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Sustainable panels with recycled materials for building applications: environmental and acoustic characterization

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Abstract

Sound absorption materials structure is generally based on porous synthetic media (rock wool, glass wool, polyurethane, polyester, ect.): they have expensive production processes, important energy consumptions, and high environmental impact. Recycled materials are becoming an interesting alternative, due to their good acoustic behavior, similar to traditional porous materials; they also allow low impact production costs, thanks to the use of wastes derived from other production cycles.

This work focuses on the evaluation of the acoustic absorption properties of new panels made of recycled paper and other scrap materials, as wool and nonwoven polyester fabric: different samples were produced and tested by means of impedance tube, according to ISO 10534-2. In order to present the environmental benefits, Life Cycle Assessment was carried out in terms of primary embodied energy and greenhouse gas emissions, considering a "cradle-to-gate" approach.

Furthermore, the behavior of innovative absorption materials was investigated in order to improve the acoustic performance of a lecture room, by means of an acoustic simulation software. A comparison with traditional materials was also carried out for both acoustic and environmental aspects. In the simulation model, calibrated by an in-situ experimental campaign of the main acoustic quality indexes (Reverberation Time, Clarity and Definition Indexes, Speech Transmission Index), different acoustic correction solutions were implemented: both the new recycled and traditional panels were applied as wall and ceiling absorbers.

The analysis of the acoustic absorption trends, in 100 - 5000 Hz frequencies range, shows that the new materials are suitable as acoustic correction systems, especially the panel composed by waste paper and wool fibers. The LCA analysis results show that, considering the same acoustic performance, the recycled panels allow to reduce the environmental effects and the global production costs.

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1. Introduction

The monitoring of the environmental impact of building processes is actually very important as the building industry is one of the largest industry sector. Moreover it is responsible for 40% of overall waste production in the EU [1-2]. Recently new insulating solutions with recycled and discard materials are becoming more common on the market [3-5]. Sustainable materials are products that provide environmental, social, and economic benefits while protecting the environment over their entire life cycle, from the extraction of raw materials until the final disposal.

The whole life cycle of a material includes the extraction, the production process, the in-situ installation, the maintenance, and finally the disposal or the recycling procedures. Both *natural* materials and *recycled* ones could be considered eco-friendly materials: the first types derive directly from raw materials, such as wood, hemp, clay, pumice; the second ones are produced from discard waste materials or components and they represent an excellent alternative from an environmental point of view, allowing the reduction of the quantity of waste to be treated.

The importance of these solutions is also due to their thermal and acoustic properties: in particular materials with high porosity are very interesting because they can absorb the sound that enters their matrix and can be dissipated.

This work is focused on the acoustic characterization of sound absorbing panels, constituted by recycled materials [6-7]; the panels were assembled by a paper mill in the north of Italy by means of innovative production systems. They are made of polyethylene fibers mats, waste paper and wool discards.

The acoustic absorption coefficient at normal incidence was measured in order to identify the frequencies range in which the panels are more effective for the acoustic requalification of a room. Also the life cycle analysis of these solutions was carried out in order to identify the panels with the less environmental impact in terms of CO_2 equivalent and Embodied Energy [8]. The last step aimed at improving the acoustic performance of a University classroom and evaluating the effectiveness of the panels by means of the acoustic simulation software Ramsete: the investigated panels were applied to the walls and the ceiling of the lecture room and they were also compared with traditional solutions. The final acoustic quality of the room indexes was examined; a costs analysis and the environmental impact of various proposed solutions were also analyzed.

2. Materials and methods

2.1. Samples description

Three kinds of panels were investigated: the first one (named D-type) is composed by waste paper and textile fibers, joined by glue, with a total thickness of 18 mm. The second sample, named E, is constituted by only a waste paper layer glued and pressed (10 mm thick); the last one is named G and it is a panel with a total thickness of 50 mm, composed by two layers (a glued wool fibers panel (45 mm thick) and a single layer of waste paper, pressed and glued (5 mm thick)). The thicknesses of the tested panels are the standard ones commercialized by the manufacturer. For the acoustic tests, cylindrical samples with diameters of 29 and 100 mm were manufactured. Figure 1 shows the samples tested; Table 1 shows the internal structure of the examined panels.

Fig. 1. General view of the cylindrical samples tested in laboratory (D, E, and G from left to right).

Table 1. Internal layers of the examined panels.

Samples	First layer	Second layer	Third Layer	Total thickness (mm)
D	Polyethylene fibers mat (4 mm)	Waste paper layer glued and pressed (10 mm)	Polyethylene fibers mat (4 mm)	18
E	Waste paper layer glued and pressed (10 mm)	-	-	10
G	Waste paper layer glued and pressed (5 mm)	wool fibers panel (45 mm)		50

2.2. Sound absorption measurements

Sound absorption properties of the samples were investigated. The normal incidence absorption coefficient was measured by means of two-microphone impedance tube by using the transfer function method and cylindrical samples with diameters of 29 and 100 mm (combined frequency from 100 to 5000 Hz), according to ISO 10534-2 standard [9]. The normal incidence sound absorption coefficient indicates the part of the acoustical energy of the incident wave that is absorbed by the tested sample in a specific configuration; the not absorbed part is reflected back to the source side. For absorption coefficient measurements by means of impedance tube it is important to consider the environmental setting of air temperature, relative humidity, and atmospheric pressure inside the room at the beginning of the procedure and the sample's insertion and sealing by means of plasticine. The sound pressures are measured at the same time in two microphone positions and the transfer function H_{12} between them is calculated. The absorption coefficient α can be evaluated from the direct measurement of the reflection coefficient r.

2.3. Environmental analysis

In order to assess the life cycle impacts of innovative panels and to perform a comparison with conventional sound absorbing materials, a LCA analysis was carried out based on ISO 14040 standard series [10].

Energy and mass flows were evaluated from the production of recycled materials to the final product, following a "cradle to gate" approach, due to the lack of data for the installation, maintenance, and end-of- life stages, being the materials at a prototype line.

The functional unit, in compliance with ISO 14040, is defined as the unit to all impacts are referred; in this study, in order to compare innovative and traditional sound absorbing panels, two different functional units were chosen:

- 1 absorption unit, as the corresponding panel area (m^2), for acoustic performance comparison;
- 1 m^2 of absorbent surface applied, in order to compare the environmental impact of each acoustic requalification solution.

The analyzed impact categories were Global Warming Potential (IPCC 2013, 100-years) and Cumulative Energy Demand, that give information about greenhouse gas emissions and energy consumption related to the production of different panels.

IPCC 100-years Global Warming Potential (GWP) characterization factors were applied to convert greenhouse gas emissions into carbon dioxide equivalent (CO_{2eq}) emissions: the characterization factors used were 1, 25 and 298 for carbon dioxide, methane, and nitrous oxide, respectively.

The inventory data, when available, were directly collected at individual process level (primary data) at the manufacturing company, such as the consumption of the production process of the panels and the distances with suppliers of recycled materials and glue. The secondary data were derived from international databases (Ecoinvent), or calculated with suitable models (IPCC).

The environmental impact values of the conventional material were obtained from the available process in the Ecoinvent database, because they are common materials in building applications.

In Table 2 the inventory analysis of production stage of panels components (wastes and glue) is reported; the panel production phase involves a consumption of 0,04 kWh of electricity and 0.7 kg of water for 1 m^2 of produced panel.

Table 2. Inventory analysis (for 1 kg of single produced component).

Sample D	Process	Amount
Recycled cardboard (6.8 kg)		
	Recycled cardboard	1 kg
	Transportation (30 km)	0.03 t km
Recycled TNT (2.72 kg)		
	Recycled polypropylene	1 kg
	Transportation (28 km)	0.028 t km
Glue (1.4 kg)		
	Sodium silicate	0.33 kg
	Water	0.67 kg
	Polyethylene for packaging	0.0357 kg
	Transportation (320 km)	0.32 t km
Sample E	**Process**	**Amount**
Recycled paper (5.06 kg)		
	Recycled paper	1 kg
	Transportation (30 km)	0.03 t km
Glue (1.4 kg)		
	Sodium silicate	0.33 kg
	Water	0.67 kg
	Polyethylene for packaging	0.0357 kg
	Transportation (320 km)	0.32 t km
Sample G	**Process**	**Amount**
Recycled cardboard (3.4 kg)		
	Recycled cardboard	1 kg
	Transportation (30 km)	0.03 t km
Wool scraps (1.4 kg)		
	Recycled wool	1 kg
	Electricity	0.03 kWh
	Transportation (360 km)	0.36 t km
Glue (0.7 kg)		
	Sodium silicate	0.33 kg
	Water	0.67 kg
	Polyethylene for packaging	0.0357 kg
	Transportation (320 km)	0.32 t km

3. Results

3.1. Acoustic properties

The normal incidence acoustic absorption coefficient trends in 200-5000 Hz range of the three samples and conventional absorption materials are shown in Figure 2; they are obtained by combining the measurements of the large and small tube: they are represented in one octave band. Good sound absorption values were found, especially for the panel type G, that has a very good acoustic behavior for frequencies higher than 1000 Hz. The good properties of the materials are probably due to the high thickness of the samples and to the internal structure of the wool fibers layer.

In order to compare the innovative solutions with standard materials available on the market and generally used as absorption panels (glass wool and extruded polystyrene), a single index (NRC) that represents the acoustic absorption properties of the materials is usually adopted [11]. In the present study the same index was calculated to data obtained by the Kundt's tube instead of the reverberation room and the calculation was extended also to the frequency of 4000 Hz. It is therefore the arithmetic average, rounded to the nearest multiple of 0.01, of the absorption coefficients determined at the one octave band centre frequencies of 250, 500, 1000, 2000 and 4000 Hz. This index represents the sound energy absorbed by a surface when it is hit by a sound wave and it was conventionally named α_{mean}. Figure 2 presents also the mean acoustic absorption values obtained for the sustainable panels (D, E, and G) and two additional traditional systems (glass wool and extruded polystyrene).

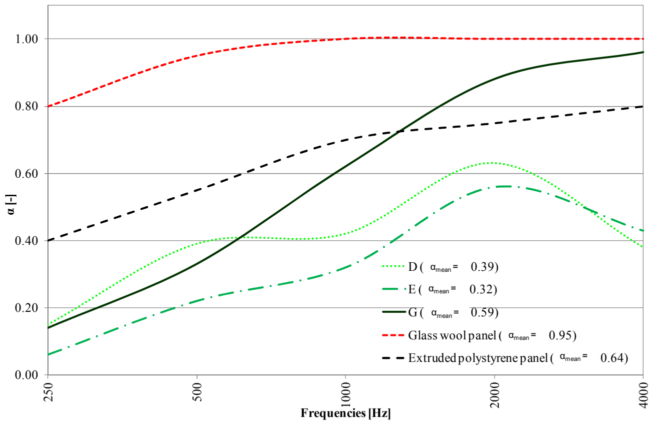

Fig. 2. Acoustic coefficient at normal incidence: comparison between sustainable samples D, E, and G.

3.2. LCA results

In Table 3 the environmental impact values in terms of GWP and CED categories are shown for conventional and innovative panels. LCA results show that recycled materials, characterized by neglected impact for the production of the raw material source, can significantly reduce greenhouse gas emissions and energy consumption from the production process. In terms of produced area, the best environmental performances are obtained for panel G, made up of wool scraps and recycled paper, thanks to the lower amount of material required and density. In reference to the absorption unit, the environmental performance of conventional and innovative materials are closer, due to better sound absorption capacity of glass wool and extruded polystyrene; however, comparing the two materials with similar acoustic properties such as the extruded polystyrene and the panel G, in both comparisons, it is clear the significant environmental advantage obtainable by the adoption of recycled materials.

Table 3. Environmental impacts for the production of conventional and recycled panels in terms of GWP (kg CO_{2eq} /f.u.) and CED (MJ/f.u.).

Sound absorbing panels	α_{mean} **(-)**	**GWP (kg CO_{2eq}) (1 m^2 of panel)**	**GWP (kg CO_{2eq}) (1 absorption unit)**	**CED (MJ) (1 m^2 of panel)**	**CED (MJ) (1 absorption unit)**
Glass wool	0.95	21.8	23	381.6	401
Extruded polystyrene	0.64	19.4	30.3	182	283.8
D	0.39	8.0	20.7	73.5	188.7
E	0.32	4.7	14.7	14.8	46.3
G	0.59	3.1	5.2	14.4	24.4

4. The case study

The examined case study is a classroom of the University of Perugia, located in a historic building from the early thirteenth century. The lecture room has a rectangular shape with a surface area of approximately 100 m^2 and it can hold up to 45 students when seated. An experimental acoustic campaign was carried out in order to characterize the room; the measurements took into account the reasonable and representative positions of real listening conditions. The measurements were carried out by emitting the noise by a twelve-sides speaker placed at 1.8 m from the floor near the teaching position, in order to simulate the actual position of a speaker, in compliance with the requirements of UNI EN ISO 3382 [12]; the microphones (receivers) were uniformly positioned in the room at a height of about 1.5 m from the ground. A Symphonie system by 01 dB, used in all measurements, generates and register an MLS signal for all the positions. Figure 3 shows the mean value of reverberation time vs. frequencies. For low - mean frequencies, until 2000 Hz, values are high, about 1.5 – 2.5 seconds more than the optimal range; at high frequencies the mean value of T_{60} is higher than the optimal value, but the gap is smaller (about 1 – 0.5 seconds).

Also the mean acoustic indexes (Clarity and Definition, C_{50} and D_{50}) were measured and they are represented in Figure 4 (a) and (b). The mean D_{50} index for each frequency is far from 50%, the minimum value for a correct speech definition, above all for low – mean frequencies. Also the C_{50} values are lower than 3 dB at all the frequencies. The mean values obtained in this second phase of the campaign for STI and RaSTI are respectively 0.43 and 0.44. Comparing data to the optimal range found in the Literature [13], global classes of intelligibility poor or fair were found.

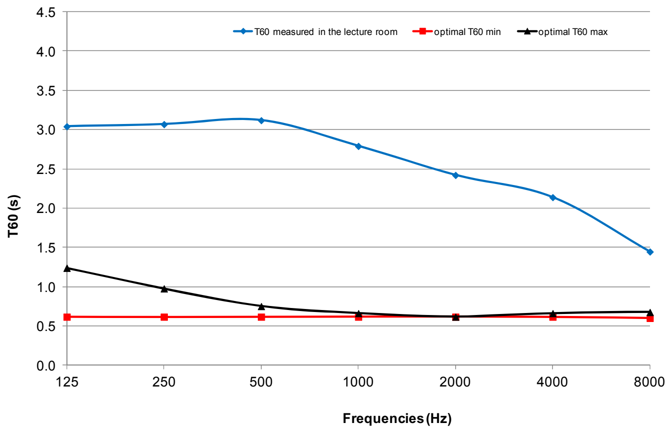

Fig. 3. Reverberation Time measured and optimal range for the lecture room.

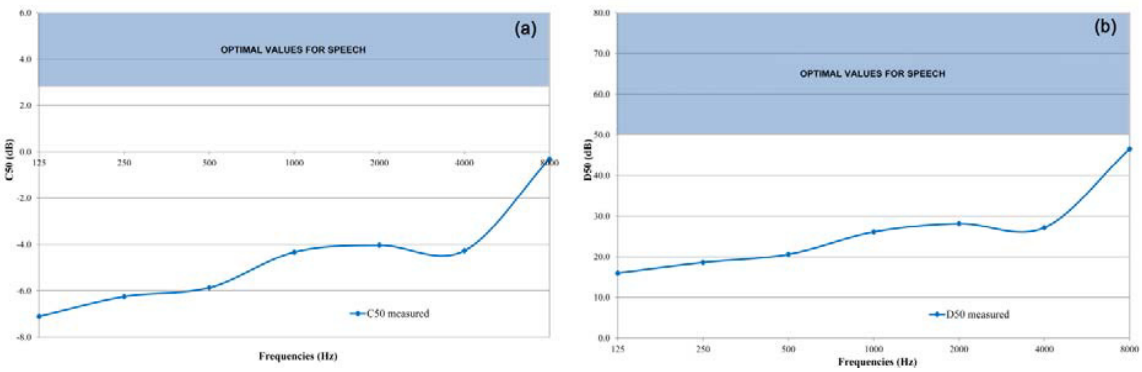

Fig. 4. Clarity Indexes C_{50} (a) vs. frequencies; Definition Indexes D_{50} (b) vs. frequencies (mean values).

4.1 Simulation and acoustic design

The software used to develop the acoustic design of the lecture room is RAMSETE, that provides to simulate the sound field based on geometrical acoustics and employs a pyramidal divergent ray tracing algorithm. The aim of the model calibration is to obtain the overlap of the reverberation time by RAMSETE to the measured values; after the calibration it is possible to employ it for simulating the different design conditions. Different design solutions were implemented in the model with conventional and innovative materials. In Table 4 the five acoustic design solutions are described: the absorption surfaces of each material were chosen considering an equal mean T_{60} abatement in the classroom.

Table 4. Description of five acoustic designs with different kinds of acoustic absorption panels and the mean acoustic indexes simulated for each case.

Panel	**Acoustic design**	**Panels surfaces (m^2)**	**α_{mean} (-)**	**Mean abatement of T_{60} (s)**	**Mean value of C_{50} (dB)**	**Mean value of D_{50} (%)**	**STI (-)**	**RaSTI (-)**
Glass wool	back wall and ceiling	64.3	0.95	0.88	3.4	68.2	0.79	0.78
Extruded polystyrene	back wall and ceiling	88.9	0.64	0.88	4.0	69.7	0.79	0.78
D	back wall, ceiling and side walls	132.2	0.39	0.89	4.2	70.2	0.81	0.77
E	back wall, ceiling and side walls	151.1	0.32	0.82	4.4	68.7	0.80	0.76
G	back wall and ceiling	103.6	0.59	0.83	5.2	71.6	0.81	0.77

So all the project interventions can be considered equal in terms of final acoustic behavior. In Table 4 also the mean simulated values of the acoustic indexes C_{50}, D_{50} and STI/RaSTI are shown, in the post-operam conditions: it can be observed that the mean value of the clarity index C is higher than 3 dB and the definition index D exceeds 50% for all the solutions (the minimum values suggested by the Literature for a correct speech definition). Also STI and RaSTI values correspond to an excellent class of intelligibility. Therefore, all the five design solutions are effective for the acoustic requalification of the lecture room. Anyway the best acoustic absorption panel is the type G: considering a small area (about 100 m^2) this solution produces the highest acoustic indexes.

4.2 Technical-economic analysis

Total costs of the acoustic designs are shown in Table 5, on the basis of the cost of the single panel (in €/m^2). As shown in the table, the best acoustic intervention in economic terms is the last one, with a cost saving of about 68% compared with the extruded polystyrene and 50% compared to the glass wool. Moreover this is also the best solution in terms of environmental impact. The final reduction in comparison with the second acoustic design (extruded polystyrene), is about 80% considering GWP and 90% in terms of CED.

Table 5. Description of five acoustic designs: mean costs and global environmental impacts of the interventions.

Type of absorption panel	**Description of the acoustic design**	**Panels surfaces (m^2)**	**α_{mean} (-)**	**Mean cost of the panel (€/m^2)**	**Total cost of the acoustic solution (€)**	**GWP (kg CO_{2eq})**	**CED (MJ)**
Glass wool	back wall and ceiling	64.3	0.95	18.0	1160.0	1401.7	24536.9
Extruded polystyrene	back wall and ceiling	88.9	0.64	20.0	1780.0	1724.7	16179.8
D	back wall, ceiling and side walls	132.2	0.39	12.0	1590.0	1057.6	9716.7
E	back wall, ceiling and side walls	151.1	0.32	7.0	1060.0	710.2	2236.3
G	back wall and ceiling	103.6	0.59	5.5	570.0	321.2	1491.8

5. Conclusions

In the present paper three types of recycled sound absorbing panels were investigated: they are composed by waste paper, textile, and wool fibers. Experimental analysis were carried out in order to evaluate both acoustic performance and the Life Cycle Assessment. The best performance was obtained for material type G, made of wool scraps and waste paper; its acoustic performance is comparable to the classic extruded polystyrene, with a significantly lower environmental impact.

The second part of the paper examined a case study: a lecture room of the University of Perugia. By means of a measurement session, it was possible to define the acoustic parameters such as Reverberation Time, Clarity and Definition Indexes, STI and RaSTI. These first results were later used to develop a model in a software and using the simulation output to study the real behavior of the room by choosing the sustainable acoustic materials and some standard solutions. The simulation results showed that, despite of lower acoustic properties, the innovative materials allow to achieve significant environmental benefits compared with conventional ones, with a reduction of GHG emissions between 60 and 80% (samples E and G). The economic assessment finally showed that the G-panel solution allows a cost saving of 68% compared with the extruded polystyrene and 50% compared to the glass wool.

References

[1] Struhala K, Stránská Z, Pěnčík J, Matějka L. Environmental assessment of thermal insulation composite material. Int J Life Cycle Assess 2014;19:1908–1918.
[2] Fraunhofer ISI (2009) Study on the energy savings potentials in EU Member States, Candidate Countries and EEA Countries final report. Fraunhofer-Institute for Systems and Innovation Research (Fraunhofer ISI; Coordinator).
[3] Del Rey R., Alba J., Arenas J.P., Sanchis V.J. An empirical modelling of porous sound absorbing materials made of recycled foam. Applied Acoustics 2012;73:604–609.
[4] Patnaik A., Mvubu M., Muniyasamy S., Botha A., Anandjiwala R.D. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. Energy and Buildings 2015;92:161–169.
[5] Ricciardi P, Belloni E, Cotana F. Innovative panels with recycled materials: thermal and acoustic performance and life cycle assessment. Applied Energy 2014;134:150–162.
[6] Sutcu M, Akkurt S, Bayram A, Uluca U. Production of anorthite refractory insulating firebrick from mixture of clay and recycled paper waste with sawdust addition. Ceram Int 2012;38:1033–41.
[7] Maier PL, Durham SA. Beneficial use of recycled materials in concrete mixtures. Constr Build Mater 2012;29:428–37.
[8] Asdrubali F. The role of Life Cycle Assessment (LCA) in the design of sustainable buildings: thermal and sound insulating materials. Euronoise 2009, Edinburgh, Scotland, 26-28 October 2009.
[9] ISO 10534-2. Acoustics – determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method; 1998.
[10] ISO 14040. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardisation, Geneva, Switzerland; 2006.
[11] ASTM: Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Riverberation Room Method, 2001.
[12] UNI EN ISO 3382. Acustica – Misurazione del tempo di riverberazione di ambienti con riferimento ad altri parametri acustici, in italian.
[13] International Standard IEC 60268-16: Objective rating of speech intelligibility by Speech Transmission Index, 1998.