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Article

Acoustic Properties of Larch Bark Panels

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Abstract: The potential of tree bark, a by-product of the woodworking industry, has been studied for more than seven decades. Bark, as a sustainable raw material, can replace wood or other resources in numerous applications in construction. In this study, the acoustic properties of bark-based panels were analyzed. The roles of the particle size (4–11 mm and 10–30 mm), particle orientation (parallel and perpendicular) and density (350–700 kg/m^3) of samples with 30 mm and 60 mm thicknesses were studied at frequencies ranging from 50 to 6400 Hz. Bark-based boards with fine-grained particles have been shown to be better in terms of sound absorption coefficient values compared with coarse-grained particles. Bark composites mixed with popcorn bonded with UF did not return the expected results, and it is not possible to recommend this solution. The best density of bark boards to obtain the best sound absorption coefficients is about 350 kg/m^3. These lightweight panels achieved better sound-absorbing properties (especially at lower frequencies) at higher thicknesses. The noise reduction coefficient of 0.5 obtained a sample with fine particles with a parallel orientation and a density of around 360 kg/m^3.

Keywords: bark-based panels; acoustic performance; sound absorption coefficient; sustainable materials; construction materials

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1. Introduction

The negative effects of chronic exposure to noise are, nowadays, an important issue [1]. The outdoor noise levels directly influence housing market prices, which can decrease by 0.3 to 3% in areas with noise pollution [2]. The noise level in a building is influenced by a variety of factors such as location [3], city planning [4], building design [5], vegetation [6], façade elements [7], construction features and material selection [8–10]. A proper selection of materials improves the noise control in buildings to a great extent. It facilitates minimizing many costly techniques of noise control in buildings.

The use of natural insulation materials with minimal production processing is an emerging trend in construction. The use of sustainable and recyclable materials is an important aspect to warrant a healthy environment. Many studies scrutinized the environmental and technical benefits of using sustainable materials (natural or recycled) as basic elements to produce commonly used as well as new porous materials (granular or fibrous) [11–18] such as rice husk, cotton stalk, jute fiber, straws of wheat, hemp, flax, coconut fibers, stalks of maize and sheep's wool [19–25]. These lignocellulosic materials, when used appropriately, can provide thermal and acoustic insulation performance comparable with the most used insulation materials, but with excellent environmental properties [26].

The sound absorption coefficient is the measure for the acoustical effectiveness of a material and is defined as the fraction of the energy of incident sound waves absorbed by the material [27]. The sound absorption coefficient can range between 0 (no absorption) and 1 (complete absorption) [28].

The acoustic performance of insulation materials made of lignocellulosic materials was examined in various studies [29–32]. Plenty of natural products were investigated and tested for acoustic applications [33] such as kenaf, coir fiber, reeds, sisal, flax, bamboo fibers and corn husk [34–36]. These materials are becoming increasingly popular because they are nonabrasive, renewable and cheap and have lower health risks during processing [37,38]. These materials are susceptible to absorbing a large amount of moisture [39]. In addition, they are affected by heat, have low anti-fungal/bacteria activity and are prone to decomposition [40]. Chemical treatment of the surface of materials made from natural products can reduce these disadvantages [41].

Bark can contribute to the modern construction philosophy: to use materials with a low environmental impact and a high proportion of recycled materials while maintaining the parameters of a healthy building [42,43]. Besides showing advantageous properties such as a low density, a high resistance against microorganisms and fire, a low thermal conductivity and excellent thermal diffusivity [44,45], bark also presents a high heat storage capacity [46–48]. Bark also acts as an excellent formaldehyde scavenger [49–52]. From an economic point of view, bark as a by-product of timber manufacturing is available at low prices [53–55]. Previous research shows that the best acoustic properties of bark-based boards as thermal insulation panels are achieved at densities of around 350 kg/m^3 [56,57] and reported on the possibilities of bark insulation panel utilization as a means of absorbing formaldehyde emissions in the indoor environment of buildings. The sound absorption coefficient of spruce and larch bark-based boards was the tested parameter when using selected frequencies between 125 and 4000 Hz [8]. The density of spruce bark-based boards ranged from 400 to 500 kg/m^3, and that for larch bark-based boards ranged from 500 to 700 kg/m^3. The analysis of the results showed that such bark panels have comparable values of the sound absorption coefficient to lignocellulosic insulation materials, and it is possible to describe them as a material with the potential to meet the acoustic functions in boundary structures [58,59].

The aim of this work is to compare the frequency-dependent flow of sound absorption coefficients of different types of larch bark-based boards, to study if these values are comparable with other industrial established sound absorption materials and then to determine the potential of bark-based boards as an element used in boundary structures which would also fulfill the acoustic function.

2. Materials and Methods

The larch bark (*Larix decidua* Mill.) was sourced from the Graggaber sawmill in Unternberg, Salzburg, Austria, specialized in larch processing. The bark was dried by means of a vacuum kiln dryer (Brunner–Hildebrand High VAC-S, HV-S1, Hannover, Germany) from 100% to 9% moisture content. The drying temperature was 60 °C at a pressure of 200–250 mbar. The bark was subsequently crushed in a 4-spindle shredder (RS40) at Untha Co. in Kuchl, Austria, and repeatedly screened to obtain different distributions of the particle size: 4–11 mm, 10–30 mm and 10–45 mm. One board was manufactured with a mixture of 10–45 mm larch bark particles and 50 wt-% (based on the dry mass) of pre-expanded industrial corn (Balanceboard, Pfleiderer, Neumarkt, Germany) in order to lower the density.

Urea formaldehyde (UF) type Prefere 10F102 (Metadynea, Krems, Austria) was used as an adhesive. The resination factor (solid content), according to Tables 1 and 2, was calculated based on the dry mass of bark and mixed with the particles in a plough share mixer ENT type WHB-75.

Table 1. Overview of parameters of tested specimens made of bark-based boards.

Panel Nr.	1	2	3	4	5
Image					
Particle size (mm)	4–11	4–11	10–45 (with popcorn)	10–30	4–11
Orientation	parallel	perpendicular	parallel	parallel	parallel
Density (kg/m^3)	688 ± 14	344 ± 7	308 ± 8	477 ± 25	536 ± 11
Resination factor (%)	10	10	20	10	10

Table 2. Overview of parameters of tested specimens made of bark-based boards.

Panel Nr.	6	7	8	9
Image				
Particle size (mm)	10–30	10–30	4–11	10–30
Orientation	perpendicular	parallel	parallel	perpendicular
Density (kg/m^3)	354 ± 8	369 ± 12	362 ± 9	470 ± 6
Resination factor (%)	20	20	10	10

The panels with a size of (320 × 320 × 30) mm were pressed in a Höfer HLOP 280 (Taiskirchen, Austria) hydraulic laboratory press at a plate temperature of 180 °C and a press factor of 20 s/mm (significantly higher than in an industrial application). After pressing, the panels were stored in a climate room (temperature 20 °C/relative humidity (RH) 65%) until a constant mass was achieved. Afterwards, the samples were cut according to EN 326-1 [60].

The dependence of the sound absorption coefficient on the frequency was determined on nine types of bark-based boards. The individual larch bark panels differ from one to another in particle size, density, thickness and resination factor (Tables 1 and 2).

The sound absorption coefficient of the bark-based boards was compared with commercially available insulating materials (Tables 3 and 4). These samples were also stored in a climate room (20 °C/65% relative humidity (RH)) until a constant mass was achieved.

For the acoustic measurements, samples with 30 mm and 100 mm diameters and thicknesses of 30 and 60 mm were used.

Table 3. Overview of parameters of tested commercially available insulating materials.

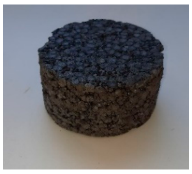
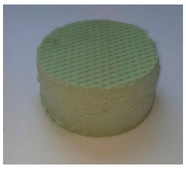
Panel	Graphite Polystyrene [61]	White Polystyrene [62]	Extruded Polystyrene [63]	Fiberboard [64]	Recycled Textile [9]
Image					
Density (kg/m^3)	30 ± 1.9	25.2 ± 0.2	35.1 ± 0.5	59.9 ± 1.2	59.8 ± 1.09

Table 4. Overview of parameters of tested commercially available insulating materials.

Panel	Mineral Wool [65]	Masonite Board [66]	Cereal Straw	Cork [67]
Image				
Density (kg/m^3)	100 ± 15	265 ± 21	250 ± 23	280 ± 1

The measurement of the sound absorption coefficient was performed in accordance with EN ISO 10534-2 [68]. It is a two-microphone method of measuring acoustic absorption which is based on the decomposition of a broadband random signal into a signal from a source and a reflected signal. The complex acoustic transfer function is calculated from the obtained values of the complex acoustic pressure. It is possible to determine the coefficients of sound absorption and reflectivity from it for selected frequencies [9,69].

The measuring device consisted of an impedance (Kundt) tube Brüel & Kjær type 4206, a PULSE 14 system, the only module LAN-XI Brüel & Kjær type 3050 with two active inputs and CPB (constant percentage band—constant percentage width of the frequency band) analysis, sound generator signals from two identical microphones and a computer to display and store the measured data (Figure 1).

The measurement of the sound absorption coefficient was performed in the frequency range of 20 to 1600 Hz using a Kundt tube with a diameter of 100 mm and in the frequency range of 1600 to 6400 Hz using a Kundt tube with a diameter of 30 mm. When measuring the sound absorption coefficient, the test specimens had a corresponding circular cross-section with a thickness of 30 and 60 mm. Four test specimens were created from each type of sample [9]. The noise reduction coefficient (NRC) is used as an evaluation parameter in the frequency range of the spoken word. It is a single number rating which represents the average of sound absorption coefficients of a material at specific mid-range frequencies (tested at 250, 500, 1000 and 2000 Hz octaves) rounded to the nearest 0.05. This value is influenced by the thickness and density of the material. Based on this parameter, the samples were assessed in sound absorption classes, which are weighed by A–E, where absorption class A is the best, calculated according to EN ISO 11654:2017 [70].

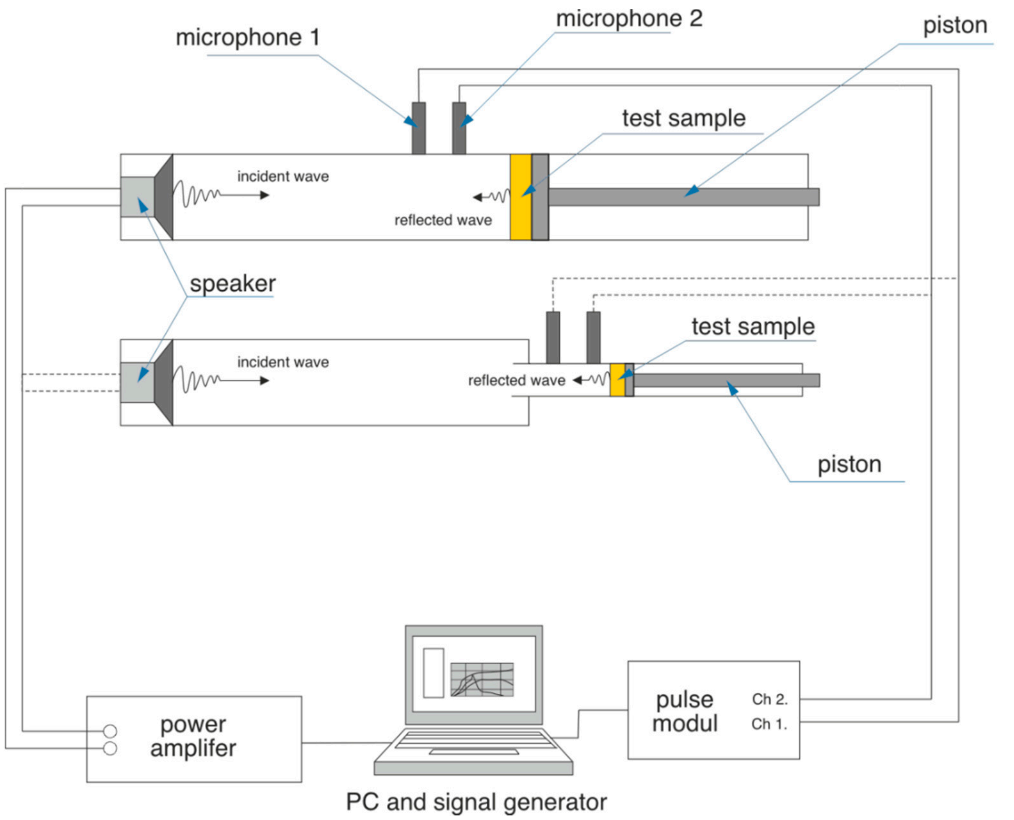


Figure 1. Scheme of the apparatus for measuring the sound absorption coefficient.

3. Results and Discussion

3.1. Sound Absorption Coefficient

All tested specimens were examined by the method of the sound absorption coefficient by the impedance tube method. The measurement results are shown in Figures 2–5. To ensure the clarity, the graphs of the dependence of the sound absorption coefficient on the frequency are combined into two pairs of graphs. The displayed frequency range is from 50 to 6400 Hz. Figures 2 and 3 show the sound absorption coefficient for test specimens with a 30 mm thickness, and Figures 4 and 5 show the sound absorption coefficient for the 60 mm samples. The distribution parameter was the grain size (the first of the pair—the graph for the fraction 4 to 11 mm, and the second of the pair—the graph for the fraction 10 to 30 mm).

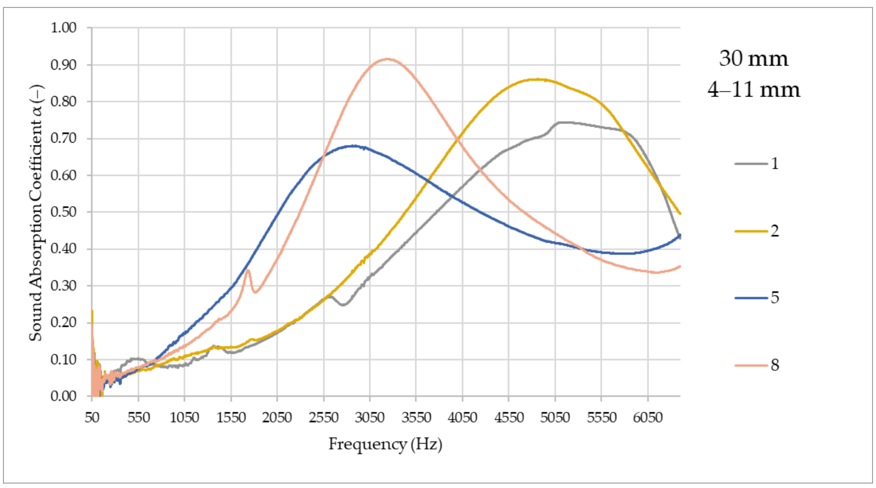


Figure 2. Sound absorption coefficient as a function of frequency of tested specimens of bark panels 1, 2, 5 and 8 with a thickness of 30 mm and a particle size of 4 to 11 mm.

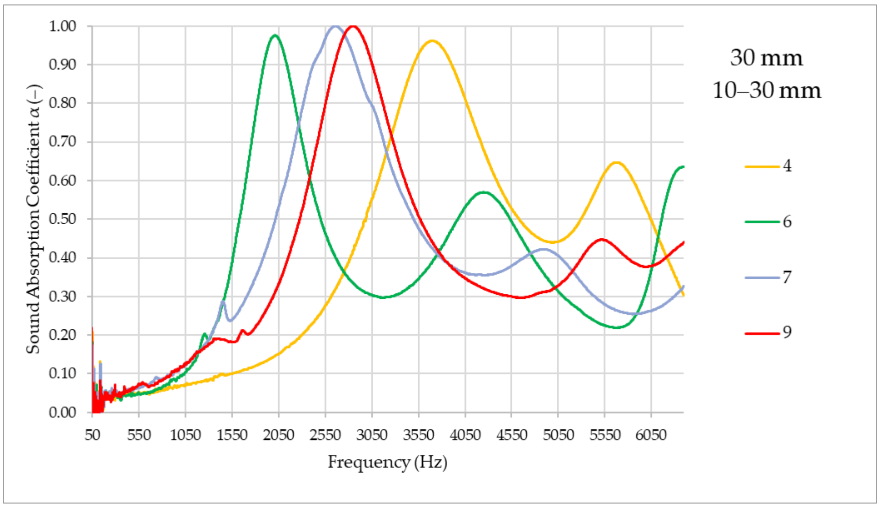


Figure 3. Sound absorption coefficient as a function of frequency of tested specimens of bark panels 1, 2, 5 and 8 with a thickness of 30 mm and a particle size of 4 to 11 mm.

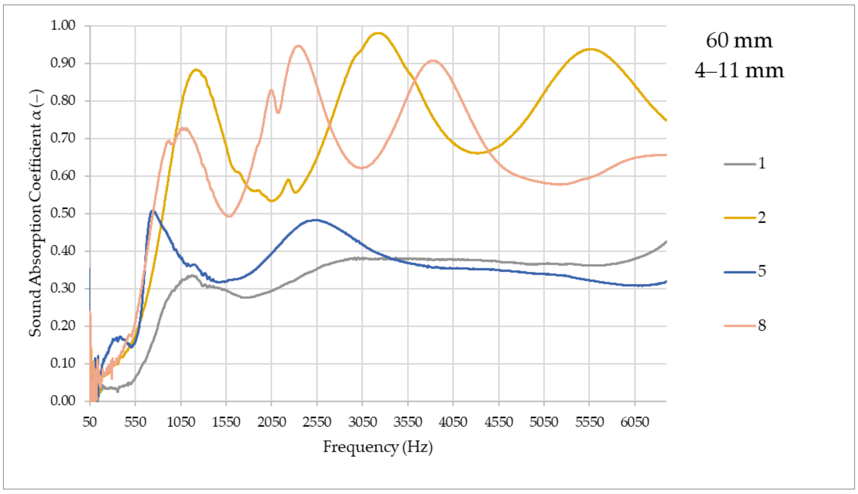


Figure 4. Sound absorption coefficient as a function of frequency of tested specimens of bark panels 4, 6, 7 and 9 with a thickness of 30 mm and a grain fraction of 10 to 30 mm.

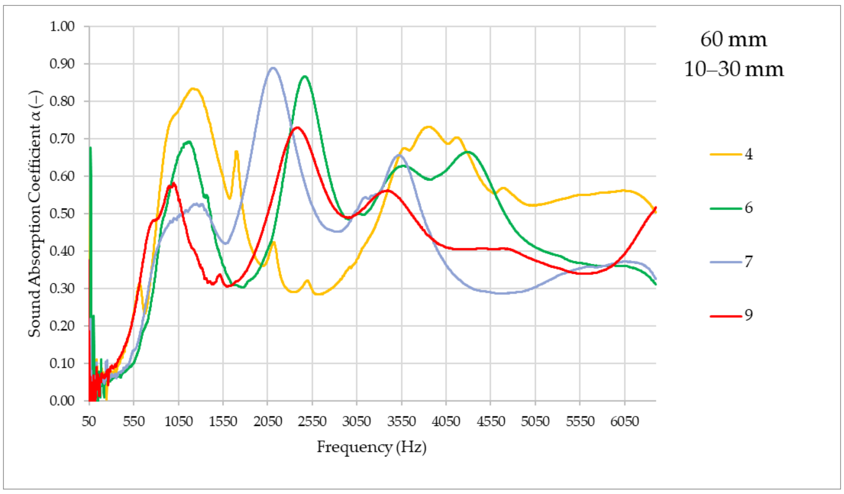


Figure 5. Sound absorption coefficient as a function of frequency of tested specimens of bark panels 4, 6, 7 and 9 with a thickness of 30 mm and a grain fraction of 10 to 30 mm.

The graph for panel type 3 is not depicted in Figures 2 and 3, due to its formulation as a board manufactured with a mixture of larch bark particles and popcorn. This combination proved to be problematic in the determination of the sound absorption coefficient by the transformation function method. The results for type 3 of the bark popcorn board can be described as inconclusive due to the large air gaps between the individual board elements. This did not ensure the condition of repeatability of the measurement. This board would probably also appear unstable in a real structure.

The sound absorption coefficient as a function of the frequency of the selected tested specimens with a thickness of 60 mm is shown in Figures 4 and 5. In comparison with Figures 2 and 3, there is a significantly changed course of the curves. In the case of the 60 mm samples, more peaks are formed, and the first maxima are shifted to shorter wavelengths, which is a very desirable phenomenon for noise reduction in both cases (4–11 mm and 10–30 mm). The graph can even be interpreted in the sense that the absorption capacity increases with the increasing thickness at low frequencies at the same time. This result is consistent with previous studies of porous materials that revealed that low-frequency sound absorption has a direct relationship with the thickness [71–73]. An increase in the thickness also provides a better absorption of the wave [74]. This improvement in properties was best seen on types 2 and 8 of the test specimens. The other test specimens showed better acoustic properties at important lower frequencies as well. Only the tested specimens types 1 and 5 showed a different course. This is due to their solid structure (high density and low porosity), and, with sufficient thickness, they behave as reflective materials. These results are consistent with those of [75] that suggest a denser and less open structure absorbs worse sound of lower frequencies. On the contrary, a lower density is connected to a much higher porosity. As it can be seen from the results, a lower density and a higher porosity allow the sound to enter the matrix more easily, for dissipation, which contributed to greater sound energy absorption, thus a better acoustic absorption property [76]. This theory also explains differences due to the resin content. As it can be seen from Figures 3 and 5, the sound absorption coefficient increases with the increasing resin content. This is in agreement with the fact that, with the increasing resin content, smaller pores are formed, which in turn results in increasing the flow resistivity [77]. The results about the density, porosity, board thickness and reflectivity influence on sound absorption are also confirmed by [8,78,79].

The results show that the sound absorption is better with fine-grained particles (4 to 11 mm) and lower densities (in this case, it showed a critical value of 500 kg/m^3) than with the tested specimens with coarse-grained particles (10 to 30 mm). The increase in the sound absorption is mainly due to the different pore structures. When the sound wave reaches pores containing air molecules, they will vibrate and cause the sound energy to be converted to heat under the action of the air viscosity [80,81]. On the other hand, there is a sufficient energy transfer with an acceptable range of porosity, which means that open pores with continuous channels prevail with better sound absorption due to the multiple reactions between the sound wave and the walls of the pores. That is why test specimens with coarse-grained particles absorbed more sound at lower frequencies. Results showing better absorption with shorter elements were also confirmed in research by [82,83] in the case of bamboo panels, where a higher sound absorption coefficient was obtained with the smaller particle size. The results are also in accordance with the findings of [73]. The authors investigated the dependence of the sound absorption coefficient for redwood classes (chips and sawdust). They found that the sound absorption coefficient increases regularly over the entire frequency range as the particle size decreases (particle sizes were from 1.25 to more than 16 mm).

The effect of the particle orientation on the sound absorption of testing specimens made of coarse-grained particles was also analyzed. This phenomenon was mostly visible in the case of samples 6 and 7 at a thickness of 30 mm, which differed only in the orientation of particles. It was shown that, when the particles were oriented perpendicular to the panel's plane, maxima were reached at frequencies of 2060 Hz (board type 6) and 2560 Hz (board type 7). This result is in agreement with the results of [84] on the influence of the particle orientation on the sound absorption coefficient.

3.2. The Noise Reduction Coefficient

The calculated values of the noise reduction coefficient (NRC) for the tested bark boards are shown in Table 5. The values displayed in Table 5 show that these materials achieved the highest sound absorption class, E, at a thickness of 30 mm, except for type 6 of the test specimen, which reaches class D. When doubling the thickness for types 2, 4, 6, 7, 8 and 9 of the test specimens, the NRC value also reaches class D. The best results were obtained with types 2, 7 and 8 of the bark-based board with a thickness of 60 mm in terms of the absolute value of the NRC parameter (0.4, 0.4 and 0.50, respectively).

Table 5. Noise reduction coefficient (NRC) for the tested bark boards (* sample 3 is scored-out due to inconsistent results).

Sample	NRC for 30 mm	NRC for 60 mm
1	0.10	0.15
2	0.10	0.40
3	*	*
4	0.10	0.35
5	0.20	0.25
6	0.30	0.30
7	0.20	0.40
8	0.15	0.50
9	0.15	0.35

The noise reduction coefficient (NRC) is used as an evaluation parameter in the frequency range of the spoken word. It is calculated as the arithmetic mean of the sound absorption coefficient values for frequencies of 250 Hz, 500 Hz, 1000 Hz and 2000 Hz. The calculated values for bark boards are shown in Table 5.

The bark-based boards were compared with other panels commercially used in boundary structures to express their potential as an element where they perform a thermal insulation and acoustic function. The calculated NRC value shown as a function of the density of the tested material is a parameter to be compared (Figure 6).

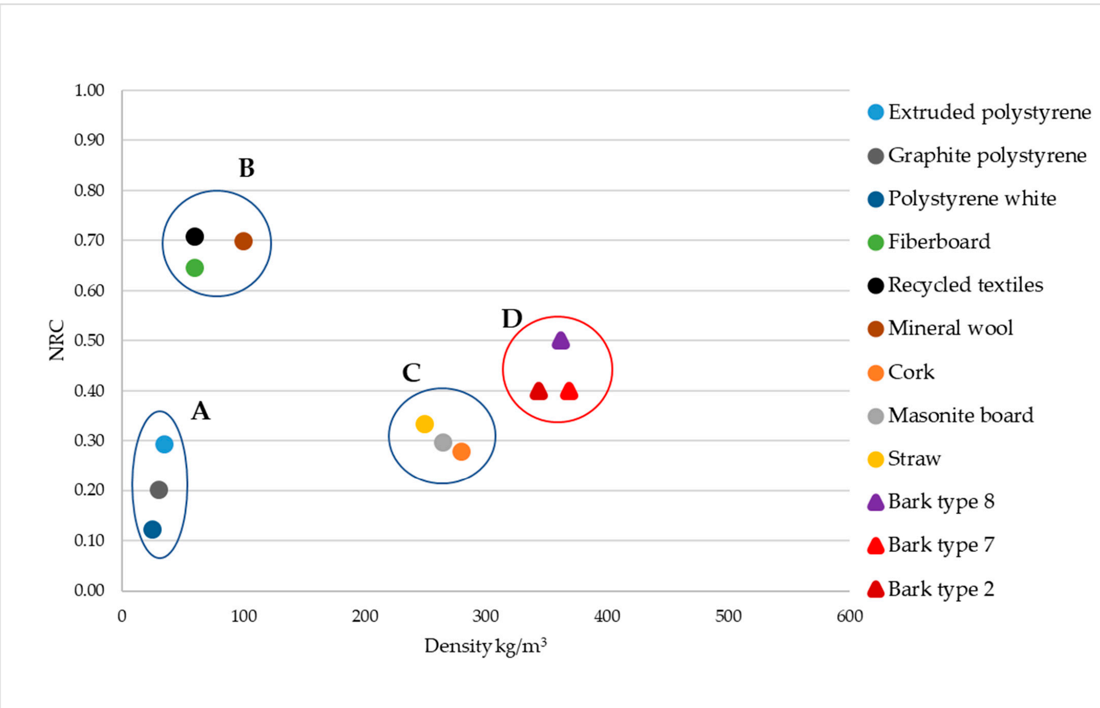


Figure 6. The NRC value of selected materials depending on the density of the tested material (**A**–polystyrene based materials, **B**–typical sound-insulating materials, **C**–cellulose-based insulations, **D**–bark-based boards).

From Figure 6, it can be observed that polystyrene-based materials (extruded, white and graphite polystyrene), which are grouped in area A, have a very low density (25 to 35 kg/m^3), and their NRC values range from 0.1 to 0.3. Area B contains typical sound-insulating materials (very soft fiberboard, recycled textiles, mineral wool) with a density from 60 to 120 kg/m^3, whose NRC values range from 0.65 to 0.75. Area C belongs to natural cellulose-based insulations (cork, slightly harder fiberboard and straw) with a density ranging from 250 to 280 kg/m^3, and their NRC values range from 0.25 to 0.35.

Most conventional insulation materials (such as polystyrene, polyurethane foams, mineral wool) and their processing offer many different options with easy installation and have excellent thermal properties. On the other hand, these materials are derived from petrochemical substances and are environment-impairing [85].

The tested bark-based boards formed a separate group D which contains natural insulations based on raw materials similar to group C. Their density is slightly higher (around 350 kg/m^3), and they have better sound insulation properties (NRC is in the range from 0.40 to 0.50). From group C, lignocellulosic materials straw and cork, together with bark sample types 2, 7 and 8 (group D), have in common good thermal insulation properties, no harmful effects on health and being available in large quantities, often as a waste product of other production cycles. The same problem occurs with low-density fiberboard (group B), which also has a poor mechanical property [86,87]. This is not the case of bark, which naturally has excellent resistance against microorganisms and very good fire-resistant properties [45,88].

The NRC is a commonly used value for classifying materials into absorption classes, although for materials with a fluctuating sound absorption coefficient, for a more accurate comparison, it is necessary to analyze the whole frequency spectrum. Figure 7 shows a more accurate comparison of the sound absorption coefficients of bark-based boards with selected commercially available materials (cereal straw, polystyrene graphite, fiberboard). These materials were selected to include material from each of groups A, B and C (Figure 7). As it can be seen from Figure 7, the NRC proves to be relatively inaccurate for materials that have a very fluctuating sound absorption coefficient. Bark-based board type 8 was selected from group D because it showed the best acoustic properties (sound absorption coefficient of 0.9 at 2250 Hz and 3575 Hz). The compared specimens had a thickness of 60 mm, and the frequency dependence of the sound absorption coefficient is, again, shown in the range from 50 to 6400 Hz.

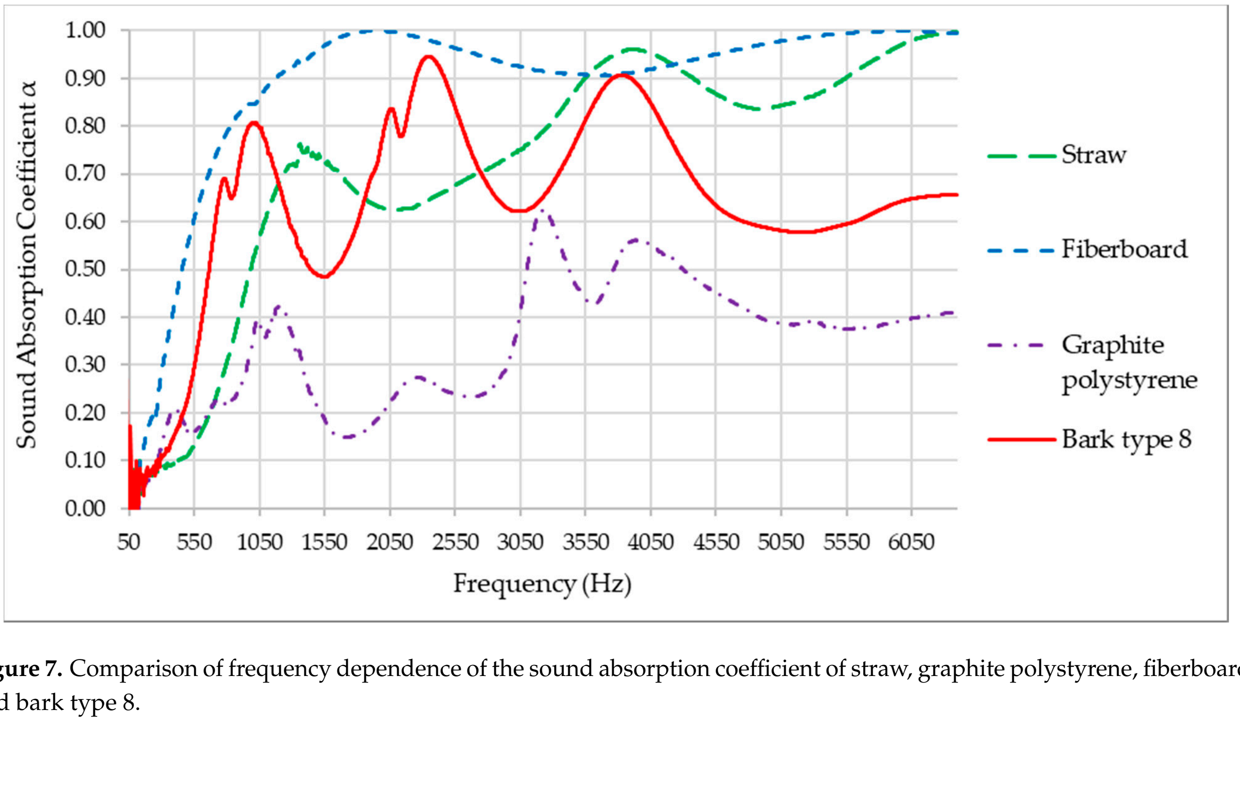


Figure 7. Comparison of frequency dependence of the sound absorption coefficient of straw, graphite polystyrene, fiberboard and bark type 8.

The bark composite type 8 shows a slightly better value of the sound absorption coefficient than straw at frequencies up to 1 kHz. This result is consistent with research by [89–91]. Cereal straw is a better sound absorber at frequencies higher than 3 kHz due to the structure of the composite [92]. Graphite polystyrene shows no significant acoustic property, and it achieves lower values of this parameter comparing to bark board type 8 at all frequencies due to its very low density and closed porosity. The course of the dependence curve is very similar, typically for the materials with a granular structure with closed porosity [93]. Bark achieves a slightly lower value of the sound absorption coefficient in the whole frequency spectrum when comparing the type 8 bark with a low-density fiberboard, where the difference is more visible at frequencies higher than 3575 Hz.

4. Conclusions

The best density of bark-based boards is around 350 kg/m^3 for performing the acoustic functions in a structure. This density coincides with the density of the bark-based boards for the correct performance of thermal insulation functions in boundary structures. The critical upper density limit is 500 kg/m^3. At densities over 500 kg/m^3, due to their solid structure (high density and low porosity), and with a sufficient thickness, bark-based boards behave as reflective materials. Mixing bark with popcorn resinated with UF did not return the expected results, and it is not possible to recommend this solution.

Bark-based boards with fine-grained particles have been shown to be better in terms of sound absorption coefficient values compared with coarse-grained particles.

The key finding is that the bark-based panels can be better evaluated in terms of the parameter of the sound absorption coefficient compared to cereal straw, fiberboard with a slightly higher density and cork, despite their higher density.

The results show that the sound absorption is better for fine-grained particles (4 to 11 mm) and lower densities than for the tested samples with coarse-grained particles (10 to 30 mm). A board manufactured with a mixture of larch bark particles and popcorn is problematic in the determination of the sound absorption coefficient by the transformation function method due to the large air gaps between the individual board elements.

In the case of the 60 mm samples, more peaks were formed, and the first maxima were shifted to shorter wavelengths than in the case of the 30 mm samples. The most significant improvement in sound absorption occurred in the case of boards 2 and 8. From the NRC's point of view, the same boards with board number 7 are the best. These reached sound absorption class D at a thickness of 60 mm.

The sound absorption coefficient for the best samples, 2 and 8, ranged from 0.5 to 1 at frequencies higher than 750 Hz and at a thickness of 60 mm. Sample 2 obtained an NRC value of 0.4, and sample 8 even obtained an NRC value of 0.5. An NRC value of 0.4 was achieved by sample 7. It can be seen from this sample that the NRC value does not describe the completely correct properties of materials with a fluctuating course sound absorption coefficient.

Bark boards achieve relatively good absorption properties compared to polystyrene-based materials and similar properties to straw. However, they are much worse sound absorbers than fiberboards or textile materials.

The potential of bark-based composites in applications such as insulation layers with increased requirements for the mechanical stability of roofs, floors or façades should be further studied. New applications could encompass boundary structures where it is necessary to maintain the defined basis weight of the structure and, at the same time, to maintain airborne soundproofing.

Bark-based panels can contribute to the modern building philosophy: to use materials with a low density, low thermal conductivity, excellent thermal diffusivity, high heat storage capacity and high natural resistance against microorganisms and fire.

It is necessary to consider bark boards with a thickness higher than 50 mm as a material with the potential to perform an acoustic function in boundary structures. At thicknesses of less than 50 mm, the individual layers of the bark elements are not overlapped, and such a panel has large air gaps and therefore cannot act as an effective sound absorber.

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