DOI: 10.61782/fa.2025.0733

RECYCLED MATERIALS AS ABSORBENT LAYER IN ACOUSTIC CEILINGS: NON-WOVEN POLYPROPYLENE

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ABSTRACT

Polypropylene is widely used nowadays, generating an important volume of waste that, in general, has a very low recycling rate. This study proposes the use of non-woven polypropylene, discarded in hospital - sanitary uses and not reused for other uses, as an absorbent layer for acoustic ceilings. For this purpose, and in comparison with absorbent layers of mineral wool from international manufacturers commonly used in the construction sector, the combination of thickness and treatment of the waste is sought, which offers the most suitable acoustic absorption coefficient depending on the density for the usual thicknesses used by commercial houses. The results obtained are comparable to or better than those of mineral wool. The study is complemented by a comparative life cycle analysis of both materials, considering the optimal combination of density and treatment of polypropylene waste. This analysis shows an improvement for non-woven polypropylene over mineral wool in all impact categories.

Keywords: *Sustainable materials, Sound absorption, Acoustic ceilings, Life cycle assessment, Polypropylene nonwoven waste.*

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1. INTRODUCTION

The challenge of sustainability in the building materials sector leads to the prioritization of the use of environmentally friendly materials to reduce environmental impact. At the same time, comfort standards in buildings constructed today establish acoustic insulation as a fundamental aspect [1-2]. In this line of research Pedroso *et al.* [3] analyse different materials available in the market, concluding that there are alternative materials that, from the point of view of their acoustic behaviour, embodied energy and costs, are a viable alternative to replace those commonly used in the sector.

The use of natural fibres as thermal and acoustic insulation material has been analysed by different researchers [4-6]. However, researchers point out limitations regarding the behaviour of these materials against humidity, parasites and fungi that may make it necessary to spray the fibres with silicones and apply specific treatments, thus reducing sustainability. Another aspect to be considered is the limitation of the fire performance of natural fibres, which must conform to the requirements of the inherent limitations of building materials.

Islam and Bhat [7], jointly analyse different investigations, observing that recycled polyester, wool, cotton and jute fibres have good acoustic absorption properties at medium and high frequencies. With respect to polypropylene, they analyse studies using composite materials (polypropylene (PP) with bamboo, banana, cotton, wool, jute), with the absorption coefficients being more favourable when incorporating PP.

The significant increase in demand for nonwoven fabric products, including PP, was a consequence of the COVID 19 pandemic, although in later years, such as in 2023, with the critical stage of the pandemic over, a growth trend in the volume of this waste generated continued to be observed [8]. As indicated by Karimi *et al.* [9], the good chemical behaviour, low moisture absorption and density, as well as its good thermal and acoustic properties, make PP fabrics a material with potential use in the field of construction. Therefore, the increase in the volume of waste produced, its good acoustic behaviour and the opportunity to give a second life to waste products, focus the interest on the study of PP nonwovens for applications in the field of construction.

In this field, the works carried out by Ali *et al.* [10], Maderuelo *et al.* [11], Fabiani *et al.* [12] and Dehdashti *et al.* [13] should be highlighted. The joint analysis of the four referenced investigations allows us to establish the significant aspects when analysing the possibility of using nonwoven fabric from recycled face masks as an acoustic absorber. The main ones are the following:

- Disinfection treatment: To eliminate biological contaminants only Ali and Maderuelo introduce in their methodology disinfection processes applying temperature on the samples, Ali at 120ºC for 1 h and Maderuelo 70ºC for 30 minutes. In the case of Ali's research, the result of heating at 120ºC is to melt the material generating a rigid sample.

- Sample treatment: Maderuelo crushed short fibres, Fabiani 1x1 cm^2 squares and the samples analysed by Dehdashti are prepared using a fibrous mass to which he adds bio-base binder. Finally, Ali keeps the masks stacked one on top of the other.

- Thickness: The investigations analyse varying thicknesses. Ali 1.2 cm, Maderuelo 3, 6 and 9 cm, Fabiani 0.5, 1, 2 and 3 cm and Dehdashti between 1 and 3 cm with steps every 0.5 cm.

- Density: Expressing densities in g/cm^3, Ali 0.11, Maderuelo, variable for the different thicknesses between 0.05 and 0.15, Fabiani 0.127 and Dehdashti between 100 and 300.

- Test method: In all cases the impedance tube is used.

- Life cycle study: Only Fabiani and Dehdashti analyse the life cycle for the tested material, although they do not compare with life cycles of materials commonly used as acoustic absorbers in construction processes.

As for the results Ali and Fabiani obtain the absorption coefficient α, although in the case of Ali for 580 Hz and Fabiani for 2 kHz. The Sound Absorption Average (SAA) values vary between 0.58 and 0.83 for Maderuelo's tests and between 0.28 and 0.53 for Dehdashti and, finally, only Maderuelo obtains the Noise Reduction Coefficient (NCR=0.60, 0.75, 0.75 values, (density=0.10, 0.07, 0.005 g/cm^3). The values obtained are hardly comparable since the treatments used for the samples are disparate, as well as the thicknesses and densities.
The research work presented here has been developed within the RAECE research project, which analyses the treatment of these materials, with special emphasis on the analysis of the sustainability of the proposal based on the life cycle study in comparison with mineral wool insulation. The full results can be found in the publication by Galindo et al. [14].

2. ACOUSTIC TESTING

For the acoustic analysis, several factors were studied on which the sound absorbing layer depends: disinfection of the waste, its treatment, density and thickness.

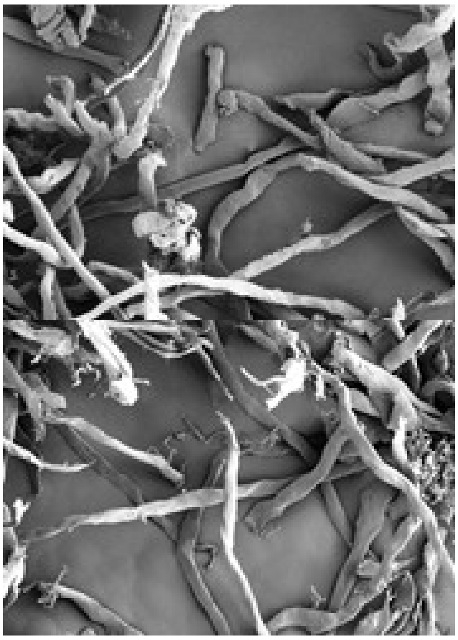

Figure 1. Microscopy. Detail of nonwoven fabric fibre from face masks. Up. Unwashed fabric. Down. Washed fabric.

For disinfection, a treatment with a bleach wash cycle at concentrations between 500 mg/L and 1000 mg/L was chosen [15-17]. In addition, the possibility that the mechanical properties of the material are affected by the washing cycle has been investigated [18]. Fig. 1 shows an electron microscopic scan of fibres of the material used before and after the washing process. It can be seen that the fibres do not undergo a structural change after the washing cycle.

The treatment of the material summarises the two possibilities most commonly used by other researchers, a finish after shredding the sample or its execution in strips (see Fig. 2). For this, a treatment has been carried out that can be faithfully reproduced. In the case of shredding, the RESTCH SM 2000 cutter was used, which produces pieces of material with a fineness of 2 mm. For the strips, an A3 PROFESSIONAL GUILLOTINE from MTEXTIL was used.

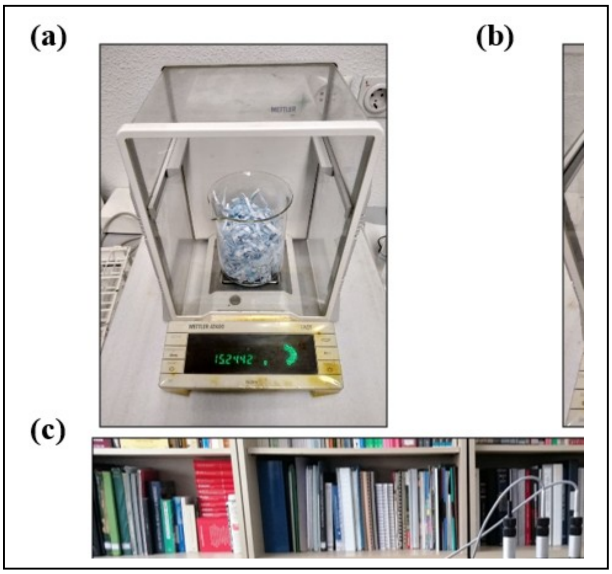

Figure 2. Tested samples. a) Strips of PP, b) Shredded PP, c) Impedance tube and power amplifier.

The density of each treatment is closely linked to the measuring equipment used to determine the sound absorption. An Impedance Tube Kit Type 4206 from B&K has been used (Fig. 2), which combines the material in a fixed diameter portion of the tube, so the densities are limited by this diameter. The layer of material tested must be uniform, without the material collapsing due to low densities or becoming reflective due to excess density. The described equipment complies with ISO 10534-2:2023 [19] and ASTM E1050 [20], which allows the determination of the sound absorption coefficient, the complex reflection coefficient and the acoustic impedance of the material, under conditions of normal sound wave incidence. In addition, the dimensions of the impedance tube also force a certain frequency range corresponding to the interval from 50 Hz to 6.4 kHz. Two different tubes are used to cover this range. The large 100 mm tube covers the range from 50 Hz to 1.6 kHz, while the small 29 mm tube covers the range from 500 Hz to 6.4 kHz.

Under these conditions, the shredded PP layer has been tested for three densities (0.15, 0.20 and 0.25 g/cm^3), while seven different densities (0.050, 0.075, 0.080, 0.085, 0.090, 0.095 and 0.100 g/cm^3) have been tested for the strip-finished layer.

In order to compare the results obtained, a sample of mineral wool (MW) from an international manufacturer was tested and used as a reference. This fact has conditioned the thickness of the tested solutions, as the usual thicknesses used by this manufacturer have been used, which are approximately the same as those used worldwide by the rest of the manufacturers (20, 48 and 65 mm).

All these factors resulted in tests of 33 layers of absorbent (PP and MW).

The Impedance Tube Kit Type 4206 from B&K allows the transfer function of the sample to be obtained by measuring the sound pressure at two fixed positions on the tube. For this purpose, two B&K Type 4187 ¼' condenser microphones and a stationary acoustic signal generated by a sound source located at the opposite end of the tube to the sample location are used. This signal is adjusted with a 2735 B&K power amplifier. During the measurement, the atmospheric conditions of air pressure, temperature and relative humidity are adjusted. In addition, the impedance tube rested on an elastic anti-vibration material.

3. RESULTS

The results correspond to the averaging of 3 different samples for each diameter analysed. For the 33 samples and in order to compare and qualify them on a commercial and technical level, different single number or letter indices have been calculated. These correspond to the Noise Reduction Coefficient (NRC), ASTM C423-22 [21], Sound Absorption Average (SAA), ASTM C423-22, Practical Sound Absorption Coefficient (α_p), ISO 11654 [22], Weighted Sound Absorption Coefficient (α_w), ISO 11654 and Absorption Class (A_E), ISO 11654.

Table 2 shows all samples tested, labeled as S1 to S33. These correspond to the reference MW and the two different PP finishes, for each density and thickness, together with the single letter or number indices. The results of these indices appear in bold when they are better for the PP than for the MW, remaining unemphasized when the results are equal, or underlined when they are lower.

Table 2. Tested materials, densities, thicknesses and rating indexes

Material	Density (g/cm^3)	Samples	Thickness (cm)	NRC	SAA	α_w	Absorption Class
MW	0.023	S1	2.0	0.30	0.32	0.20 (H)	E
		S2	4.8	0.70	0.68	0.50 (MH)	D
		S3	6.5	0.75	0.78	0.65 (MH)	C
Shredded PP	0.150	S4	2.0	**0.40**	**0.42**	**0.25(MH)**	E
		S5	4.8	*0.65*	*0.67*	**0.65**	**C**
		S6	6.5	0.75	*0.73*	**0.75**	C
	0.200	S7	2.0	**0.45**	**0.45**	**0.30 (MH)**	**D**
		S8	4.8	*0.60*	*0.58*	**0.60**	**C**
		S9	6.5	*0.60*	*0.58*	*0.55 (H)*	*D*
	0.250	S10	2.0	**0.50**	**0.49**	**0.40 (MH)**	**D**
		S11	4.8	*0.55*	*0.49*	0.50 (H)	D
		S12	6.5	*0.45*	*0.43*	*0.45*	*D*
Strips PP	0.050	S13	2.0	0.30	*0.28*	*0.15 (H)*	E
		S14	4.8	*0.55*	*0.57*	*0.40 (MH)*	D
		S15	6.5	*0.65*	*0.65*	*0.45 (MH)*	*D*
	0.075	S16	2.0	**0.45**	**0.45**	0.20 (MH)	E
		S17	4.8	0.70	0.68	0.50 (MH)	D
		S18	6.5	0.75	*0.76*	**0.70**	C
	0.080	S19	2.0	**0.50**	**0.47**	**0.25(MH)**	E
		S20	4.8	0.70	**0.69**	**0.55(MH)**	D
		S21	6.5	0.75	*0.77*	**0.75**	C
	0.085	S22	2.0	**0.50**	**0.50**	**0.25(MH)**	E
		S23	4.8	0.70	**0.70**	**0.60(M)**	**C**
		S24	6.5	0.75	*0.76*	**0.75**	C
	0.090	S25	2.0	**0.50**	**0.49**	**0.25(MH)**	E
		S26	4.8	0.70	**0.70**	**0.65**	**C**
		S27	6.5	0.75	*0.75*	**0.80**	**B**
	0.095	S28	2.0	**0.50**	**0.50**	**0.30(MH)**	**D**
		S29	4.8	0.70	**0.72**	**0.70**	**C**
		S30	6.5	0.75	*0.75*	**0.80**	**B**
	0.100	S31	2.0	**0.50**	**0.52**	**0.30 (MH)**	**D**
		S32	4.8	0.70	**0.70**	**0.70**	**C**
		S33	6.5	0.75	*0.73*	**0.75**	C

The results of the table show equal or better index values for PP than for MW for PP densities higher than MW.

The values for shredded PP only exceed or equal all single number or letter indices for the densities of 0.200 and 0.250 g/cm^3 and a thickness of 2 cm, so no better results are found for the usual thicknesses of acoustic ceilings. Only the value of α_w is exceeded by PP versus MW for all thicknesses when the density is 0.150 g/cm^3. This rules out the results of crushed PP samples versus strips for use in an acoustic ceiling.

For PP strips, similar or better results than for MW are achieved at densities of 0.075 g/cm^3 and above. In addition, all single letter or number indices improve for the 2 cm and 4.8 cm thicknesses. For the 6.4 cm thickness, the only exception is for the SAA index with values slightly lower than those of the MW. Taking into account these variables, the most appropriate density is 0.095 g/cm^3, which manages to improve, compared to MW, the single letter index for each thickness. This seems to worsen at higher densities.

Fig. 3 presents the values of the sound absorption coefficient versus frequency in thirds of octave for the operating range of the impedance tube. For each thickness, the values for MW, shredded PP and strips are presented. For each of the finishes, three densities are shown. These correspond to the 3 densities used in the crushed material and, for reasons of visual clarity, to only 3 of the 7 tested in the strips, one of them being the one with the best acoustic performance.

Figure 4 shows the absorption coefficient against frequency, measured in third-octave bands, for four densities of PP across all thicknesses tested. MW is included as reference. Figure 4(a), with the lowest density, relates to shredded PP, while the other three depict PP strips. Looking at the ratings, only this shredded PP option is considered commercially viable. Furthermore, Figure 4(d) is deemed the optimal choice within the studied density range (0.080 to 0.100 g/cm³). Figures 4(b) and (c), which represent the lower density values, are included to demonstrate how the absorption behaviour changes as density increases.

Across all samples, the absorption characteristics of PP closely resemble those of MW. The shredded layer, within the impedance tube's limitations, effectively eliminates any air gap between the sample and the tube's rigid wall. This leads to an increase in absorption with increasing frequency. The three PP strip densities exhibit behaviour like MW, thus validating PP's correctness as a porous sound-absorbing material.

4. LIFE CYCCLE ASSESMENT

A Life Cycle Analysis has been carried out, comparing the absorbing material layer selected for the PP with the commercial MW one. MW is the most common insulating and acoustic material in the Spanish construction market.

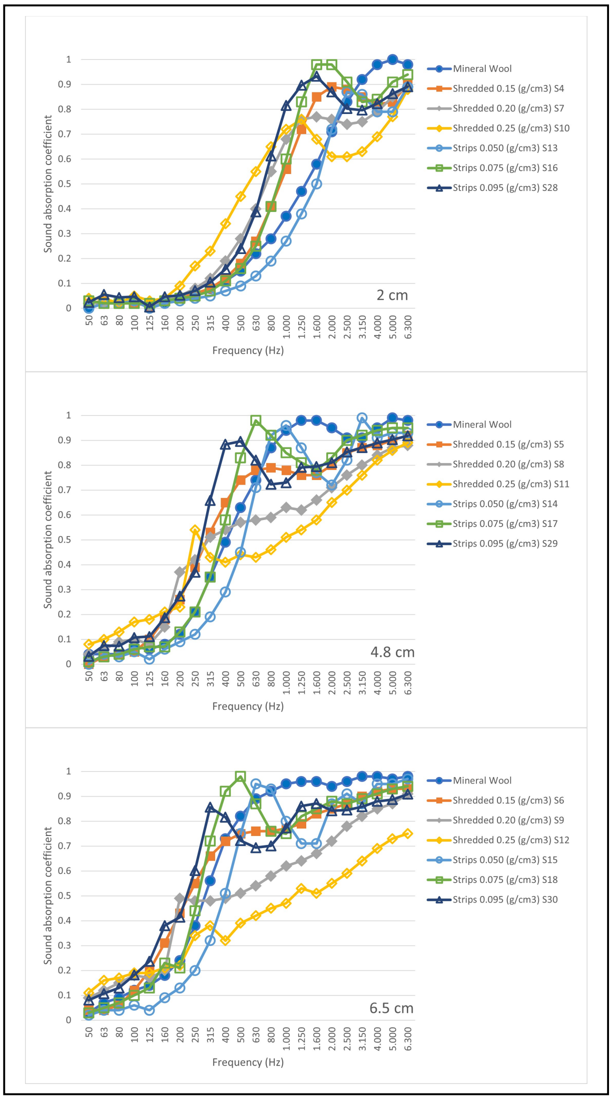

Figure 3. Sound absorption coefficient versus frequency in third octave bands for the different materials and thicknesses.

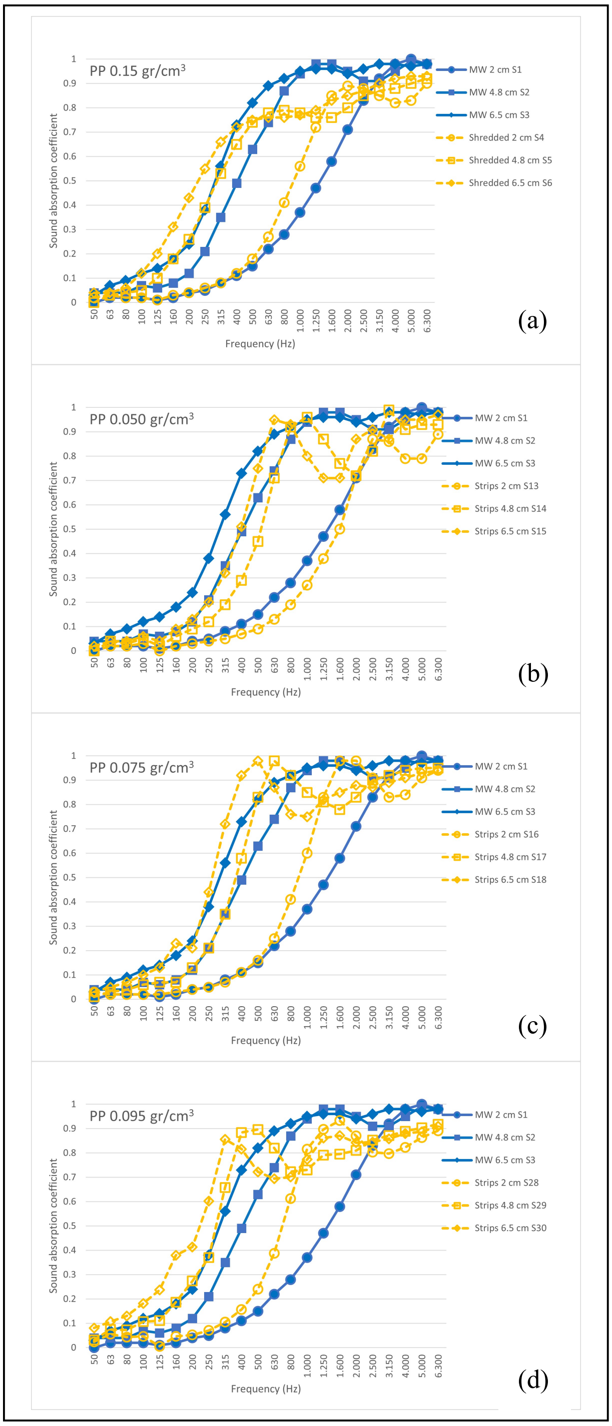

Figure 4. Absorption coefficient versus frequency in thirds of octave for the different materials and sample thicknesses.

A “cradle to gate” analysis (Stages A1 to A3, EN 15804 [23]) was performed. The data obtained to evaluate the consumption and emissions of the samples tested for the PP have been obtained from the prototype production process. The environmental data used for the MW were obtained from the corresponding Environmental Product Declaration of the commercial product.

This LCA study follows the attributional approach, which represents current market conditions in Spain. The impact score calculations have been calculated according to the Ecoinvent and ELCD databases [24], which represent the current technology in Europe. The Simapro tool from Pré Consultants was used to calculate the impact scores.

The result of the calculation shows significantly lower scores for PP in all impact categories evaluated.

In addition, the sensitivity analysis performed shows that the reduction of electricity use in PP production results in a further reduction of the impact scores obtained in all categories. It should be emphasized that this scenario can be achieved following current trends in the green electricity market.

5. CONCLUSIONS

The present work studies discarded materials from healthcare protective equipment made of non-woven polypropylene, for use as an absorbent layer in acoustic ceilings.

Two forms of waste treatment have been analysed, strips of 4×100 mm^2 and shredded PP with a fineness of 2 mm. The study contemplates samples for different thicknesses, typical of commercial solutions common in the international market for mineral wool layers, and different densities, making it possible to obtain the most suitable density of PP for use as an absorbent layer in acoustic ceilings.

For this purpose, we have compared the achievable values obtained for PP, of acoustic indices to number or single letter, with those declared for the reference mineral wool. These indexes have been obtained from the results of the acoustic absorption coefficient for each sample obtained in impedance tubes under normal incidence conditions.

According to the results, the environmental performance of the PP layer outperforms that of conventionally produced acoustic MW and benefits environmental sustainability.

Future research will analyse the acoustic performance and life cycle of the complete acoustic ceiling solution, including the thickness of the air gap and the plasterboard sheet.

6. ACKNOWLEDGMENTS

The project PID2021-123192OB-I00 was financed by the Spanish Ministry of Science and Innovation, the State Research Agency and the EU ERDF. (Ministerio de Ciencia e Innovación, la Agencia Estatal de Investigación y por el Fondo Europeo de Desarrollo Regional de la Unión Europea).

The authors would like to thank the FCT (Fundação para a Ciência e Tecnologia) and the support of the CERIS Research Centre (UIDB/04625/2020). The cutting process for the shredded PP was performed in the LAPIST lab at CERENA (Centro de Recursos Naturais e Ambience).

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