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Experimental Analysis of Sound Absorption and Flow Resistivity of Pulper Waste

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Abstract

This research aims to analyze potential uses for paper mill pulper waste, a by-product generated by paper mills that recycle paper-based composite materials, which are currently disposed of almost entirely in landfills or incinerators. The paper presents some preliminary results from sound absorption tests in an impedance tube and airflow resistance bench test. The results show promising performance values and encourage the continuation of the study.

Keywords: *paper pulper waste, sustainable materials, sound absorption*

1. Introduction

T he research conducted by the Department of Architecture at the University of Florence, the Italian National Consortium for the Recovery and Recycling of Cellulose-Based Packaging (COMIECO) and the Department of Mechanical and Industrial Engineering at the University of Brescia addresses the critical need to identify viable applications for pulper waste, in particular to improve the energy and acoustic efficiency of indoor or outdoor spaces.

Pulper waste represents the most significant and problematic byproduct generated by the paper recycling industry and is produced during the recycling process as a result of the increasing prevalence of composite materials in the global market. It is classified as non-hazardous waste in accordance with the EN 643 [1] standard, as it derives from common materials and does not undergo chemical treatments that alter its nature during pulping.

In Italy, the annual production is estimated at approximately 250,000 tons across 90 facilities—a figure projected to rise alongside the increasing consumption of paper-based and multi-layered composite products.

Italy ranks second in Europe in terms of paper waste usage, which accounts for 60% of the fibrous raw material used, and although in 2024 the recycling rate for cellulose-based packaging has reached 92.5%, pulper waste is an inevitable byproduct of the paper recycling process [2]. This waste, in fact, stems from the recycling of paper from industrial and domestic sources, primarily from packaging composed of multiple layers pressed together (usually paper, plastic, and aluminum). The blend is designed to provide the barrier properties necessary for specific functions or for aesthetic reasons; it is therefore composed of heterogeneous materials originally present in the sorted waste stream (see Fig.1). Its typical composition in the dry fraction includes [3]:

- Plastics 60–70%: Primarily lightweight, mixed polyolefin-based plastics such as LDPE, HDPE, and PP.
- Residual fiber 20–30%: Cellulose that remains adhered to other materials or that is not properly pulped.
- Metals 6%: Aluminum (foil and laminated films) and iron (staples, paper clips).
- Other materials 4%: Wood, glass, sand, rubber, textiles, and adhesives.

Figure 1. Picture of the pulper waste at the DS Smith paper mill in Porcari (LU), Italy.

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The waste originates, at the initial stage, from the processing of recycled paper, which is fed into a cylindrical machine called "pulper" along with water. Here, huge rotating blades separate the cellulose fibers, suspending them in the water. While the cellulose fibers break down to form the fibrous pulp used for paper production, contaminant materials (plastics, metals, etc.) are mechanically separated using gravity, centrifugal force, and screens through successive filters. These solid residues are discharged and typically pressed to reduce their volume and water content before disposal [4].
Due to its mixed nature and high water content, managing pulper waste is complex and costly for paper mills, and historically, it has ended up in landfills or waste-to-energy plants.

2. Previous experimental results with paper waste and its potential applications

Composite products collected through separate waste collection and then recycled, inevitably produce waste—approximately 5–6% of all recycled material—due in part to the lack of dedicated sorting lines for beverage cartons at paper mills. Analysis of data on Italian paper mills indicates that, to date, pulper waste is disposed of in landfills or, more commonly, used for energy recovery through combustion [3]. This material, therefore, can constitute a resource, given the large quantities produced, its current end use, and the disposal costs it represents for paper mills.
The objective of this study is to characterize pulper waste and propose how to use it to improve the energy and acoustic efficiency of indoor or outdoor spaces. The acoustic measurements conducted in this study constitute the preliminary phase for planning the use of pulper in a potential acoustic panel.
The literature contains examples of incorporating various paper industry waste materials into construction materials, with the aim of improving the sustainability and technical properties of the final products.
The study proposed by Agulló et Al. [5] evaluated the use of paper pulp waste as a component in gypsum mortars for non-structural elements. Different mixing ratios of gypsum and wet pulp were analyzed, along with three mixing methods. The use of pre-dried pulp yielded the best results, with a flexural strength of approximately 3 MPa and a compressive strength of 6.5 Mpa.
Another study by Demir et Al. [6] investigated the use of Kraft pulp production residues (short cellulose fibers) as organic porogens in clay bricks to improve their thermal insulation, testing additions of 2.5%, 5%, and 10% by weight of the residue, fired at 900 °C.
Sludge from the paper industry has been used as a substrate for growing the fungus Trametes versicolor to create biodegradable insulation materials. The materials exhibited noise reduction coefficients and sound absorption comparable to those of extruded polystyrene and polyurethane, as measured using an impedance tube with two microphones (according to ASTM E1050 or ISO 10534.2) to calculate the noise reduction coefficient and average sound absorption, while the measured thermal conductivity was close to that of sheep's wool [7].
Panels made from beverage container waste (Tetrapak) coated with beech veneer were also evaluated, using various adhesives: polyurethane, phenol-formaldehyde, urea-formaldehyde, and melamine-urea-formaldehyde (see Fig.2). These panels were considered viable alternatives to traditional materials such as particleboard or MDF for furniture, flooring, and countertops, with the advantage of not emitting formaldehyde when produced via hot pressing without added resins, thanks to the polyethylene already present [8].
Another approach was adopted utilizing recycled newspaper and a starch-based bio-binder to develop sustainable sandwich partitions where the sound transmission loss and heat insulation properties were assessed employing agro-industrial residues as core materials [9].

Figure 2. Prototype panel made from recycled beverage cartons covered with beech veneer, image taken from the article by Ayrilmis et al., 2008.

This research evaluates the use of pulper waste as a sound-absorbing material incorporated into noise barrier panels or as a material for interior sound-absorbing panels. Unlike the studies cited above, which focused on the analysis of specific fractions of paper mill waste (such as cellulose only, plastic only, or Tetra Pak waste exclusively), this research focuses on evaluating the performance of pulper waste as a whole. Given the high heterogeneity of the materials it comprises, the aim is to test its overall behaviour and identify a concrete opportunity for its valorization.
This would not only ensure competitive performance compared with traditional porous materials of fossil or mineral origin but would also offer a significant advantage in terms of environmental sustainability. The analyses carried out are essential for understanding the performance of the pulper and the feasibility of the project.
The Lucense Research Center in Lucca, Italy conducted a study on the production and composition of pulper waste through the LIFE ECO-PULPLAST project (https://www.lucense.it/progetti/eco-pulplast), which began in September 2015 and concluded in the summer

of 2018—a research and technological development initiative funded by the European LIFE program. The main objective of the project was to demonstrate the feasibility of recycling pulper waste to produce mixed-material plastic pallets. And the PLACET project (https://lucense.it/progetti/placet), which began after the LIFE ECO-PULPLAST project—although the two operated partly simultaneously and in close synergy with one another—was funded by the Ministry of the Environment through a 2017 call for proposals related to the circular economy and concluded in 2019. This project further explored and tested separation technologies to recover up to 90% of the cellulose from the waste and reintegrate it into industrial production and heterogeneous plastics.
The research highlights how proper management of this waste allows for the recovery of a large portion of the fiber and reduces waste volumes by 30–50%. The study also explores the reuse of mixed plastics extracted from pulper waste for the manufacture of products such as pallets, promoting a circular economy model in the paper industry [10].

3. Materials and methods

The preliminary phase of the research, which began in 2024 with a study of paper-based materials and their use in the architectural and acoustic sectors [11], subsequently focused on mapping the production of pulper waste in Italy. The analysis of the data, obtained through dedicated surveys, confirmed significant variability in the waste composition depending on the mix of paper waste used and the efficiency of the mechanical separation systems. Consequently, this research limited the scope of the investigation to materials from the Lucart paper mills located in Diecimo and Porcari (LU), Italy, which provide waste characterized by the composition consistency and homogeneity necessary for the validation of subsequent tests. Lucart is one of the most prominent players in the European paper industry. They were the first to launch "Project Natural", a technology capable of recycling beverage cartons such as TetraPak. Lucart uses pre-consumer paper for pulping, that is, manufacturing waste from companies, white paper, trimmings, and Tetra Pak (see Fig.3). They focus primarily on recovering the fiber and producing 100% recycled tissue paper.
Since 2010, Diecimo has been home to facilities for the separation and processing of the polymer component extracted from Tetra Pak, which result in the production of Fiberpack, recycled fibers used for toilet paper, Ce.Pe, a residue from the recycling of post-industrial products consisting of non-recoverable cellulose fibers and polyethylene, Al.pe, a residue from post-consumer composite products consisting of polyethylene and aluminum from TetraPak, from which granules are produced for items such as dispensers for the paper itself, or sold to other companies; and finally, the actual pulper waste produced by the de-inking machine during the first processing stage.

Figure 3. Post-industrial paper waste used to produce Ce.Pe, from the Lucart paper mill in Lucca, Italy.

3.1 Sample preparation

Samples were prepared by utilizing three different types of paper residues (see Fig.4): (1) Al.Pe, a mixture of aluminum and polyethylene, (2.1) a first type of Pulper waste, which is too wet and heterogeneous, therefore It is excluded from the analysis, (2.2) a second type of drier Pulper waste, a composite comprising the aforementioned components along with additional polymer types, (3) Ce.Pe a mixture of cellulose and polyethylene. The Pulper sample was characterized by a higher degree of heterogeneity compared to the other two. Morphologically, all materials were employed in the form of fibers approximately 50–100 mm in length. The density was maintained at a constant value of 125 kg/m^3 to ensure consistent comparison of their acoustic properties. Variations in degrees of compaction were achieved depending on the specimen, and the influence of these differences is further discussed in the results section.

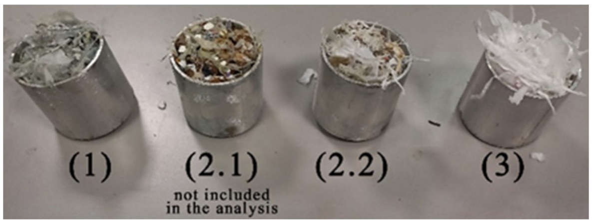

Figure 4. Samples for the Impedance tube measurements: (1) Al.Pe, (2.1) pulper type too wet, (2.2) Pulper, (3) Ce.Pe.

3.2 Impedance tube measurements

The sound absorption coefficient was assessed in a two microphones impedance tube according to the standard ISO 10534-2 [12]. A loudspeaker placed at one end of the tube generates a broadband pink noise as the test signal. The samples were assembled introducing 10 g of loose material inside 46 mm diameter and 50 mm height sample holders and placed on the other end of the tube under rigid end boundary conditions. Two ¼'' microphones (PCB Type 130F22) were spaced by 45 mm and used to register the transfer function, through an OROS Type OR36 acquisition system, and assess the surface impedance and absorption coefficient in the frequency range of 100 to 3500 Hz (see Fig. 5).

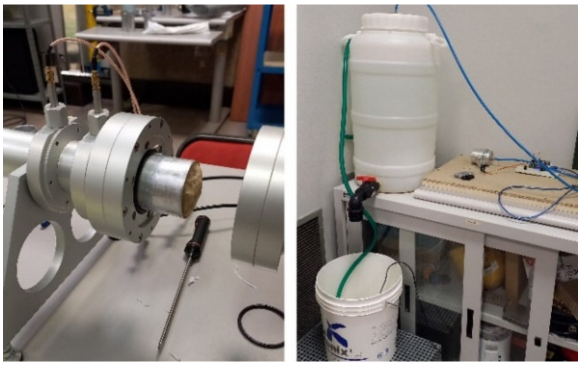

Figure 5. On the left is the impedance tube; on the right there is the experimental setup for airflow resistivity measurement.

3.3 Air-flow resistivity measurements

The experimental setup for flow resistivity measurement was developed in accordance with ISO 9053-1 [13]. A custom test rig, constructed in the laboratory, comprising a water reservoir to generate controlled depression, with a manual valve used to regulate airflow (see Fig.5). The samples (the same as for the impedance tube) were placed within a sealed chamber, exposing one face to the ambient airflow, while the pressure difference and airflow resistance were measured on the opposite side. The differential pressure across the sample, Δp, was determined by measuring the pressure difference between the two sides, and the volumetric airflow rate, q_v, was monitored at various flow levels. The airflow resistivity, σ, was calculated using the relation $\sigma = R.(A/d)$, where $R = \Delta p/q_v$, A is the cross-sectional area, and d is the sample thickness. Stepwise measurements were performed at multiple volumetric airflows, allowing the calculation of the resistance R for each step. A quadratic regression was applied to fit the data and estimate the air flow resistivity σ, at a flow rate of 0.5×10^{-3} m/s, following the guidelines specified in the standard.

4. Results and discussion

The sound absorption properties of the three types of materials are presented in Fig. 6. The solid lines represent the mean values of three identical samples for each type, and the light color indicates the standard deviation.

The absorption curves show maximum peak absorptions at different frequencies depending on the material. The Pulper sample exhibits a peak value above 0.8 at frequencies above 1000 Hz. The Al.Pe sample has higher peaks, around 600–700 Hz, reaching maximum absorption close to unity. The Ce.Pe sample, although having a lower peak amplitude, shifts the peak towards lower frequencies and presents less rippled curves. This may be attributed to higher porosity in this sample, as highly rippled curves are typical of low-porosity materials. It is interesting to note that the effect of compaction in the Ce.Pe and Al.Pe samples shifts the resonance towards lower frequencies, achieving higher absorption within the same thickness.

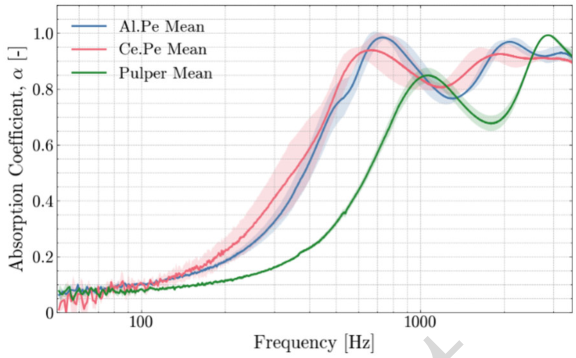

Figure 6. Measured sound absorption coefficient of the three samples. The solid line corresponds to the meaning of three identical samples, while the colored areas represent the standard deviation.

The airflow resistivity is presented in Table 1 for each sample. The values reported are the mean of three identical samples with their corresponding standard deviation.

Table 1 - Measured airflow resistivity.

Sample	Resistivity [Rayl/m]
AL-PE	**3994.8** ± 949.6
CE-PE	**9681.1** ± 2188.7
PULPER	**813.6** ± 95.1

As can be seen, the Al.Pe and Ce.Pe present higher resistivity values than the Pulper. This corresponded well with the degree of compaction of each material. An increase in airflow resistivity, up to a certain amount, tends to enhance the sound absorption performance of porous materials.

While a full statistical sensitivity analysis was restricted by the preliminary sample size (three samples per absorber type), a clear physical interdependence between the measured parameters can be observed. Specifically, an increase in airflow resistivity corresponds to higher viscous losses as the sound waves propagate through the pore network, which subsequently shifts and elevates the peak sound absorption coefficient, as can be seen by comparing Table 1 with Fig. 6.

For the acoustic characterization via the two-microphone impedance tube, the results are highly sensitive to sample fitting and edge constraints; any air leakage can alter the measured absorption coefficient. Similarly, in the airflow resistivity test rig, structural compaction of the fibrous samples during mounting and peripheral air leakage along the cell walls represent

primary contributors to experimental uncertainty. Consequently, special attention was paid to these factors during testing, with sample densities strictly controlled and replicated to minimize these geometric and boundary variations.
The promising preliminary results emerging from acoustic and flow resistivity analyses pave the way for practical industrial applications of pulper waste in the field of environmental and architectural noise control. In particular, the fibrous structure of the material makes it an ideal candidate as a sound-absorbing filler within noise barriers for transport infrastructure or for the soundproofing of outdoor technical installations. Furthermore, the high porosity observed and the ability to modulate air permeability through varying degrees of mechanical compaction (as seen in the Ce.Pe and Al.Pe samples) make it possible to optimise sound absorption according to the specific source spectrum to be mitigated.
Although the acoustic results for the selected samples are promising, the main obstacle to the industrial-scale technology transfer of pulper waste lies in its high heterogeneity and variability in moisture content. The laboratory measurements themselves confirmed this critical issue: the material's high sensitivity to the degree of compaction and wettability directly affects its resistance to air flow, resulting in non-uniform sound absorption curves across the different samples. This issue became clearly apparent during the sampling phase, where the excessive moisture content and lack of homogeneity of the material (sample 2.1) precluded its use for analytical purposes.
To overcome these limitations and ensure reproducible and consistent performance over time, the use of pulper waste necessarily requires a prior stabilization phase. Industrial pre-drying and mechanical screening processes, aimed at standardising the dry fraction, are essential to mitigate the variability of the raw material. Once standardised, the material could be incorporated into acoustic barriers or panels using natural binders or adhesives to stabilise the fibrous matrix.

5. Conclusions

The results of the preliminary analyses carried out on the three pulper waste samples are promising, particularly for Ce.Pe, a residue from the recycling of post-industrial products consisting of non-recoverable cellulose fibers and polyethylene, and Al.Pe, a residue from post-consumer composite products consisting of polyethylene and aluminum from TetraPak.
As might be expected for a porous material, the sound absorption coefficient increases with rising frequency but already shows promising values, higher than 0.8, at 500 Hz for a material thickness of 50 mm.
Future work will focus on expanding the dataset with a larger sample size to enable a rigorous relationship between the acoustic and physical parameters of the samples. Subsequent studies will analyze samples from other paper mills and samples obtained by binding Pulper waste with natural glue.

6. Acknowledgments

The research was conducted in collaboration with COMIECO, the Italian Consortium for the Recovery and Recycling of Cellulose-Based Packaging.
The material samples were provided by Lucart and came from the paper mills in Diecimo and Porcari, Italy.

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