Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 321 – 326

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Innovative cardboard based panels with recycled materials from the packaging industry: thermal and acoustic performance analysis

F.Asdrubali[a], A.L. Pisello[a,*], F. D'Alessandro[a], F. Bianchi[a], M. Cornicchia[a], C. Fabiani[a]

a CIRIAF, University of Perugia,via. G. Duranti 93, 06125 Perugia, Italy

Abstract

An effective use of thermal insulation materials can significantly reduce energy consumption in buildings, while a correct use of acoustic materials helps to guarantee good acoustic environments indoors and to reduce noise pollution. This work aims at determining the thermal and acoustic performance of corrugated cardboard panels usually applied in the packaging industry, by means of experimental in-lab analysis of thermal and acoustic properties. In particular, transmission loss and thermal conductivity were measured. Results show that the cardboard panels usually applied in packaging industry present promising performance in terms of acoustic insulation capability and thermal insulation performance, slightly lower than commonly used insulation panels. Further developments of the work will concern the analysis of the life cycle environmental and economic impact of the studied systems for building thermal-energy and acoustic performance optimization.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Thermal and acoustic insulation; Recycled materials; Innovative panels; Corrugated cardboard.

1. Introduction

In Europe 25% of the industrial production is due to the construction sector which environmentally speaking accounts for 42% of the overall energy used in the continent and about 30% of carbon dioxide emissions [1]. For this reason the European Directive 2010/31/EU [2] requests to reach nearly zero energy buildings by the year 2020, thus recognizing that green building strategies can be extremely efficient in fossil fuel savings and greenhouse gas reduction. Thermal insulation is acknowledged as one of the most effective way to ensure energy savings, but a competitive insulation material should not only fulfil good thermal performances, but also present good acoustic characteristics in terms of sound insulation and a low environmental impact and cost production [3-4]. In this

---

* Corresponding author. Tel.: +39-075-585-3563; fax: +39-075-585-3697.
E-mail address: pisello@crbnet.it

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.652

context, the increasing attention that recently has been focused on sustainable and natural materials is easily understandable. Researches that enhance recyclability and develop eco-friendly materials as alternatives to many currently used ones are very up-to-date, especially in order to minimize the use of non-sustainable or harmful materials, *e.g.* mineral wools, which have good performances and low cost but, when inhaled, their fibers can accumulate in the lungs and can cause skin irritation [5].

In this panorama, natural fibres have gathered increasing attention because of their internal structure, which can generally guarantee high porosity. Among these fibres, cellulose is the most representative biopolymer and it is widely used for producing paper and cardboard. Therefore, different insulation materials with cellulose as the main raw material have been recently developed [6]. An insulation material made from waste newspapers and magazines with heat insulation and sound absorbing properties was also developed by Jun-Oh Yeon et al. [7]. Physical and mechanical properties of cardboard panels made from used beverage carton with veneer overlay were examined by Nadir Ayrilmis et al. [8]. The simultaneous heat and mass transport in paper sheets during moisture sorption from humid air was evaluated by Foss et al. [9]. Within this context, the main purpose of this work is to investigate the thermal and acoustic properties of corrugated cardboard panels, made of waste paper, usually applied in the packaging industry, and completely recyclable in their turn. The absence of any raw material in the panel manufacturing leads to promising performance in terms of life cycle environmental impact (cradle to gate approach) , as demonstrated be the life cycle studies performed in [10]. Furthermore, the characteristic internal geometry of the panels can guarantee a very low density with respect to packed cardboard panels, and a reliable resistance to be compact and self-supporting. Nevertheless, the presence of still air inside the flutes and the stiffness guaranteed by the internal structure allow to reach promising thermal and acoustic performance.

2. Materials and methods

2.1. Description of the cardboard panels

The investigated panels were prepared by overlapping a variable number of single (double-faced) boards, consisting of two facings (liners), adhered to one inner fluted medium which can have different standardized height. Two types of flutes (C-flute and E-flute), respectively 4.1 and 1.9 mm thick , were considered (Fig. 1). The unique geometry of the cardboard allowed to investigate the behavior of different samples prepared by changing the total thickness of the panel, the relative orientation of the single boards, and the thickness of the flute. In particular for the sound absorption analysis, panels made by overlapping 18, 22, and 26 C-flutes, for a total thickness of 76, 95 and 112 mm, respectively, were tested. Additionally panels made by overlapping 40, 46 and 52 E-flutes, for a total thickness of 76, 87 and 99 mm, respectively, were considered for comparative purpose. For the sound insulation properties, panels made by overlapping 8, 12, and 16 C-flutes, for a total thickness of 33, 50 and 67 mm, respectively, and panels made by overlapping 20, 26 and 32 E flutes, for a total thickness of 39, 51 and 64 mm, respectively, were considered.

Fig. 1. Samples and experimental facilities: (a) E-flute; (b) C-flute; (c, d, e, f) Concordant, orthogonal 1×1 and 2×2, and sandwich (4E-10C-4E) samples; (g, h) Kundt's tube and hot plate apparatus.

All of these panels were investigated with both a concordant, *i.e. parallel*, orientation of all the layers and by rotating one and two layers at a time by 90°. Two other kinds of panels were also prepared and investigated by mixing C and E-flutes in six sandwich configurations. The first kind of panel was composed by considering an internal fixed layer of 10 flutes and two external layers of a variable number of E flutes (2, 4, and 6, with a total thickness of 51, 60, and 68 mm, respectively). The latter one was prepared with fixing the external layers configuration at 5 C-flutes per side, and with varying the internal E-flutes number from 4, to 8 and finally 12, for a total thickness of 51, 59 and 68 mm respectively. As for the thermal analysis, panels of a total thickness of 50 and 75 mm made by overlapping 12 and 18 C-flutes, 26 and 40 E-flutes were considered with a concordant orientation of the flutes. Furthermore, one sample with an orthogonal orientation of 18 C-flutes, and one sandwich configuration (6E-10C-6E flutes) were tested, for a total thickness of 50 and 68 mm, respectively.

For the thermal measurements, the samples had a plant dimension of 500×500mm, while for the acoustic tests, cylindrical samples with diameter of 100mm were prepared.

2.2. Description of the methodology

For the acoustic characterization of the samples, both sound absorption and sound insulation properties were investigated in an impedance tube, measuring the normal incidence absorption coefficient (α) and the Transmission Loss (TL) of the panels. The first one indicates the part of acoustical energy of the incident wave that is not absorbed by the tested sample and it is experimentally determined, according to the ISO 10534-2 standard [11], by measuring the sound pressures in two fixed positions. Then the transfer function between them is defined, allowing to obtain the reflection coefficient of the sample and its absorption coefficient [12]. Transmission Loss on the other hand, is a key factor for the quantification of the insulation properties of acoustical materials. It is related to the sound transmission coefficient (τ) by the law presented in equation (1):

$$TL = 10 \cdot \log(1/\tau) \tag{1}$$

It is measured by means of the ‘two-load’ transfer function method improved by Pispola et al. [13], acquiring the sound pressure in four fixed microphone positions and repeating the measurements with two configurations of the termination, anechoic and rigid.

The thermal characterization of the samples is carried out by defining their thermal conductivity (λ) in monodimensional heat flux conditions, thus considering the simplified version of the Fourier’s law (2):

$$\phi = (\lambda/d) A \Delta T \tag{2}$$

where Φ is the heat quantity transferred through the total area of the sample A, d is the total thickness of the material and ΔT is the temperature difference in the specific direction considered. The thermal conductivity is thus determined from the heat flow rate at steady state conditions and the temperature difference between the hot and cold surfaces of the samples, according to the ISO 8302 [14], UNI EN 12664 [15] and UNI EN 12667 [16] standards. Finally a numerical validation of the obtained value is reached applying the UNI EN ISO 10077-2 [17].

3. Experimental campaign

3.1. Acoustic characterization

The acoustic characterization in terms of absorption coefficient and Transmission Loss was carried out with an impedance tube (Brüel & Kjær, model 4260), using a two (α) and a four microphones method (TL) respectively. For the absorption coefficient measurements several steps were performed. First of all, the environmental parameters of the room i.e. atmospheric pressure, air temperature, and relative humidity, were defined. Microphones calibration was accomplished. Then, after the sample positioning, the evaluation of the signal-to-noise ratio was made and finally the transfer function calibration for the channels phase displacements was evaluated. The measurements of the Transmission Loss were carried out with the two-load method, which consisted of these main steps: first of all, as for the absorption measurement the environmental settings were defined and the microphones were calibrated. Then the background noise calibration measurement was performed with an anechoic and a rigid termination of the tube. Finally, after the insertion of the sample, signal measurements were done with again the anechoic and the empty end of the tube as before. All the measures to determine the absorption coefficient and the Transmission Loss were carried out using the large tube (sample diameter 100 mm) in order to cover the range of frequencies between 50 and 1600 Hz for all the considered samples.

3.2. Thermal characterization

The thermal characterization was carried out by means of a guarded hot plate facility which required a single sample in the form of a square slab with size 500×500 mm. The apparatus was constituted by:

- a main heater split into a square element of 250×250 mm (the central heater), supplied with an assigned power rate, and a frame element with a total thickness of 125 mm (the guard heater), kept at the same temperature of the previous one by a closed-loop control system, and both realized in aluminum with a thickness of 30 mm and internally heated by heating cartridges supplied with direct current;
- a second guarded hot plate placed beneath the main heater and sandwiched between two panels of an insulator 40 mm thick (of 500×500 mm plan dimension), also kept at the same temperature of the main heater as to prevent a downward heat flux;
- a cooling system (cold plate) (500×500 mm), constituted by a stainless steel container with an internal spiral circuit in which a liquid refrigerator (water) can flow;
- a chiller to chill the liquid;
- an acquisition and control system and a software developed in a LabView environment for both temperature regulation and data acquisition.

The temperature monitoring was carried out by means of 26 screened thermocouples J-type placed inside the apparatus, which can be divided in two kinds of sensors: 16 thermocouples were addressed in monitoring the thermal balance between the measure zone and the guard zone, while 10 thermocouples were used to detect the average temperatures in the cold and hot sides of the sample. During the measurements a fixed heat rate was delivered by the electric heater at the bottom of the apparatus, producing a heat flow through the sample towards the upper plate chilled by the liquid cooling system. Once the steady state conditions were reached, the power supplied to the measure zone and the average temperature gradient between the two sides of the sample were acquired respectively every 100 ms and 5 s.

4. Analysis of the results

4.1. Results of the acoustic analysis

As expected, all the samples tested do not present a particularly interesting sound absorption behavior because of the inner structure of the cardboard (closed channels between the flutes) and the excessive flow resistivity ensured by the paper liners of the single cardboard layer. On the other hand, all the samples exhibit interesting properties in terms of acoustic insulation (fig. 2). Considering the samples constituted by the only C-flutes, in all the investigated configurations (concordant, orthogonal 1×1, and orthogonal 2×2 orientation), it is possible to notice a general increasing value of TL as the thickness of the samples grows. Furthermore, the orientation itself clearly produces significant changes in its trend. In fact, in the concordantly orientated samples a significantly better insulation behavior is detected in the range between 100 and 600 Hz (peak of 70 dB of TL at 400 Hz, for the maximum thickness analyzed of 66 mm). For higher frequencies the insulation behavior steadies at lower values. In both the orthogonal 1×1 and 2×2 configurations (having a consistent trend of TL), a significant improvement on the TL is reached in the range 800÷1600 Hz, and a peak of 80 dB is reached at 1400 Hz, for the thickness of 66 mm in the 1×1 configuration.

This sensible change in the insulation properties of the samples can be explained noticing that the single concordant panels, when impinged by a sound wave, tend to oscillate simultaneously while in the orthogonal configuration the flutes of two subsequent layers creating a 90° angle creates a stiffer system. If the E-flute samples are considered, it is also possible to appreciate the increase of TL together with their thickness, but the significant difference between the concordant and the orthogonal configurations is not that important as on the previous case. This is probably imputable to the geometry of the single panel: the rigidity of the single E-flute is much higher than that of the C-flute. Therefore the change on the reciprocal orientation does not affect appreciably the system. By comparing the same configuration of panels made by C or E-flute layers, in general, the E-flute panels present a better behavior at frequencies 900÷1600 Hz than the C-flute panels, especially in the concordant orientated samples.

The last analyzed configuration is the sandwich one described as follows. All the sandwich configurations were prepared by considering the only parallel flutes' layers. The large number of C-flutes does not allow the system to reach a significant rigidity, and its behavior is comparable to that of the concordant C-flutes samples, even though a general slight increase of the TL level is detectable because of the presence of the E-flutes.

The obtained results allow to make useful comparisons between the three tested configurations. However future development of the research will also focus on testing larger samples in reverberation rooms in order to define significant comparisons with other common sound insulation materials.

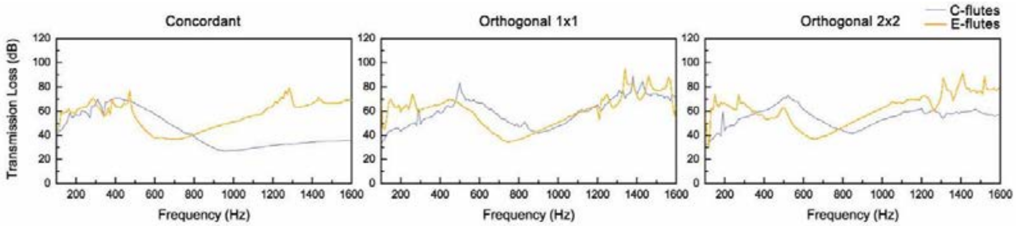

Fig. 2.Transmission Loss of the three different configurations considered for the C-flute and E-flute samples with a total thickness of 66 mm.

4.2. Results of the thermal analysis

Thermal analyses were all conducted at a temperature around 23°C and 30% of RH. C-flute concordant samples of 50 and 75 mm show a thermal conductivity of 0.053 W/mK with an error of 0.001 W/mK. E-flute concordant samples present slightly different λ, both within their maximum permissible error *i.e.* 0.058 ± 0.001 and 0.060 ± 0.001 W/mK, for 50 and 75 mm, respectively (Table 1). Therefore, it is noteworthy that the two values of thermal conductivity for the E and C-flute are close to each other, considering the significant difference in the percentage of cardboard volume between the two flutes (24% for the C-flute and 55% for the E-flute) and that the thermal conductivity value of the cardboard is significantly greater than that of the air cavity (one order of magnitude more). To investigate the heat exchanges in the cardboard, the effect of conductive and radiative phenomena inside the air cavities (according to the UNI EN ISO 10077-2 [17]) was studied. An equivalent thermal conductivity of air, of 0.034 W/mK for the C-flute and of 0.028 W/mK for the E-flute was defined. This values denote that the larger dimension of air cavities inside the C-flute panels, probably allows the development of much significant convective flows within these layers, with respect to the E-flute's ones. This phenomenon explains why their λ is still comparable despite the different quantity of cardboard exists between the two flutes. By considering the effect of flute mutual orientation, the hot plate apparatus shows that the conductivity of the sample constituted by 18 orthogonal C-flutes, does not change significantly with respect to that of the concordant one i.e. 0.052 ± 0.001, since the experimental facility allows to investigate the only horizontal thermal flux perpendicular to the panel. The tested sandwich configuration, as expected, has an intermediate value of λ i.e. 0.055 ± 0.001.

Tab 1.Experimentally measured values of λ for the investigated samples (s= thickness, w = weight)

Sample	s (mm)	w (kg)	λ (W/mK)	Description	Sample	s (mm)	w (kg)	λ (W/mK)	Description
12Cp	50,60	1,655	0,053 ± 0,00118	12 parallel C-flutes	**40Ep**	74,96	5,315	0,0598 ± 0,0010	40 parallel E-flutes
26Ep	50,69	3,600	0,058 ± 0,00120	26 parallel E-flutes	**18Co**	50,04	1,659	0,0524 ± 0,0011	18 orthogonal 1x1 C-flutes
18Cp	74,86	2,480	0,053 ± 0,00098	18 parallel C-flutes	**4E-10C-4E**	56,26	2,417	0,0547 ± 0,0011	sandwich with 4E-10C-4E

5. Conclusions and future developments

In this work, innovative, thermal-acoustic insulation panels made by promising corrugated cardboard were experimentally studied. In particular, cardboard layers typically used in packaging industry were optimized in terms of geometry and stratigraphy design to be ready for sustainable constructions' market. The acoustic analysis showed that, even though the absorption behavior of the investigated panels is not particularly notable, their sound insulation properties are quite remarkable, reaching even a TL of 80 dB at specific frequencies, i.e. higher than 1200 Hz. The thermal conductivity analysis showed that these panels do not reach the thermal insulation capability of high-performance commercialized products. Nevertheless, the thermal conductivity value achieves 0.0524 W/mK, and it can still be considered as acceptable to be considered as thermal insulation panels. Furthermore, the mechanical properties of the corrugated cardboard panels, together with the obtained sound and thermal insulation ones, make them suitable to be used as light insulation solutions in the building sector, especially in internal partitions. Their use can also be extended to open space's acoustic control and temporary exhibition areas.

As a future development of this work, full-scale panel integrated within a real wall stratigraphy will be tested by means of an hot box apparatus [18] to assess thermal conductivity and in reverberation rooms to evaluate sound reduction index. Furthermore, it could be interesting to develop a virtual reference model that enables to take into account all the possible configurations and to predict their specific insulation properties. Lastly, the Life Cycle Assessment and economic evaluation of the proposed panels will be carried out using data provided by the manufacturer to properly define the environmental impact and the economic performance of the cardboard panels as thermal-acoustic insulation materials for the construction industry.

Acknowledgements

The authors would like to thank Mauro Benedetti S.p.A. for providing the samples.

References

[1] Fernando Pacheco Torgal, Said Jalali ; Eco-efficient Construction and Building Materials; Ed. Springer (2011).

[2] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings. Official Journal of the European Communities, L 1/65; 2003.

[3] Nuno Pargana, Manuel Duarte Pinheiro, Jose Dinis Silvestre, Jorge de Brito; Comparative environmental life cycle assessment of thermal insulation materials of buildings; Elsevier Energy and Buildings (2014).

[4] A.M. Papadopoulos; State of the art in thermal insulation materials and aims for future developments; Elsevier Energy & Buildings (2004).

[5] F. Asdrubali; S, Schiavoni, K.V. Horoshenkov; A Review of Sustainable Materials for Acoustic Applications, Building Acoustics, 19 (4), 283–312 (2012).

[6] Shi J., Lu L., Guo W., Cao Y.; Heat insulation performances, mechanics and hydrophobic modification of cellulose-Si-O2 composite aerogels; Carbohydr Polym (2013);98:282-9.

[7] Jun-Oh Yeon, Kyoung-Woo Kim, Kwan-Seop Yang, Jea-Min Kim, Myung-Jun Kim; Phycal properties of cellulose sound absorbers produced using recycled paper; Elsevier Construction and building materials (2014).

[8] Nadir Ayrilmis, Zeki Candan, Salim Hiziroglu; Physical and mechanical properties of cardboard panels made from used beverage carton with veneer overlay; Elsevier Materials and Design (2008).

[9] W.R. Fosss, C.A. Bronkhorst, K.A. Bennet; the simultaneous heat and mass transport in paper sheets during moisture sorption from humid air; Pergamon Heat and Mass transfer, (2002).

[10] European Federation of Corrugated Board Manufacturers, Cepi ContainerBoard; European Database for Corrugated Board Life Cycle Studies; Technical report; (2012)

[11] ISO 10534-2. *Acoustics – determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method; (1998)*.

[12] F. Asdrubali, G. Baldinelli, F. D'Alessandro, Evaluation of the acoustic properties of materials made from recycled tyre granules, Proceedings of 36th International Congress and Exhibition on Noise Control Engineering, INTER-NOISE 2007; Istanbul; Turkey (2007).

[13] G. Pispola, V. K. Horoshenkov, F. Asdrubali; Transmission loss measurement of consolidated granular media, J. Acoust. Soc. Am. 117 (5), (2005).

[14] ISO 8302. *Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus; (1992).*

[15] EN 12664, *Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Dry and moist products of medium and low thermal resistance.*

[16] EN 12667, *Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance, (2001)*.

[17] UNI EN ISO 10077-2, Thermal performance of windows, doors and shutters -Calculation of thermal transmittance - Part 2: Numerical methodfor frames, (2012).

[18] G. Baldinelli, F. Asdrubali, C. Baldassarri, F. Bianchi, F. D'Alessandro, S. Schiavoni, C. Basilicata; Energy and environmental performance optimization of a wooden window: A holistic approach, Energy and buildings, 79, 114-131 (2014).