Article

A Novel Acoustic Sandwich Panel Based on Sheep Wool

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Abstract: The aim of this paper is to propose a novel sandwich panel, which would be suitable for sound absorption and airborne sound insulation, used as applied cladding or independent lightweight partition wall. As far as the authors are concerned, this is the first sheep wool-based sandwich panel using only natural materials. The structure was prepared using hydrated lime-based composite face sheets and a sheep wool-based core. Several parameters of the sandwich panel were determined, including sound absorption coefficient, airborne sound insulation, thermal conductivity, thermal resistance, compressive strength, and bending strength, respectively. The results indicate that the maximum sound absorption value of 0.903 was obtained at the frequency of 524 Hz in the case of the unperforated sample, 0.822 at 536 Hz in the case of the sample with 10% perforations, 0.780 at 3036 Hz in the case of the sample with 20% perforations, and 0.853 at 3200 Hz in the case of the sample with 30% perforations. The registered airborne sound insulation index of the panel was 38 dB. Based on the obtained data, it can be concluded that the studied panel recorded comparable values with other synthetic noise control solutions, which are suitable as applied cladding or an independent lightweight partition wall, with good acoustic properties.

Keywords: sound absorption; mechanical properties; natural composite; applied cladding; lightweight partition wall

1. Introduction

The use of materials that have a reduced impact on the environment is of great importance, especially today, when the consequences of human intervention on the biosphere have become alarming. Many of the currently manufactured coating materials are of synthetic origin, which, during their service life, might affect the well-being of humans by emitting harmful substances, such as formaldehyde or other volatile organic compounds. These materials, if inappropriately discarded, can damage the natural environment as well. In the building industry, the use of surface treatments is suitable to the field of acoustics. These functional coating panels are usually made of synthetic foams or perforated sandwich panels. In light of environmental consciousness, new materials should be designed, which would perform similarly or better than the existing synthetic ones. These new coating surfaces might be formulated with natural or recycled materials.

Natural materials and natural materials-based composites have several advantages, such as easy processing [1], use of local materials [2], high availability [3], carbon sequestration during the plant's life [4], and, after the end of service life, they can be introduced into the natural environment without causing damage [5]. Besides these advantages, they also possess a few disadvantages, such as low fibre-matrix compatibility [6], high risk of attack of microorganisms [7], fibre defects, and structural differences that can lead to variable mechanical strengths [8].

A sandwich panel is constructed by assembling multiple layers of different materials. In general, a sandwich structure consists of a core that is placed between two faces or skins [9]. Regarding the use of the materials, sandwich panels may be natural, hybrid, or fully synthetic. There are several studies reported in the literature about natural and hybrid sandwich structures, constructed with various materials, but only a few of these assess the sandwich panel's acoustic properties [10–13]. The majority of them focuses on mechanical strength. These structures are mainly used in engineering, automotive, and aeronautical applications. The skins are mainly produced from hardwood plates [14], veneer [15], flax fibers-epoxy resin composite [10,12], bamboo, and cotton bound with a vinyl ester matrix [11], natural silk fiber and epoxy resin [16], glass fiber mat [17,18], aluminum sheets [19,20], and carbon fiber-epoxy resin composite [13]. Similarly, the core of the structures could be prepared from mushroom foam [14], agglomerated cork [10,13], balsa wood [11,12], pine wood [11], medium density fiberboard [20], a textile fibers-bone glue composite [15], natural fibers (palm leaf, coconut, raffia, oil palm) and polyester resin [17], natural fibers (jute and hemp) and epoxy resin [18,19], and synthetic foams [16]. The manufacturing method of these sandwich structures also varies from gluing the elements together [14], using a vacuum-assisted resin transfer method [10,18], gluing and vacuuming [11,13], gluing and pressing [19], and hot pressing [12], to using the resin employed for the core [15,17] or using the resin employed for the skin and pressing [16].

In the field of construction materials, the sandwich or multi-layered structures are commonly used as wall panels. Brenici et al. [21] designed several multi-layered wall structures consisting of different core materials, such as wood shavings, recycled acrylonitrile butadiene styrene (ABS), and rock wool as well as different face plates such as oriented strand board and gypsum board. Buratti et al. [22] studied a multi-layered wall panel consisting of a straw core and an air gap fixed between wooden plates, with the assembly being plastered on both faces. La Rosa et al. [23] evaluated different types of wall systems. Some of the wall structures were formulated with an eco-sandwich panel, consisting of a cork core and flax fibers-epoxy resin composite skin.

Besides the wall structures, sandwich panels are being used as acoustic or thermal insulations. Ricciardi et al. [24] prepared a hybrid sandwich panel consisting of recycled paper core and recycled textile fibers (polyethylene) based skins. The 12-mm and 20-mm thick panels were assessed regarding their thermal and acoustic properties. It was observed that thermal conductivity varies between 0.034–0.039 W/m·K, and the noise reduction coefficient is between 0.23–0.38. Moreover, after conducting a life cycle assessment of the panels, it was evident that these sandwich composites have a high environmental impact, regarding the energy consumption and global warming potential.

The aim of this paper is to discuss the performance of a natural material-based sandwich panel, which would find its application as an acoustic absorption and airborne sound insulation material, with a proper thermal conductivity, having comparable characteristics with synthetic materials. As far as the authors are concerned, this is the first sheep wool-based sandwich panel using only natural materials. The structure is designed using hydrated lime, rice paste, and wool fibers for the face sheets and hydrated lime, wheat flour, and wool fibers for the core. On the prepared composite, different tests were effectuated, including acoustical, thermal, and mechanical determinations in order to evaluate its suitability as an insulation material.

2. Materials and Methods

2.1. Materials

The aim of this paper is to obtain a natural panel of comparable acoustic performances with the synthetic ones, destined for indoor spaces. Natural materials are known to have a positive impact on human health and psyche [25] and to regulate indoor temperature and humidity [26].

For the preparation of the sandwich panel's face sheets, the following materials were used: hydrated lime (type CL80-S), commercially available wool fibers, rice paste, and water. The wool fibers were obtained from the Romanian sheep breed "țigaie." This type of wool fiber is characterized by fineness and a high degree of crimps, so it is mainly used in the textile industry. The fibers were not chemically treated due to environmental considerations. The wool was only washed and carded. The carded wool mats were cut, which resulted in fibers with a length of 1–10 mm. The rice paste was prepared by boiling a mixture of ground rice grains and water. The maximum dimension of the rice granules was 1 mm and the ratio of granules to water was 0.125. Several properties of the sandwich panel's face sheets were reported elsewhere [27,28]. The recipe of the composite can be observed in Table 1.

Table 1. The recipes of one of the face sheets, the binder used for the core, and the core of the sandwich panels, respectively.

	Material	Rice Paste (g)	Hydrated Lime (g)	Wool Fibers (g)	Water (mL)	Wheat Flour (g)
1	Face sheet	821.1	2395.3	61.2	1317.5	-
2	Core	-	-	600	-	-
	Binder	-	609	-	2878	263

In order to prepare the sandwich panel's core, the following materials were used: wool fibers, hydrated lime, wheat flour, and water. The wool fibers and hydrated lime have the same properties as those used for the preparation of the face sheets, with the exception that the wool mats used for the core preparation were cut, according to the final dimensions of the panel. The wheat flour used is commercially available, marketed as "type 000," which has the finest granulation available. The recipe of the core and the binder can be observed in Table 1.

2.2. Preparation of Samples

In total, nine panels with the dimensions of 595 mm × 350 mm × 50 mm (for the determination of airborne sound insulation), four cylindrical samples with the diameter of 63.5 mm and height of 50 mm (for the determination of sound absorption) were prepared. One panel was cut to obtain the samples for the determination of mechanical (150 mm × 150 mm × 50 mm and 150 mm × 300 mm × 50 mm) and thermal (150 mm × 150 mm × 50 mm) properties.

The preparation of samples was carried out both mechanically and manually. First, the cores were manufactured by using the following steps: laying out the fiber mats on a flat surface, pulverizing half of the quantity of the binder over the fibers with a pressure sprayer, carefully turning the fiber mats with their unsprayed side up, pulverizing the remaining binder over the fibers, placing the binder-fiber assembly into molds with dimension of 595 mm × 350 mm × 30 mm, and applying a pressure to the samples. The samples were turned over periodically (at intervals of 2–3 days) to aid their ventilation and drying process. The cores were kept in standard conditions until one of the skins was cast.

The casting of the skins started when the cores had dried to the point that they could be easily manipulated. The two skins were cast separately. The composite was prepared by mechanical mixing. A mold with the dimensions of 595 mm × 350 mm × 50 mm was prepared in which a 10-mm thick layer was cast. The 30-mm thick core was placed on top of the fresh composite. The contact surface

of the core with the skin was previously sprayed with the binder used to prepare the core itself to improve its adhesion to the skin. A rigid 10-mm thick sheet was placed over the core to completely fill the mold and the mold was pressed. When the second skin was cast, the pressure and the rigid sheet were removed. Before applying the second skin, the surface of the core was again sprayed with the binder used for the core. Then a layer of 10-mm thickness was evenly distributed over the core. The sandwich structure was again pressed. The panels were unmolded and the pressure was removed after 3 days. In the following period of time, the panels were regularly turned for 1–2 weeks in standard conditions (temperature of $24\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ and relative humidity of $60\% \pm 5\%$) to help the drying process. The prepared sandwich structure is presented in Figure 1.

Figure 1. The prepared sandwich panels: (a) Overview of the full-sized panels and (b) cross section.

For the preparation of cylindrical samples, the same method was followed, but on a smaller scale. Three of the samples had one of its skins perforated in order to evaluate the sample's sound absorption. The perforation ratios were: 10%, 20%, and 30%, with the perforation diameter being 10 mm. Based on the studies realized in the Patent Application no. "a 2018 00288"/24.04.2018, it was concluded that the perforations with a larger diameter develop better acoustic absorption performances on the entire frequency range. An unperforated control sample was also prepared. The prepared samples are presented in Figure 2.

In order to assess the sandwich structure's airborne sound insulation and sound reduction index, a panel with the dimensions of $1500\text{ mm} \times 1250\text{ mm}$ had to be constructed. Eight prepared panels with dimensions of $595\text{ mm} \times 350\text{ mm} \times 50\text{ mm}$ were fixed through 30-mm width battens inside a wooden frame 50 mm in height. In order to avoid acoustic bridges created by the frame, an elastic band of 18-mm width was applied under the wooden fixing battens. The details of the panel are presented in Figure 3.

2.3. Methods of Determination

The prepared sandwich composite was subjected to the following determinations: sound absorption, airborne sound insulation, thermal conductivity, thermal resistance, compressive strength, and flexural strength.

Figure 2. Samples for acoustic absorption with different perforation ratios: (a) 0%, (b) 10%, (c) 20%, and (d) 30%.

Figure 3. Details of the panel prepared for airborne sound insulation: (a) wooden frame and (b) detail of elastic band applied under the battens.

The determination of the sound absorption coefficient was carried out according to SR EN ISO 10534-2 [29], using an impedance tube type 4206A (Brüel&Kjær, Nærum, Denmark). The results were recorded for the frequency band of 100–3.2 kHz, with the help of the transfer function method. For this determination, four types of samples were prepared with the diameter of 63.5 mm in order to fit inside the impedance tube's sample holder and thickness of 50 mm, which have different percentages of skin perforations: 0%, 10%, 20%, and 30%. The noise reduction coefficient (NRC) was also calculated using Equation (1) [30].

$$\text{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} [-] \quad (1)$$

The determination of airborne sound insulation (Figure 4) was carried out according to SR EN ISO 10140-2 [31]. For this determination, a panel with the dimensions of 1500 mm × 1250 mm × 50 mm was prepared. The panel can be observed in Figure 4. The weighted sound reduction index, R_w , was calculated according to SR EN ISO 717-1 [32].

Figure 4. Determination of airborne sound insulation: (a) The prepared insulating panel and (b) the installed system for the determination.

The determination of the thermal conductivity coefficient and thermal resistance was carried out according to SR EN 12664 [33], using a heat flow meter type FOX 200 (TA Instruments, New Castle, DE, USA). For this determination, a sample with the dimensions of 150 mm × 150 mm × 50 mm was prepared. The sample was dried in standard conditions. The drying process being considered was complete when the difference between two successive weighing was smaller than 0.1 g. The thermal properties were evaluated at a temperature of 20 °C.

The determination of mechanical strength (Figure 5) was carried out according to SR EN 826 [34] for the compressive strength and SR EN 12089 [35] for the bending strength. A universal testing machine type ZD10-90 (Fritz Heckert, Dolnośląskie, Poland) was employed to perform the mechanical experiments. The dimensions of the prepared samples were of 150 mm × 150 mm × 50 mm for the compressive strength test and 150 mm × 300 mm × 50 mm for the bending test, respectively.

Figure 5. Determination of compressive strength: (a) sample before the determination and (b) sample during the determination.

3. Results and Discussion

3.1. Sound Absorption

In order to evaluate the panel's acoustic absorption, four types of samples were tested with one of their face sheets perforated, as follows: P0—unperforated, P1—with 10% perforations, P2—with 20% perforations, and P3—with 30% perforations. The acoustic absorption of the core was also assessed (PC). The obtained results represent the mean value of three different measurements due to the core

non-uniformity. The variation of the acoustic absorption coefficient as a function of frequency is shown in Figure 6.

Figure 6. Variation of the sound absorption coefficient as a function of frequency of the tested samples.

From the obtained results (Figure 6), it can be observed that the maximum value of sound absorption ($\alpha_{\max}$) decreases with an increasing perforation percentage for the samples P0–P2, but, for the sample P3, the maximum value increases. Even with three measurements effectuated, the trend of the sample P2 seems to be influenced by the core non-uniformity. The registered curve of the absorption is almost linear for the core (sample PC) at frequencies higher than 916 Hz, which corresponds to the maximum value of sound absorption. The curves of P0 and P1 have their peak values at around 500 Hz, after which the absorption decreases. In the case of P2 and P3, the absorption peaks shifted toward the frequency of 3000 Hz, but still maintained increased values at lower frequencies. Regarding the values of NRC (Table 2), PC shows the highest values, being followed by P1, but all the samples exhibit close values to that of the core.

Table 2. NRC values of the tested samples compared to glass wool (GW) with a thickness of 25 mm and expanded polystyrene (EPS) with a thickness of 25 mm [36].

Sample	P0	P1	P2	P3	PC	GW	EPS
NRC (-)	0.521	0.543	0.512	0.521	0.590	0.57	0.275

Thus, the influence of perforations and perforation ratios is significant. First, with perforations, the maximum value of acoustic absorption decreases. Second, by increasing the percentage of perforations, the absorption peak is shifted toward higher frequencies. Third, there is no significant influence of the perforation's percentage on NRC. However, their positive influence is evident in the case of P0–P1.

In the literature, the available data on natural fiber-based sandwich panels' acoustic performance is scarce, but there are a few studies regarding the determination of acoustic absorption of hybrid composites. Zulkifli et al. [37] evaluated the acoustical properties of a multi-layered panel consisting of treated coconut coir fiber core and coconut fiber-polyester resin composite skin. The obtained results show that the highest values of sound absorption are between 0.70–0.80 for the frequencies of 1000–1800 Hz. Huang et al. [38] prepared a multilayered composite by needle punching and thermal bonding, which consists of polyester fibers and coconut fibers laid alternatively in several layers. The average sound absorption coefficient of the panel was situated between 0.604–0.711. Wang et al. [39] studied the acoustical properties of a multi-layered composite made by hot-pressing from sisal fibers-polyurethane based composite and polyethylene film, laid alternatively in several

layers. It was found that the maximum sound absorption coefficient of the composite can reach 0.71 at the frequency of 3150 Hz.

The performance of the tested samples compared to synthetic materials, which is expanded polystyrene (EPS) and glass wool (GW) [36], is presented in Figure 7. It can be observed that, at almost all frequencies (exception being P0 at 125 Hz, P1 at 125 Hz, PC at 125 Hz, and PC at 250 Hz), the samples have a higher acoustic absorption than EPS. On the other hand, the sandwich samples (P0, P1, P2, and P3) at 250 Hz and 500 Hz showed higher values than GW. Furthermore, the values of PC (the core without face sheets, with a thickness of 30 mm) are close to those of GW, mainly at higher frequencies (exceeding the values of GW at frequencies of 500, 1000, and 2000 Hz), which is an expected result, considering that both materials have a fibrous structure, which facilitates acoustic absorption. Regarding the values of NRC, the measured values of the sandwich samples are positioned between the values of EPS and GW, with the values of PC being higher than the values of both synthetic materials.

Figure 7. Variation of sound absorption according to standardized frequency bands of the tested samples compared to glass wool (GW) with a thickness of 25 mm and expanded polystyrene (EPS) with a thickness of 25 mm.

3.2. Airborne Sound Insulation

The determination of the sound attenuation indices, $R_i(f)$, was made with Equation (2) [31].

$$R_i(f) = L_1 - L_2 + 10 \lg \frac{S}{A} \quad (\text{dB}) \quad (2)$$

where: L_1 —sound pressure level in the source room (dB), L_2 —sound pressure level in the receiving room (dB), S —the panel's surface (m^2), A —the equivalent absorption area (m^2).

The weighted sound reduction index, R_w , was obtained according to the provisions stipulated in Reference [32] by comparing the curve of the sound attenuation indices with the reference curve.

The results of the airborne sound insulation test can be observed in Figure 8. Besides the measured curve, R_i , there are also reference and translated curves presented, respectively. The value of airborne sound insulation follows the “mass law.” The greater the mass of the insulating element, the greater the value of sound insulation. In order to achieve a sample with the highest mass, the perforations of the face sheet were neglected.

Figure 8. Values of measured sound reduction index, reference curve, and translated reference curve as a function of frequency.

The tested panel has a value of weighted sound reduction index, R_w (C ; C_{tr}), of 38 (−2; −8) dB. Díaz et al. [40] studied the airborne sound insulation of a natural sandwiched panel of reed core and MDF (medium density fiberboard) skins. The authors found that the 82-mm thick panel has its weighted sound reduction index of 39 dB.

Most of the available multi-layered structures for airborne sound insulation are based on mineral wool. Such a sandwich structure, composed of a mineral wool core and gypsum board face sheets with a total thickness of 125 mm, has its weighted sound reduction index of 41 dB [41].

3.3. Thermal Conductivity and Thermal Resistance

According to the Romanian Norm C107/2-2005 [42], a material can be considered thermal insulating if its thermal conductivity is lower than 0.065 W/m·K and its thermal resistance is higher than 0.50 m²K/W. Asdrubali et al. [43] suggests that the thermal conductivity value of insulating materials might be considered to be lower than 0.07 W/m·K.

The results of the determination of thermal conductivity and thermal resistance of the sandwich panel are presented in Table 3. It can be observed that the value of thermal resistance fulfills the requirement imposed by the national norm.

Table 3. Results of thermal parameters of the tested sample.

Parameter	Value
Thermal conductivity (W/m·K)	0.07699
Apparent density (g/cm ³)	0.546
Thermal resistance (m ² K/W)	0.6056
Temperature (°C)	20

The value of thermal resistance was calculated using Equation (3).

$$R = \frac{d}{\lambda} \text{ [m}^2 \text{ K/W]} \quad (3)$$

where: d —thickness of the material (m), λ —thermal conductivity of the material (W/m·K).

Huang et al. [38] determined both the acoustical and thermal properties of their studied structure, obtaining a value of thermal conductivity of 0.0279–0.0495 W/m·K. Efe et al. [44] investigated a sandwich structure made of whole sunflower stalks and epoxy resin core and MDF skins through hot-pressing. The value of thermal conductivity of the composite ranges between 0.045–0.060 W/m·K, according to the method of determination. Binici et al. [45] studied a multi-layered panel based on layers of sunflower stem, cotton waste, and textile waste bound with epoxy resin. The resulting composites had low thermal conductivity where the value ranges from 0.2616 to 0.0728 W/m·K.

Synthetic materials, such as EPS and GW, are preferred over natural materials due to their low thermal conductivity. In general, thermal conductivity varies between 0.031–0.038 W/m·K for EPS and between 0.031–0.037 W/m·K for GW, for densities of 15–35 kg/m³ for EPS and 15–75 kg/m³ for GW [46]. Usually, the thermal insulating property of a material is aided by the entrapped air between the fibers or cells since air has a low thermal conductivity. Thus, the density of these materials is also reduced.

In spite of the sandwich composite having relatively high apparent density (546 kg/m³), it still presents low thermal conductivity. This fact might be attributed to the hollow structure of wool fiber. The core of the fibers, which are also called medulla, is a canal filled with air [47]. The fibers are also present in the face sheets, which further could contribute to lowering the thermal conductivity of the sandwich structure. Furthermore, it was demonstrated that the thermal conductivity of wool assemblies decreases as their density increases [48].

3.4. Compressive Strength

The results of the determination of compressive strength are presented in Figure 9 and Table 4. It can be observed from Figure 9 that the sandwich panel has a highly elastic behavior. The variation of displacement as a function of the applied load is almost linear between 1–4 mm. Moreover, after removing the applied load, the sandwich panel regained 80% of its original thickness.

Figure 9. Variation of displacement as a function of the applied compressive load.

Table 4. Compressive strength and other parameters of the tested sample.

Parameter	Value
Relative deflection of 10% (mm)	5
Applied load afferent to the relative deflection of 10% (kN)	1.559
Compressive strength afferent to the relative deflection of 10% (MPa)	0.208

Binici et al. [45] presented their hybrid thermal insulating panel, but the composite had low compressive strength. They reported values of compressive strength that varies between 0.283–0.312 MPa.

The tested panel has higher compressive strength than commercially available EPS and GW. A commercially available 50-mm thick EPS sheet usually has a compressive strength between 0.05–0.10 MPa. Products of stone wool were subjected to the determination of compressive strength by Buska and Mačiulaitis [49]. It was found that their strength varies between 0.0475–0.0574 MPa. Referring to these values, the results obtained in the present study are higher, which might be attributed to the high compressive strength of the face sheets reported elsewhere [27].

3.5. Bending Strength

The results of the determination of bending strength are presented in Figure 10 and Table 5. It can be observed that the bending strength has a value of 0.042 MPa and the maximum deflection is 7.5 mm.

Figure 10. Variation of displacement as a function of the applied bending load.**Table 5.** Bending strength and other parameters of the tested sample.

Parameter	Value
Maximum load (kN)	0.042
Deflection (mm)	7.5
Distance between support edges (mm)	250
Bending strength (MPa)	0.042

Yang et al. [50] prepared a sandwich panel by hot pressing, which consisted of bamboo chips based corrugated particleboard core laminated between two face plates of MDF. After evaluating the multi-layered panel's mechanical properties, it was observed that the bending properties increase with increasing density of the panel.

Binici et al. [45] also presented their results regarding the flexural strength of some samples, with the value varying between 0.06–0.09 MPa. Regarding the synthetic materials, the bending strength of EPS is around 0.075–0.25 MPa [51].

4. Conclusions

In this work, a natural materials-based sandwich panel was prepared and studied. The panel is proposed to be used as a sound absorbing and airborne sound insulating solution. Based on the presented experimental study, the following conclusions can be drawn.

- The sound absorption of the sandwich panel depends on the ratio of skin perforations. The maximum values vary between 0.708–0.903, which are very high values in the category of natural sandwich composites;
- The measured weighted sound reduction index of the panel was of 38 dB;
- Thermal conductivity of the sandwich panel (0.07699 W/m·K) was low;
- Mechanical strength of the panels was comparable to the reported values in the literature (compressive strength of 0.208 MPa and bending strength of 0.042 MPa), considering that only natural materials were used in the manufacturing process of the panels.

It can be concluded that the studied sandwich structure could be optimized regarding its mechanical properties, without compromising its acoustical or thermal performance, which will be the aim of the authors' future works. Other future research works would also assess the panel's resistance to the attack of microorganisms, and its durability in indoor environments with high moisture content. Based on the current results, it is suggested that this panel would be suitable as applied cladding or an independent lightweight partition wall, since the presented sandwich structure has good acoustic characteristics.

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