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Article

Study of Acoustic Prototypes Based on Plastic Cap Waste

Romina Del Rey [1,*], José Enrique Crespo Amorós [2], Joan Escales Tur [1] and Jesús Alba [1]

[1] Escola Politècnica Superior de Gandía, Center of Physics Technologies (CTFAMA), Universitat Politècnica de València, 46730 Gandía, Spain; joaestu@upvnet.upv.es (J.E.T.); jesalba@fis.upv.es (J.A.)
[2] Higher Polytechnic School of Alcoi, Universitat Politècnica de València, 03801 Alcoi, Spain; jocream@dimm.upv.es
* Correspondence: roderey@fis.upv.es

Abstract: This paper presents the initial prototypes of solutions designed using plastic caps, seeking acoustic applications for both airborne sound insulation and the acoustic conditioning of rooms. Plastic caps are a waste product from the packaging sector and they constitute a major waste problem, given that, if they are not attached to the packaging, they get lost during the recycling cycle and end up in landfill. Finding an application for this waste that can provide acoustic improvements is a sustainable alternative. This paper shows the results of airborne sound insulation measurements obtained in a scaled transmission chamber and sound absorption measurements obtained in a scaled reverberation chamber for different combinations of single and double plastic caps and combinations with thin sheets of sustainable materials, such as jute weaving, textile waste, hemp felt and cork board. Tests have shown that obtaining sound reduction index values of up to 20 dB is possible with plastic cap configurations, or even up to 30 dB is possible at some frequencies with combinations of caps and certain eco-materials. With regard to the sound absorption coefficient tests, close to unity absorption values have been achieved with the appropriate configuration at frequencies that can also be selected. The results indicate that these panels can be eco-solutions for airborne sound insulation as lightweight elements, or they can be used for the conditioning of rooms, tailoring the sound absorption maximums to the desired frequencies.

Keywords: plastic; recycling; sound insulation; acoustic conditioning; building acoustics; circular economy

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1. Introduction

The search for new materials and new eco-sustainable solutions in different fields of civil engineering is constant [1]. Today's society is aware of the need for a circular economy and, furthermore, all public and legislative bodies encourage responsible consumption or make it compulsory. In the field of construction, the search for new materials and eco-sustainable solutions remains a topic of interest. To list a few examples, over the last year alone, studies of new recycled tyre materials to improve acoustic performance [2], the development of new more environmentally friendly concretes [3,4] and gypsum boards with biological additives [5] have aroused interest. All these projects use some kind of material that has reached the end of its useful life, and which has already been turned into waste. Other projects are even able to quantify the sustainability of these new eco-solutions with a life cycle analysis [6–8]. These projects are examples of the importance of the circular economy in the building sector.

One of the most abundant waste products stemming from human activity is plastic. Plastic is one of the most widely used materials around the world due to its versatility, durability and low cost. However, its excessive use has led to an environmental crisis of worrying proportions. Plastics are extremely persistent in the environment and they take hundreds of years to decompose. The new European awareness and regulation [9,10] require circular economy initiatives with innovative resource management, readjusting the manufacturing and product reuse models. The current product flows should serve as secondary sources of resources in the future [11]. The reuse of plastics is a key strategy when it comes to reducing pollution and promoting sustainability. Single-use disposable plastics must disappear from our daily lives or be given a useful second life. The reuse of plastics can bring numerous environmental benefits. Reducing the amount of plastic that ends up in landfills minimises soil and water pollution, prevents the release of toxic chemicals potentially resulting from its decomposition or burning and cuts the greenhouse gas emissions associated with the production and disposal of plastic.

Plastic caps constitute waste from the light packaging sector, and they should be deposited in the selected containers for potential recycling. Lightweight packaging is the kind with a low weight/volume ratio. This type of packaging includes plastic bottles and jars, film, cans, cartons and other mixed packaging. According to Ecoembes, Spain's leading waste management company (www.ecoembes.com) (accessed on 1 April 2024), over 1.5 million tonnes of household packaging were handed in for recycling in Spain in one year alone (2022), of which 708,596 tonnes were plastic packaging.

Plastic caps are chiefly made of high- or low-density polyethylene and are fully recyclable by means of different processes. Bottle cap recycling is mainly carried out by mechanical recycling and separated by flotation due to the different densities between the bottle and the cap. Caps are not recycled if they are not deposited in the appropriate containers, and are often left as litter or put into landfills. The problem with recycling these caps stems from the fact that they are not attached to the packaging and, when they are separated or sieved, they are discarded together with other materials in the landfill or they get lost during the transport process. Different European Union countries have adapted and continue to adapt the use of plastic materials to the new community legislation. The directive (EU) 2019/904 [10] of the European Parliament and of the Council (2019) requires plastic caps to be attached to bottles. This European measure seeks to prevent the loss of caps and facilitate the recycling process. The above European directive stipulates that caps must be permanently attached to disposable PET packaging containing up to three litres, as part of a strategy to reduce the amount of plastic waste in the environment. This ensures that the cap is attached to the bottle and that the recycling process is carried out jointly, avoiding caps and lids from being left as litter and preventing them from making their way into the ocean. If selective cap selection is successful, these caps can be directly used to obtain new products by directly transforming them into pellets and manufacturing other products. With mechanical recycling, there is no problem with reintroducing the caps into the new product stream. Each EU country is moving towards a circular economy with different measures and deadlines, but all packaging must be recyclable by 2030 and, if possible, reusable. In the meantime, we will continue to find plastic caps that are not attached to their packaging, entailing difficult and costly recycling processes.

This paper presents prototypes of acoustic solutions designed using plastic plugs, seeking applications in both sound insulation and acoustic conditioning. These designs have been created using plastic caps collected from the catering sector, more specifically the cafeteria of the Higher Polytechnic School of Alcoy (EPSA)—Polytechnic University of Valencia. In addition, thin sheets of eco-sustainable materials such as jute weaving, textile waste, hemp felt, and cork board are added to these designs to study the influence of these absorbents. As the need for greater acoustic comfort has increased, so has the need for new solutions. And, at the same time, there is a rising awareness of re-use. There are already proven solutions out there today, for example, based on discarded masks [12], which would have been unlikely just five years ago. The prototypes presented herein as acoustic solutions are not intended to replace the existing successful plastic recycling processes. Rather, it seeks a second use for waste that too often, due to its low density–volume ratio, does not reach the recycling point.

There are recent studies on waste incorporated into building materials to study their airborne sound insulation properties, including tyre debris combined with wood [2] and marble and ceramic debris mixed with concrete [3,13]. Moreover, a new approach to building with 3D printing to reduce costs and waste is gaining ground. This new building philosophy also looks for mixtures of waste with concrete [14–17]. There are also recent studies on waste-based solutions for room acoustics that study their sound absorption capacity: agricultural waste [18], cardboard waste [19], shell fibres [20], posidonia waste [21], textile membranes [22] and even polyvinyl chloride (PVC) plastic waste from bottle labels [4]. The influence of diffuser panels on room quality parameters is well-known [23]; we regard our panels designed with plastic caps as eco-diffusers. The study of diffusers in the trend of understanding the acoustic behaviour of metamaterials is a topical issue. With a review of the work [24], the plastic caps used in this study are considered as resonators with possible applications in the field of room acoustics. In this work [24], with a view to validating the theoretical study, 3D prints are made with plastic material (PLA), where the diameter of the printed resonator plays an important role in the sound absorption characteristics. In other metamaterial-based work [25], some of the resonators studied have a circular part similar to the configuration of the caps used in our study. The solutions presented in this paper are intended to perform the dual function of sound insulation and acoustic conditioning. This alternative is becoming increasingly common in eco-sustainable wood panelling [26] and it may even be the only alternative in small rooms such as radio studios [27]. The innovation of the solution presented lies in the reuse of waste, which must also be addressed in accordance with the EU regulations. The tests carried out for this paper allow us to choose the most optimal design configuration in keeping with the acoustic needs of the room, in terms of both insulation and acoustic conditioning.

2. Materials and Methods

2.1. Panel Design

Panels made of plastic caps are designed as potential sustainable solutions for airborne sound insulation and the acoustic conditioning of rooms. All the plastic caps used for the design of the panels have the same dimensions: 52 mm in diameter, an average thickness of 0.6 mm and 22 mm in height (plenum thickness). The panels designed as a sound insulation solution are a rectangular matrix with 15 × 9 caps and a perimeter wooden frame. The dimensions of the panels are adjusted to the sample holder of the transmission chamber used for their characterisation (0.9 m × 0.6 m) [27]. A total of 22 configurations have been defined: 2 simple (flat (F) and hollow (H)), 4 double (flat–flat (FF), flat–hollow (FH), hollow–flat (HF) and hollow–hollow (HH)) and 16 sandwich-type configurations with 4 different types of sustainable (M) low-thickness materials (M–M–F, M–F–F–M, F–M–M–F and F–M–F). Table 1 shows the description of the materials used and Table 2 lists the 22 configurations designed for the airborne sound insulation study. Figure 1 shows images of the caps in a simple configuration ((a: flat) and (b: hollow)), one of the double configurations (c: flat–flat) and an example of a designed panel (d). Figure 2 shows the different configurations of the panels designed with the caps and combinations of eco-sustainable materials.

Table 1. Sustainable materials used for the design of the sandwich-type configurations. Reference, density (kg/m^3) and thickness (mm).

Material	Reference	Density (kg/m^3)	Thickness (mm)
Jute weaving	J	420	0.75
Textile waste	T	150	1.5
Hemp felt	Hp	242	5
Cork board	C	200	5

Table 2. Panels made with plastic caps and sustainable materials for the airborne sound insulation study. Configuration, reference and thickness (mm).

Configuration	Reference	Thickness (mm)
Hollow	H	22
Flat	F	22
Flat–Flat	FF	44
Flat–Hollow	FH	44
Hollow–Flat	HF	44
Hollow–Hollow	HH	44
Jute–Jute–Flat	JJF	23.5
Jute–Flat–Flat–Jute	JFFJ	45.5
Flat–Jute–Jute–Flat	FJJF	45.5
Flat–Jute–Flat	FJF	44.8
Textile–Textile–Flat	TTF	25
Textile–Flat–Flat–Textile	TFFT	47
Flat–Textile–Textile–Flat	FTTF	47
Flat–Textile–Flat	FTF	45.5
Hemp–Hemp–Flat	HpHpF	32
Hemp–Flat–Flat–Hemp	HpFFHp	54
Flat–Hemp–Hemp–Flat	FHpHpF	54
Flat–Hemp–Flat	FHpF	49
Cork–Cork–Flat	CCF	32
Cork–Flat–Flat–Cork	CFFC	54
Flat–Cork–Cork–Flat	FCCF	54
Flat–Cork–Flat	FCF	49

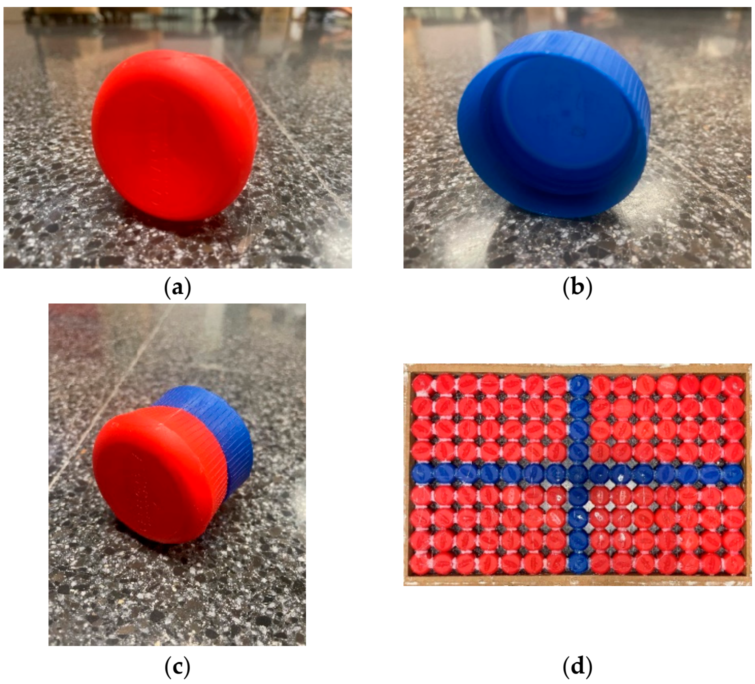
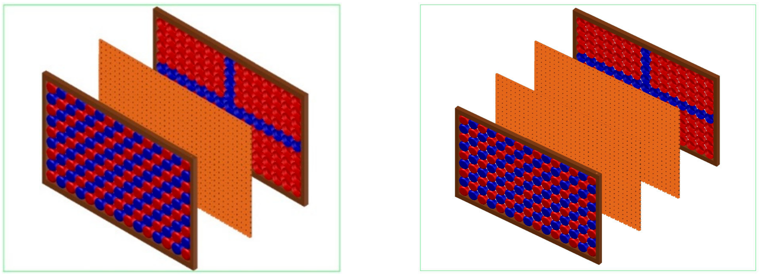


Figure 1. List of some configurations to be tested: (**a**) H; (**b**) F; (**c**) F–F; (**d**) example of 15 × 9 matrix of panel to be tested.



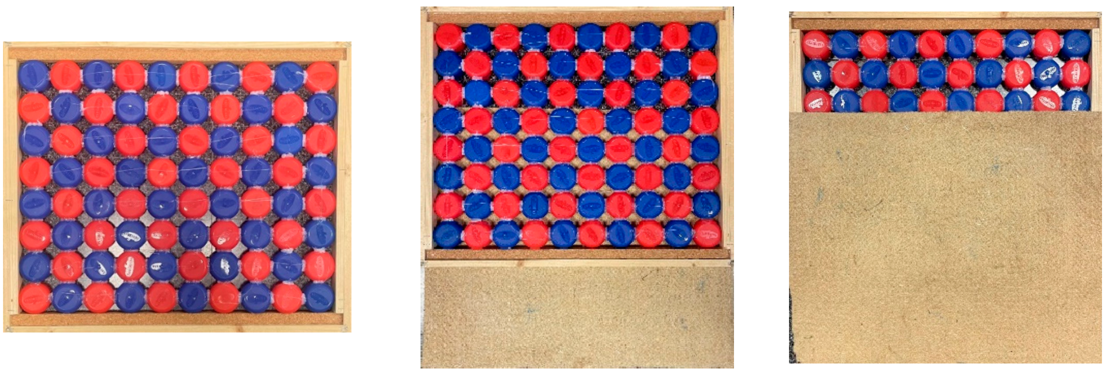
(**a**) (**b**)

Figure 2. Example of sandwich-type configurations: (**a**) F–Material–H; (**b**) Fast–Material–Material–H.

For the room conditioning study with the evaluation of the sound absorption, panels 0.5 m × 0.6 m in size in the form of a rectangular matrix with 10 × 8 caps and a wooden frame around the perimeter have been developed. The dimensions of these panels are adapted to the dimensional scaling of the features marked by the test surface according to [28]. A total of 10 configurations have been designed for the sound absorption study: 2 simple ones (H and F), 4 configurations with the layers of eco-sustainable materials shown in Table 1 placed on top of the flat configuration (Material-Flat) and 4 configurations with the layers of eco-sustainable materials shown in Table 1 placed on the bottom of the flat configuration (Flat–Material). These designs are listed in Table 3. Figure 3 shows images of 3 of these configurations by way of example.

Table 3. Panels made with plastic caps and sustainable materials for the acoustic conditioning study. Configuration, reference and thickness (mm).

Configuration	Reference	Thickness (mm)
Hollow	H	22
Flat	F	22
Jute–Flat	JF	22.8
Textile–Flat	TF	23.5
Hemp–Flat	HpF	27
Cork–Flat	CF	27
Flat–Jute	FJ	22.8
Flat–Textile	FT	23.5
Flat–Hemp	FHp	27
Flat–Cork	FC	27



(**a**) (**b**) (**c**)

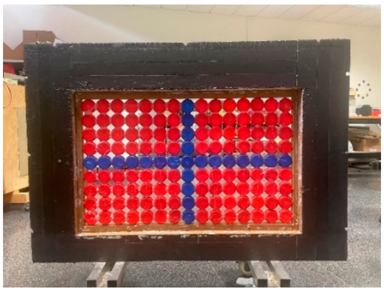
Figure 3. List of some configurations to be studied for acoustic conditioning: (**a**) Matrix with 10 × 8 caps: Flat configuration (F); (**b**) Matrix with hemp felt on top (HpF) and (**c**) Matrix with hemp felt on bottom (FHp).

The configurations with combinations of eco-sustainable caps and foils are reminiscent of one of the structures studied in [29] where a new membrane-like acoustic metamaterial is developed by reusing pins and buttons. Ref. [29] highlights the importance of reusability in designing new metamaterials, and evaluates the absorption coefficient of different compositions in impedance tubes.

2.2. Acoustic Characterisation—Evaluation of the Airborne Sound Insulation

In order to evaluate the panels designed as airborne noise insulation solutions, tests were carried out in a transmission chamber for small samples at the Higher Polytechnic School of Gandia of the Polytechnic University of Valencia. The insulation tests in this small chamber enable us to obtain the value of sound reduction index R(dB) from 400 Hz upwards. The tests are carried out in accordance with the UNE-EN ISO 10140-2:2022 standard [30]. The small transmission chamber or transmission chamber for small samples is a basic tool in the field of characterisation of materials which are still in the research and development phase [2–31]. The details of the manufacture and start-up of this transmission chamber can be found in certain references [31]. The acoustic performance of certain rooms has been improved; in particular a radio room, with acoustic solutions characterised by this small transmission chamber [27], and a sound barrier work line is currently being explored, also thanks to the advantages of this working tool [32]. Figure 4 shows images of this transmission chamber, as well as images of the sample holder used with one of the tested configurations.

(**a**)

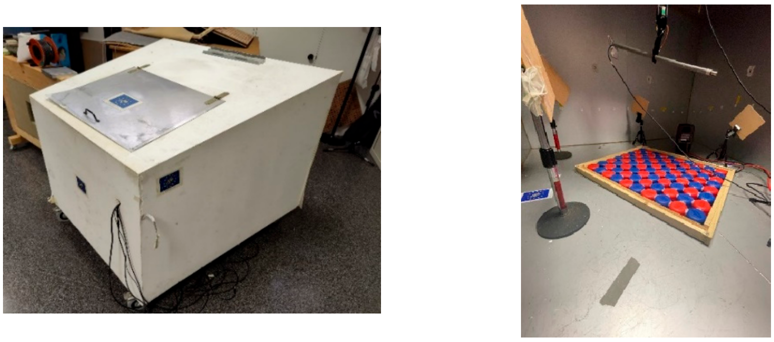


(**b**)

Figure 4. (**a**) Transmission chamber for small samples used; (**b**) sample holder used for the carrying out of the tests.

2.3. Acoustic Characterisation—Evaluation of the Sound Absorption

The sound absorption tests on the configurations described in Table 3 are carried out in a reverberation chamber for small samples at the Higher Polytechnic School of Gandia of the Polytechnic University of Valencia. These tests enable us to ascertain the sound absorption of new configurations from 400 Hz upwards. The tests are carried out in accordance with the UNE-EN ISO 354:2004 standard [28]. The scaled reverberation chamber, like the small transmission chamber, is a basic tool in the field of the characterisation of materials which are still in the research and development phase. The details of the manufacture, start-up and calibration of this chamber can be found in [33]. This tool can obtain the value of the sound absorption in a diffuse field from the third of an octave between 400–500 Hz. A comparison of sound absorption values obtained in a standard reverberation chamber and in this reduced size reverberation chamber is shown in [34]. Figure 5 shows this reverberation chamber, as well as one of the configurations tested in this chamber.



(**a**) (**b**)

Figure 5. (**a**) Scaled reverberation chamber; (**b**) Details of scaled reverberation chamber test.

3. Results

3.1. Evaluation of the Airborne Sound Insulation—Sound Reduction Index, R(dB)

In order to study the behaviour of the panels made with plastic caps as a potential solution for acoustic insulation, regarding these panels as lightweight elements, tests are carried out in the small transmission chamber of the Higher Polytechnic School of Gandia of the Polytechnic University of Valencia. The tested configurations are those shown in Table 2. Figure 6 compares the sound reduction index (R(dB)) of the two single configurations (F, H) and the double configurations (FF, HH, FH and HF). We can observe that simple configurations F and H display the lowest sound reduction index values. The HH double configuration improves this value at low frequencies, although the configurations with the highest R(dB) values are the FF, FH and HF configurations. The FF configuration displays a highly pronounced resonance between 1500–2000 Hz; this resonance moves to higher frequencies (2000–2500 Hz) in the FH and HF configurations. Although it is not easy to explain the frequency position of these resonances, they may be due to the caps, and the move towards higher FH and HF frequencies set against FF may be due to a change in volume.

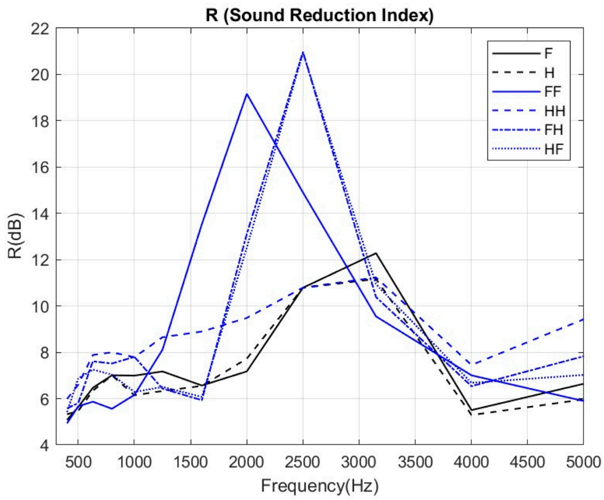


Figure 6. Sound reduction index (R(dB)) (400–5000 Hz) in small transmission chamber. Flat, Hold, Flat–Flat, Hold–Hold, Flat–Hold and Hold–Flat configurations.

The simple F configuration and the double FF configuration are chosen for the design of the sandwich-type configurations. Figure 7 shows the results for the double material layer designs covering the flat panel (Material–Material–Flat). Figure 8 shows the results for the FF core configurations covered on both sides (Material–FF–Material). We can observe that, in the designs covered by a double layer of material, the highest sound reduction index values can be found in the cork board design, and the designs with hemp felt, textile waste and jute weaving display very similar airborne sound insulation values. In the frequency-dependent sound reduction index values shown in Figure 7, we can observe how the resonance displayed by the configurations without any material disappears. However, in the case of the FF core configurations covered with material on both sides (Figure 8), the resonance remains at 2000 Hz. The highest sound reduction index values continue to be those with the cork board design, and the designs with hemp felt, textile waste and jute weaving display very similar airborne sound insulation values.

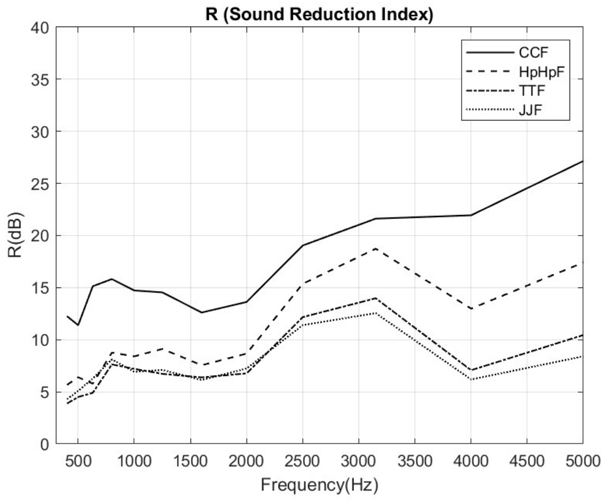


Figure 7. Sound reduction index (R(dB)) (400–5000 Hz) in small transmission chamber. Cork board–Cork board–Flat, Hemp–Hemp–Flat, Textile waste–Textile waste–Flat and Jute weaving–Jute weaving–Flat configurations.

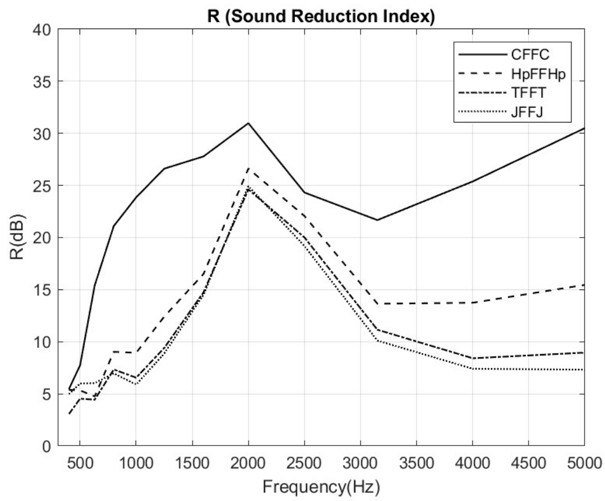


Figure 8. Sound reduction index (R(dB)) (400–5000 Hz) in small transmission chamber. Cork board–Flat–Flat–Cork board, Hemp–Flat–Flat–Hemp, Textile waste–Flat–Flat–Textile waste and Jute weaving–Flat–Flat–Jute weaving configurations.

Figure 9 compares the results of the sandwich-type configurations with the material in the core, whether simple or double (F–Material–F/F–Material–F–Material–F). Resonance or a broadband peak between 2000 Hz and 2500 Hz can be observed in all the configurations shown in this figure. The simple and double configurations with the highest insulation values are those with the cork board sheet, with the other configurations displaying very similar values.

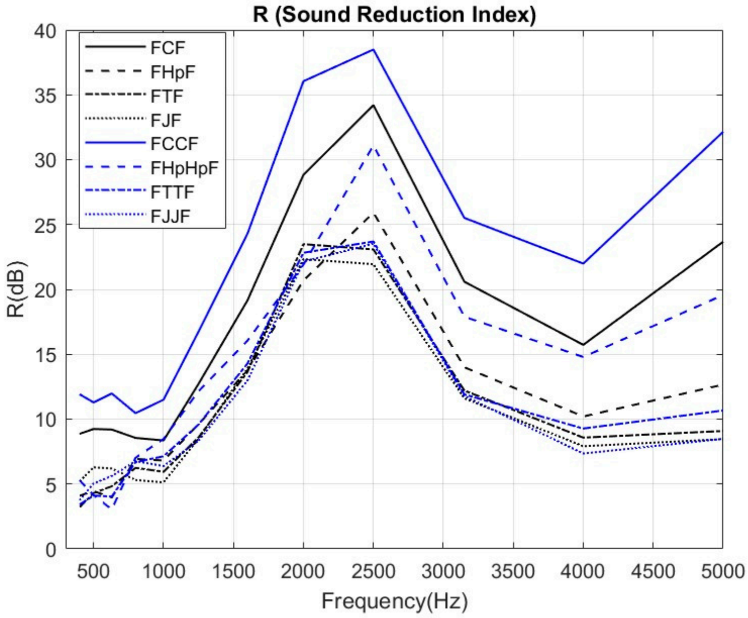


Figure 9. Sound reduction index (R(dB)) (400–5000 Hz) in small transmission chamber. Configurations: Flat–Cork board–Flat, Flat–Hemp felt–Flat, Flat–Textile waste–Flat, Flat–Jute weaving–Flat, Flat–Cork board–Cork board–Flat, Flat–Hemp–Hemp–Flat, Flat–Textile waste–Textile waste–Flat and Flat–Jute weaving–Jute weaving–Flat.

3.2. Evaluation of the Sound Absorption

In order to study the behaviour of the panels made with plastic caps as a potential solution for acoustic conditioning, tests were carried out in the small reverberation chamber of the Higher Polytechnic School of Gandia of the Polytechnic University of Valencia. The tested configurations are those shown in Table 3. Figure 10 compares the sound absorption values for the flat (F) and hold (H) configurations. The panel made solely with the caps in the hold arrangement displayed a very low sound absorption value in the whole frequency range studied (400–5000 Hz); in practically the whole frequency spectrum it displayed values below 0.2. The panel with the flat configuration (F) did not display the same behaviour, with a highly pronounced resonance of around 1000 Hz and absorption values close to unity. We decided to continue studying the sound absorption by combining different layers of eco-sustainable materials (Table 1) with the flat configuration (F).

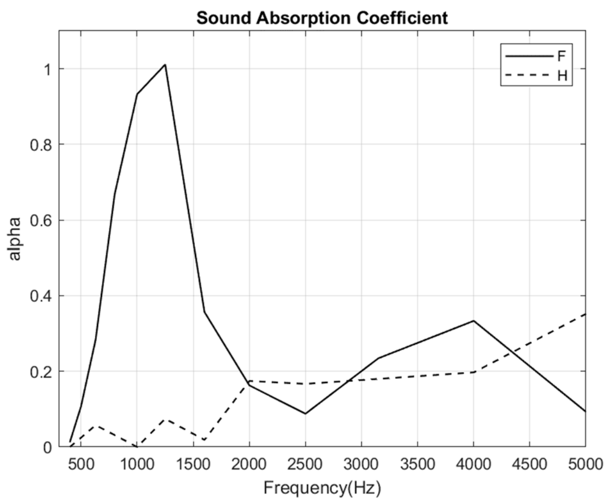


Figure 10. Sound absorption coefficient (500–5000 Hz) in small reverberation chamber. Configurations: Flat and Hold.

Figures 11–14 compare the sound absorption results of the Flat, Material + Flat and Flat + Material configurations (Figure 11: cork board, Figure 12: Jute weaving, Figure 13: Textile waste and Figure 14: Hemp felt).

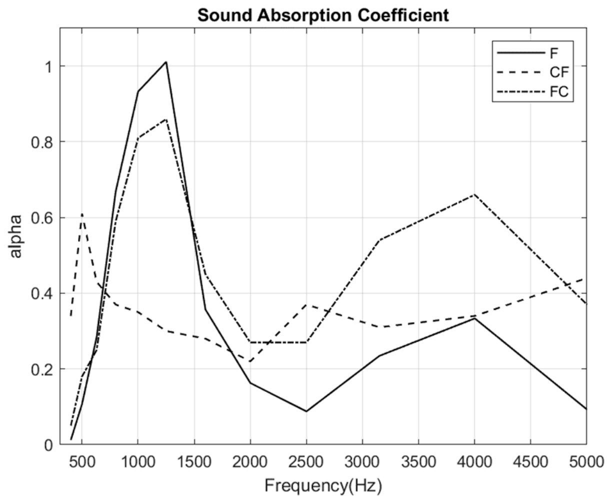


Figure 11. Sound absorption coefficient (500–5000 Hz) in small reverberation chamber. Configurations: Flat, Cork board–Flat and Flat–Cork board.

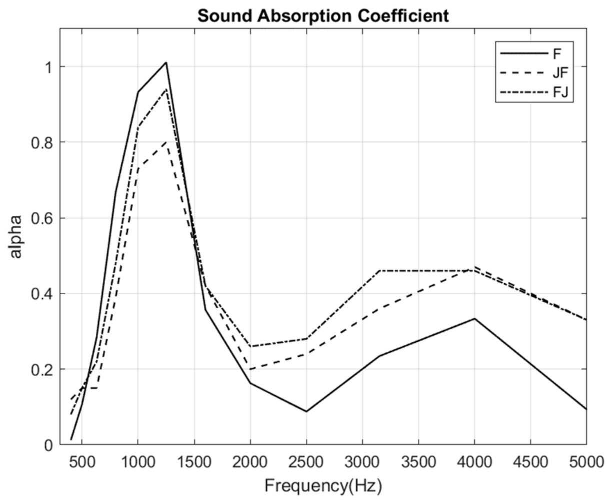


Figure 12. Sound absorption coefficient (500–5000 Hz) in small reverberation chamber. Configurations: Flat, Jute weaving–Flat and Flat–Jute weaving.

In all the configurations studied as potential solutions for room conditioning by combining plastic caps and eco-sustainable sheets, we can observe the effect of combining a perforated one with an absorbent one—the sound absorption at a high frequency increases. They display a higher sound absorption at high frequencies with Cap–Material combinations than with the cap plates alone. This behaviour, together with the resonance observed in all the flat configurations (with or without material) presents the cap panels as perforated panels. This resonance, highly pronounced in the 1250 Hz third octave, is caused by the Helmholtz resonator effect of the gaps generated when the caps for the panel design are fitted. This resonance (f_0) depends on the thickness of the cap, the average perforation radius, the perforation percentage and the rear plenum (Equation (1)):

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{p}{dD'}}, \tag{1}$$

In which

p is the perforation percentage (expressed individually)

d is the thickness of the plenum

c is the speed at which the sound in the air spreads

D' is the effective length of the holes, which is calculated as D' = h + 1.6a, h being the thickness of the perforated plate and the radius of the holes in the plate.

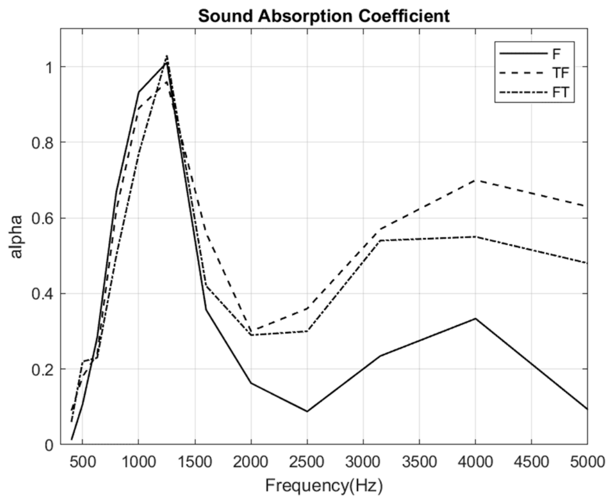


Figure 13. Sound absorption coefficient (500–5000 Hz) in small reverberation chamber. Configurations: Flat, Textile waste–Flat and Flat–Textile waste.

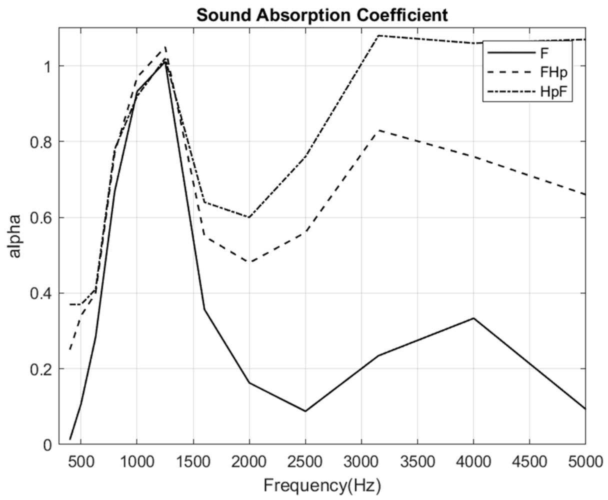


Figure 14. Sound absorption coefficient (500–5000 Hz) in small reverberation chamber. Configurations: Flat, Hemp felt–Flat and Flat–Hemp felt.

The caps used for the design of the panels are 52 mm in diameter, with an average thickness of 0.6 mm (thickness of the perforated plate) and 22 mm high (thickness of the plenum). The perforation percentage can be estimated by fitting the (circular) cap into a side square with the value of the cap diameter. Thus, the resulting perforation rate is 22% (0.22). By subtracting the surface of the cap from the surface of this square, we obtain the surface of the perforation and, using this value, we can obtain "a", the effective radius of the perforations, with this value being for our 13.8 mm design. With these values, the estimate of the resonance frequency according to Equation (1) is 1146 Hz. With these panels made from plastic caps, it is possible to tailor the maximum absorption required in a room for acoustic conditioning. It is a challenge for acoustic engineering to design solutions with variable absorption, depending on the use of the room. There are recent studies that address this challenge [35]. It would be possible to cover or uncover the panels with the eco-material sheets in order to achieve the desired absorption values at high frequencies. Alternatively, it would be possible to design panels with caps of different sizes (thickness, diameter and height), tailoring the resonance and thus adapting the design to the absorption needs of the room.

4. Conclusions

This paper proposes the construction of panels using recycled plastic caps. For this purpose we have constructed a base panel, which has been combined with another similar one and materials of natural and/or recycled origin. Two acoustic applications have been studied, with their potential applications in sound insulation and acoustic conditioning.

In the case of the sound insulation, it might seem a priori that the behaviour would not be significant, as there are holes in the panel. However, the airborne sound insulation tests carried out in a scaled transmission chamber for the different configurations show that the sound insulation values in some of their configurations could be useful. In particular, the flat–flat configuration, without any sustainable material introduced, has the most pronounced maximum sound insulation over a wider frequency range than the other configurations, i.e., from approximately 1250 Hz to 3150 Hz. As a conclusion from the sound reduction index results of the sandwich configurations, it can be noted that the eco-supporting materials have been used to achieve acoustic improvements in the panel. It strives to combine natural and recycled materials with a view to increasing the sound reduction index.

In the case of the sound reduction index measurements, Figure 7 shows that the cork–cork–flat combination is by far the best performer, then hemp felt–hemp felt–flat and finally jute–jute–flat. The sound reduction index could be affected by thickness, as jute is very thin. However, the thickness of cork and hemp felt is the same, 5 mm, and cork returns much higher values. Figure 8 shows the same behaviour and the reflection is the same. The same applies to Figure 9. Therefore, for the sound reduction index, cork behaves better, followed by hemp felt, although the effect of jute with such low thickness should not be underestimated. These values could justify its use as a partition panel or interior screen.

To evaluate the sound absorption, different configurations have been tested and the results show a large difference between the sound absorption values of the hold (H) and flat (F) configurations. The hold (H) configuration displays absorption values below 0.3 in the whole frequency spectrum studied. In contrast, the flat (F) configuration displays very pronounced absorption maximums at medium frequencies (630–1600 Hz). It has been shown that this peak can be estimated by studying the panel under the hypothesis of a conventional perforated panel. Different sheets of natural and/or recycled origin have been added to the cap panel. All the sheets add sound absorption to the panel, as occurs with a perforated panel. It is also worth noting the findings of the sound absorption coefficient of the combinations of flat caps with the eco-materials. Figures 11–14 show the behaviour when placing the material in front of or behind the cap panel. Hemp felt performs best, then cork and finally jute, although the results of cork are close to those of jute. Therefore, for the sound absorption coefficient, it is the hemp felt configuration that shows the best results, followed by cork. Nor should the performance of jute be underestimated, given its low thickness.

Therefore, these panels, combined with ecological sheets, are useful for room conditioning, given their sound absorption, as well as for tailoring the desired absorption.

The results therefore show that it is possible to use plastic caps as eco-sustainable and environment-friendly acoustic solutions. For future studies, it would be desirable to search for other eco-sustainable materials for the design of other sandwich-type combinations that can increase the range of acoustic possibilities and their redesign with other sizes of caps or combinations of different sizes.

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