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Experimental thermo-acoustic characterization of innovative common reed bio-based panels for building envelope

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A B S T R A C T

Natural and bio-based construction materials represent a promising solution for optimizing buildings' environmental sustainability. In this view, the paper presents the multipurpose experimental thermo-acoustic characterization of common reed-based building panels. Different geometries, densities, humidity rates and stalk shapes were considered and tested by means of hot-plate, hot-box and impedance tube in-lab experimental benches. The thermal analysis showed that the geometry scarcely affects the thermal conductivity, which is around 0.05 W/mK and, therefore, comparable to other materials already commercialized for the same scope. On the other hand, the acoustic behavior is strongly affected by the stalk configuration, e.g. perpendicular, parallel or combined orientation with respect to the incident wave. In particular, the longitudinal stalk layout showed a significant sound absorption performance. The exhaustive experimental original characterization of such by-product, therefore, showed a very promising overall thermo-acoustic behavior. At the same time, for optimizing the panel field performance, the acoustic requirements should represent the panel design drivers, given the high sensitivity of the panel layout characteristics affecting the acoustic performance.

1. Introduction

Energy efficiency in buildings represents a fundamental topic to deal with by means of continuous research investigation and technology innovation effort. In fact, buildings count for around 40% of the total final energy consumption in Europe [1,2], and around 41% of primary energy consumption in the United States [3]. In particular, the amount of energy consumption in residential constructions for air conditioning is up to 68% in Europe, and around 53% in the USA [1], confirming the very relevant need to reduce energy requirement by keeping high indoor air quality and thermal comfort conditions. This same alert is also underlined by the European research framework Horizon 2020 [4] whose aim for 2020 is to consistently reduce greenhouse gas emissions up to 80–95% in 35 years. For all these reasons, research and technology innovation about sustainable and efficient solutions to save energy and to improve indoor environmental quality in buildings represent a key scientific issue to be urgently addressed. In this panorama, new environmentally friendly materials, and passive solutions in general, are identified to be optimal strategies to foster this purpose. The careful employment of selected materials, depending on the building layout-design and orientation, climate context, possible microclimate inter-building effects [5] can help reaching increased hygrothermal conditions for users and/or optimal balance between passive and active technologies for energy saving and occupants' satisfaction purpose [6].

Natural, sustainable and bio-based materials [7] are achieving attention both in the global market and in the research context, thanks to their fourfold effect of:

i) reducing peak energy demand and cost for building sector [8],
ii) mitigating local climate change phenomena such as urban heat island [9],

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iii) improving acoustic and thermal performance of indoors [10–12],
iv) on a global scale, producing worldwide reduction of carbon emissions imputable to HVAC system operation and to their inner environmental sustainability characteristics, being natural materials already available with limited post-process impact [13].

Given this inner characteristic, they also decrease environmental impact due to manufacture processes in the LCA balance [14], which require less industrial and technology transformations than those of most common artificial materials. Some natural materials conveniently combine low embodied energy, low cost and intrinsic optimal characteristics to improve building thermo-acoustic performance and comfort [15]. For instance, natural gravels, cool clay tiles and marble envelopes are able to reduce the solar radiation thermal gain entering the building, with a consequent reduction of cooling energy need and indoor thermal comfort improvement in summer conditions [16], with a relatively much lower penalty in winter conditions in Mediterranean climate [9,17]. A more general analysis was carried out in Refs. [18], where the same findings were confirmed by a wide analysis of such solutions with varying climate conditions, demonstrating the year-round beneficial effect in terms of cooling/heating load variation due to a solar reflectance roof increase of 0.65 [18].

The greenery itself is gaining increasing interest for its inner capability to perform as promising sound absorption technique, as studied in Ref. [19] and for its indoor–outdoor environmental optimization potential. More in details, the analysis carried out in Ref. [19] confirmed that plants contribute to absorb a significant amount of acoustic energy, when they are equipped with their soil substrate in particular. In fact, such soil substrate tends to absorb up to 80% of the acoustic incident energy for frequencies above 1000 Hz. The further contribution of the greenery specie further optimizes the acoustic absorption in the whole frequencies' range.

In this panorama, the utilization of natural resources, like common reed [20–24], and other green materials [15], with intrinsic low environmental impact and satisfactory thermo-acoustic insulation properties, represents a key research deal which is addressed in this work, building upon previous investigations showing how reed is a valuable raw material for a multitude of manufactured products [25] even in low-cost constructions [26]. In particular, the application of common reed based materials for building thermal-energy efficiency and acoustic performance optimization will be the focus of this paper. This choice has been motivated by several key studies about this material confirming its wide availability in several worldwide habitats and its fast renovation rate with varying boundary conditions, which make the selected vegetation even more competitive from an environmental impact reduction perspective. More in details, in optimal conditions, the common reed (i.e. *phragmites australis*) can grow up with up to 200 rood stocks per square meter, with a growing rate of 40 cm/year, with a maximum height of about 20 m above the ground level [27]. The common reed, as previously mentioned, could adapt to various climate conditions and humidity level [26]. In fact, this vegetation has spread around the world, populating swamps, estuaries and shores of rivers and lakes, usually at altitudes between 0 and 1200 m above sea level [27], but it can survive up to 2200 m a.s.l [28]. It adapts well to different contexts. Thanks to this adaptability, in North America, common reed is located in semi-arid climates and deserts (where the rhizomes typically sink more in deep to find the water source) and in the wetlands of Subtropical climates. The selection of this material is also enforced by its massive diffusion also in territories where it could be mostly required as acoustic and thermal insulation for buildings, given that Allirand & Gosse [29] calculated that all the humid areas occupied by rushes are around 10 million of hectares, with an estimated production above the ground level varying between 3 and 30 tons/year per hectare [29]. Such wide availability makes the material very attractive for green buildings' applications as installed within internal partitions gaps between gypsum based panels, typical of several countries' construction practice. Its fire resistance capability is enforced by the gypsum layers and it could be considered similar to the one obtained by kenaf and sheep wool based materials already commercialized for the same scope and tested according to the EN 13501-1:2007A1+2010, as specified in Ref. [15]. Also the durability performance is not particularly compromised by indoor applications while, in future developments, possible application for external partitions will be investigated by mineralizing procedure of common reed based material.

2. Experimental procedure

The common reed based material representing the fulcrum of this study was characterized by means of both the thermal and the acoustic experimental setups and analysis procedures, properly implemented for this purpose. In particular, longitudinal, perpendicular and crossed reed layouts were selected in order to investigate optimal geometry configuration for maximizing the combined thermo-acoustic performance of such insulation panels. To this aim, section 2.1 deals with the thermal characterization and sample description, while section 2.2 deals with the acoustic investigation.

2.1. Characterization of the thermal properties

The thermal properties of the reeds were evaluated with two methods that mainly differ for the sample size: guarded hot-plate [30] and hot box [31]. The *guarded hot plate apparatus* has been built according to the international standard ISO 8302 [32], in order to allow testing the thermal conductivity in steady state conditions. Fig. 1 shows the apparatus composed by two plates kept at two different temperatures creating a 1-dimention thermal flux passing through the sample.

The cold plate of the apparatus consists of a stainless steel container with a spiral circuit and a refrigerator liquid (water) flowing in and chilled by an active refrigeration system. The hot plate is composed by different zones, two guard sections and a metering section that are separately controlled by a dedicated in-house original software developed within *LabVIEW* environment in order to avoid lateral and downward dispersions of the heat flux. The three different sections of the hot plate apparatus are controlled by 16 thermocouples installed within the sample boundaries. Most of the heat flux passes perpendicularly through the sample and it is calculated by Joule effect by metering the electricity flowing in the cartridge heaters. Furthermore, the acquisition system (*LabVIEW* environment) records the data monitored by 6 dedicated thermocouples, which are positioned on the sample surfaces. Finally, the thermal conductivity is calculated according to Fourier law. The guarded hot plate measurements produce an equivalent value of thermal conductivity of the reed samples, since the sample is characterized by a solid phase section (wood) and air cavities located in each reed channel and among the reeds within a sample panel. However, the guarded hot plate can be considered as a reliable instrument also for investigating materials composed by non-homogeneous but repeatable geometrical modules [12].

In order to increase the accuracy of the thermal characterization of the reed samples, a larger, and therefore more representative, sample was created and installed in the *hot box apparatus*. The hot