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INEXPENSIVE AND ENVIRONMENTALLY FRIENDLY MANUFACTURING METHOD OF A HEAT INSULATION WOOD FOAM-BASED BUILDING MATERIAL

BY

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Abstract. A new building material was designed and investigated to determine its physical-thermal and mechanical performances. Unlike most construction materials, the one chosen by the authors was oak wood recycled following typical processing processes. A suitable surfactant (sodium dodecyl sulfate) and distilled water added to the wood waste-based mix facilitated the formation of a wet slurry. It was expanded by stirring and dried at 80°C. In physical-thermal terms, the properties of the new material were excellent. The compressive strength did not reach high values, but they were considered acceptable, having into account the destination of this material type. The results were almost similar to those presented in the literature characterizing other foam types.

Keywords: oak wood, surfactant, wood foam, insulation properties, low density.

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1. Introduction

The global hydrocarbon crisis emerged and became more intense in the 1970s, leading to the development of strategic plans for the conservation of energy sources in the world (Aperjis, 1982). On the other hand, the effectiveness of building thermal insulation materials became a concern of specialists in this field, highlighted at the beginning of the new millennium.

Typically, the main materials currently used for thermal insulation of buildings are plastics such as: polyurethane foam, expanded polystyrene, or glass wool. Despite their energy efficiency, these materials have an important disadvantage regarding the possible damage to human health due to the inhalation of very fine fibres existing in their composition. Another disadvantage affecting the environment quality is the difficulty of recycling this material type at the end of its normal life (Ferreira *et al.*, 2023).

Replacing some plastics with environmentally friendly materials, without compromising the quality of polymer-based thermal insulators, by adding biomaterials or raw materials of natural origin, are suitable options (Ferreira *et al.*, 2023). Thus, polyurethane sintered with biomaterial-based polyols (Mukhopadhyaya *et al.*, 2014) as well as polyurethane foams with lignin derived from polyols (Peyrton and Avérous, 2021) have been prepared having similar features compared to conventional polyurethane.

By introducing a gas phase into liquid polymers or molten plastics during the synthesis process, the conditions for the production of polymer foams are met. Cellulose fibre foams can also be made by the aqueous foam drying method (Alimadadi and Uesaka, 2016). Blowing air under low pressure into the aqueous dispersion fibres with the surfactant contribution leads to the production of wet foams, which are then dried in an oven (Ferreira *et al.*, 2021; Hjelt *et al.*, 2022).

Qualitatively, the manufacture of a thermal insulation material involves the suitable distribution of its structure to prevent the heat circulation. Practically, insulators can be produced from various types of cellulosic substances, that contain micro-fibrillated cellulose (Zheng *et al.*, 2019), cellulose nanocrystals (Seantier *et al.*, 2016), cellulose nano-fibres (Jimenez-Saelices *et al.*, 2017), bacterial cellulose (Fleury *et al.*, 2020), and regenerated cellulose (Feng *et al.*, 2015). Cellulose-based materials prepared by supercritical drying, spray drying, or lyophilization provide the conditions for obtaining extremely low thermal conductivities with values between 0.013-0.075 $W \cdot m^{-1} \cdot K^{-1}$, similar to those of polyurethane foams and silica aerogels (Pierre and Pajonk, 2002).

The wood foam was produced using a residual pine wood, originally from North America (Ferreira *et al.*, 2023). Polyvinyl alcohol was introduced into the mix as a binder. Also, sodium dodecyl sulfate and sodium bicarbonate were added as surfactants as well as deionized water. By drying at 70°C in an oven, pine wood foam was obtained with very low density (between 0.12-0.14 $g \cdot cm^{-3}$) and thermal conductivity around 0.042 $W \cdot m^{-1} \cdot K^{-1}$.

Thermal insulation materials made from wood fibre are known, being already applied in the construction sector, but their dimensional stability is quite low. Also, the insulation effect of this type of material is inferior to the level achieved with traditional materials of petrochemical origin (Insulation materials, 2000).

Intensive research activity to perfect wood foam as an excellent thermal insulation material is reported in the German Fraunhofer Institute (Foam wood Fraunhofer, 2023). Finely mechanically processed beech wood was expanded using adequate surfactants to the stage of a wet suspension. Further, the suspension was dried and hardened in an insulated, humidity-free room. The wood foam had density values within the limits of 0.04-0.28 $g \cdot cm^{-3}$, being manufactured in the form of boards or elastic foam.

Wood-furanic foam, a bio-based insulation material, obtained by combining fine wood powders with furanic polymers was prepared through chemical foaming using diethyl ether as an expanding agent (Srivastava and Pizzi, 2014; Pizzi and Khan, 2021). Low values of density (between 0.03-0.08 $g \cdot cm^{-3}$) and heat conductivity (between 0.034-0.048 $W \cdot m^{-1} \cdot K^{-1}$) were obtained, due to the porous closed-cell structure of the wood-furanic foam.

Authors' team of this paper had previously been concerned with the production of oak wood foam by the technique of removing lignin from the wood composition (Paunescu *et al.*, 2023). The adopted technique was of a chemical nature, the wood being treated with an aqueous solution containing NaOH, $Ca(OH)_2$ and distilled water. The excellent thermal insulation properties of the foam (density of 0.024 $g \cdot cm^{-3}$ and thermal conductivity of 0.031 $W \cdot m^{-1} \cdot K^{-1}$) constituted the technical performance of this product, despite the acceptable low level of compressive strength (0.9 MPa).

The work developed further represents a contribution of the Romanian authors to the manufacture of wood foam with very good heat-insulating properties. The method designed and researched by the Fraunhofer Institute, which is undoubtedly qualitatively superior to the lignin removal technique, was also adopted by the authors' team of the current paper, the tests being focused on a type of wood (oak) unused until now.

2. Methods and Materials

The wood type adopted for the experiment presented in the paper (i.e. oak wood) was recycled as sawdust from a Romanian wood-working workshop. The wood waste thus recovered was ground under pre-wetting conditions using a small laboratory knife grinding equipment. The grain size of the wood waste was achieved and selected within the limits of 100-500 μm. The surfactant chosen to reduce the surface tension of the wet slurry was sodium dodecyl sulfate (SDS) with a high purity of over 99 %. It was added to the ground wet waste in the form of a slurry.

Expanding the slurry was carried out in an electric homogenizing device through stirring at 750 rpm for a maximum of 10 min, until the volumetric increase of the foam was no longer noticeable. After the foaming process was completed, the wet froth was loaded into a parallelepiped-shaped stainless steel mould and placed in a laboratory electric oven for drying and hardening at 80°C for 10 hours.

As mentioned above, the materials experimentally utilized were: oak wood waste as a biomaterial, sodium dodecyl sulfate as a surfactant, and distilled water to facilitate obtaining the wet slurry.

The latest techniques applied in the world for making high-performance wood foam did not include oak wood. As stated in this paper, oak wood was tested by the work's authors using the lignin removal method (commonly applied in the pulp and paper industry) obtaining a wood foam with poorer thermal insulation properties. In this study, oak wood waste was tested for the first time by the more effective chemical foaming method, currently researched. The wood, recycled in the form of sawdust, was ground to sizes less than 500 µm.

Experimentally, it was observed that it is very important to reduce the solvent surface tension for the production of wood foam. This result is possible by using surfactants. These chemical compounds create the conditions for obtaining the froth and enter into the composition of its membranes, giving them the appropriate characteristics of superficial elasticity and viscosity (Moldovan, 1978). The surfactant type adopted by the authors was sodium dodecyl sulfate $C_{12}H_{25}NaO_4S$ with very advanced purity (over 99%). Commercially available, both in crystalline and powder state (Sodium dodecyl sulfate, 2018), its second state was chosen for this experiment.

The wet slurry production was carried out by adopting four experimental variants presented in Table 1. The surfactant amount was varied between the four variants of the mix, its values increasing in the range of 15-30 mg, while the wet slurry kept its weight value of 200 g unmodified.

Table 1

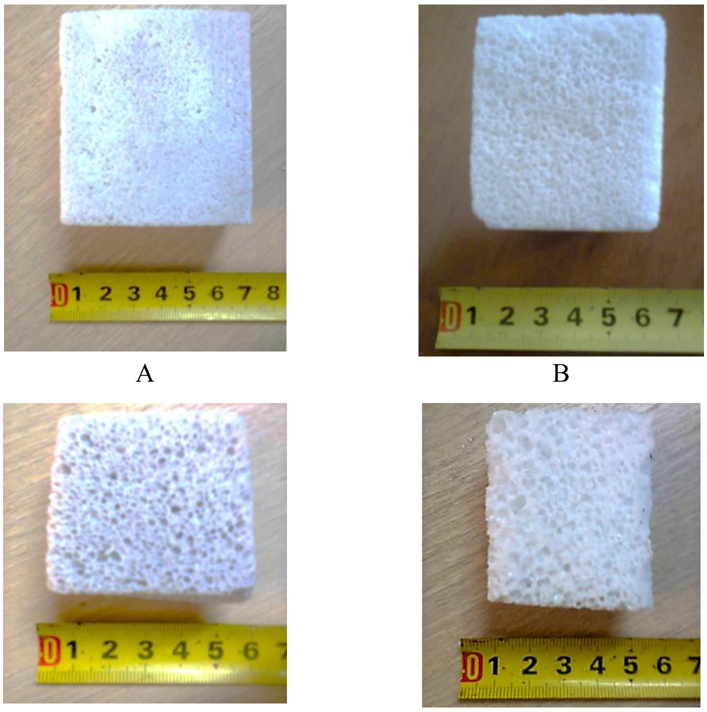
Wet slurry composition

Composition	Sample A	Sample B	Sample C	Sample D
Oak wood waste (g)	37	37	37	37
SDS surfactant (mg)	15	20	25	30
Distilled water (g)	163	163	163	163
Wet slurry amount (g)	200	200	200	200

Methods for investigating the sample features are showed further. Archimedes' principle was used to measure the apparent density of wood foam samples. Using ASTM C642-97 standard, the apparent porosity was determined by dividing the difference between wet and dry weight by the difference between wet weight and suspended weight of the sample. Heat conductivity was determined at room temperature using the HFM448 Lambda heat-flow meter (SR EN 1946-3:2004). Measuring the compressive strength was performed using a universal testing machine. The samples were compressed at 1.4 mm·min^{-1} (ASTM D695) and the compressive resistance was determined at 10% compression (ASTM D1621-16). The microstructural appearance of foams could be investigated with the Biological Microscope MT5000 model, 1000 x magnification. Water uptake was determined by maintaining wood foam samples in humidity chamber at 85% humidity for 30 days, according to ASTM C272/C272M-18.

3. Results and Discussion

After drying and hardening the wet slurry at 80°C for 10 hours, characteristics of wood foam samples, exhibited in Fig. 1, were investigated using the methods noted above. Results of these investigations regarding to physical, thermal, mechanical, water-absorbing features, and microstructural peculiarities are exposed further in Table 2.



A B C D

Fig. 1 – Surface aspect of wood foam specimens
A – variant 1; B – variant 2; C – variant 3; D – variant 4.

Table 2
Features and peculiarities of wood foam samples

Feature	Sample 1	Sample 2	Sample 3	Sample 4
Apparent density ($g \cdot cm^{-3}$)	0.12	0.09	0.06	0.04
Apparent porosity (%)	88.6	89.8	90.7	91.5
Heat conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.053	0.043	0.039	0.035
Compressive strength (kPa)	875	813	750	734
Water uptake (wt. %)	5.8	5.0	4.9	4.5
Pore size (mm)	0.4-0.9	0.6-1.1	0.8-1.2	1.3-1.7

The results shown in Table 2 prove remarkable thermal insulation properties of foamed wood materials, particularly those that benefited from the highest amount of surfactant (variant D). Thus, the apparent density dropped to 0.04 $g \cdot cm^{-3}$ and the thermal conductivity decreased to 0.035 $W \cdot m^{-1} \cdot K^{-1}$. The compressive strength, directly influenced by the highly porous structure of the material, also decreased to 734 kPa, but this value is acceptable for applications in building thermal insulation. The moisture absorption level measured by keeping the wood foam specimens in a chamber with constant high humidity (85%) for 30 days was within the normal limits for this type of porous material (4.5-5.8 wt. %).

The microstructural appearance of wood foam samples is shown in Fig. 2.

A variation in the microstructural appearance influenced by the increasing addition of surfactant can be observed. Examining the pictures in Fig. 2, the pore dimension could be determined. The largest pore sizes (1.3-1.7 mm) were identified in the case of the sample corresponding to experimental variant 4, characterized by the use of 30 mg SDS surfactant (i.e. the highest amount of this). The exceptional results obtained by German researchers at the Fraunhofer Institute for Wood Research (Foam wood Fraunhofer, 2023) on the thermal insulation peculiarities of beech foams (density below 0.04 $g \cdot cm^{-3}$ and thermal conductivity less than 0.04 $W \cdot m^{-1} \cdot K^{-1}$), at a value level comparable to that of polystyrene and wood fibre insulation panels, were approximately reproduced in the experiment presented here, using wood waste, water, and a surfactant appreciated in the manufacture of cellular concrete (Moldovan, 1978) to form the required wet slurry.

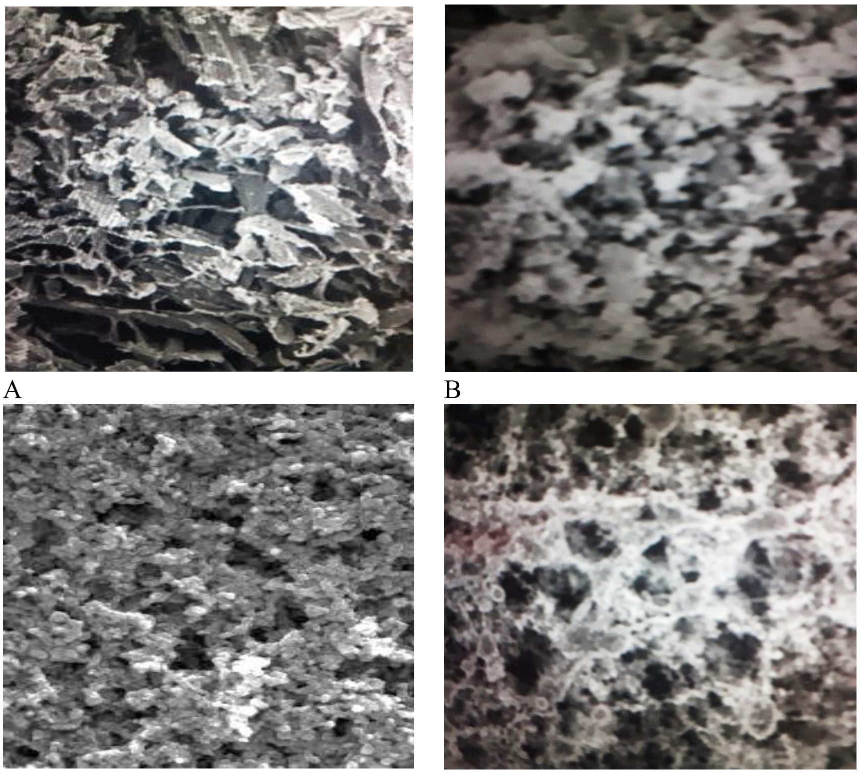


Fig. 2 – Microstructural appearance of wood foam specimens
A – variant 1; B – variant 2; C – variant 3; D – variant 4.

The optimal variant of the current experiment was determined to be version 4, in which the oak wood waste had the amount of 37 g, the surfactant represented 30 mg, the water amount was 163 g, and the amount of wet slurry was 200 g. The wood foam corresponding to the optimal version had the following characteristics: apparent density of 0.04 $g \cdot cm^{-3}$, heat conductivity of 0.035 $W \cdot m^{-1} \cdot K^{-1}$, water absorption of 4.5 wt. %, and compressive strength of 734 kPa.

4. Conclusions

The work aimed to create an alternative thermal insulation material adequate for buildings, based on the high-performance foaming technique of wood waste. The new material type is designed to replace current plastic-based thermal insulation materials. Currently, researchers involved in the field of construction materials are testing various manufacturing procedures as well as different types of wood waste, the results being considered promising, although the option for industrial-scale manufacturing has not yet been finalized. The current paper aimed at testing an oak wood waste, untested in previous experiments, to achieve a wood foam with physical-mechanical, thermal, and morphological characteristics adequate for applications as a thermal insulation material in construction. The results indicated remarkable values of apparent density (0.04-0.12 $g \cdot cm^{-3}$), heat conductivity (0.035-0.053 $W \cdot m^{-1} \cdot K^{-1}$), water absorption (4.5-5.8 wt. %) as well as a low, but satisfactory, level of compressive strength (734-875 kPa). The material obtained by the optimal variant having a density of 0.04 $g \cdot cm^{-3}$, heat conductivity of 0.035 $W \cdot m^{-1} \cdot K^{-1}$, water absorption of 4.5 wt. %, and compressive strength of 734 kPa demonstrated the possibility of reaching the value level of the type of material produced so far in the experiments shown in the literature. Taking into account the current trend of replacing plastics commonly used in construction as well as the continuation of research for this purpose carried out in the world, the authors' team of the current paper intends to further develop the own research in the future.

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METODĂ DE FABRICAȚIE NECOSTISITOARE ȘI ECOLOGICĂ A UNUI MATERIAL DE CONSTRUCȚIE PE BAZĂ DE SPUMĂ DE LEMN PENTRU IZOLAȚIE TERMICĂ

(Rezumat)

Un nou material de construcție a fost proiectat și investigat pentru a determina performanțele sale fizico-termice şi mecanice. Spre deosebire de majoritatea materialelor de construcție, cel ales de autori a fost lemnul de stejar reciclat, urmând procese tipice de prelucrare. Un surfactant adecvat (dodecilsulfat de sodiu) şi apă distilată adăugate la amestecul pe bază de deșeuri lemnoase au facilitat formarea unei suspensii umede. Aceasta a fost expandată prin agitare şi uscată la 80ºC. Din punct de vedere fizico-termic, proprietățile noului material au fost excelente. Rezistența la compresiune nu a atins valori ridicate, dar acestea au fost considerate acceptabile, ținând seama de destinația acestui tip de material. Rezultatele au fost aproape similare cu cele prezentate în literatura de specialitate, care caracterizează alte tipuri de spumă.