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Innovative Microwave Foamed Egg White-Cork Composite for Enhanced Acoustic Absorption: Valorizing By-Products into Sustainable Construction Materials

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Abstract

This study explores an innovative approach to enhancing the sound absorption properties of cork-based composites for sustainable construction applications. We developed and compared two types of composites: a conventional cork-mortar mixture and a novel composite incorporating microwave-foamed egg white-cork composite. The foamed composite was created by subjecting a mixture of cork granules and liquid egg white to 2.45 GHz microwave radiation, resulting in a highly porous structure. This foamed composite was then embedded in a mortar mix to create the final composite. Acoustic testing revealed significant improvements in sound absorption properties for the composite containing microwave-expanded foamed egg white-cork compared to the conventional cork-mortar mixture. The enhanced performance is attributed to the increased air content and complex pore structure of the foamed composite. Mechanical and morphological tests were conducted to assess the overall material properties of both composites. Additionally, fire resistance tests demonstrated favorable results for both materials, with the foamed composite maintaining good flame-retardant properties. Our findings suggest that this innovative, easy-to-produce composite offers an effective solution for noise attenuation in building applications. The use of potential waste materials (cork by-products and eggs) in the production process further enhances the sustainability profile of this material. This research contributes to the development of eco-friendly, sustainable acoustic materials that align with circular economy principles in the construction industry. The MCEWP composite achieved sound absorption coefficients of up to 0.313 at 4000 Hz and 0.286 at 1000 Hz, with an open porosity of 33.3%, compared

to 0.05 and 6.3% porosity for plain mortar, while maintaining flame resistance up to ~400 °C without ignition. An estimated NRC-like value of 0.15 was obtained for comparative purposes.

Keywords: Cork composite; Sound absorption coefficient; Microwave foaming; Egg white protein; Mortar; Circular economy; Bio-based materials; Sustainable construction

1. Introduction

The use of sustainable biomass is essential in promoting the transition towards greener construction practices [1]. Cork, derived from the bark of the *Quercus suber* tree, is a lightweight, renewable, and biodegradable material. With around 200,000 tons produced annually—mostly in Portugal and Spain—it is a valuable resource [1,2]. During processing, leftover cork can be repurposed into engineered materials like cork agglomerates which can be used in various applications. Its unique structure, made of suberin-rich cell walls and air-filled chambers, enhances sound absorption, and makes it ideal for creating acoustic panels offering a sustainable and effective solution for noise control [2–5]. The introduction of a foaming binder phase, as proposed in this work, is expected to further enhance both thermal and acoustic performance.

The application of cork by-products in the construction sector has been extensively investigated both for thermal and acoustic insulation in buildings [6–9]. Marques et al. [6] developed innovative polymer-based composite materials incorporating expanded cork by-products and rice husk, aiming to enhance thermal, mechanical, and acoustic properties for residential applications. Maderuelo-Sanz et al. [7] characterized bio-composites composed of water-based acrylic resin combined with white and expanded cork granulates, intended for use as sound-absorbing ceiling tiles. Their findings demonstrated that these materials could serve as sustainable alternatives to traditional noise control solutions. In the study of Lakreb et al. [8], six types of cork-based sandwich panels were fabricated and evaluated for their physical and thermal properties. The results suggested that these panels could effectively reduce energy consumption in buildings due to their efficient thermal insulation performance. Also, in another study, the mortar-cork replacement was shown to have the greatest impact on the thermal conductivity of the mortars, significantly reducing it [10].

Recent studies have further expanded the application of cork-based materials in sustainable buildings, highlighting their potential not only for thermal insulation but also for acoustic regulation and multifunctional building systems. Recent reviews have likewise emphasized the growing role of cork in low-carbon construction, sustainable building envelopes, and multifunctional bio-based materials [11-14,22].

El-Seidy et al. [9] investigated mortars incorporating polymeric aggregates or fillers, demonstrating their potential as effective solutions for acoustic insulation in construction materials.

This study investigates a novel approach by integrating cork granules with egg white proteins (EWPs). Ovalbumin—the primary protein in egg white—has been explored as a model protein for wood adhesives and EWPs are known for their exceptional stabilizing properties in food foams. EWPs also have been widely used across multiple industries and can be obtained as a by-product, making it a sustainable choice for our approach [15–17].

It was hypothesized that these combined properties could result in a sticky, highly porous foam, making it an ideal binder for assembling cork pieces. At the same time, the open-cell nature of the EWPs foam was designed to improve sound absorption, while the closed-cell structure of the cork granules was expected to enhance both thermal and acoustic insulation [7,18–24].

As previously demonstrated, in order to enhance the sustainability of the production process, microwave (MW) heating can be implemented as the primary heat source. This method is well-recognized within the food industry, where extensive research has focused on its effects on egg proteins. Also, over time, its adoption in materials science has grown, driven by its ability to reduce processing times and energy consumption [25–27].

Accordingly, three different formulations were prepared and compared: conventional mortar, cork-modified mortar, and MW-foamed egg white-cork mortar composites.

The present findings have the potential to contribute to more sustainable building practices by offering an eco-friendly alternative for sound absorption in various architectural settings.

Although several studies have investigated cork-based composites and bio-based acoustic materials, the combined use of microwave-foamed EWPS as a structural binder in cork-mortar composites, together with a preliminary screening cradle-to-gate LCA, has not yet been reported. This work aims to fill this gap by repurposing cork from industrial by-products into sustainable acoustic materials, aligning with circular economy principles and addressing the growing need for environmentally responsible construction solutions [28,29].

Beyond achieving satisfactory acoustic performance, the environmental implications of the proposed material must also be considered. For this reason, a preliminary cradle-to-gate life cycle assessment (LCA) was performed to quantify the environmental benefits associated with the microwave-assisted manufacturing process and the use of bio-based constituents.

While traditional acoustic composites often rely on energy-intensive curing or petroleum-derived binders, integrating microwave-assisted foaming and bio-based binders presents

a promising pathway to reduce both embodied energy and carbon footprint. However, utilizing bio-based resources such as EWPs in construction requires a careful balance to avoid competing with the food supply chain. To address this ethical concern, the proposed approach utilizes non-edible industrial egg by-products or poultry waste streams, fully aligning with circular economy principles. Therefore, alongside morphological, mechanical, and acoustic characterization, this work introduces a preliminary screening-level cradle-to-gate LCA. This analysis aims to quantify the energy savings of the rapid microwave-assisted process and highlight the formulation's potential as a low-carbon, circular alternative to traditional mortar-based acoustic barriers.

Therefore, the objectives of this study are:

- 1) to develop a novel microwave-foamed EWPs–cork composite,
- 2) to investigate its microstructural, mechanical, and acoustic properties, and
- 3) to perform a preliminary cradle-to-gate life cycle assessment in order to evaluate its environmental advantages compared with conventional mortar-based acoustic materials.

2. Materials and Methods

2.1. Materials

Commercial liquid egg white (EW) from "Le Naturelle" (1 kg brick) eggs were purchased from a local market. It is worth noting that while a commercial, food-grade product was used in this study to demonstrate the feasibility of the concept, the goal for future scale-up is to source liquid egg white from industrial by-products, thereby avoiding competition with the human food supply.

Cork granules (1–3 mm particle size) were obtained from Kork-deco.de. Sand and calcium oxide (CaO) were bought from a local reseller (Stefano Bianchi e Figli 1853 s.r.l.). Tap water was used for the mixtures.

To perform acoustic, flame, and mechanical measurements, two types of disc-shaped samples were prepared: 3 cm and 10 cm in diameter, and 2 cm in thickness. The cork-EW mixture was prepared by blending cork granules with liquid EW in a predetermined ratio (see Table 1). The compositions reported in Table 1 correspond to the initial amounts of raw materials used for sample preparation. Only the MCEWP formulation underwent the microwave foaming and consolidation treatment described in Section 2.1.1.

For each formulation, three independent specimens were prepared and used for the subsequent characterization tests. Unless otherwise specified, the reported values correspond to the average of three replicates.

Liquid egg white was manually whipped using a hand whisk until a stable foam was obtained. The foaming process was considered complete when additional whipping no longer produced a noticeable increase in foam volume and the foam level remained

essentially unchanged after a short resting period. To ensure reproducibility, all batches were prepared following the same procedure and under the same laboratory conditions.

2.1.1. Microwave Cork-Egg White Mixture Foaming and Consolidation

Process:

The prepared mixture was heated in a MW-oven (Samsung M/O 20LT GE71A) (volume 20 L, 2.45 GHz frequency). The microwave treatment consisted of two stages:

1. Foaming stage: 3 minutes at 750 W,
2. Drying stage: 20 minutes at 150 W.

Preliminary trials were performed at different microwave power levels. The selected conditions (750 W for foaming and 150 W for drying) provided the most stable expansion while avoiding excessive overheating and structural collapse of the foam. Infrared thermography was used during process optimization to verify that no significant localized overheating occurred. Once the operating conditions had been established, all specimens were processed using the same microwave program.

Infrared temperature measurements performed with a thermal camera did not show values exceeding 100 °C, consistent with the presence of water; therefore, the heating process was continued until the water evaporated completely.

As the liquid egg white contains predominantly water, the microwave foaming and drying treatment resulted in extensive moisture removal, leaving a consolidated protein-rich network that acted as the binder phase in the final composite.

2.1.2. Sample Composite Preparation:

After the microwave foaming process, the foamed EW-cork was incorporated into a mortar matrix composed of one part tap water, four parts sand, and one part CaO to create the final composite. We also prepared reference samples using cork granules and mortar without MW-foamed EW. The samples were named according to the following convention: M for mortar, MC for mortar-cork, and MCEWP (mortar-cork-EW-based composite prepared through MW-foaming).

The mortar phase was prepared by mixing sand, CaO and water until a homogeneous and workable consistency suitable for casting was obtained. The resulting mortar was then combined with the microwave-foamed cork-egg white phase and transferred into silicone molds.

Table 1. Composition of the investigated formulations expressed as weight ratios of the raw materials used for sample preparation.

Samples	Mortar	Cork	Liquid Egg White	Weight ratio composition
M	1	0	0	1:0:0
MC	1	1	0	1:1:0
MCEWP	1	1	1	1:1:1

2.2. Methods

2.2.1 Morphological Characterization

The morphological analysis of the developed composite samples was performed using a Hitachi TM3000 benchtop scanning electron microscope (SEM) operating at 15 kV (Hitachi High Tech, Naka, Japan), equipped with an energy dispersive X-ray (EDX) analyzer.

2.2.2 Density and Porosity Measurements

Bulk density was calculated as the ratio of mass to volume. Mass was determined using a Mettler Toledo AE 240 precision balance. Volume was calculated based on measurements of the sample dimensions obtained with a caliper.

Skeletal density was obtained using a helium pycnometer (Quantachrome SPY-3) with a calibrated cell having a volume of 35.4 cm³. Then, the open porosity Φ (%) was calculated according to:

$$\text{Eq. 1} \quad \Phi = 100(1 - \rho_b / \rho_s),$$

where ρ_b is the bulk density, and ρ_s is the skeletal density of the sample.

2.2.3 Mechanical Testing

Mechanical compression tests were conducted on a Shimadzu ASG-X 10 kN universal testing machine (Kyoto, Japan) at room temperature (RT) using a 10 kN load cell. Cylindrical specimens, 10 mm in height and 30 mm in diameter, were cut from longer cylinders and compressed to strains ranging from 7% to 16% at a constant strain rate of 1 mm/min. At least three replicates were tested for each formulation. Young's modulus was determined from the slope of the initial linear-elastic region of the compressive stress-strain curve. Since the objective of this work was to comparatively evaluate the effect of the different formulations rather than to provide a complete mechanical characterization, the compression tests were primarily used to identify the relative trends in mechanical behavior.

2.2.4 Preliminary Flame-Exposure Testing

The flame resistance of the composites was assessed by exposing the samples to a torch flame, after which the affected area was photographed and measured. A modified procedure based on EN ISO 11925-2 [30] was adopted: the samples were secured on a metallic clamp, positioned 15 cm above the ground, and subjected to a torch flame near one edge for 10 minutes [27]. Infrared photos on the surface of the samples in contact with flame were taken with a thermal imaging camera SEEK (Santa Barbara, CA, USA) Shotpro, which operates in the temperature range of 0 - 600 °C. The thermal camera was also employed for monitoring the foaming and consolidation thermal processes.

Temperatures were also measured and recorded on the back of the surface exposed to the flame, with the TC-08 Data Logger equipped with a type N thermocouple.

2.2.5 Acoustic Measurements

The ISO standard 10534-2 [31] was used to determine the acoustic performance of cork-based composites. The sound absorption coefficient at normal incidence was obtained according to this standard using an impedance tube type 4206T and a portable PULSE System, both from Brüel & Kjaer. The impedance tube system was composed of two different tubes. The first tube, with a diameter of 100 mm, was used for measurements in the frequency range of 100 Hz to 1600 Hz, while the second tube, with a diameter of 29 mm, covered frequencies from 500 Hz to 6400 Hz. The tube was sealed, featuring a loudspeaker at one end and a rigid termination at the other. The sample was positioned against the rigid termination, with its surface oriented perpendicularly to the incoming sound waves generated by the loudspeaker. The loudspeaker generated random pink noise inside the impedance tube, and the generated signals were analyzed using the PULSE system. The influence of atmospheric pressure in the variation of the sound velocity, relative humidity and air temperature was previously measured and introduced in the software PULSE system. Three independent samples were prepared and tested for each formulation. Each sample was measured five times on each of its two faces, due to its non-symmetrical structure, and the results were averaged to obtain the representative sound absorption spectrum and the corresponding standard deviation. This aligns with the ISO 10534-2 recommendation to perform measurements in different orientations by rotating the sample 180° within the impedance tube under identical testing conditions.

To evaluate and compare the sound absorption performance of materials over the entire studied frequency range, it is often more practical to use a single-number rating method that is not frequency-dependent. For this purpose, an estimated NRC-like value, for comparative purposes, was calculated from the normal-incidence impedance-tube data following the same arithmetic approach used in the ASTM C423 standard [28] for the Noise Reduction Coefficient (NRC). It should be noted that the standard NRC is defined for reverberation-room measurements under diffuse-field conditions according to ASTM C423 [32], whereas the absorption coefficients in this study were measured at normal incidence according to ISO 10534-2. As stated in ISO 10534-2, normal-incidence absorption coefficients from impedance-tube measurements are not directly comparable with random-incidence coefficients from reverberation-room measurements. The estimated NRC-like value was calculated as the arithmetic average of the sound absorption coefficients at the octave band center frequencies of 250, 500, 1000, and 2000 Hz, rounded to the nearest multiple of 0.05, and is reported here for comparative purposes only.

Furthermore, a screening cradle-to-gate simplified life cycle assessment (LCA) was performed to evaluate the environmental profile of the MCEWP composite. The functional unit was defined as 0.7 kg of prepared composite (1 kg raw material). Primary inventory data for energy consumption during microwave foaming and curing were derived from laboratory measurements. Given the exploratory nature of this work, the LCA was intended to provide an initial indication of the environmental performance of the developed composite rather than a complete environmental certification. Finally, the results were interpreted to identify the main environmental hotspots and key contributors along the production chain. Consequently, the results should be interpreted as a preliminary estimation rather than a complete environmental assessment.

3. Results and Discussion

The developed samples were characterized through:

1. Morphological and structural analysis by SEM
2. Density and Porosity
3. Mechanical compressive tests
4. Fire resistance tests
5. Acoustic absorption measurements

3.1. Morphological and Structural Characterization by SEM

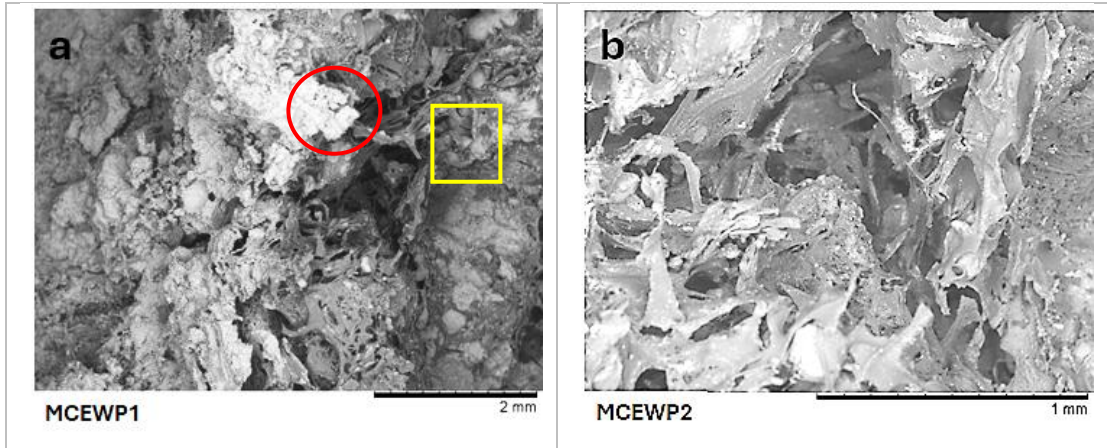


Figure 1. SEM images of MCEWP sample at different magnifications a) 30x and b) 100x.

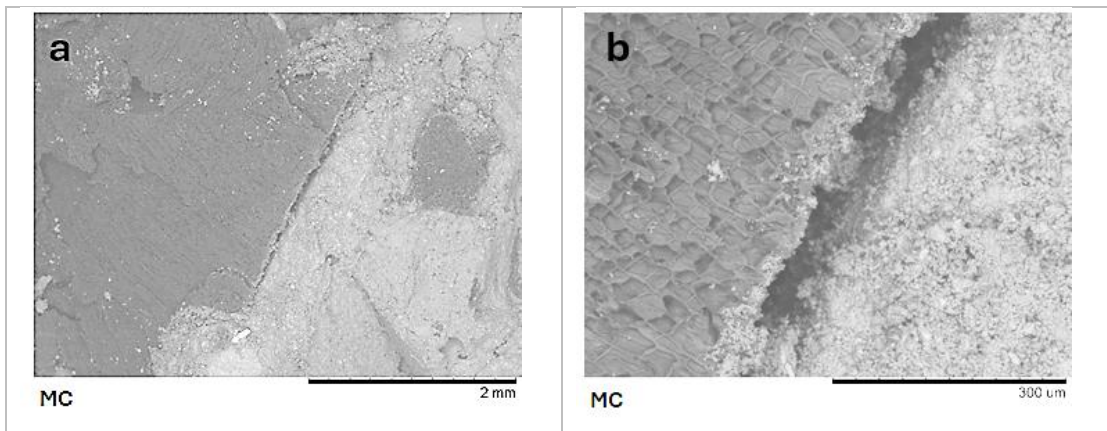


Figure 2. SEM images of the MC sample at different magnifications a) 40x and b) 300x.

To study the internal morphology and structure of the samples without artifacts, we sectioned them with a scalpel.

In Figure 1a and b, we present two images relative the composite material composed of mortar and foamed egg white-cork mixture (MCEWP). The electron microscopy analysis reveals the presence of filament-like structures (square), which are likely associated with the microwave-foamed egg white phase and appear to contribute to the bonding between cork granules and mortar

In the upper right corner (triangle), typical cork cells are visible, while the lighter areas of the micrograph indicate the mortar (circle). The presence of the foamed egg white phase contributes to a more heterogeneous and compliant microstructure, which is expected to favor sound dissipation within the material.

In Figure 2, we show a sample where EW was not utilized as a binder (MC). This texture appears more uniform, lacking the visible filaments observed in the previous Figure 1,

and reveals a clear distinction between the cork (dark) and the mortar (bright). Moreover, the interface between the cork and mortar is very distinct, showing no interpenetration; the two materials remain separate. The absence of the foamed egg white phase results in a more compact and less interconnected morphology compared with MCEWP.

SEM images of the mortar reference are not reported, as they did not show significant microstructural features relevant to the present discussion.

Overall, the MCEWP formulation exhibits a more heterogeneous and interconnected microstructure, characterized by filament-like features associated with the foamed egg white phase, which appear to enhance cohesion between cork granules and mortar. In contrast, the MC formulation displays a clearer separation between cork and mortar regions, suggesting a weaker interfacial interaction.

3.2. Density and Porosity

The bulk density, skeletal density, and calculated open porosity values of the investigated samples are reported in Table 2. Open porosity values were calculated from the average bulk and skeletal density values according to Eq. 1.

Table 2. Bulk and skeletal densities and open porosity of the samples

Samples	ρ_b [g/cm ³]	ρ_s [g/cm ³]	Open Porosity [%]
M	1.5 ± 0.1	1.6 ± 0.1	6.3
MC	1.0 ± 0.1	1.2 ± 0.1	16.7
MCEWP	0.8 ± 0.1	1.2 ± 0.1	33.3

Table 2 shows a clear trend of decreasing density and increasing open porosity as the formulation evolves from mortar to cork-containing and MW-foamed egg white-cork composites.

Sample M, consisting solely of mortar, exhibited the highest bulk and skeletal density values and the lowest open porosity. The incorporation of cork granules in sample MC resulted in a noticeable reduction in density and a corresponding increase in porosity, reflecting the lightweight and cellular nature of cork.

The lowest bulk density was observed for sample MCEWP, which combines mortar, cork granules, and microwave-foamed egg white. This reduction can be attributed to the microwave-induced foaming of the egg white phase, which generates additional voids within the composite structure and increases the overall pore volume. Consequently, MCEWP exhibited the highest open porosity (33.3%), approximately twice that of MC and more than five times that of the reference mortar sample.

The progressive increase in open porosity from M to MC and finally to MCEWP is consistent with the SEM observations discussed in Section 3.1, where the foamed egg white phase produced a more heterogeneous and interconnected microstructure. Such a highly porous structure is expected to favor sound-wave dissipation and may contribute to the enhanced acoustic performance observed in the following sections.

3.3. Compressive Mechanical Tests

The representative stress–strain curves reported in Figure 3 highlight the influence of cork and microwave-foamed egg white on the compressive behavior of the investigated formulations.

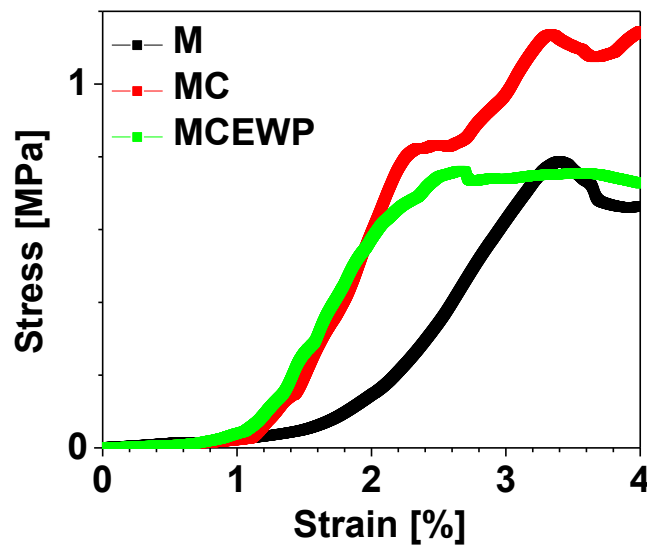


Figure 3. Representative compressive stress–strain curves for the investigated formulations.

The cork granules incorporation in the MC sample resulted in the highest compressive strength (1.2 ± 0.1 MPa), representing an increase of approximately 50% relative to the plain mortar reference. Following the initial yielding stage, the MC formulation continued to sustain increasing loads up to failure, suggesting that the cork particles contribute to a more effective stress redistribution within the composite.

The MCEWP formulation reached a compressive strength of approximately 0.8 ± 0.1 MPa, comparable to that of the plain mortar sample within experimental uncertainty. This result indicates that the introduction of the microwave-foamed egg white–cork phase substantially decreases density while maintaining the overall load-bearing capacity of the material.

In agreement with the density and porosity results discussed in Section 3.2, the MCEWP composite exhibited a smoother post-yield response than the reference mortar, indicating

a more progressive deformation behavior. Such behavior may be associated with the porous microstructure generated by the foamed egg white phase and could contribute to stress redistribution within the composite.

Overall, MC exhibited the highest compressive strength, whereas MCEWP achieved the best compromise between mechanical performance and lightweight design. Despite its substantially lower density and higher porosity, MCEWP retained a compressive strength comparable to that of the reference mortar while offering additional sustainability benefits and the potential for improved acoustic performance

Table 3. Average compressive strength (σ_B), strain at failure (ϵ_B), and Young's modulus (E_Y) of the investigated formulations.

Samples	σ_B [MPa]	ϵ_B [%]	E_Y [MPa]
M	0.8 ± 0.1	3.4 ± 0.3	35.0 ± 9
MC	1.2 ± 0.1	3.5 ± 0.4	45.0 ± 8
MCEWP	0.8 ± 0.1	2.7 ± 0.2	38.0 ± 10

3.4. Fire Resistance Tests

The temperature-versus-time profiles recorded by the thermocouple located on the unexposed side of the specimens (opposite to the flame-exposed surface) are reported in Figure 4.

During the first stages of the test, the plain mortar sample (M) exhibited a relatively rapid increase in backside temperature, reflecting the heat transfer through the dense inorganic matrix. The MC sample showed a slower temperature rise, confirming the beneficial insulating effect provided by the cork granules.

The MCEWP formulation initially followed a thermal response comparable to that of MC. During approximately the first 150 s of flame exposure, the temperature recorded on the rear face remained relatively low despite the direct action of the torch flame on the opposite surface. This behavior is consistent with the high porosity and low bulk density of the foamed structure, which initially limited heat transfer through the specimen thickness. The progressive degradation of the foamed phase also contributed to delaying the temperature increase on the rear surface.

However, visual observations performed during the test revealed that the flame-exposed side of the MCEWP sample progressively underwent localized thermal degradation. The highly porous egg white-cork phase carbonized and gradually detached from the specimen, resulting in a continuous loss of material without the development of sustained flaming combustion. This progressive consumption likely contributed to delaying the rise in backside temperature by dissipating a portion of the incoming thermal energy.

After approximately 150 s, a sudden increase in backside temperature was observed. Based on simultaneous visual and infrared observations, this behavior is attributed to the

progressive formation of a localized burn-through zone that eventually evolved into a large through-hole. Once the opening formed, hot combustion gases and part of the flame front were able to penetrate the specimen thickness and reach the vicinity of the thermocouple, causing the abrupt temperature rise recorded in Figure 4.

Following the temperature peak, the MCEWP profile exhibited moderate oscillations and a gradual decrease, suggesting that the remaining carbonized porous structure partially stabilized under continued thermal exposure.

Therefore, the temperature peak observed for MCEWP should not be interpreted solely as a consequence of enhanced thermal conduction through the material. Rather, it reflects a localized failure mechanism associated with the progressive thermal degradation of the foamed core and the subsequent formation of a burn-through path across the specimen thickness.

Importantly, despite this localized degradation and perforation, the MCEWP composite did not exhibit sustained flaming combustion or flame propagation. All investigated formulations successfully resisted ignition under the applied flame exposure conditions, demonstrating self-extinguishing behavior.

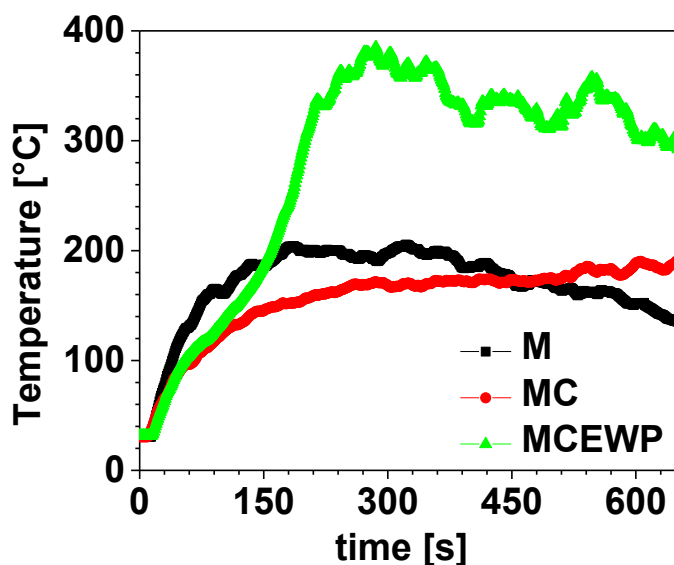


Figure 4. Temperature-versus-time profiles measured by the thermocouple on the unexposed side of the specimens during direct flame exposure.

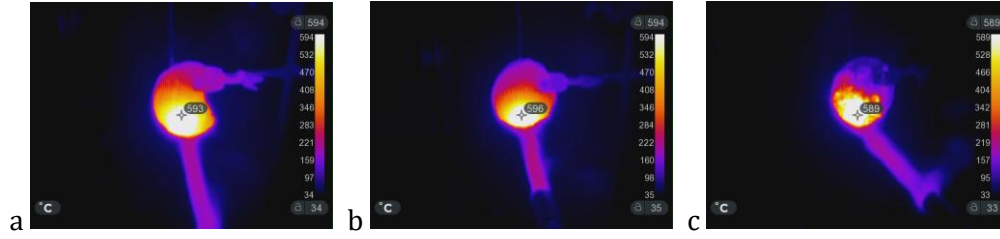


Figure 5. Infrared thermographic images of the flame-exposed surface after approximately 650 s of flame exposure for M (a), MC (b), and MCEWP (c), respectively.

The infrared thermography observations provide additional evidence supporting the interpretation of the temperature profiles shown in Figure 4.

Table 4. Temperature values recorded via IR imaging on the surface directly exposed to the flame at time $t = 0$ and 650 s

Samples	T [°C] @	T [°C] @
	T = 0 s	t = 650 s
M	30	592
MC	30	596
MCEWP	30	587

Although the surface temperatures measured by infrared thermography were comparable for all formulations (Table 4), the localized burn-through observed in MCEWP created a preferential pathway for hot gases, explaining the higher backside temperatures recorded by the thermocouple.

While the M and MC samples maintained a relatively uniform thermal distribution and preserved their structural integrity, the MCEWP specimen exhibited a localized darker region associated with the onset of burn-through. This observation is consistent with the abrupt temperature increase recorded on the rear surface and confirms that the thermal response of the MCEWP formulation was governed by localized structural degradation rather than by uniform heat conduction through the material.

3.5. Acoustic Absorption Measurements

The mortar-only sample (M) exhibits the lowest sound absorption coefficients among the three materials. The average measurement curve remains relatively flat and low, not exceeding 0.1 across the entire frequency spectrum. This indicates that mortar alone has limited sound absorption properties, particularly at low and mid-range frequencies. This is reflected in the low estimated NRC-like value (Table 5).

MC shows improved sound absorption compared to mortar alone. Notably, MC exhibits higher absorption coefficients than MCEWP at lower frequencies (125–500 Hz), while MCEWP outperforms MC at 1000 Hz and above. The markedly lower performance of MCEWP at 125 Hz can be attributed to the longer wavelength at this frequency, which significantly exceeds the sample thickness (2 cm) and thereby limits effective sound dissipation. Its absorption coefficient increases more notably at higher frequencies, reaching above 0.4 around 6000 Hz, although the standard octave bands up to 4000 Hz are capped at lower values in Table 5. There is a noticeable absorption peak around 1000 Hz, which could be beneficial for specific applications. However, its performance at mid-to-high frequencies (≥ 1000 Hz) is not as strong as MCEWP (Figure 6). For frequencies above 3000 Hz, the high standard deviation values indicate variability in acoustic performance, which could be attributed to the inhomogeneity of the samples.

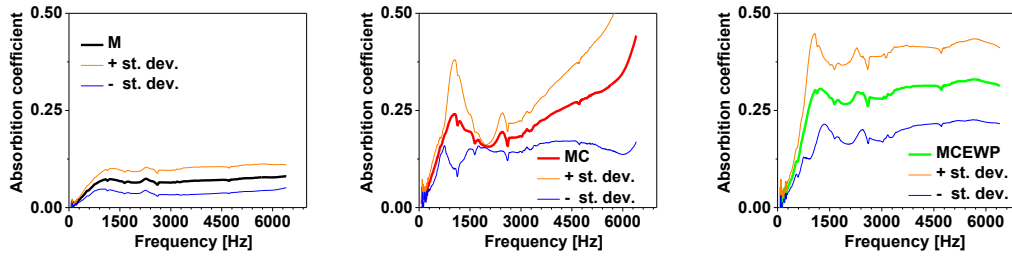


Figure 6. Sound absorption coefficient as a function of frequency for the investigated samples, together with the corresponding standard deviation bounds.

MCEWP upon closer inspection demonstrates superior sound absorption properties at mid-to-high frequencies (≥ 1000 Hz). The average absorption coefficient curve shows higher values compared to the other materials at these frequencies, reaching approximately 0.3–0.35 at higher frequencies (Table 5). Notably, it maintains higher absorption coefficients at mid-to-high frequencies (≥ 1000 Hz) compared with reference formulations. The wider standard deviation indicates some variability in performance, which could be due to the heterogeneous nature of the composite.

The first absorption peak occurred at approximately 1048 Hz for MC ($\alpha = 0.240$) and at approximately 1232 Hz for MCEWP ($\alpha = 0.306$). The higher absorption coefficient associated with the MCEWP peak further confirms the beneficial effect of the microwave-foamed egg white phase on the acoustic performance of the composite.

Table 5. Sound absorption coefficient in one octave band and estimated NRC-like value for the studied samples.

Samples	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC _{est.}
M	0.002	0.015	0.040	0.071	0.064	0.070	0.05

MC	0.023	0.052	0.116	0.239	0.157	0.245	0.15
MCEWP	0.001	0.039	0.106	0.286	0.267	0.313	0.15

In the following we can then resume the acoustic absorption data recognized by relative measurements such as:

Pure mortar (M) exhibits the lowest sound absorption coefficients, as expected from a hard, reflective material characterized by a low porosity.

The addition of cork and egg white to the mortar (MCEWP) significantly enhances sound absorption at mid-to-high frequencies (≥ 1000 Hz). This composite outperforms the other materials at 1000 Hz and above, although MC shows higher absorption at lower frequencies (125–500 Hz).

The combination of mortar and cork (MC) improves upon pure mortar, mainly due to the porosity introduced by the cork, increasing from 6.3% to 16.7%, but does not match the broadband absorption capabilities of MCEWP. MCEWP formulation emerges as the superior sound-absorbing composite at mid-to-high frequencies. Its ability to maintain higher absorption coefficients at mid-to-high frequencies (≥ 1000 Hz) makes it particularly valuable for applications requiring sound control in these ranges.

The addition of MW-foamed egg white to the mortar-cork formulation creates a complex, open-cell cellular network with interconnected, branched filaments visible in SEM (Fig. 1). This fibrous structure not only increases total porosity (up to 33.3%) but also enhances tortuosity by lengthening the effective path of sound waves and promoting interactions with the solid matrix. However, porosity alone does not fully determine acoustic absorption performance; parameters such as airflow resistivity, tortuosity, pore size distribution, and surface impedance are critical in governing energy dissipation via viscous friction and thermal losses, particularly at medium and high frequencies. The interconnected and fibrous nature of the foamed egg white phase suggests a porous network capable of providing suitable airflow resistivity to facilitate these dissipation mechanisms. Future studies will incorporate measurements of these additional parameters to further elucidate the underlying absorption mechanisms.

The obtained estimated NRC-like values ranged from 0.05 to 0.15, which are comparable to those reported in similar studies where the composite matrix consisted of natural hydraulic lime or gypsum [33-35].

4. Preliminary Environmental and Energy Screening Assessment

The growing interest in bio-based construction materials has also stimulated the development of environmental assessment approaches specifically focused on circularity and life-cycle performance of insulation systems [38].

4.1. Goal and Scope Objective

The objective is to evaluate and compare the potential environmental impacts associated with the production of mortar-cork-EWP composite (MCEWP) against a traditional cementitious mortar (M) and a mortar-cork composite (MC).

- Functional Unit (FU): ~0.7 kg of ready-to-use composite material after water evaporation by microwave heating.
- System Boundaries: Cradle-to-Gate approach is adopted, encompassing:
- Extraction and processing of raw materials (industrial waste cork, sand, quicklime/CaO, water, and liquid egg white).
- Transportation of raw materials to the production facility.
- The manufacturing phase: microwave-assisted (MW) foaming and drying processes followed by mixing with the inorganic mortar matrix.

4.2. Life Cycle Inventory

For the MCEWP sample the preliminary estimated inventory for the FU (0.7 kg of composite) can be summarized as follows:

4.2.1. Material Inputs (1 kg of MCEWP)

Mortar (Inorganic): 333 g (composed of sand, CaO, and mixing water in the formulation ratio 4:1:1).

Sand: 222 g.

Lime (CaO): 55.5 g.

Water: 55.5 g.

Cork By-Products: 333 g (industrial granulation waste 1–3 mm fractions).

Liquid Egg White (EWP): 333 g (liquid form). Starting from an initial input of 333 g of liquid egg white, microwave-assisted processing yielded a dry solid residue of approximately 33 g, corresponding to a mass yield of 10 wt%. Based on the biochemical composition of avian egg white, this non-volatile solid fraction is composed predominantly of proteins (≈ 90 wt%, mainly ovalbumin), alongside inorganic mineral salts (≈ 10 wt%, primarily sodium, potassium, and chloride ions) and trace amounts of carbohydrates and lipids.

4.2.2. Energy Inputs (Microwave Process)

The laboratory-scale microwave thermal processing for a single sample requires the following operational parameters:

Foaming step: 3 min at 750 W = 0.0375 kWh.

Drying step: 20 min at 150 W = 0.050 kWh.

Estimated total electricity consumption (laboratory): 0.0875 kWh per sample.

Scale-up note: At industrial scale, continuous-convection industrial microwave ovens show significantly higher energy efficiency than traditional convection ovens, reducing indirect CO₂ emissions.

4.3. Preliminary Life Cycle Assessment (LCA)

4.3.1. Global Warming Potential (GWP) - Carbon Footprint

Quicklime (CaO) represents the main emission hotspot due to the upstream calcination process of limestone ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$). However, the use of only 55.5 g of CaO per kg of MCEWP suggests reduction of the overall carbon footprint compared to standard cement mortar.

Cork contains biogenic carbon captured from the atmosphere during tree growth and may contribute to temporary carbon storage within the composite, although this consideration should be regarded as a preliminary estimation pending a full LCA allocation analysis.

Electricity (MW): The localized impact depends on the national grid's energy mix. The deployment of microwaves optimizes heat transfer via volumetric rather than surface heating, mitigating energy losses compared to conventional kiln curing.

4.3.2. Resource Depletion and Water Depletion

Cork is considered a by-product of the stopper and agglomerate production chain. Under a by-product allocation approach, only a limited share of the upstream environmental burden may be assigned to cork granulation residues.

If EWP from industrial egg waste, e.g., eggs unfit for human consumption or by-products of industrial processing) is declared, the associated environmental burden is expected to be significantly lower than that associated with food-grade egg products.

Net water consumption is strictly limited to the baseline hydration of the mortar matrix, resulting in a significantly lower fluid requirement than traditional autoclaved aerated concrete (AAC).

4.4. Core Sustainability Pillars of the MCEWP

1. Replacement of Synthetic Binders.

The MCEWP composite completely replaces petroleum-derived polyurethane (PU) or acrylic binders—ubiquitous in commercial acoustic panels—with a fully biological, nontoxic, and biodegradable protein binder (EW).

2. Process Efficiency (MW vs. Conventional Thermal Oven).

Direct microwave coupling allows the heating and drying in just 23 minutes total, reducing the thermal energy required compared to the several hours required for convection curing cycles of lightweight polymer cementitious composites.

3. Structural Lightweighting.

Lowering the bulk density from 1.5 g/cm³ (pure mortar) to 0.8 g/cm³ (MCEWP) enhances acoustic attenuation while yielding downstream environmental dividends during transport (lower mass = reduced logistical fuel burn).

4.5. Environmental Sustainability and Circular Economy Perspectives

The development of the bio-based cork composite via microwave processing must be evaluated not only for its technical performance but also through the lens of environmental sustainability and circular economy (CE) principles. To assess the viability of this material, this section analyzes two main pillars: process energy consumption and End-of-Life (EoL) recyclability.

4.5.1. Process Energy and Industrial Scalability

A critical metric for evaluating microwave-assisted processing is its specific energy consumption. In this study, the total energy (E_{total}) absorbed during the dual-stage curing process is governed by the power ratings (P) and operating times (t) of the equipment:

$$\text{Eq.2 } E_{\text{total}} = (P_{\text{Foaming}} \cdot t_{\text{foaming}}) + (P_{\text{drying}} \cdot t_{\text{drying}})$$

$$\text{Eq.3 } E_{\text{total}} = 0.75 \text{ kW} \cdot 0.05 \text{ h} + 0.15 \text{ kW} \cdot 0.333 \text{ h} = 0.0875 \text{ kWh}$$

Given that the mass of the processed specimen was $m = 100 \text{ g}$ (0.1 kg), the laboratory-scale specific energy consumption ($E_{\text{spec, lab}}$) amounts to:

$$\text{Eq.4 } E_{\text{spec, lab}} = \frac{E_{\text{total}}}{m} = \frac{0.0875 \text{ kWh}}{0.1 \text{ kg}} = 0.875 \text{ kWh/kg}$$

This value is highly competitive, sitting already slightly below conventional industrial manufacturing benchmarks for standard insulation materials (which typically range between 1.0 kWh/kg and 1.5 kWh/kg). This primary efficiency highlights the intrinsic thermodynamic advantage of microwave processing over traditional thermal methods, even within a non-optimized batch configuration.

When transitioning from laboratory batch processing to industrial continuous-feed systems (such as conveyor-belt or tunnel microwave reactors), the energy efficiency scales even further. Modern industrial magnetrons yield electrical-to-microwave conversion efficiencies exceeding 85%. Furthermore, the volumetric and selective dielectric heating mechanisms inherent to microwave fields ensure that energy is

deposited directly within the lossy aqueous and protein phases of the composite, eliminating the thermal inertia and structural heat losses typical of conventional convection kilns.

Extrapolating these performance factors to a continuous industrial line yields a preliminary industrial-scale estimation of specific energy consumption in the range of 0.25–0.45 kWh/kg. These values should be regarded as projected estimates based on laboratory-scale data and literature-reported microwave efficiencies. This could potentially represent an energy saving of 50–70% compared with conventional thermal curing technologies, according to this preliminary estimation.

4.5.2. End-of-Life (EoL) Recyclability and Waste Management

Concurrently, the circularity of the MCEWP composite is fundamentally guaranteed by its bio-based and non-toxic components. Unlike traditional expanded polystyrene (EPS) or rigid polyurethane (PU) insulation boards, which face severe mechanical recycling barriers and are routinely directed to landfills or waste-to-energy incineration plants, this green composite offers two benign end-of-life pathways:

Closed-Loop Technical Cycling: At the end of its operational lifespan as an acoustic or thermal insulation panel, the material can be mechanically crushed and shredded. The resulting granulate can be directly re-incorporated as a secondary raw material into new MCEWP batches, replacing fractions of pristine sand and cork aggregate.

Biological Cycling: Due to the organic nature of cork and the natural protein-based binder (egg white), the organic fraction may be potentially compatible with biological treatment routes, although dedicated compostability and ecotoxicity studies are required. However, dedicated biodegradation, compostability, and ecotoxicity studies are required to verify this potential and to assess the behavior of the residual mineral fraction under end-of-life conditions.

5. Comparison and Conclusions

The present study reports on the preparation and characterization of a novel composite material prepared by microwave-assisted foaming and curing of cork granules, egg white protein, and mortar. The composite, characterized by balanced mechanical, fire-resistance and acoustic properties, suggests to be a promising proof-of-concept composite for sustainable, non-load-bearing sound-absorbing panels in civil applications.

Comparing the properties of these mortar-based samples highlights distinct mechanical behaviors influenced by compositional changes, and in particular:

1. The incorporation of cork (MC) resulted in the highest compressive strength and Young's modulus among the investigated formulations, suggesting a beneficial contribution of cork particles to load redistribution within the mortar matrix.

2. The introduction of microwave-foamed egg white in MCEWP reduced density while maintaining Young's modulus and compressive strength values comparable to those of the plain mortar reference.

From a thermal and fire-safety perspective, MCEWP, M, and MC samples exhibited a high maximum temperature limit ($> 200\text{ }^{\circ}\text{C}$), completely inhibiting ignition and the formation of an open flame. This behavior, coupled with the absence of sustained ignition and flame propagation under the tested conditions, suggests potential applicability of the material in non-load-bearing indoor insulation systems, although further standardized fire testing is required before any fire classification can be assigned [36].

Acoustically speaking, the MCEWP composite demonstrated superior sound absorption at mid-to-high frequencies ($\geq 1000\text{ Hz}$) compared to both mortar-only and mortar-cork samples, with absorption coefficients of 0.286 at 1000 Hz and 0.313 at 4000 Hz, compared to 0.071 and 0.070 for plain mortar, respectively. This behavior is attributed to the increased open porosity of the matrix, which enhances the dissipation of sound energy within the specimen. The estimated NRC-like value, which serves as a supplementary single-number comparison, ranged from 0.05 to 0.15, indicating a clear improvement in mid-to-high-frequency sound absorption compared to the mortar reference. These results demonstrate the potential applicability of the developed composites in architectural acoustics and indoor noise control [28].

Similar trends have recently been reported for bio-based acoustic systems and cork-containing sound absorbing materials developed for sustainable building applications [11-12].

A key innovation in this study is the use of microwave technology to foam and consolidate the sponge-like cork-egg white core, thereby reducing the total amount of mortar required. This method presents a more energy-efficient production process compared to traditional curing methods, potentially reducing production time and energy consumption, according to the preliminary environmental assessment performed in this study [5]. Furthermore, utilizing industrial cork residues and recoverable egg albumen directly aligns with circular economy principles by turning discarded resources into value-added building materials [37].

Regarding long-term durability, after two years of storage under standard indoor ventilation conditions, no visible mold growth or biological degradation was observed in the MCEWP specimens.

To ensure reliable performance under more severe environmental conditions, eco-friendly anti-mold agents or fungicides could be easily integrated into the matrix without compromising the sustainability profile of the composite.

While these preliminary results are promising, the environmental results reported herein should be considered preliminary estimations instead primarily comparative purpose. Future studies will focus on:

Conducting a comprehensive ISO 14040/14044-compliant life cycle assessment (LCA) to fully quantify the environmental and economic impacts of this production process compared to conventional acoustic materials;

Testing the material's performance under accelerated aging and high-humidity environments to validate long-term structural integrity.

In conclusion, this study demonstrates the potential of MCEWP as a lightweight, multifunctional, and sustainable composite for building acoustics. The material combines enhanced sound absorption, reduced density, satisfactory mechanical performance, self-favorable flame-exposure behavior, and a low-energy microwave-assisted manufacturing process, making it a promising candidate for circular-economy-oriented construction applications.

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Data Availability

Data available upon request

Conflicts of Interest

The authors declares that there is no conflict of interest regarding the publication of this article.

During the preparation of this work the authors used Perplexity.ai in order to check the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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