forum acusticum 2026
8-12 September · Graz, Austria

Design And Evaluation of New Sound Absorbing Panels in Perforated Honeycomb Cardboard and Cellulose Fibers

Lucia Magnini[1], Veronica Amodeo[1], Francesco Bianco[2], Fabio Brocchi[2], Simone Secchi[1], Marta Somigli[1]

[1]*Department of Architecture, University of Florence, Italy*

[2]*Freelance acoustic engineer, Pistoia, Italy*

This paper is a revised version of the authors' submitted manuscript that was peer-reviewed by at least two anonymous reviewers.

Abstract

This article presents the preliminary results of a study conducted by the Department of Architecture at the University of Florence in collaboration with the Italian National Consortium for the Recovery and Recycling of Cellulose-Based Packaging (COMIECO), focusing on the use of recycled cellulose-based materials for acoustic comfort in indoor environments. The study investigates various configurations of honeycomb cardboard panels (smooth or laser perforated with 1, 5, and 10 mm holes) coupled with layers of cellulose flakes or polyester fibers. The main objective is to overcome the limitations of traditional paper-based materials, which are typically effective only at medium and high frequencies, in order to achieve significant performance across a broad range of the sound spectrum. Experimental tests, conducted in a simplified reverberant environment and validated using a pressure-velocity (p-u) probe, demonstrate the effectiveness of acoustic and membrane resonance mechanisms, the latter being particularly active around 200 Hz in unglued panels. The results confirm that these eco-design solutions can offer performance comparable to traditional synthetic materials, supporting the principles of the circular economy in the construction sector.

Keywords: *Recycled cardboard, perforated panels, sustainable sound-absorbing materials, acoustic resonance.*

***Corresponding author**: lucia.magnini@unifi.it.*

1. Introduction

The research conducted by the Department of Architecture at the University of Florence and COMIECO is based on the growing awareness of the issue of acoustic quality in indoor spaces used for listening to speech or music, and on the need to move toward the gradual replacement of synthetic or non-recyclable materials—which have been used in this context until now—with sustainable and more easily recyclable materials.

There are many sectors in which paper and cardboard elements, appropriately designed in terms of their shape and layering, could replace—or at least complement—products commonly used for acoustic correction in spaces. Consider entertainment and dining venues, as well as trade show booths and classrooms. To date, the market for sound-absorbing products is largely dominated by mineral fibers, synthetic fibers or foams, or systems consisting of laminated materials that are difficult to separate when the products are disposed of, whereas paper and cardboard are materials that have a lower environmental impact.

However, several studies have shown that cardboard panels generally have modest acoustic performance, providing good sound absorption only at mid and high frequencies [1,2,3,4]. Through careful design of cardboard products, it is possible to achieve sound-absorbing performance comparable to that of products made, for example, from synthetic matrix materials, by exploiting the mechanisms of acoustic resonance and the interaction between different layers of cellulosic materials (stretched cardboard, cellulose flakes, honeycomb cardboard, tubes of various diameters and thicknesses).

The research project conducted a workshop to study innovative systems for the acoustic improvement of interior spaces, involving a select group of students from the Architecture and Industrial Design degree

programs at the University of Florence in the initial phase to develop preliminary design concepts (see Fig. 1).
The projects developed during the workshop have been published and are available on the Didapress (see Fig.2) publishing house website (https://didapress.it/pubblicazione/recardables-recycled-carboard-for-design-of-acoustic-sustainable-solutions).

Figure 1. Photo taken during the workshop organized by the University of Florence in collaboration with Comieco.

Figure 2. Design of a sound-absorbing system made of cardboard and other materials by Carmela Benevento e Cataldo Malena, created during the workshop.

Subsequently, simplified prototypes of several promising design solutions were constructed. These were tested in a reverberant environment to experimentally determine the sound absorption coefficient for diffuse incidence.
This article presents the preliminary results of the technical solutions tested.

2. The acoustic properties of cardboard

There is growing interest in natural fibrous materials, as they offer an alternative to the most common synthetic materials while combining acoustic performance with sustainability, biodegradability, recyclability, and cost-effectiveness. As shown in the text below this trend is also reflected in numerous scientific studies exploring the potential of new materials with a lower environmental impact [5,6]. Among the natural materials generating the most interest are those derived from cellulose, such as recycled cardboard, including both its most common types—corrugated and honey-comb cardboard—and less common but everyday items, such as egg cartons or disposable tea and coffee cups.

The measurement techniques used in the literature to evaluate the sound-absorbing properties of paper and cardboard-based products involve either impedance tube measurements or measurements in a reverberation chamber [1]; the former requires less time and allows for the use of small material samples [7], while the latter requires a material surface area of approximately 10 m^2 [8].
A study from 2015 confirms that the tested corrugated cardboard samples exhibit rather poor sound absorption behavior, due to the internal structure of the material itself and its excessive resistance to sound flow [2]. Conversely, interesting properties related to sound insulation have been highlighted. It can be observed that the orientation of the cardboard elements causes changes: if the panels are arranged in the same direction as the sound wave striking them, better sound insulation values are achieved, whereas in the orthogonal configuration there are fewer oscillations, creating a stiffer system and thus one with poorer acoustic performance.
Some samples of corrugated cardboard tested for cutting resistance using an impedance tube—with the corrugated sheet arranged to form perforation channels along the tube's length—revealed, however, that this particular arrangement, exhibiting low airflow resistance due to air passing through the long open channels (250 $\pm$ 50 Rayl/m), demonstrates good sound absorption at mid-to-high frequencies, with little contribution below 400 Hz [3].
In the same year, following a comparative analysis and subsequent testing in a reverberation chamber, Secchi et al. highlighted that among the most promising cellulose-based products is a sandwich panel, composed of two honeycomb cardboard panels and filled with cellulose fibers. The analysis revealed that this prototype, in addition to having a higher sound absorption coefficient than other traditional sound-absorbing materials, represents a more attractive solution in terms of sustainability [9]. Kang et al. also obtained interesting results by testing perforated corrugated cardboard panels with different perforation patterns [10].
At the 2016 International Conference on Advanced Material Technologies (ICAMT), Amelia Trematerra and Ilaria Lombardi analyzed the acoustic properties of cellulose, both in its molten state and when mixed with an adhesive. In both cases, acceptable absorption values were observed above frequencies of 500 Hz, while at lower frequencies the material partially loses its ability to absorb sound, regardless of the thickness of the element under examination. Although performance does not improve significantly, combining loose cellulose with adhesive results in a stiffer framework and thus one that is easier to use [4].
Also noteworthy are the acoustic panels designed and tested in 2023 by Sel et al., which are made from recycled tea and coffee grounds and covered on the front with a layer of disposable paper cups, perforated at the bottom and applied to adherer tightly. This system demonstrates good absorption at mid-to-high frequencies, with a particular increase at 500 Hz [6].

In response to the growing demand for materials with low environmental impact, Polimax has also embraced eco-design by creating UAcoustics sound-absorbing panels, which are made of recycled cellulose fiber with an engineered internal honeycomb structure designed to trap sound waves [11]. They dissipate sound energy through the material's porosity and the geometry of the cells.

In general, therefore, an analysis of scientific literature suggests that cellulose-based materials are the subject of considerable interest due to their ecological properties. Unfortunately, however, primarily because of the material's composition, although it often exhibits good acoustic properties at mid-to-high frequencies, concerns remain regarding its performance at low frequencies.

The purpose of this study is therefore to investigate new forms and methods of combining paper and cardboard products in order to achieve significant acoustic performance across a wide frequency range.

3. Cellulose-based and polyester-based systems

In terms of sustainability, natural-based materials offer clear advantages over synthetic ones. Cellulosic fibers are derived from renewable and abundant sources, such as plants, agricultural residues or microorganisms, whilst polyester is synthesised from non-renewable petrochemical sources, resulting in a significantly higher carbon footprint. In general, the production of natural-fiber absorbents requires less energy and generates fewer greenhouse gas emissions than the high-temperature processes required for synthetic materials. However, as highlighted by Majid Mohammadi, it should be noted that the processing of certain natural polymers into finished products can still involve intensive use of fossil fuels [12].

A further critical factor is the product's end-of-life: polyester, being a plastic, is not biodegradable and contributes to the problem of microplastic pollution during production, use and disposal. In contrast, natural fibers are generally non-toxic, biocompatible and safe for human health.

In terms of sound insulation effectiveness, both materials act as porous media in which sound energy is dissipated as heat through viscous friction within the pores, and increasing the thickness improves the absorption of low frequencies (see Fig.3).

Despite the environmental benefits of cellulose, polyester retains certain key practical properties that justify its widespread use. The main drawbacks of cellulose lie in its sensitivity to moisture and poor fire resistance, in contrast to the superior water-repellent properties of synthetic materials. To compensate for these limitations, natural fibers require chemical treatments (alkaline or flame-retardant) which may, however, increase their environmental impact [13]. There is also a discrepancy in terms of dimensional stability: synthetic fibers guarantee greater structural uniformity, whilst natural fibers exhibit inconsistencies that make it more difficult to predict their performance accurately. To combine the best of both worlds, hybrid materials are often developed. In these composites, polyester fibers are used as binders for the natural fibers, imparting structural integrity, stability and low hygroscopicity, which makes the final product much more resistant to moisture than pure cellulose.

The idea of using sandwich panels made from recycled cardboard, as proposed in this research, represents a turning point in the comparison between natural and synthetic materials, as it aims to overcome the historical limitations of cellulose through eco-design and structural engineering. The proposed panels use honeycomb cardboard derived from recycled packaging (in collaboration with COMIECO), ensuring one of the lowest possible environmental impacts and ease of disposal at the end of their life.

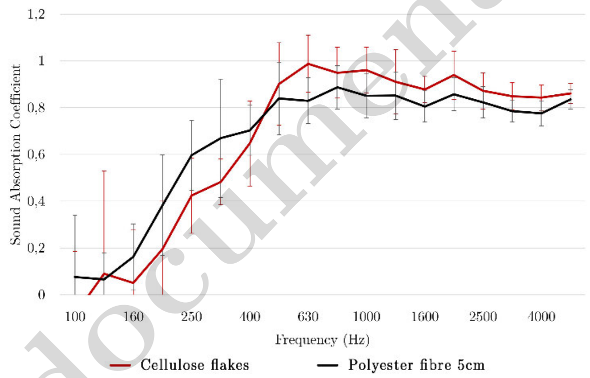

Figure 3. Comparison of sound absorption coefficients: polyester fiber offers superior performance at low and medium frequencies, compared to cellulose, which is more effective at medium and high frequencies, peaking at 630 Hz.

4. Materials and methods

The research aims to study the sound-absorbing properties of systems composed primarily of products derived from recycled cardboard. To this end, starting with cellulose-based materials, possible combinations of materials were investigated in order to maximize sound absorption across various sound frequency ranges.

The initial materials identified were honeycomb cardboard, flat cardboard, and cellulose flakes.

Following a preliminary evaluation based on empirical models of acoustic performance, several prototypes of the most promising designs were produced. The objective was to analyze the best layer configurations obtained by combining honeycomb cardboard with different pore sizes and a layer of cellulose flakes.

The honeycomb cardboard studied, supplied by GEM CO srl, has 60 mm thick cells and is equipped with a 170 g/m^2 cover, corresponding to a thickness of approximately 0.2–0.3 mm, applied by gluing on a single side. The cover was perforated using a laser technique to create holes with diameters of 1 mm, 5 mm, and 10 mm at a constant spacing of 18 mm, corresponding to the spacing between the cells of the cellular panel. The corresponding perforation percentages of the cover are therefore 0.2%, 6.4%, and 24.2%. The cellulose flake layer, on the other hand, is approximately 40 mm thick and has a surface mass of about 2.6 kg/m^2 and a density of about 65 kg/m^3 (see Fig. 3).

The study tested a total of 24 configurations (see Fig.4), considering combinations of various hole diameters (no holes, 1 mm, 5 mm, and 10 mm), various substrate types (cellulose flakes, polyester fiber, and rigid flooring), and various honeycomb arrangements (with exposed cardboard holes or exposed bare honeycombs). All samples, each measuring 4.8 m^2 (2 × 2.4 m^2), were tested in an environment that simplifies the characteristics of a reverberation chamber. The purpose of these measurements was to allow for a preliminary evaluation of the various coupling configurations between the different components in order to identify the highest-performing solutions, which would then be subjected to measurements in a reverberation chamber in accordance with ISO 354 [8].

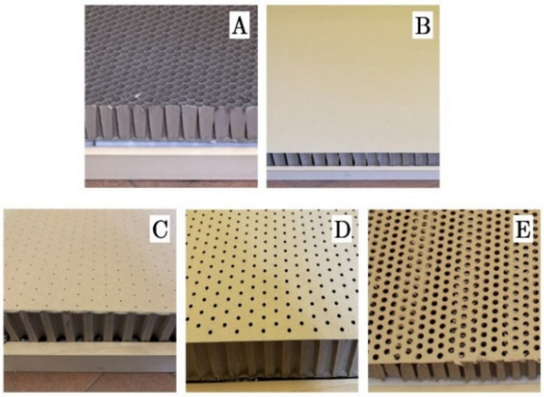

Figure 4. Schematic representation of the variants analysed. Each configuration was first measured on a polyester fiber substrate and then on cellulose flakes insulation: uncoated honeycomb cardboard (A), honeycomb cardboard with a non-perforated coating (B), and honeycomb cardboard covered with cardboard with holes of 1 mm (C), 5 mm (D) and 10 mm (E) in diameter.

The volume of the test environment used for these preliminary measurements is approximately 80 m^3, and the average reverberation time between 500 and 1000 Hz is approximately 2.9 s. For each test, measurements were taken at 16 points with two different sound source positions. The reverberation time was measured using the interrupted stationary noise (pink noise) technique, generated by a dodecahedron and detected by ½-inch diffuse-field microphones (see Fig. 5). The two-channel analyser is the Symphonie model from 01 dB.

The sound absorption coefficient, on the other hand, was measured for all samples using a velocity-pressure probe capable of determining the ratio between the incident sound wave and the reflected wave, and from this, the absorption coefficient under spherical wavefront conditions.

The method for evaluating sound absorption using a p-u (pressure-velocity) probe allows for in-situ measurements to be taken directly on the test specimen. Using this probe, it is possible to simultaneously measure two parameters of the sound field at the same point: pressure (p) using a microphone, and velocity (u) using a sensor based on the hot-wire anemometry principle.

By using an acoustic signal emitted from a source located at a known distance from the test specimen, the acoustic impedance of the surface can be determined and, consequently, the sound absorption evaluated.

Figure 5. Preliminary tests were conducted in a simplified anechoic chamber with a volume of 72 m^3. The surface area of the test specimen was 4.8 m^2. In its empty state, the chamber exhibited an average reverberation time of 2.9 s across the frequency range of 250–2000 Hz. Acoustic excitation was provided by a 01dB dodecahedron loudspeaker, and data acquisition was performed using a 01dB Symphonie two-channel analyzer. For each sample, measurements were recorded at sixteen distinct receiver positions, utilizing two different source locations.

5. The results

The measurement results for the most interesting solutions are presented in a comparative chart in Figure 6.

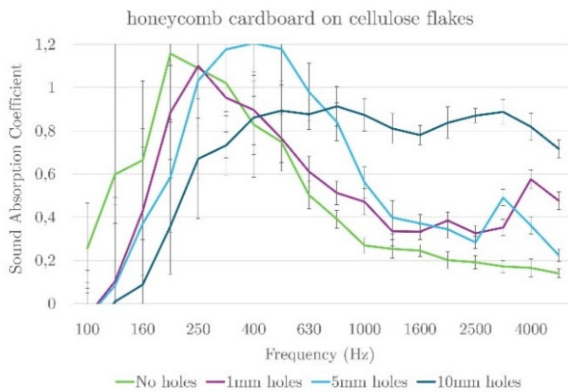

Figure 6. Sound absorption coefficient measured in the reverberation chamber for some of the most promising honeycomb panel solutions on a cellulose base. The error bars are expressed as ± standard deviation.

Specifically, the chart shows the sound absorption coefficient across the frequency range in 1/3-octave bands between 100 and 5000 Hz for four solutions with increasing percentages of perforations in the overlying cardboard: a 60 mm thick honeycomb cardboard panel

with 1 mm holes is placed on a 40 mm layer of cellulose flakes, covered with a smooth, unperforated card-board cover, a cover with 1 mm holes (perforation per-centage 0.2%), with a cover featuring 5 mm holes (perforation percentage 6.4%), and with a cover featuring 10 mm holes (perforation percentage 24.2%).
The measurements show a significant standard deviation at low frequencies, likely due to resonance modes in the test environment. Despite this, given the preliminary experimental nature of these tests, the results reveal an interesting resonance absorption effect, particularly for samples with a lower percentage of perforations. Even the unperforated honeycomb cardboard exhibits an interesting resonance absorption effect at 200 Hz. In this case, it should be noted that the facing cardboard was not glued but simply resting against the honeycomb cells and was therefore free to vibrate without constraints across its entire surface. It is therefore likely that the sound absorption, which is particularly evident at low frequencies, is due in this case to the membrane resonance effect of the facing cardboard.
Low-frequency uncertainty is linked to the measurement conditions in the environment. In particular, at low frequencies, non-diffuse field conditions occur. The Schroeder frequency, which defines the upper frequency limit for the applicability of the diffuse field theory (Sabine), is in this case equal to 2000*radq(T/V) = 2000*radq(1.55/73) = approximately 290 Hz. Consequently, as diffuse field conditions do not apply at low frequencies, the measurement results are subject to greater uncertainty, as indicated by the error bars in the results graphs.
Subsequent measurements will be carried out in environments compliant with ISO 354, which can ensure greater reproducibility at low frequencies.
The results obtained in the reverberation chamber are consistent with those measured using the pressure-velocity probe and thus confirm that the tested systems are effective in absorbing mid and low frequency sounds (see Fig. 7).
The behaviour exhibited by the tested samples can be attributed to the resonant model of a perforated panel, and the frequency peaks identified by the measurements correlate well with the estimates obtainable using Helmholtz resonator theory (Allard – Champoux). In the case of non-perforated panels, the behaviour observed is more closely comparable to that of a vibrating membrane, although in this case the boundary conditions between the cladding panel and the honeycomb core – which are not precisely defined – make it more difficult to relate the behaviour to a specific physical model.

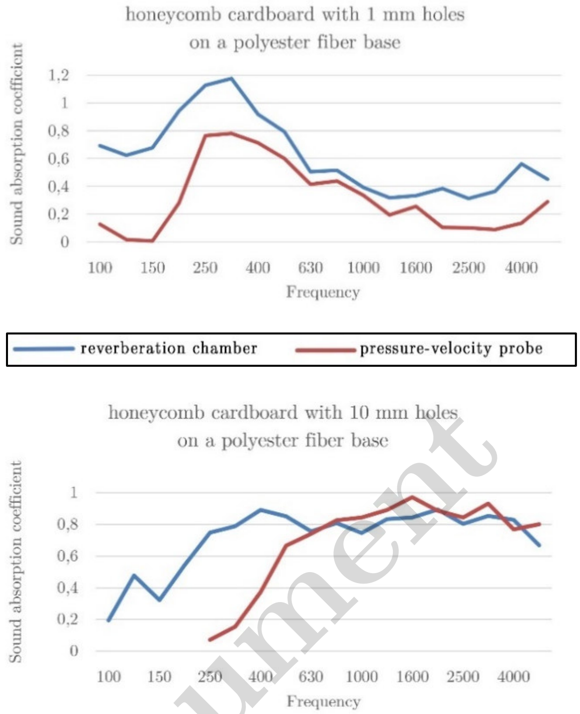

Figure 7. Comparison of sound absorption coefficients measured on honeycomb cardboard (with 1 mm and 10 mm holes) placed on polyester fiber, measured in the diffuse field (using the p-u probe) and in a reverberation chamber.

6. Conclusion

The research highlights the significant potential of cellulose-based systems for acoustic treatment of spaces, confirming that the design of the layered structures and perforations can compensate for the material's inherent limitations.
Preliminary results demonstrate the effectiveness of perforated honeycomb board, even with lightweight 170 g/m² facings; in particular, samples with a lower percentage of perforations exhibited an interesting resonance absorption effect. The presence of sound-absorbing material in the cavity proved to be decisive. The integration of cellulose flakes or polyester fiber significantly improves the overall acoustic performance of the system. Non-perforated honeycomb cardboard demonstrated significant performance at low frequencies (around 200 Hz). This phenomenon is likely attributable to membrane resonance of the facing layer, when it is not fully bonded to the honeycomb cells and remains free to vibrate. The data obtained in a reverberant environment were confirmed by measurements taken with a pressure-velocity (p-u) probe, which validated the effectiveness of the tested systems, particularly in the absorption of mid and low frequencies.
The study demonstrates that it is possible to achieve acoustic performance comparable to that of traditional synthetic materials by using products derived from recycled paper and cardboard, thereby meeting the

growing demands for a circular economy and sustainability in the construction sector.
As the research progresses, the samples will be tested in a reverberation chamber in accordance with ISO 354, and further investigation will be carried out into the issues relating to the type of binder to be used for the cellulose flakes, which were kept in a loose state during these preliminary tests. The flame-retardant treatment techniques for the products will also be the subject of further investigation.

7. Acknowledgments

The research was conducted in collaboration with COMIECO, the Italian Consortium for the Recovery and Recycling of Cellulose-Based Packaging (Comieco).

References

[1] J. F. Łątka, A. Jasiołek, A. Karolak, P. Niewiadomski, P. Noszczyk, A. Klimek, S. Zielińska, S. Misiurka, and D. Jezierska, "Properties of paper-based products as a building material in architecture – An interdisciplinary review," in *Journal of Building Engineering*, vol. 50, Elsevier Ltd, 2022.

[2] F. Asdrubali, A. L. Pisello, F. D'Alessandro, F. Bianchi, M. Cornicchia, and C. Fabiani: "Innovative cardboard-based panels with recycled materials from the packaging industry: Thermal and acoustic performance analysis," *Energy Procedia*, vol. 78, pp. 321–326, 2015.

[3] U. Berardi and G. Iannace: "Acoustic characterization of natural fibers for sound absorption applications," *Building and Environment*, vol. 94, pp. 840–852, 2015.

[4] A. Trematerra and I. Lombardi, "Acoustic Properties of Cellulose," in *Proc. of the IOP Conference Series: Materials Science and Engineering*, (Online), vol. 225, p. 012082, 2017.

[5] S. E. Kishore, R. Sujithra, and B. Dhatreyi, "A review on latest acoustic noise mitigation materials," in *Materials Today: Proceedings*, vol. 47, pp. 4700–4707, 2021.

[6] E. Sel, I. Duzova, Z. Sü, İ. Düzova, and Z. S. Gül, "From waste to design: the potentials of recycled coffee, tea residue and cardboard cups as acoustical panels," in *Proc. of the 10th Convention of the European Acoustics Association, Forum Acusticum*, (Torino, Italy), 2023.

[7] ISO 13472: 2022, Acoustics — Measurement of sound absorption properties of road surfaces in situ - Part 1: Extended surface method.

[8] ISO 354: 2003, Acoustics - Measurement of sound absorption in a reverberation room.

[9] S. Secchi, F. Asdrubali, G. Cellai, E. Nannipieri, A. Rotili, and I. Vannucchi: "Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard," *Journal of Building Engineering*, vol. 5, pp. 1–12, 2016.

[10] C. W. Kang, M. K. Kim, and E. S. Jang: "An experimental study on the performance of corrugated cardboard as a sustainable sound-absorbing and insulating material," *Sustainability (Switzerland)*, vol. 13, no. 10, 2021.

[11] Website Polymax Italia:

https://polymaxitalia.it/pannelli-fonoassorbenti-decorativi/

[12] M. Mohammadi, E. Taban, W. H. Tan, N. B. Che Din, A. Putra, and U. Berardi: "Recent progress in natural fiber reinforced composite as sound absorber material," Journal of Building Engineering, vol. 84, no. 108522, pp. 1–28, 2024.

[13] T. Yang, L. Hu, X. Xiong, M. Petrů, M. T. Noman, R. Mishra, and J. Militký: "Sound Absorption Properties of Natural Fibers: A Review," Journal of Sustainability, vol. 12, no. 20, pp. 8477, 2020.