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Experimental and numerical characterization of innovative cardboard based panels: Thermal and acoustic performance analysis and life cycle assessment

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A B S T R A C T

Efficient thermal insulating materials can significantly reduce energy consumption for both heating and cooling of buildings. When selecting an insulation material, however, it is important to consider other important aspects, such as acoustic performance, environmental impacts, effects on human health and costs of production. That is the reason why key research developments are recently achieved in the field of sustainable, highly efficient materials. Within this context, this paper deals with the thermal and acoustic performance and the environmental impact analysis of two kinds of corrugated multi-layer cardboard panels, usually applied in the packaging industry. Thermal analyses were conducted in order to measure the thermal conductivity by means of both an experimental campaign and numerical methods. The acoustic absorption coefficient and the transmission loss were experimentally determined by means of an impedance tube. Finally a Life Cycle Assessment of the considered panels was implemented and compared to the performance of other commonly used insulation materials. The main results of the study show that the cardboard-made panels usually applied for low-cost packaging present promising performance in terms of both acoustic and thermal insulation potential, i.e. of the same order of magnitude than high-performance commercialized products. The environmental impact evaluation also reveals an interesting behavior of the corrugated cardboard panels, which can by any means be considered as a promising recycled insulation material.

1. Introduction

In Europe 25% of the industrial production is due to the construction sector which 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 [3,4], nevertheless a competitive insulation material should not only fulfill good thermal performances, but also present good acoustic characteristics in terms of sound insulation and a low environmental impact and production cost [5–9]. In this context, the increasing attention that recently has been focused on sustainable and natural materials is easily understandable [10,11]. Researches that enhance recyclability and develop eco-friendly materials as alternatives to many currently used ones are very up-to-date [12], 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 whose fibers can cause irritation [13], or expanded products, such as EPS, which are derived from petrol and present a high amount of embodied energy [14].

In this panorama, natural fibers have gained increasing attention because of their internal structure, which can generally

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guarantee high porosity. Among these fibers, 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 [15]. Acoustic performance was investigated in natural fibers panels by Berardi et al. [16]. An insulation material made from waste newspapers and magazines with heat insulation and sound absorbing properties was also developed by Yeon et al. [17]. Physical and mechanical properties of cardboard panels made from used beverage carton with veneer overlay were examined by Ayrilmis et al. [18]. The simultaneous heat and mass transport in paper sheets during moisture sorption from humid air was evaluated by Foss et al. [19]. Furthermore, the International Organization for Standardization (ISO) has also published different standards to be applied as reference models for the numerical validation of experimentally obtained data, like the ISO 10077-2 standard [20], which can be used for the calculation of windows, doors and shutters thermal transmittance. Additionally, in recent years, numerical simulations have also been flanked to standard-based analytical evaluations to verify experimental results or, if developed before the experimental procedure, select specific experiments to be run, thus leading to huge time and money savings.

For example a simulation methodology was developed by Arambakam et al. [21] to study the role of microscale geometry of a fibrous material on its performance as an insulation medium and a one dimensional transient model for coupled heat and mass transfer (HAM) in porous materials was developed by Steeman et al. [22].

When considering the environmental problem related to the production of a building or of building materials, on the other hand, the most acknowledged method to be used is the Life Cycle Assessment (LCA), regulated by ISO 14040 [23], which considers the principles and framework for an LCA, and ISO 14044 [24], which specifies the requirements and guidelines for carrying out an LCA study. This methodology was applied by Ardente et al. to the case study of kenaf-fibers insulation board [25] and by Asdrubali et al. for the environmental impact evaluation of buildings [14].

Within this context, the main purpose of this work is to investigate the thermal and acoustic properties and the environmental impact of corrugated cardboard panels, made of waste paper, usually applied in the packaging industry, and completely recyclable in their turn. Because they are made of very widespread and common wastes, these panels are very cost effective with respect to typical insulation panels and the absence of any raw material in the panel development also suggests promising performance in terms of life cycle environmental impact. 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 air cavity structure, improving 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 heights. Two types of flutes (C-flute and E-flute), respectively 4.1 and 1.9 mm thick, were considered (Fig. 1). Table 1 reports all the analyzed samples and while Fig. 2 shows all the tested configurations. 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.

The different analyses carried out on the considered corrugated cardboard samples are resumed in Fig. 3.

2.2. Methods for assessing thermal properties

The thermal characterization of the samples was carried out by means of the guarded hot plate apparatus (Fig. 4), by defining their thermal conductivity (λ) in monodimensional heat flux conditions, thus considering the simplified version of the Fourier's law (2):

$$\phi = (\lambda/d)A\Delta T \tag{1}$$

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 [26], EN 12664 [27] and EN 12667 [28] standards.

Additionally a numerical validation of the obtained values was reached both applying weighted average of the air and cardboard thermal conductivities, with respect to their superficial area in an orthogonal section of the panel, and defining a computational model by means of a Finite Element Method software.

2.3. Methods for assessing acoustic properties

For the acoustic characterization of the samples, both sound absorption and sound insulation properties were investigated in an impedance tube (Fig. 5), measuring the normal incidence absorption coefficient (α) and the Transmission Loss (TL) of the panels.

The first parameter 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 [29], 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 [30]. Transmission Loss on the other hand, is a key factor for the quantification of the insulation properties of acoustic materials. It is related to the sound transmission coefficient (τ) by the law presented in Equation (2):

$$TL = 10\cdot\log(1/\tau) \tag{2}$$

It is measured by means of the 'two-load' transfer function method [31,32], acquiring the sound pressure in four fixed microphone positions and repeating the measurements with two configurations of the termination, anechoic and rigid.

3. Acoustic and thermal analysis

3.1. Experimental campaign for 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.