

$$c = \sum_{t=0}^{t=\Delta t} (Qh(t) - Qc(t))\Delta t / (\Delta T t \rho A d) \tag{4}$$

where: $Q_h(t)Q_c(t)$ is the heat flow across the internal and external surface of the sample at time t (W); d is the thickness of sample (m); A is the surface area of sample (m^2).

Eq 4 considers the heat a board accumulates and then releases in each turn on/off interval of the heating system. Specifically, the values of heat capacity (J/kg/K) shown in Table 2 were obtained from the average of three samples of the same board for a turn on/off interval of the heating system of $\Delta t = 120$ min.

Table 2. Thermal properties of investigated samples.

Sample	Conductance (W/m/K)	Conductivity (W/m/K) 10^{-1}	Specific heat capacity (JK/kg)	Diffusivity (m^2/s) 10^{-8}	Emissivity
A	5.51 ± 0.69	0.77 ± 0.10	2859.70 ± 36	7.26 ± 0.91	0.93 ± 0.51
B	7.52 ± 0.95	0.83 ± 0.10	2862.40 ± 36	7.70 ± 0.97	0.91 ± 0.41
C	2.79 ± 0.35	0.81 ± 0.10	1974.70 ± 25	10.50 ± 1.32	0.93 ± 0.52
D	2.52 ± 0.32	0.52 ± 0.07	2491.90 ± 31	9.38 ± 1.18	0.94 ± 0.21
E	1.76 ± 0.22	0.54 ± 0.07	3228.20 ± 41	10.60 ± 1.33	0.92 ± 0.10
F	2.27 ± 0.29	0.47 ± 0.06	5467.50 ± 69	7.75 ± 0.97	0.93 ± 0.13

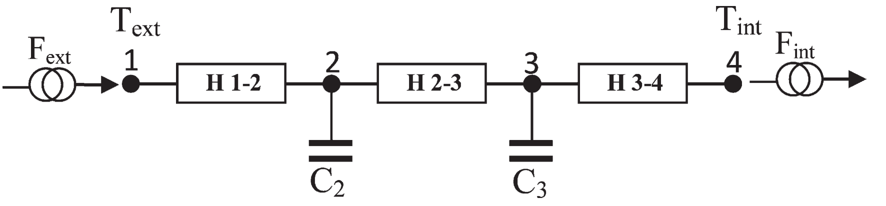

Figure 4. RC model of the testing apparatus.

Assuming a one-dimensional heat flow, numeric check of the data from the measurements taken with the testing apparatus were carried out with an Resistor-Capacitor (RC) model (Bouchair 2008) by means of the system identification technique of LORD 2000 (Ljung 1999). Figure 4 shows the model of the system.

By analogy, the RC model shown in Fig 4 represents the thermophysical behavior of the tested sample. In particular, the sample was schematized by two internal nodes (2 and 3) and two edge nodes (1 and 4). Resistances H 1-2, H 2-3, and H 3-4 represent heat resistance, whereas capacities C2 and C3 represent the overall heat capacity of the sample. Node 1 was associated with the values of the flows and temperatures measured on the outer face of the sample, whereas node 4 was associated with the values of the flows and temperatures measured on the inner face of the cold box. The software LORD solved the system with consideration of the values measured during the transient period. Particularly, the temperature measured at node 4 and the flow measured at node 1 were considered as output values for the correction of the calculated values.

Emissivity

IR thermography was used to calculate the emissivity of the boards. In particular, samples were heated to about $40 \pm 5°C$ (Fig 5) by means of electrical plates positioned at the center of their faces, at which a strip of black dielectric material with emissivity equal to 0.97 was also applied. The surface temperature of the dielectric material and the sample were measured with a contact thermometer with penetration probes and certified precision of $\pm 0.2°C$ in the range $-20°C$ to $80°C$. Then, the emissivity value of the cork agglomerate sample was obtained through a software program for the analysis of IR images, assuming that the IR-measured temperatures coincided with the contact-measured ones. Analysis of the emissivity values of each sample showed a moderate difference between opposite faces of the same sample. Such a difference may have been caused by the different surface finish. Actually, a coarser surface usually increases emissivity and decreases its sensitivity to emission angle variations.

Actually, because of the different granulate sedimentation during the compression and heating phases and the consequent expansion of the board, the finest part of the granulate settles more on one of the two faces, thus determining a more compact surface and a lower presence of voids.

RESULTS AND DISCUSSION

Table 2 shows the results obtained. Regression analyses were performed to find the possible relations between the measured values and the

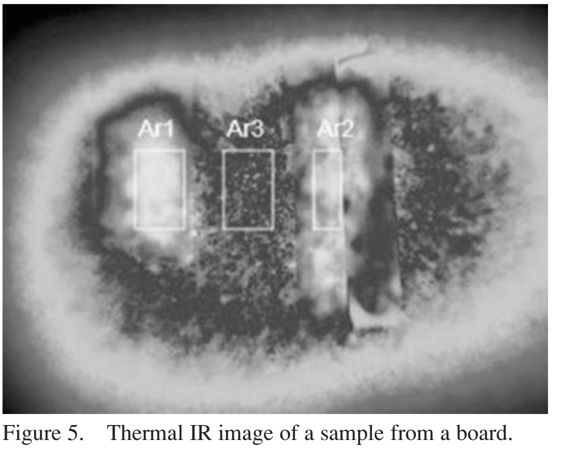

Figure 5. Thermal IR image of a sample from a board.

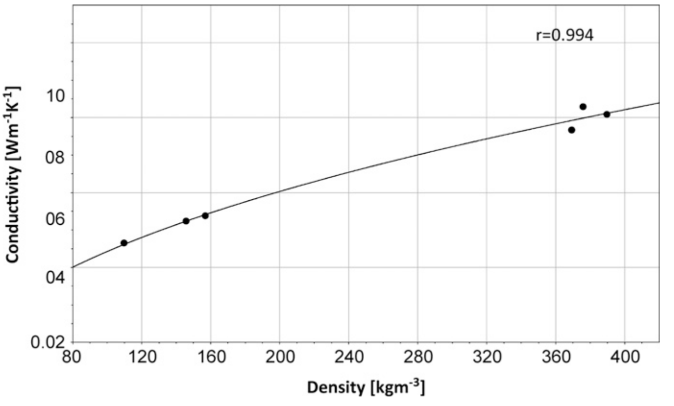

Figure 6. Conductivity regression curve in relation to board density.

main physical characteristics of the boards. Worth mentioning are the relations among the density value, conductivity, and specific heat capacity of agglomerated cork, which are expressed by Eqs 5 and 6. Eq 5 shows that the thermal conductivity tended to increase as board density increased (Fig 6). This was because of the voids decreasing inside the matrix of the material, thus making it more compact and decreasing its insulating characteristics.

$$\lambda = a \cdot \rho^b \tag{5}$$

where: λ is the conductivity (W/m/K); a = 5.687E – 03, $b = -4.456$E – 01, and correlation coefficient $r = 0.994$.

The regression function, which best fits the variation of the specific heat capacity as a function of density, is expressed by Eq 6. The high value of correlation of Eq 6 with the experimental data allows the assumption of a limited error of the calculated values, particularly for low density values. Furthermore, this is also a nonlinear function and shows that the specific heat capacity of the samples rapidly decreased as the board density decreased (Fig 7). However, in hot climate areas, the value of thermal diffusivity, ie the ratio between conductivity and the product of density and specific heat capacity, is most important to an insulating material. As a matter of fact, it is fundamental to describe the performance of the material itself under non steady-state conditions.

$$c = \frac{a \cdot \rho}{b + \rho} \tag{6}$$

where: a = 2.016E + 03, $b = -6.867$E + 01, and correlation coefficient $r = 0.952$.

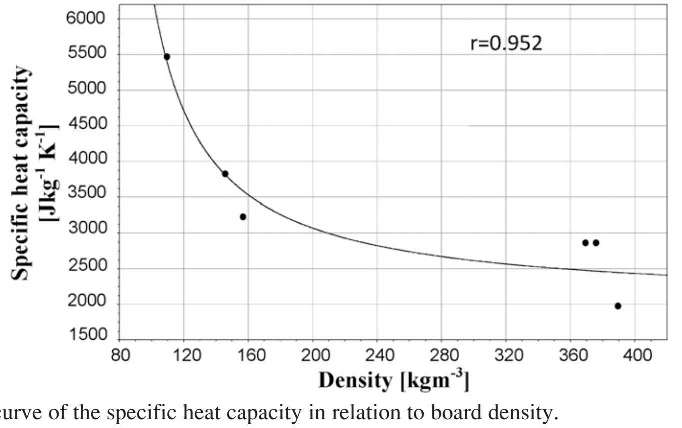

Figure 7. Regression curve of the specific heat capacity in relation to board density.

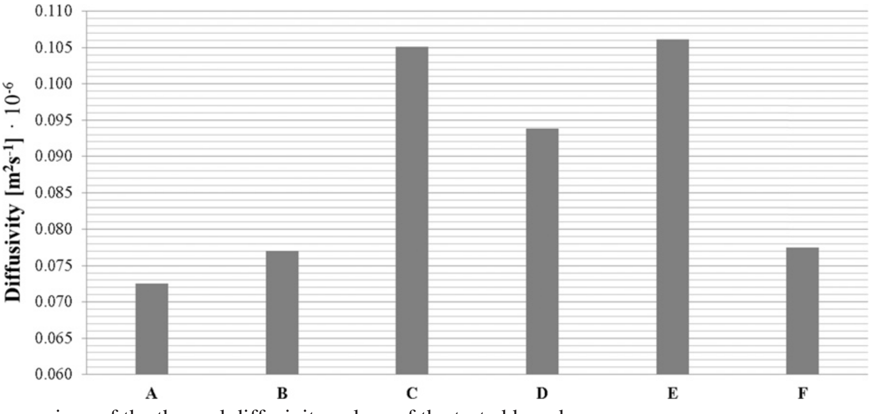

Figure 8. Comparison of the thermal diffusivity values of the tested boards.

Analysis of the values demonstrated that cork agglomerate boards had thermophysical characteristics similar to those of natural cork (Silva et al 2008), which, however, has a value of thermal conductivity slightly lower (0.045 W/m/K) than the average value of cork agglomerate boards (0.065 W/m/K), a specific heat capacity definitely lower (350 J/kg/K) than the average specific heat capacity of agglomerate boards (3370 J/kg/K), and a value of thermal diffusivity (1.00×10^{-6} m^2/s) one order of magnitude greater than the average of cork agglomerate boards (1.04×10^{-7} m^2/s). Among the various tested boards, sample Board A (Fig 8) demonstrated the best thermal insulation performance, especially in buildings located in hot climate areas, because it had the lowest value of thermal diffusivity (0.73×10^{-6} m^2/s).

As previously mentioned, the thermal diffusivity value of an insulating material is one of the most important indicators of its thermal resistance, because it measures heat propagation through a wall of a temperature field under non steady-state conditions.

CONCLUSIONS

The values obtained confirmed the good insulating characteristics of the boards made of cork granules, which, to a certain extent, are even better than those of natural cork. In particular, agglomerated cork boards have a much lower commercial value because cork granules are mostly made from waste and recycled material. These data are particularly important to choose and properly apply the insulating material depending on the external environmental conditions typical of the area in which the building is located as well as on the internal environmental conditions that should be assured.

As a result, a simple methodology was developed to simulate the dynamic thermal conditions of a hot Mediterranean climate and to carry out a comparative evaluation of the conductivity and specific heat capacity of boards characterized by decreased thickness, made up of natural materials, and under conditions close to real-life application. The method was applied and tested to assess the thermal performance of boards of cork agglomerate, a material that, because of its natural characteristics, is used in green building and in premises that should assure high levels of healthiness and well-being, such as schools, health care facilities, and buildings for storage of agri-food products. For the last few years, a growing demand for this natural material has been recorded not only in the green building sector but also in the building industry as a whole. In fact, cork has important characteristics that may contribute to better comfort and internal quality of buildings, eg improving internal acoustic conditions through acoustic insulation and reverberation control and controlling internal humidity, because cork does not let water in and, at the same time, let vapor out. The cork agglomerate boards are an efficient and cheap alternative to the more expensive boards of virgin cork, especially if they are made without using any synthetic binder. Also, they not only encourage recycling and reuse of cork waste but also help meet the growing demand for low-cost sustainable buildings.

This study is the first part of more detailed research on the development of adequate technical solutions based on the rational and optimal use of green materials in the building sector. Another thing to consider is that sustainability is not only achieved by using renewable sources but also by being aware of the time they need to regenerate, which, in the case of cork, can be as long as 20 yr.

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