BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 70 (74), Numărul 3, 2024
Secţia
CHIMIE şi INGINERIE CHIMICĂ
DOI: 10.5281/zenodo.13837887

ADVANCED WOOD FOAM PRODUCTION TECHNIQUE AS AN ALTERNATIVE HEAT-INSULATING MATERIAL FOR BUILDING CONSTRUCTION

BY

LUCIAN PĂUNESCU[1,*] and ENIKÖ VOLCEANOV[2,3]

[1]Daily Sourcing & Research SRL Bucharest, Romania
[2]National University of Science and Technology “Politehnica” Bucharest,
Faculty of Engineering in Foreign Language Bucharest, Romania
[2]Metallurgical Research Institute SA Bucharest, Romania

Received: April 24, 2024
Accepted for publication: July 5, 2024

Abstract. The paper has tested an alternative heat-insulating material for building construction based on wood foaming. The wood waste chosen for this test was oak wood not used in other previous experiments presented in the literature. The purpose of the work is to replace the plastics currently used for the production of heat-insulating materials. Using ground wood waste, a suitable surfactant (sodium dodecyl sulfate), and distilled water, wet suspension was prepared, foamed by stirring and then dried at 80°C. Thus, it was obtained an optimal specimen with excellent heat-insulating properties (apparent density of 0.014 $g·cm^{-3}$, heat conductivity of 0.035 $W·m^{-1}·K^{-1}$). The compressive strength had a rather low value of 715 kPa, but satisfactory for the intended purpose. By comparison with other experimentally prepared wood foams, the oak wood foam properties fell within the performance required by the use of the new material as a thermal insulator in construction, being able to replace similar polymer-based materials.

Keywords: wood foam, oak wood, surfactant, heat-insulating property, heat conductivity.

[*]Corresponding author; *e-mail*: lucianpaunescu16@gmail.com

1. Introduction

Under conditions that in the last decades of the 20th century, the global hydrocarbon crisis broke out (Aperjis, 1982) with severe implications on the requirement for energy economy in all aspects of life, energy conservation by improving the effectiveness of building thermal insulation has become one of the specific concerns of researchers. The concern at the global level for the efficient management of energy consumption remained valid even in the current period of beginning the new millennium.

Currently, the main materials used in construction for the building thermal insulation are plastics: polyurethane foam, expanded polystyrene and glass wool. Problems related to the effect of the possible inhalation of fine fibers on human health as well as the difficulties of recycling these materials after decommissioning the building, are disadvantages of using these insulating materials (Ferreira *et al.*, 2023).

The substitution of plastics with more environmentally friendly versions without affecting the valuable characteristics of this material type is possible by adding some bio-materials and natural feedstocks into the composition of products available on the market (Ferreira *et al.*, 2023). Thus, polyurethane foams with polyols derived from lignin (Peyrton and Avérous, 2021) and sintered polyurethane with polyols based on bio-materials (Mukhopadhyaya *et al.*, 2014) were made with similar features compared to the known traditional polyurethane.

The incorporation of a gaseous phase in polymeric liquids during the synthesis process (as in the case of polyurethane foam) or in melted plastics (as in the case of polystyrene or polyolefin) is the method of producing polymeric foams. The drying technique of aqueous foam is for the production of cellulose fiber foams (Alimadadi and Uesaka, 2016). The incorporation of air into aqueous dispersion fibers with the addition of surfactant allows the production of wet foams, further drying in the oven (Ferreira *et al*., 2021; Hjelt *et al*., 2022).

Making an appropriate quality thermal insulator requires adequate arrangement of the material structure to avoid the heat transfer. Thermal insulation materials can be made from various types of cellulosic masses including microfibrillated cellulose (Zheng *et al*., 2019), cellulose nanocrystals (Seantier *et al*., 2016), cellulose nanofibers (Jimenez-Saelices *et al.*, 2017), cellulose bacterial (Fleury *et al*., 2020), and regenerated cellulose (Feng *et al*., 2015). Cellulose-based products manufactured by lyophilization (in which water in the form of low-pressure ice is removed by sublimation), supercritical drying or spray drying, allow obtaining very low thermal conductivity values (within the limits of 0.013-0.075 $W \cdot m^{-1} \cdot K^{-1}$), in general, similar to those of polyurethane foams and silica aerogels (Pierre and Pajonk, 2002).

Recently, (Ferreira *et al*., 2023) designed and tested making froth from residual pine wood, available as a forestry waste in North America. The froths were made from stable aqueous foam precursors, containing polyvinyl alcohol as a binder. Sodium dodecyl sulfate, sodium bicarbonate, and deionized water were also used. By drying in the oven at 70°C into rectangular moulds, products with low values of density (0.12-0.14 $g \cdot cm^{-3}$) and thermal conductivity (0.042 $W \cdot m^{-1} \cdot K^{-1}$) were obtained as well as satisfactory mechanical features, as alternative materials to those based on plastic applied as insulation materials in building construction.

According to (Foam wood, 2023), researchers from the German Fraunhofer Institute consider that wood foams are suitable as heat-insulating material for building construction. Some heat-insulating materials are already made of wood (e.g. wood fiber), but the main disadvantage is the low dimensional stability than that of polymer-based materials. On the other hand, the degree of insulation obtained with wood fiber panels is lower (thermal conductivity between 0.038-0.043 $W \cdot m^{-1} \cdot K^{-1}$) compared to the level reached by petrochemical materials (Insulation materials, 2000). In present, specialists from the Fraunhofer Institute are conducting research for the manufacture of wood foam as a high-performance material with heat-insulating properties. According to (Foam wood, 2023), the adopted method consists in fine grinding of wood in the presence of a high content of deionized water until the suspension is formed. This can be chemically or physically expanded with gas bubble-suppliers coming from suitable surfactants introduced into the mixture or from external blowing a gas. The expanded suspension is then hardened into an insulated room free of moisture. The froth strength is the result of the own binding forces of the wooden material, no synthetic adhesives being required. The tests performed on a beech wood led to obtaining a lightweight product (density between 0.04-0.28 $g \cdot cm^{-3}$), with a porous structure (with most open cells). According to the adopted technology, the material can be processed in the form of boards or elastic foam. The designed technology is still being optimized.

A fine wood powder allowed the manufacture of wood-furanic foam with the dominant proportion of the wooden component (Srivastava and Pizzi Pizzi, 2014). The main characteristics of the foamed composites were the low density and thermal conductivity values. The method of preparing wood foam composites was that of chemical foaming and the used expanding agent was diethyl ether. This contributed to the formation of porous structure with closed cells, but with variable sizes and relatively irregular shapes.

The authors' team of the current paper tested a method of obtaining a porous structure of wood waste (oak wood in the form of sawdust) by removing the lignin from the wood composition (Paunescu *et al.*, 2023). The method adopted, inspired by the technique of manufacturing cellulose and paper by removing lignin for other technological purposes, was based on the chemical treatment of wood using the aqueous solution composed of NaOH, $Ca(OH)_2$ and distilled water. The result was obtaining very low values of density (0.024 $g \cdot cm^{-3}$) and thermal conductivity (0.031 $W \cdot m^{-1} \cdot K^{-1}$), compressive strength having a satisfactory value (0.9 MPa) for applications in thermal insulation of the building construction.

The paper exposed further is an authors' contribution to developing the new wood foam preparing technique in order to obtain a material with exceptional thermal insulating properties, suitable for use as an insulating material in construction, a valuable alternative to the existing plastic-based materials.

2. Methods and Materials

The wooden material subjected to tests was oak wood in the form of sawdust recycled from a wood-working workshop. The waste was ground in pre-wetting conditions in a small laboratory knife-grinding device. Over the finely ground wood (grain size between 150-800 µm selected after the sieving process) an adequate surfactant was added in very small ratios to reduce the surface tension of the wood/water suspension and facilitate foam formation. The surfactant chosen was sodium dodecyl sulfate SDS (purity over 98.5%). The wood together with the surfactant were subjected to homogenization by mechanical agitation. The suspension had a content of about 19 wt. % solids, the rest being distilled water. The suspension expanding was carried out in an electrically operated homogenizing device by stirring at 7000 rpm for no more than 10 min, until it was found that the froth volume remained constant. After completing the foaming, the wet froth was loaded into stainless steel rectangular moulds. These were subjected to drying in a laboratory electric oven at 80℃ for 10 hours, still keeping a theoretical moisture content of at least 5 wt. %.

The materials used in this experiment were oak wood waste as the wooden material, sodium dodecyl sulfate as a surfactant, and distilled water for the suspension formation.

According to the data in literature, the oak wood waste has not been tried before in the wood foaming process. It was recycled in form of sawdust and after grinding had grain size under 800 µm.

Foams are dispersed gas-liquid systems. They can never be obtained from pure liquids and substances from the solution enter into their composition, as is the case of surfactants called also foaming agents. By reducing the surface tension of the solvent, surfactants facilitate the foam formation and enter into the composition of its membranes, structuring them by giving properties of viscosity and surface elasticity (Moldovan, 1978). Sodium dodecyl sulfate (SDS) with purity over 98.5% was the chosen surfactant in this experiment. Sodium dodecyl sulfate ($C_{12}H_{25}NaO_4S$) is commercially available in crystalline or powder state (Sodium dodecyl sulfate, 2018).

Four experimental versions of material composition were adopted, being shown in Table 1. The surfactant amount varied within the limits of 16-28 mg under the conditions of wet suspension kept constant at 200 g.

Table 1

Wet suspension composition in tested versions

Version	Oak wood waste (g)	Surfactant SDS (mg)	Distilled water (g)	Wet suspension (g)
1	38	16	162	200
2	38	20	162	200
3	38	24	162	200
4	38	28	162	200

The investigation methods utilized in this work are usually used in research activities. Archimedes' principle was used to measure the apparent density of wood foam specimens. 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. Thermal conductivity was measured 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 specimens were compressed at 1.4 $mm \cdot min^{-1}$ (ASTM D695) and the compression strength was determined at 10% compression (ASTM D1621-16). The microstructural appearance of foams could be examined with the Biological Microscope MT5000 model, 1000 x magnification. Water uptake was determined by keeping wood foam samples in humidity room at 85% humidity for 30 days according to ASTM C272/C272M-18.

3. Results and Discussion

After drying the wet froth at 80℃ for 10 hours, wood foam specimens shown in Fig. 1 were analyzed in physical, thermal, mechanical, water uptake, and microstructural terms as mentioned above methods. The results of these determinations for each of the four experimental variants are presented in Table 2.

Table 2

Main characteristics of wood foam specimens

Characteristic	Version 1	Version 2	Version 3	Version 4
Apparent density ($g \cdot cm^{-3}$)	0.022	0.019	0.017	0.014
Apparent porosity (%)	88.5	89.4	90.6	91.2
Heat conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.051	0.046	0.039	0.035
Compression strength (kPa)	875	804	747	715
Water uptake (wt. %)	5.9	5.2	4.8	4.3
Pore size (mm)	0.5-0.9	0.8-1.3	1.1-1.7	1.5-1.9

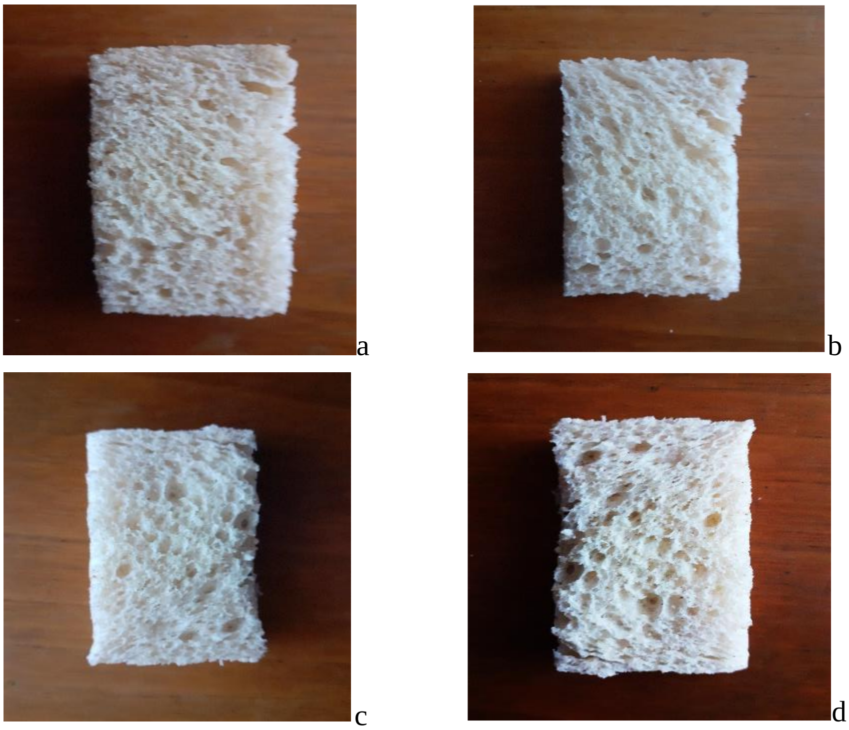

Fig. 1 – Images of wood foam specimens
a – specimen 1; b – specimen 2; c – specimen 3; d – specimen 4.

The data in Table 2 indicate performance values of heat-insulating properties of oak wood foam (apparent density between 0.014-0.022 $g\cdot cm^{-3}$ and heat conductivity in the range of 0.035-0.051 $W\cdot m^{-1}\cdot K^{-1}$). Apparent porosity reached very high values (88.5-91.2%). As expected, the mechanical strength of the wood foam was affected, having quite low values within the limits of 715-875 kPa. Among the four experimentally made samples, the specimen corresponding to variant 4 has obtained the best thermal insulation properties favouring excellent insulation and at the same time the lowest level of expanded material strength. Water uptake of specimens was at a normal level for this type of foamed material (between 4.3-5.9 wt. %).

The microstructural aspect of the wood foam specimens is shown in Fig. 2. According to these pictures, the pore size could be identified. The largest pore sizes were obtained in the case of the sample corresponding to version 4 (1.5-1.9 mm). In addition, the porous structure of the foam is partially open. The same characteristic was also observed in the sample corresponding to variant 3. The pore size range of this sample was 1.1-1.7 mm

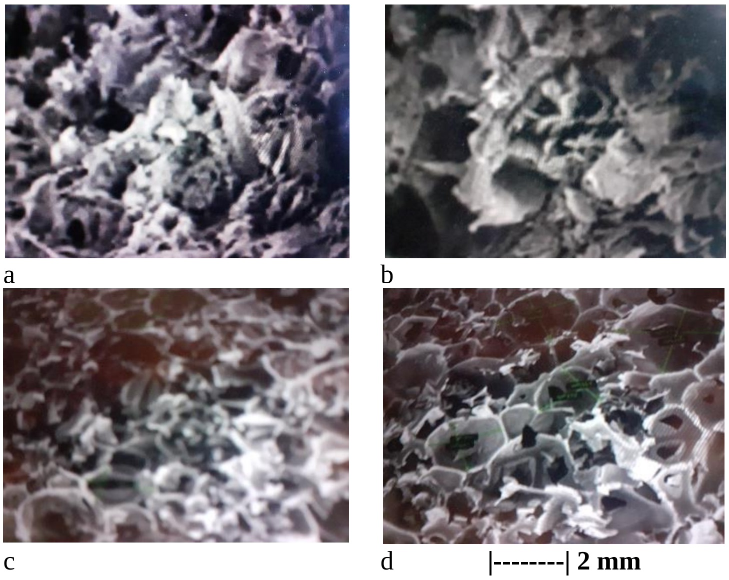

Fig. 2 – Microstructural appearance of wood foam specimens
a – specimen 1; b – specimen 2; c – specimen 3; d – specimen 4.

The excellent partial results obtained by researchers from the Fraunhofer Institute (Foam wood, 2023) regarding the apparent density (up to 0.04 $g·cm^{-3}$) and thermal conductivity (below 0.04 $W·m^{-1}·K^{-1}$) of beech wood foams, comparable in value to those of polystyrene and wood fibre thermal insulation panels, have were almost reproduced in the experiment presented in this work using oak wood waste and a surfactant (sodium dodecyl sulfate) recommended in the case of cellular concrete preparation (Moldovan, 1978), to form the necessary suspension in the presence of distilled water.

It should also be mentioned the performances reported by (Ferreira *et al.*, 2023) regarding the production of a pine wood foam under the conditions of using a residual wood available in North America, sodium dodecyl sulfate, sodium bicarbonate, polyvinyl alcohol, and deionized water, the apparent density being reduced up to 0.12-0.14 $g·cm^{-3}$ and heat conductivity to 0.042 $W·m^{-1}·K^{-1}$.

Different species of poplar wood were also used as feedstock in other experiments mentioned in the literature.

In principle, worldwide research for the manufacture of wood foam as a substitute for heat-insulating materials based on polymers is in full swing. Specialists from the Fraunhofer Institute examine the possibility of also applying other lignocellulosic materials and estimate that in a few years the manufacture of wood foams could reach an industrial-scale.

4. Conclusions

The work objective is the production of an alternative thermal insulation material for building construction using the advanced technique of foaming wood waste. This new material should have the ability to replace the current heat-insulating materials based on plastics applied in construction. Currently, researchers in this field are testing different production techniques and several types of wood waste, the results being promising, but the optimal solution for production on an industrial-scale has not yet been reached. The current work aimed at testing an oak wood waste, un-used in previous experiments presented in the literature in order to obtain wood foam with physical, thermal, mechanical, and microstructural performance characteristics suitable for use as an insulating material in construction. The results showed excellent values of apparent density (0.014-0.022 $g \cdot cm^{-3}$), heat conductivity (0.025-0.051 $W \cdot m^{-1} \cdot K^{-1}$), water uptake (4.3-5.9 wt. %) as well as a low but satisfactory level of compression strength (715-875 kPa). The product obtained through the optimal experimental version having a density of 0.014 $g \cdot cm^{-3}$, thermal conductivity of 0.035 $W \cdot m^{-1} \cdot K^{-1}$, water uptake of 4.3 wt. %, and the compression strength of 715 kPa is at the value level of this material type produced so far in experiments reported in the literature. Considering the current trend of replacing plastic-based materials, as in the case of heat-insulating materials usually applied in construction, as well as the continuation of worldwide research for this purpose, the authors' team of the current work have as future objective developing the own research on this investigation topic.

REFERENCES

Alimadadi M., Uesaka T., *3D-Oriented Fiber Networks Made by Foam Foaming*, Cellulose, **23**, *1*, 661-671, https://doi.org/10.1007/s10570-015-0811-z(2016).

Aperjis D., *The Oil Market in the 1980s: OPEC Oil Policy and Economic Development*, US Development of Energy Office of Scientific and Technological Information, 24, https://www.osti.gov/biblio/6633202(1982).

Feng J., Nguyen S.T., Fan Z., Duong H.M., *Advanced Fabrication and Oil Absorption Properties of Super-Hydrophobic Recycled Cellulose Aerogels*, Chem. Eng. J., Elsevier, **270**, 168-175, https://doi.org/10.1016/j.cej.2015.02.034(2015).

Ferreira E.S., Rezende C.A., Cranston E.D., *Fundamentals of Cellulose Lightweight Materials Bio-Based Assemblies with Tailored Properties*, Green Chem., **23**, *10*, 3542-3568, https://doi.org/10.1039/D1GC00326G (2021).

Ferreira E.S., Dobrzanski E., Tiwary P., Agrawal P., Chen R., Cranston E.D., *Insulative Wood Materials Templated by Wet Foams*, Mater. Adv., Royal Society of Chemistry, **4**, 641-650, https://doi.org/10.1039/D2MA00852A (2023).

Fleury B., Abraham E., de la Cruz J.A., Chandrasekar V.S., Senyuk B., Liu Q., Cherpak V., Park S., Bart ten Hove J.B., Smalyukh I.I., *Aerogel from Sustainably grown Bacterial Cellulose Pellicles as a Thermally Insulative Film for Building Envelopes*, ACS Appl. Mater. Interfaces, ACS Publications, **12**, *10*, 34115-34121 (2020).

Hjelt T., Ketoja J.A., Kiiskinen H., Koponen A.I., Paakkonen E., *Foam Forming of Fiber Products: A Review*, J. Dispers. Sci. Technol., Taylor & Francis Online, **43**, *10*, 1462-1497, https://doi.org/10.1080/01932691.2020.1869035 (2022).

Jimenez-Saelices C., Seantier B., Cathala B., Grohen Y., *Spray Freeze-Dried Nanofibrillated Cellulose Aerogels with Thermal Superinsulating Properties*, Carbohyd. Polym., Elsevier, **157**, 105-113, https://doi.org/10.1016/j.carbpol.2016.09.068 (2017).

Moldovan V., *Aditivi in betoane*, Editura Tehnica, Bucuresti (1978).

Mukhopadhyaya P., Ton-That M.T., Ngo T.D., Legros N., Masson J.F., Bundalo-Perc S., van Reenen D., *An Investigation on Bio-Based Polyurethane Foam Insulation for Building Construction*, ASTM International, Special Technical Publication, **1574**, 131-141 (2014).

Paunescu L., Volceanov E., Paunescu B.V., *New Wood Foam-Heat Insulating Material Obtained through Oak Wood-Delignification Process*, Nonconv. Technol. Rev., **27**, *4*, 12-16 (2023).

Peyrton J., Avérous L., *Structure-Properties Relationships of Cellular Materials from Biobased Polyurethane Foams*, Mater. Sci. Eng.: R: Reports, Elsevier, **145**, https://doi.org/10.1016/j.mser.2021.100608 (2021).

Pierre A.C., Pajonk G.M., *Chemistry of Aerogels and their Applications*, Chem. Rev., ACS Publications, **102**, *11*, 4243-4266, https://doi.org/10.1021/cr0101306 (2002).

Seantier B., Bendahou D., Bendahou A., Grohens Y., Kaddami H., *Multi-Scale Cellulose Based New Bio-Aerogel Composites with Thermal Super-Insulating and Tunable Mechanical Properties*, Carbohyd. Polym., Elsevier, **138**, 335-348, https://doi.org/10.1016/j.carbpol.2016.09.068 (2016).

Srivastava V.K., Pizzi Pizzi A., *Characterization and Preparation of Wood-Furanic Foams*, J. Renew. Mater., **2**, *3*, 201-206, https://doi.org/10.7569/JRM.2014.634107 (2014).

Zheng C., Li, D., Ek M., *Improving Fire Retardancy of Cellulosic Thermal Insulating Materials by Coating with Bio-Based Fire Retardants*, Nord. Pulp Pap. Res. J., De Gruyter Publishing, **34**, 96-106, https://doi.org/10.1515/npprj-2018-0031 (2019).

*** *Foam Wood-From Tree To Foam*, Fraunhofer Institute for Wood Research, Braunschweig, Germany, (2023), https://www.fraunhofer.de/en/institutes.htm.

*** *Insulation Materials and their Thermal Properties*, GREENSPEC Ltd., Beverly, East Yorkshire, UK, (2000).

*** *Sodium Dodecyl Sulfate*, PubChem, National Library of Medicine, https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-dodecyl-sulfate (2018).

TEHNICĂ AVANSATĂ DE PRODUCERE A SPUMEI DE LEMN CA MATERIAL TERMOIZOLANT ALTERNATIV PENTRU CONSTRUCȚIA CLĂDIRILOR

(Rezumat)

Lucrarea a testat un material alternativ termoizolant pentru construcția clădirilor bazat pe spumarea lemnului. Deșeul de lemn ales pentru acest test a fost lemnul de stejar, neutilizat în alte experimente anterioare prezentate în literatura de specialitate. Scopul lucrării este înlocuirea materialelor plastice utilizate în mod obișnuit pentru producerea materialelor termoizolante. Utilizând deșeul de lemn măcinat, un surfactant adecvat (dodecil sulfat de sodiu) și apă distilată, a fost preparată o suspensie umedă, spumată prin agitare și apoi, uscată la 80°C. Astfel, s-a obținut un produs optim cu proprietăți termoizolante excelente (densitate aparentă de 0,014 $g \cdot cm^{-3}$, conductivitate termică de 0,035 $W \cdot m^{-1} \cdot K^{-1}$). Rezistența la compresiune a avut o valoare destul de scăzută de 715 kPa, dar satisfăcătoare pentru scopul propus. Prin comparație cu alte spume de lemn preparate experimental, proprietățile spumei din lemn de stejar s-au încadrat în performanța cerută de utilizarea noului material ca izolator termic în construcții, putând înlocui materiale similare pe bază de polimeri.