ACOUSTIC CHARACTERISATION OF A NOVEL WOOD-CORK COMPOSITE MATERIAL FOR ARCHITECTURAL APPLICATIONS

Maia Zheliazkova[1] **Andrea Giglio**[1] **Ingrid Paoletti**[1]

[1] Department of Architecture, Built environment and Construction engineering, Politecnico di Milano, Italy

maiaevgenieva.zheliazkova@polimi.it

ABSTRACT

Acoustic materials for architectural applications are typically chosen for their performance, durability and aesthetics. Most of the common sound absorptive materials result from energy-intensive transformations of non-renewable resources, which respond poorly to the contemporary demands for an environment-friendly built environment. This paper describes a novel material for architectural acoustics, which combines wood and cork into a sustainable layered composite. This new type of material can be easily machined and offers opportunities for advanced customization, and in turn, for high control of its acoustic response. In order to achieve this, the normal impedance absorption coefficients of the composite and its individual constituents were measured in an impedance tube. In particular, the paper focuses on the contribution of different design parameters (performance variables), such as the layer thickness, the open area, and the depth of the air cavity. The results show that the composite materials, with cork behind perforated wood, forming a resonant absorber, perform significantly better than cork alone.

1. INTRODUCTION

Acoustics is a factor of crucial importance for our lives and well-being in the built environment. Despite that, the design for sound is still not addressed in the practice as an element that could lead the architectural design formation [1, 2], especially regarding existing architecture. Studies show that 508 million European citizens spend about 90% of their time indoors, ⅓ of which in workplaces, schools, and public spaces [3, 4]. Unsatisfactory acoustic conditions may have a negative impact on the well-being of the inhabitants, which in the long run brings to lower productivity and economic consequences [5].

Due to the historical development of music linked to the spaces where it was performed, most of the innovative research on acoustics concentrates on performance spaces, music studios and auditoriums. However, not as much striving for novelty has been dedicated towards more ordinary architecture like offices and workspaces, educational facilities, multi-purpose space, recreational spaces, homes and others [6]. This is concerning, considering that Europe has one of the oldest building assets, with more than 40% of the buildings constructed before 1960 and 90% before 1990 [7]. At a certain point, most of them would require programmatic changes or to be rendered up to current standard regulations. This presents a huge opportunity in front of architects and designers to positively influence occupants' well-being by embedding considerations about sound, innovative acoustic solutions and sustainability during renovation.

Allowing to be shaped by design, sound is no less an architectural material than wood, glass, concrete, stone or light. It is through the manipulation of the architectural boundary, mostly by shaping its surfaces and varying its materials, that we could modulate, control or significantly reduce the sound we perceive in interiors. Determining the ways in which sound is absorbed, reflected or refracted within an interior, architects and designers can create diverse acoustic scenarios appropriate for various functions hosted within the space.

One of the fundamental factors in architectural acoustics for achieving performance differentiation is the selection of suitable materials and their acoustic characterization [8]. However, how a specific acoustic behavior is accomplished largely depends on the knowledge of the effect of certain properties of the material. Currently, custom solutions, able to provide specific target acoustic performance or following a unique design language, are developed mainly for particular types of buildings, like music halls and auditoriums, often at prohibitive cost and effort [8].

The paper describes the process of creation, typology selection and acoustic characterization in an impedance tube of cork-based composites. The goal is to provide an understanding on the contribution of each variable (layer thickness, open area, air cavity depth, etc.) to the acoustic performance. By understanding on a general level the effect of the variables on the materials, designers are allowed not only to develop custom acoustic solutions but also to fine-tune their performance according to architectural, programmatic or user needs.

The choice of acoustic materials for architectural applications is often made based on considerations related to performance, durability and aesthetics. The current demand for environmentally friendly and sustainable architectural solutions brings forward considerations related not only to choosing recycled or recyclable materials but also to the overall energy consumption, embodied energy during the manufacturing and transportation, as well as other environmental, economic and social issues [8]. In this research, cork was selected as an eco-friendly alternative to the most common acoustic materials, due to its low overall environmental impact, shown in the Life Cycle Assessment comparison with other natural and traditional acoustic materials, and promising acoustic properties (Tab. 1). The focus of this study is exploring the acoustic absorption properties of expanded insulation cork coupled with plywood, and defining strategies for improving the sound absorption through careful analysis of the variables contributing to it.

Material	Density (kgm^{-3})	Nonrenewable energy (MJ/kg)	Global warming potential (kg CO_2 eq.)	Acidification potential (g CO_2 eq.)
Natural rubber	6.4	40	2.4	8.6
Coconut fibres	50	42	0	25
Flax fibres	25	4.4	0	0
Sheep wool	30	12.3	-0.3	4.6
Cellulose flocks	35-70	4.2	0.2	2.5
Expanded polystyrene	30	95	2.3	20.1
Foam glass	130	67	3.7	22.9
Glass fibre	34	43	2.1	15.5
Mineral wool	50-60	17	1.2	5.2
Expanded cork	110	5.15	-1.3	8.9

Table 1. Comparison of environmental impacts of natural and traditional acoustic materials [9].

2. MATERIAL SYSTEM AND COMPOSITES DESIGN

The composites were created by combining cork with marine plywood from okoumè wood. Okoumé (Aucoumea klaineana) is a wood species with resistance to biodeterioration suitable for uses demanding durability and longevity. The individual veneers are bonded using a melamine modified urea-formaldehyde (MUF) system conforming to the standard BS 1088-1:2003 and in line with the requirements of EN 13986 [10]. Okoumè plywood combines high mechanical and decorative properties with facilitated capabilities for assembly with other materials and further processing.

Cork agglomerate is a wholly natural (without chemical additives), renewable and sustainable material with unique features suggesting versatile uses. Despite the extensive research on it, its applications as an acoustic absorber in architecture are still rather limited. The cork morphology is described as a homogeneous tissue of regularly arranged thin-walled cells [11]. Its inner structure is alveolar analogous to that of a honeycomb [12]. The insulation cork boards (ICB), used in this research, consist of agglomerates of granules of cork. The panels are manufactured in a closed autoclave at high temperature (~300ºC) and pressure (~40 kPa) [13,14]. The main holding agent is suberin, acting as a natural adhesive between the granules [15]. These, and other features of this granular material, define the three principal applications of cork boards for thermal insulation, acoustical absorption and vibration damping [13]. The mechanical properties of cork and its density allow it to be easily bonded with other materials.

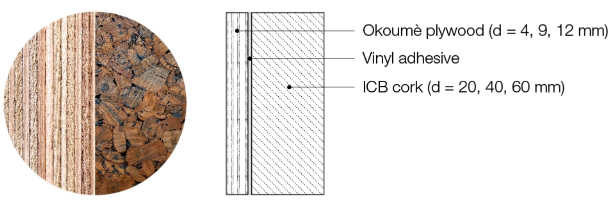


Figure 1. Basic structure of the okoumè-cork composites.

The composites created for the impedance tube acoustic characterization measurements were realized in okoumè plywood (with 4, 9 or 12 mm thickness) and ICB cork (with 20, 40 or 60 mm thickness) bonded using a vinyl adhesive (Fig. 1). Two types of performance characteristics were targeted: 1) absorption in the mid-high frequency range, and 2) absorption in the mid-low frequency range (resonant Helmholtz absorbers).

3. MATERIAL CHARACTERIZATION

3.1 Absorption coefficient measurements in an impedance tube

The acoustic characterization of the composites was performed in an impedance tube, also called a Kundt tube, which measures both the normal incidence absorption coefficient and the surface impedance. This is very useful as it enables measurement under well-defined and controlled conditions [8]. The method requires small samples of the materials to be produced, which in turn allows the facilitated measurement and characterization of a wide variety of composites needed for the panoramic analysis of their properties.

The absorption coefficient is determined according to the ISO 10534-2:2001, using the transfer function method. A plane wave is generated by a loudspeaker on one of the tube's ends, propagating down the tube before reflecting from the sample on the opposite end. The resulting pressure, altered by the impedance of the test sample, is measured at two fixed locations using wall-mounted microphones. The complex acoustic transfer function of the two microphone signals is used to compute the normal-incidence complex reflection factor (r) and from it, the normal incidence absorption coefficient α (Eqn.1) of the tested material [16].

$$\alpha = 1 - |\, r \,|^2 = 1 - r_r^2 - r_i^2 \qquad (1)$$

3.2 Performance variables and sample typologies

Combining okoumè plywood and cork allows the composites to be used on both sides. This permits the evaluation of the acoustic absorption properties, based on two principles: 1) taking advantage of the cork granular closed-cell structure and using it as a facing material and okoumè behind, intended for absorption in the mid-high frequency range; and 2) perforating the okoumè and using it as a facing material with the cork behind, creating a resonance spring-mass type absorber (Helmholtz).

3.2.1 Performance variables

For the empirical sound absorption coefficient determination, a wide range of samples was produced, taking in consideration the effect of certain variables that not only define the performance characteristics but also take part in the overall architectural features of the material composites.

The principles of resonant absorbers are well understood, and their performance can be predicted with design equations. The literature shows that the percentage of open area, the panel thickness and the depth of the air cavity, typically including porous materials, can be used

a) Single materials

	Material	Thickness (mm)	Perforation	Air cavity depth (mm)
	1. Cork	20,40,60,100,140	no	0,200
	2. Okoumè	4,9,12	no	0,200
	3. Cork	20,40,60	10%	0,20,60,100,140
	4. Cork	20,40,60	17%	0,20,60,100,140
	5. Okoumè	4,9,12	10%	0,20,60,100,140
	6. Okoumè	4,9,12	17%	0,20,60,100,140

b) Composites

	Material	Thickness Facing/Backing layer (mm)	Perforation Facing layer	Perforation Backing layer	Air cavity depth (mm)
	1. Cork/Okoumè	20/4, 40/4, 60/4	no	no	0,200
		60/9, 60/12	no	no	0,200
	2. Okoumè/Cork	4/20, 4/40, 4/60	no	no	0,200
		9/60, 12/60	no	no	0,200
	3. Okoumè/Cork	4/20, 4/40, 4/60	10%	no	0,200
		9/60, 12/60	10%	no	0,200
	4. Okoumè/Cork	4/20, 4/40, 4/60	17%	no	0,200
	5. Okoumè/Cork	4/20, 4/40, 4/60	10%	10%	0,20,60,100,140
		9/60, 12/60	10%	10%	0,20,60,100,140
	6. Okoumè/Cork	4/20, 4/40, 4/60	17%	17%	0,20,60,100,140
	7. Okoumè/Cork/Cork	4/40/20, 9/40/20, 12/40/20	10%	10%/no	0,20,60,100,140

Table 2. Properties of the measured single material and composite samples.

to design resonant systems that absorb over a desired frequency range [8]. The behaviour of granular materials like cork is different from the commonly used porous or fibrous ones, as they have lower porosity. This leads to bigger variation in frequency. The critical parameter here is considered the thickness, which over a specific value does not contribute to increase of the absorption [17]. Based on these considerations, the composites samples were developed altering the following variables:

- Facing material thickness;
- Backing material thickness;
- Open area percentage (perforation);
- Air cavity depth

3.2.2 Sample typologies

The produced test samples are divided in two groups (Tab. 2):

1) Single materials - measured with the goal to determine the absorption properties of the singular materials and understand their individual contribution to the absorption coefficient of the composites;
2) Composites - measured with the goal to assess the absorption coefficient and understand the contribution of each variable to the performance.

The density of the cork used for the samples is 110 kg/m^3.

3.3 Measurements and data elaboration

3.3.1 Setup and measurement workflow

The laboratory measurement setup[1] consists of a) signal generator, b) pre-amplifier, c) amplifier, d) microphones, e) audio card, f) Brüel & Kjær Impedance Tube Kit (50Hz - 6.4 kHz) - Type 4206 with an integrated loudspeaker, g) PC with FFT analysing system, e) power supply (Fig. 2a).

Following the guidelines of ISO 10534-2:2001 three samples for each type of composite were tested in repeated measurements using the same mounting conditions. The samples were produced with 100 mm diameter for low frequency measurements from 50-1000 Hz, and 29 mm diameter for the high frequency tests from 1000-5000 Hz. The samples were cut out from different parts of the composite sheet so that local material irregularities are considered in the measurements. The test samples were wrapped on the side with polyurethane insulation tape to avoid unwanted air gaps, and mounted at one end of the impedance tube normal to the tube axis. Before each measurement session, the microphones were calibrated. A sound sweeping for 60 seconds from 1 μHz to 2000 Hz for the 100 mm samples and from 1000 Hz to 5000 Hz for the 29 mm samples was generated. The software used for the data acquisition from the microphones was custom developed by PSVLab (Fig.2b). Three consecutive measurements were then taken for each sample so that eventual excessive background noise or disturbances are mitigated. Each measurement was saved in *.txt* format for further elaboration.

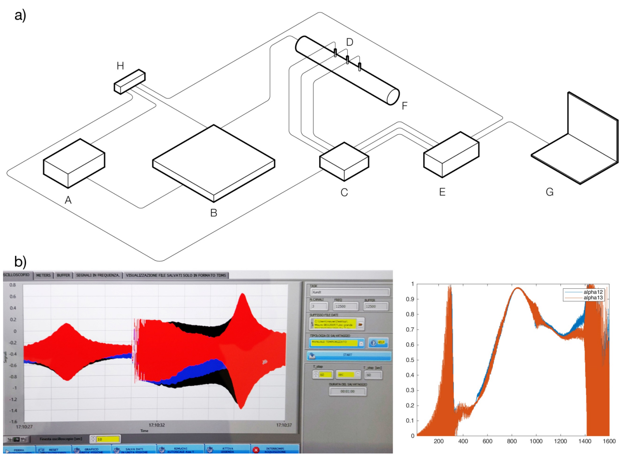


Figure 2. Diagram of a) the laboratory measurement setup and b) the data acquisition software (left) with the raw absorption coefficient results (right).

3.3.2 Data elaboration

The acquired measurement data was processed using custom MatLab code employing Eqn.1. The results were exported in Excel sheets, with an absorption coefficient value α for each frequency band measured. In order to create a meaningful representation, the values were averaged using a custom created script in Grasshopper (Rhinoceros), where graphs for the absorption coefficient in ⅓ octave bands were created.

[1] The tests were performed in PSVLab, DMECC, Politecnico di Milano.

4. RESULTS AND DISCUSSIONS

The results of the measurements are reported and discussed based on the effects of the variables, defined in the previous paragraphs, over the absorption of the single materials and the composites.

4.1 Single materials

The tests for cork and okoumè, as single materials, were essential to understand the extent of the contribution of each one to the behavior of the composites.

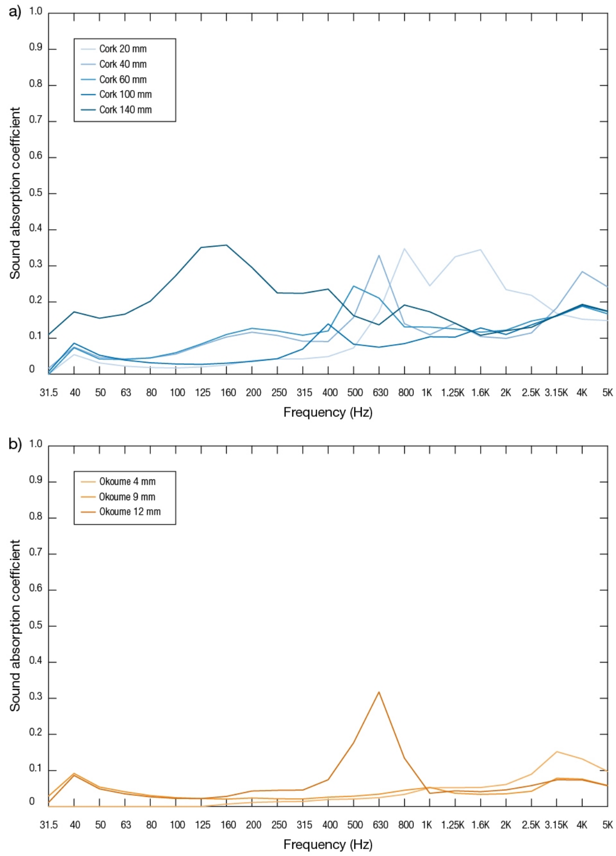


Figure 3. The measured sound absorption coefficient of a) cork and b) okoumè with different thicknesses.

Measurements were made for cork samples with 20, 40, 60, 100 and 140 mm thickness. They were selected based on the panels most requested and used for architectural applications. As expected, cork is most effective in the mid-frequency range between 500 and 2000 Hz. Increasing the thickness of the material naturally moves the peak resonant frequency towards the lower ranges, where it also decreases in value (Fig. 3a). The non-perforated okoumè is an acoustically reflective material with low sound absorption properties. The results reveal 630 Hz as the resonant frequency for the peak sound absorption coefficient a=0.32 for the 12 mm sample (Fig. 3b).

4.2 Composites

The measurement results of the non-perforated samples show that the sound absorption is overall improved when the two materials are joined and work together in a composite. Measurements were made on the same composites in two ways - with cork as a facing material (Fig. 4a) and okoumè as backing material, and reversed (Fig. 4b). The peak sound absorption coefficient remains at 630 Hz for the 12 mm non-perforated okoumè but increases double in value (α=0.63) when backed with 60 mm thick cork.

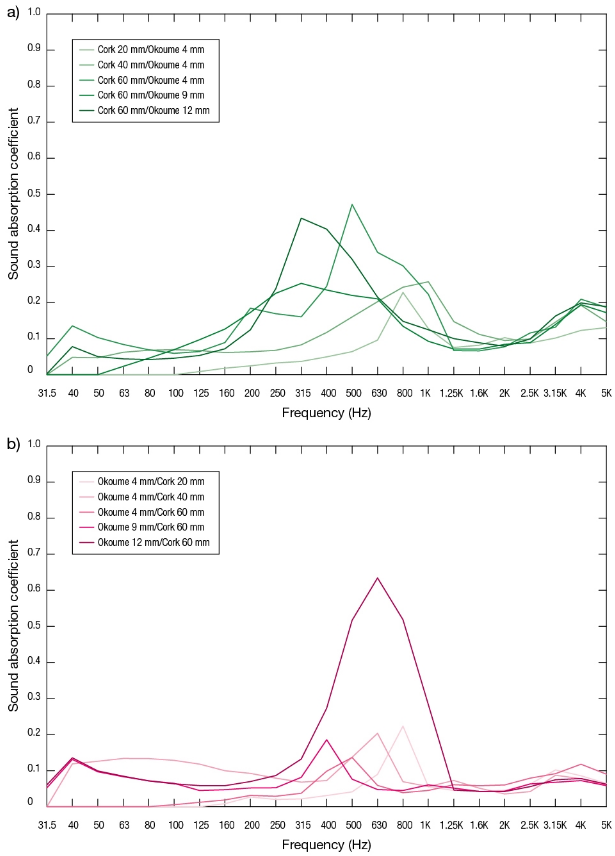
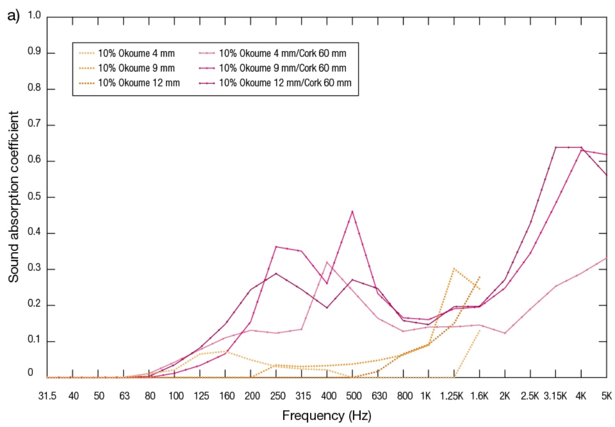


Figure 4. The measured sound absorption coefficient of composites with different thicknesses with a) cork as a facing material and b) okoumè as a facing material.

4.3 Open area

4.3.1 Perforation of the facing material

The perforation of the facing material was introduced with the goal to improve the absorption in the low frequency range, thus creating a Helmholtz type resonant system. In this case the cork is used as a backing material, taking advantage of its closed cell structure and absorption properties in the mid and high frequencies.



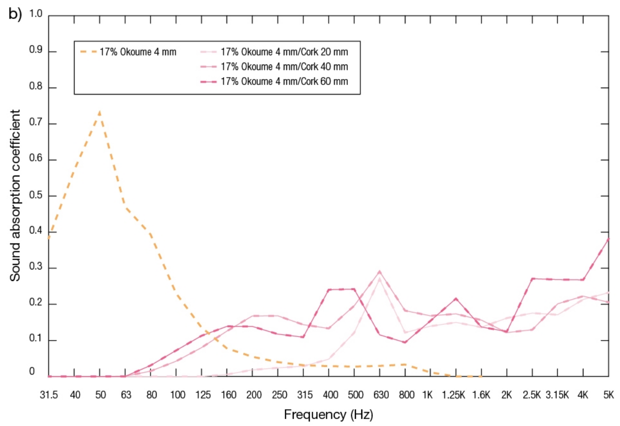


Figure 5. Comparison between perforated okoumè and perforated okoumè with a) 10% open area and b) 17% open area, in a composite with cork as a backing material with different thicknesses.

The measurements results of the composites with perforated okoumè with 10% open area reveal double peaks which are approximately 3000 Hz apart (Fig. 5a). As anticipated, the absorption coefficient increases in the high frequency range due to the cork behind. Increasing the percentage of the open area of the facing material shows a significant decrease in the overall absorption coefficient (Fig. 5b). There is, however, a significant increase in the peak resonant frequency at 50 Hz for the okoumè sample with 17% open area (a=0.75).

4.3.2 Perforation of the facing and backing materials

In order to improve the performance in the mid-high range, cork was perforated, creating samples with 10% and 17% open area. For the composites, the goal was to widen the effective bandwidth, therefore the cork behind the okoumè was also perforated with the same pattern. The hypothesis was that by introducing additional holes in the cork, the overall porosity of the material is increased leading to improvement in the absorption [18].

The results show that the sound absorption coefficient of cork, measured as a single material, is greatly improved, with values reaching 0.92 at the peak frequencies (between 630 and 1600 Hz). The increase in the open area percentage to 17%, however, leads only to a shift of the peaks towards the higher frequency range with only one octave. Similar is the effect for the samples with 10% open area percentage and bigger thickness - the thicker material shifts the peaks towards the lower frequencies with one octave (Fig. 6a).

The sound absorption of the composites also increases when cork, placed as a backing material is perforated. The composites with thicker facing material, 9 and 12 mm okoumè and 60 mm cork behind, show widening of the frequency band over which the material is effective - from 250 to 1600 Hz, with a peak at 630 Hz. The optimal performance with highest a=0.95 is achieved with 4 mm okoumè and 60 mm cork (Fig. 6b).

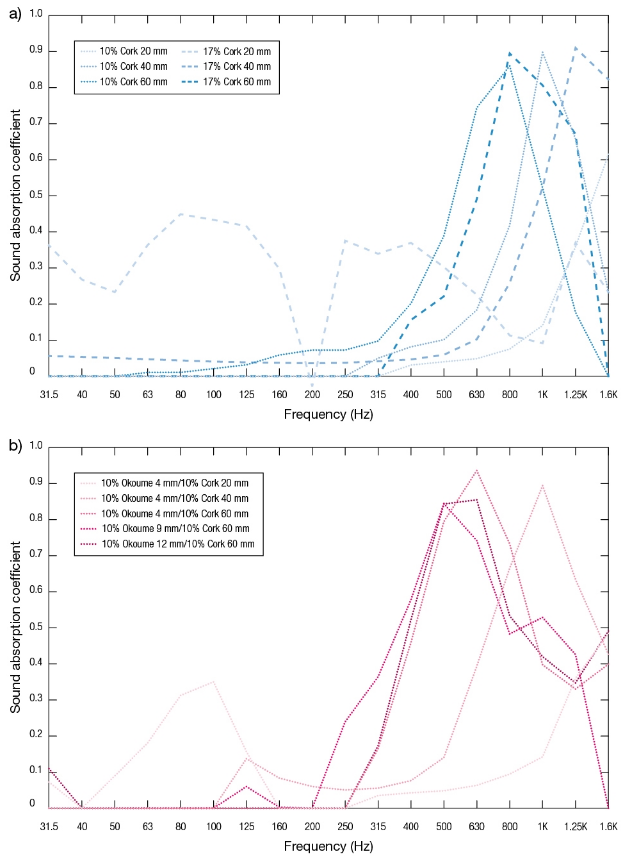


Figure 6. The measured sound absorption coefficient of a) perforated cork with 10% and 17% open area and b) perforated composites with 10% open area.

4.3.3 Partial perforation of the backing material

The sound absorption coefficients for the composites, where the cork behind is perforated until ⅔ of its thickness, were also measured. The results demonstrate an overall decrease in the absorption and an increase of the effective bandwidth. The peak α values for the absorption are at 1250 Hz and vary between 0.66 and 0.8. Increasing the thickness of the facing okoumè does not contribute greatly to the performance (Fig. 7).

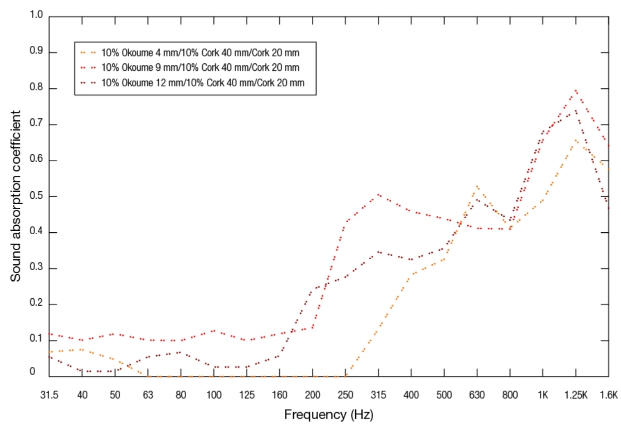


Figure 7. The measured sound absorption coefficient of composites with partial perforation.

4.4 Air cavity depth

Introducing an air cavity behind the materials is expected to broaden their absorption. The results of the measurements for cork confirm this with a more pronounced effect for the samples with 17% perforation (Fig. 8b). However, over 60 mm depth the air cavity shows minimal contribution. Instead, for the cork samples with 10% perforation there is a shift of the peak absorption towards the lower frequencies with two octaves. Similarly, over 60 mm depth the air behind tends to broaden the absorption curve (Fig. 8a).

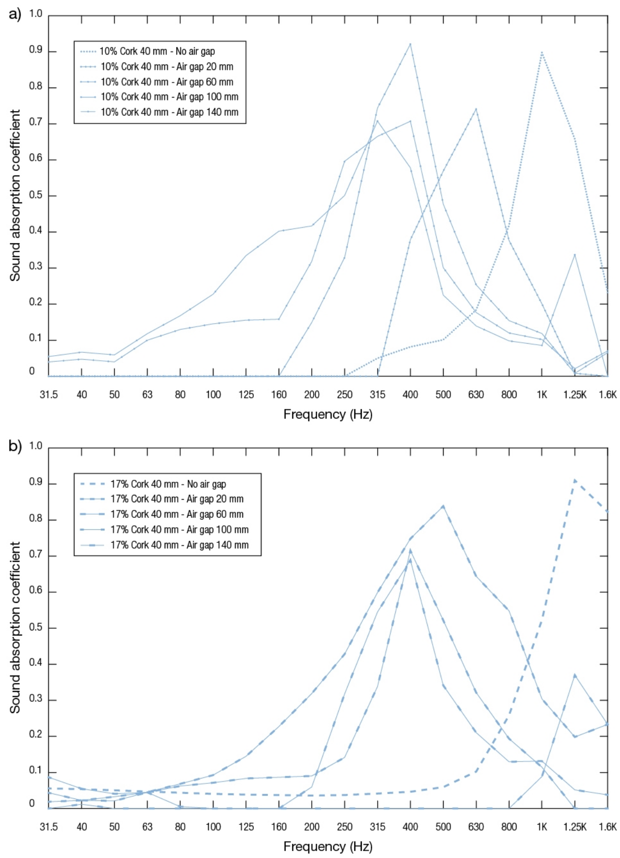


Figure 8. The measured sound absorption coefficient of perforated cork with a) 10% open area and b) 17% open area with variation in the air cavity depth.

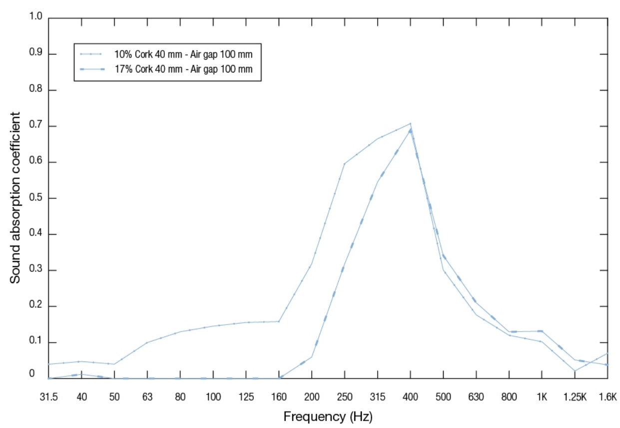


Figure 9. Comparison between the effect of the air cavity on cork with 10% and 17% perforation.

In figure 9 are compared the measurements between cork with 10% and 17% open area with 100 mm air cavity. The air behind contributes to a broader effective frequency range, with the peak sound absorption coefficient remaining at 400 Hz for both 10% and 17% perforated samples.

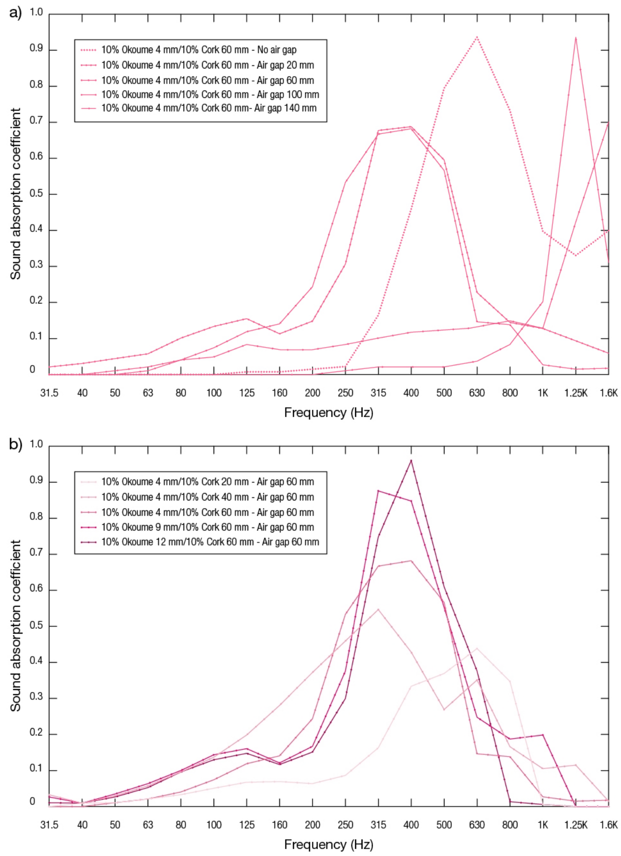


Figure 10. Comparison between a) perforated composites with 10% open area with different air gap depths and b) perforated composites with 10% open area with different facing and backing material thickness and same air cavity depth - 60 mm.

The effect of the air cavity behind the composites reveals a shift in the peak frequency with three octaves towards the lower range but not a significant broadening of the effective frequency bands. Similar to the perforated cork, when the cavity depth increases beyond 100 mm, its contribution to the overall absorption is minimal (Fig. 10a).

The comparison between different composites with 10% open area for the same depth of air behind shows that higher peak absorption can be achieved by increasing the thicknesses of both the facing and backing materials, as seen for the sample with 12 mm okoumè and 60 mm cork (Fig. 10b).

Instead, the effect of a broader frequency range is more pronounced for the composite with 4 mm okoumè and 40 mm cork, especially when compared to the same composite without an air cavity behind (Fig. 11).

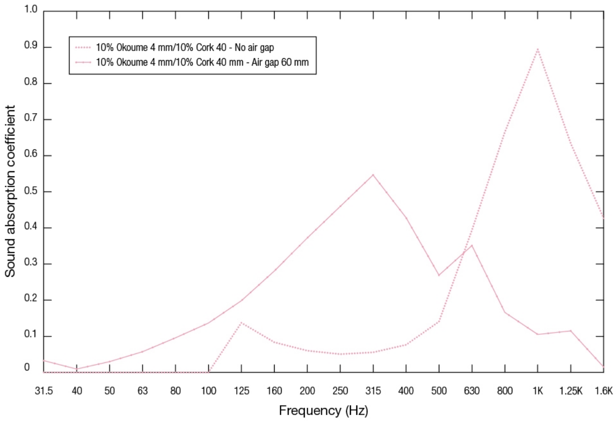


Figure 11. Comparison between 4 mm okoumè and 40 mm cork composite with 10% open area and different air cavity depths.

5. CONCLUSIONS

In this study, novel wood-cork composites were successfully developed by combining okoumè plywood with the natural and renewable expanded cork. The normal incidence sound absorption coefficient of the single materials and in composites was measured and the contribution of the four defined variables (facing and backing material thickness, open area percentage and air cavity depth behind) was evaluated. The results indicated that both materials have superior absorption properties when coupled in a composite in comparison to when used separately. From comparing all the measurement results, it can be concluded that cork, despite being often used in architectural acoustics as a facing material, performs better when placed behind an acoustically reflective perforated material, such as okoumè, forming a resonant absorber. The authors hypothesize that this can be contributed to the closed-cell structure of the expanded cork but more research is needed for confirmation. Moreover, an increase in the absorption coefficient is achieved by perforating the cork behind the okoumè, owed to its increased porosity. Introducing an air cavity behind the materials allows for shifting the peak absorption towards the lower frequency range and broadening the effective bandwidth, valid either for the single materials, or for the composites. Increasing the depth of the air cavity beyond 60 mm, however, shows little contribution to the overall absorption performance.

The measurements and analysis of the results based on the four main variables responsible for their performance allowed for creating a panoramic overview of the properties of the cork-based composites. As a consequence, the collected data can be used as an input for the development of correlation maps, where similar performance characteristics can be grouped according to the properties defining them. Unsupervised learning algorithms, like self-organising maps, could be used for complex multidimensional data clustering. The authors believe that such workflows would allow designers and architects to be able to tailor and control material and geometric properties towards a highly differentiated acoustic design.

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