dr Barbara Pietruszka [1)*)]
ORCID: 0000-0003-3268-7997
dr inż. arch. Michał Gołębiewski[2)]
ORCID: 0000-0001-7206-0369
dr Olena Oleksiienko[3)]
ORCID: 0000-0002-5329-2217

Properties of cellulose as a thermal insulation material in building partitions

Właściwości celulozy jako materiału termoizolacyjnego w przegrodach budowlanych

DOI: 10.15199/33.2024.06.05

Abstract. When developing new materials with better thermal insulation parameters to improve the energy efficiency of buildings, low energy consumption of production processes is also important. In this context, it is justified to investigate the possibilities of use of recycled resources. This paper presents the results of testing the thermal conductivity of cellulose depending on moisture content, in a large range of declared densities. The thermal conductivity of cellulose in the dry state is almost constant (on average $\lambda = 0.041$ W/(m·K)) and does not depend on the apparent density. The rise of the moisture content of the material at 50% and 80% RH shows an increase in thermal conductivity, depending on the density. The obtained results confirm the potential of cellulose as a thermal insulation material in building partitions.
Keywords: thermal insulation; cellulose; thermal conductivity.

Streszczenie. Przy opracowywaniu nowych materiałów o lepszych parametrach termoizolacyjnych, stosowanych do poprawy efektywności energetycznej budynków, ważna jest także niewielka energochłonność procesów produkcji. W tym kontekście zasadne jest badanie możliwości wykorzystania surowców z recyklingu. W artykule przedstawiono wyniki badań przewodności cieplnej celulozy w zależności od zawilgocenia, w dużym zakresie deklarowanej gęstości. Przewodność cieplna celulozy w stanie suchym jest prawie stała (średnia wartość $\lambda = 0{,}041$ W/(m·K)) i nie zależy od gęstości objętościowej. Zawilgocenie materiału przy 50% i 80% RH wykazuje wzrost przewodności cieplnej w zależności od gęstości. Otrzymane wyniki potwierdzają potencjał celulozy jako materiału termoizolacyjnego przegród budowlanych.
Słowa kluczowe: izolacja termiczna; celuloza; przewodność cieplna.

Thermal insulation of external partitions effectively reduces the energy demand of buildings during their use phase. Materials of mineral and synthetic origin are available on the European market: glass wool (36%), mineral wool (22%), expanded polystyrene (27%), extruded polystyrene (6%), and PUR and PIR foams (total 8%) [1]. They are characterized by different values of energy needed for their production, the expenditure of which should be taken into account when assessing the energy efficiency of buildings throughout their life cycle, e.g. in the case of glass and mineral wool: 16 – 31 and 21 – 66 MJ, respectively, and EPS – 44 – 78 MJ per 1 m^2 of insulation with thermal resistance of 1 (m^2·K)/W and a designed service life of 50 years [2]. Due to the need to optimize the environmental parameters of materials and to limit the consumption of non-renewable raw materials and technological processes harmful to the environment, alternative materials are being sought, especially those of organic and recycled origin [3]. A review of environmental declarations [2] indicates very different values of embodied energy and carbon footprint of thermal insulation materials. Cellulose from renewable or recycled raw materials has particularly favorable properties; its average embodied energy is lower than that of synthetic materials and rock wool, and its carbon footprint is lower than that of most commonly used thermal insulation materials [2, 4].

Cellulose thermal insulation has been used since the 1980s and was introduced to the Polish construction market in 1994. It is produced mainly in the recycling process of waste newspaper, applied by blowing and used as thermal insulation of ceilings, pitched roofs, flat roofs, walls and floors (photo 1), surfaces with complex geometry, including arches and curves, e.g. in historic buildings; no trimming is needed and no technological waste is generated.

Approx. 95% of works using cellulose are performed by dry blowing, and the remainder by wet spraying [4]. Cellulose is characterized by a low thermal conducti-

Photo 1. Example of using cellulose insulation in an unused attic
Fot. 1. Przykład zastosowania izolacji celulozowej na poddaszu nieużytkowym

1) Instytut Techniki Budowlanej, Zakład Fizyki Cieplnej, Akustyki i Środowiska
2) Politechnika Warszawska, Wydział Architektury
3) LLC UKRCERTIFICATION
*) Correspondence address: p.pietruszka@itb.pl

Original research paper (Oryginalny artykuł naukowy)

vity coefficient (λ = 0.037 ÷ 0.043 W/(m·K)), high specific heat (2150 J (kg·K)), good air tightness [5, 6], as well as favorable air sound dampening parameters, due to the application method allowing for tight filling of the insulated space [4, 5]. The literature emphasizes cellulose's resistance to moisture and fungal growth due to its hygroscopic properties and non-flammability (fire class B – flammable, non-inflammatory products), which results in no flashover and limited contribution to the spread of fire [4 ÷ 6]. The above-mentioned properties are also obtained as a result of additional impregnation, including: boron compounds, aluminum hydroxide or ammonium salts [6].

The bulk density of cellulose insulation products depends on the method and parameters of application. The thickness of the material layer decreases over the period of use, up to the target value, which is several to a dozen or so percent smaller than the initial one. Cellulose with different bulk density is distinguished [6]:

- 25 ÷ 60 kg/m^3 – used in the so-called open blowing – on flat surfaces or with an angle of inclination up to 10° (insulation of ventilated flat roofs and unused attic ceilings); if the material layer is not compacted, it settles;
- 38 ÷ 65 kg/m^3– blown into the roof slopes with an angle of 45 ÷ 70° (filling the space between the initial covering layer and the internal cladding); the use of material with a higher density allows to avoid settling and ensures dimensional stability of the insulation;
- 40 ÷ 65 kg/m^3 – blown into walls; bulk density is higher than in the case of application on pitched roofs;
- 30 ÷ 55 kg/m^3 – applied by wet spraying.

The scope of testing of cellulose material is specified in the EN 15101-1:2013 standard [7]. Products assessed in accordance with it receive a declaration of performance and are recognized as safe, which allows them to be used as thermal and acoustic insulation of internal and external building partitions [6].

Test procedure

The research program assumed measurements of the thermal conductivity coefficient of cellulose samples with different bulk densities, after conditioning in various temperature and humidity conditions characterizing the operating conditions of cellulose, as well as control of the change in sample mass and settling of the material. The test procedure was carried out according to EN 15101-1:2013 [7], and the thermal conductivity coefficient measurements were carried out according to PN-EN 12667:2002 [8].

In order to place the material sample in the plate apparatus in the state in which it appears in the building partition, wooden molds with dimensions of 600 x 600 x 150 mm (reproducing the space of the partition) were prepared and filled with cellulose material, obtaining samples with an initial bulk density ρ = 35.3 ÷ 86.1 kg/m^3 (photo 2). In the first stage, the samples were dried in a climatic chamber at temperature of 70°C and relative humidity <5% until their constant mass was obtained for 3 consecutive measurements. Then they were tightly wrapped with foil and cooled at 23°C for approx. 30 minutes and tested. Measurements of the thermal conductivity coefficient λ in conditions of steady heat flow were performed using a FOX 600 plate apparatus (photo 3), with heat flux density sensors, with horizontal orientation and sample position: bottom. Measurements were carried out at an average sample temperature of 10°C, a temperature difference across the sample thickness of 20 K and heat movement from bottom to top, at an ambient temperature of 21.0 ÷ 23.6°C. In the second stage, cellulose samples were conditioned at a temperature of 23±2°C and a relative humidity of 50±5%, after which thermal conductivity and settling of the material were determined. In the third stage, the procedure was analogous, but the material was conditioned at a temperature of 23±1°C and a relative humidity of 80±2%. The research was conducted for 4 months.

Test results

The results of testing the thermal conductivity of cellulose material samples with different bulk density at the time of measurement and different moisture content as a result of seasoning in various thermal and humidity conditions are

Photo 2. Cellulose sample prepared by blowing the material into the test mold – a homogeneous mixture fills the entire empty space

Fot. 2. Próbka celulozy przygotowana przez wdmuchanie materiału do formy – jednorodna mieszanina wypełnia całą pustą przestrzeń

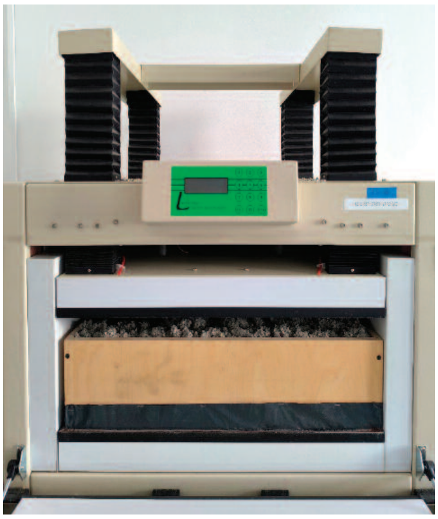


Photo 3. Cellulose sample placed in a plate apparatus during thermal conductivity test

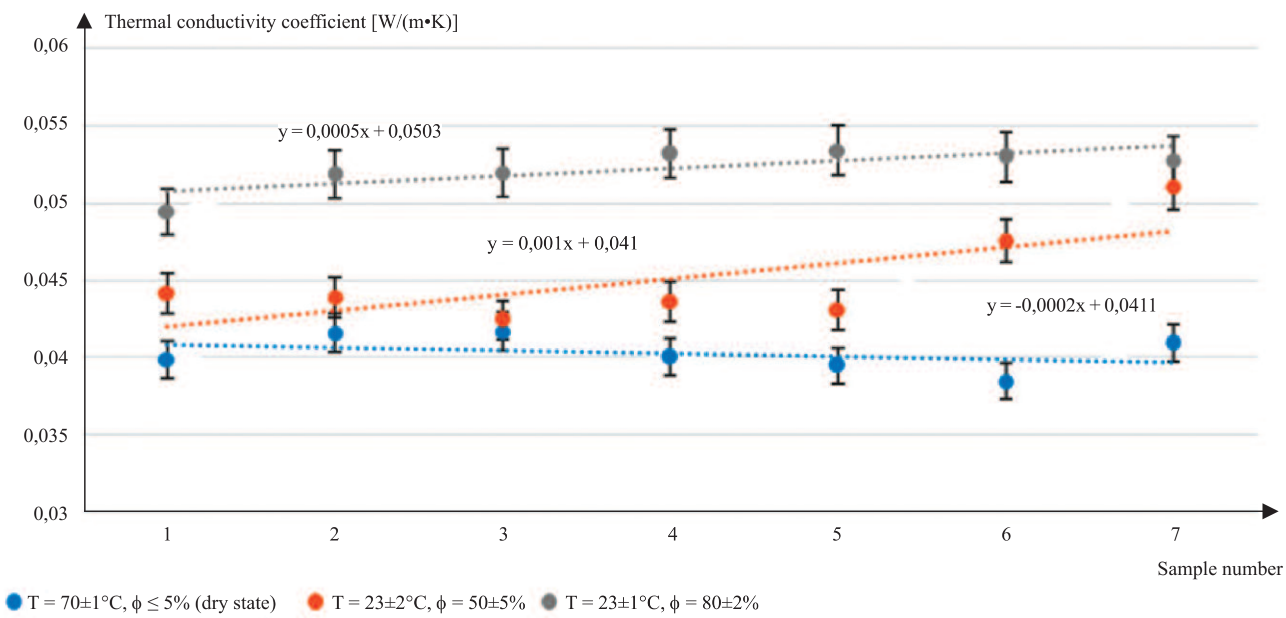
Fot. 3. Próbka celulozy w aparacie płytowym podczas badania przewodności cieplnej presented in Figure 1. The average thermal conductivity coefficient at dry state was 0.041 W/(m·K), which proves cellulose potential as a thermal insulation material, because this value is comparable to the values of other unconventional insulating materials currently available on the market [9 ÷ 13]. The thermal conductivity of cellulose in a dry state is almost constant and does not depend on the bulk density of the material. The thermal conductivity of the material conditioned at elevated humidity increases – on average by 8% in the case of a relative humidity of 50±5%, and by 15% in the case of a relative humidity of 80±2%, which is related to filling the pores of the material with moisture. Moreover, for those samples an increase in the value of the thermal conductivity coefficient was observed with an increase in bulk density. The initial bulk density and the change in cellulose mass depending on the seasoning conditions are presented in Table 1 and Figure 2. The density of dry samples and the results of cellulose sedimentation measurements are presented in Table 2. The settling of cellulose after conditioning depends on the initial bulk density of the material – the higher it is, the less susceptible the material is to settling. The results of tests on the thermal conductivity coefficient of cellulose in a dry state are consistent with the results of tests on cellulose materials carried out at ITB in 2015 (own research, unpublished). The calculation results and declared values of the thermal conductivity coefficient are summarized in Table 3.

Conclusions

The presented test results showed that cellulose is characterized by a low thermal conductivity coefficient under conditions typical of use. Taking into account many advantages of the material, including low energy consumption at the production stage, it can provide effective thermal insulation in building partitions. The measurements confirm that in the case of cellulose with a low initial bulk density, the thickness of the layer of insulating material blown onto the flat surfaces of the partitions will decrease over the service life of the material. In the case of the material with higher density, no settlement was

Table 1. Change in cellulose samples mass depending on ambient temperature and humidity conditions (in relation to their initial mass)
Tabela 1. Zmiana masy próbek celulozy w zależności od warunków cieplno-wilgotnościowych otoczenia (w odniesieniu do ich masy początkowej)

Sample number	Initial bulk density of the sample [kg/m^3]	Change in sample mass after		
		drying to constant mass at temperature 70 °C and ≤ 5% RH [%]	conditioning the sample to constant mass at temperature 23±2 °C and 50±5% RH [%]	conditioning the sample to constant mass at temperature 23±1°C and 80±2% RH [%]
1	35,3	-24,6	+19,2	+25,8
2	38,8	-22,7	+17,2	+24,0
3	46,2	-22,1	+16,0	+23,0
4	49,7	-20,3	+15,7	+22,0
5	55,2	-20,3	+15,5	+20,2
6	67,8	-18,6	+12,5	+18,9
7	86,1	-18,1	+11,8	+18,3



Expanded uncertainty, calculated using the factor k = 2, which corresponds to a confidence level of approximately 95%; is 3%

Fig. 1. Thermal conductivity of cellulose samples with different bulk density at the time of measurement and the moisture content as a result of seasoning in various ambient temperature and humidity conditions
Rys. 1. Przewodność cieplna próbek celulozy o zróżnicowanej gęstości nasypowej w momencie pomiaru i stopniu zawilgocenia w wyniku sezonowania w różnych warunkach cieplno-wilgotnościowych otoczenia

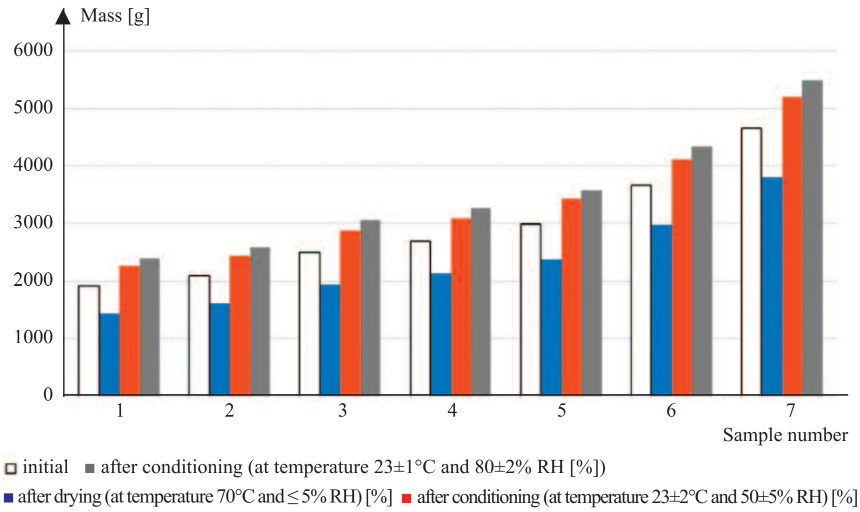


Fig. 2. Change in cellulose samples mass depending on ambient temperature and humidity conditions
Rys. 2. Zmiana masy próbek celulozy w zależności od warunków cieplno-wilgotnościowych otoczenia

Table 2. Bulk density of dry samples and susceptibility to settling of cellulose material (changes in relation to the initial thickness)
Tabela 2. Gęstość nasypowa suchych próbek i podatność na osiadanie materiału celulozowego (zmiany w odniesieniu do początkowej grubości)

Sample number	Bulk density of the sample after drying to constant mass at temperature 70°C and ≤ 5% RH [kg/m^3]	Susceptibility to settling change in the thickness of the material layer after conditioning the dry samples at temperature	
		23°C and 50% RH [%]	23°C and 80% RH [%]
1	26,6	-9,3	-18,0
2	30,0	-8,7	-16,7
3	36,0	-8,0	-14,7
4	38,9	-7,3	-13,3
5	43,7	-4,0	-7,3
6	55,2	not observed	not observed
7	70,5	not observed	not observed

observed as a result of conditioning, which confirms its suitability for insulating walls and roofs with a large angle of inclination.

Table 3. The calculation results and the declared values of the thermal conductivity coefficient of the cellulose thermal insulation materials tested in ITB in 2015
Tabela 3. Wyniki obliczeń i deklarowane wartości współczynnika przewodzenia ciepła materiałów termoizolacyjnych z celulozy badanych w ITB w 2015 r.

Determined value	Cellulose (type 1) [W/(m•K)]	Cellulose (type 2) [W/(m•K)]
Range of thermal conductivity coefficient values	0,0386 ÷ 0,0409	0,0407 ÷ 0,0425
$\lambda_{m,dry}$*	0,03947	0,04146
$S_{\lambda,dry}$**	0,000633	0,000583
k_{10}***	2,07	2,07
$\lambda_{90/90,dry}$****	0,0408	0,0427
$\lambda_{90/90,23/50}$*****	0,0423	0,0438

* $\lambda_{m,dry}$ – average value of the thermal conductivity coefficient calculated from the value of λ_i, in the case of 10 samples
** $s_{\lambda,dry}$ – standard deviation from values λ_i
*** k – coefficient related to the number of results (k = 2.07 for 10 results)
**** $\lambda_{90/90}$ – 90% quantile at 90% confidence level for thermal conductivity. Value $\lambda_{90/90,dry}$ rounded up to the nearest 0.0001 W/(m•K) – calculations according to the standard PN-EN 1SO 10436:2009+AC:2010
*****) conversion of the heat transfer coefficient from dry conditions to 23°C and 50% RH, made in accordance with PN-EN ISO 10456:2009+AC:2010

Literature

[1] European Commission, Joint Research Centre – Pavel C, Blagoeva D. Competitive landscape of the EU's insulation materials industry for energy-efficient buildings – Revised edition. Publications Office. 2018, DOI: 10.2760/750646.

[2] Grazieschi G, Asdrubali F, Thomas G. Embodied energy and carbon of building insulating materials: A critical review. Cleaner Environmental Systems. 2021; https://doi.org/10.1016/j.cesys. 2021.100032.

[3] Asdrubali F, D'Alessandro F, Schiavoni S. A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies. 2015; https://doi.org/10.1016/j. susmat. 2015.05.002.

[4] Zaorski R. Certyfikat CE dla celulozowych izolacji termicznych, na podstawie normy zharmonizowanej. Izolacje. 2014;5: 20 – 24.

[5] Drećka M. Ocieplanie przegród zewnętrznych celulozą w świetle nowych wymagań cieplnych. Izolacje. 2014;6: 58 – 62.

[6] Fabijańska M, Zaorski R. 2015. Ekologiczne aspekty wykorzystania wybranych materiałów stosowanych jako izolacje termiczne – polemika. Izolacje; 2.

[7] PN-EN 15101-1:2013-12. Wyroby do izolacji cieplnej w budownictwie. Wyroby z celulozy w postaci luźnej (LFCI) formowane in situ Część 1: Specyfikacja wyrobów przed zastosowaniem.

[8] PN-EN 12667:2002. Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance.

[9] Soto M, Rojas C, Cárdenas-Ramírez JP. Characterization of a thermal insulating material based on a wheat straw and recycled paper cellulose to be applied in buildings by blowing method. Sustainability. 2023; https://doi.org/10.3390/su15010058.

[10] Schiavoni S, D'Alessandro F, Bianchi F, Asdrubali F. Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews. 2026; https://doi. org/10.1016/j. rser. 2016.05.045.

[11] Janowska-Renkas E, Król A, Pochwała S, Pałubski D, Adamska M, Klementowski I. The fire resistance and heat conductivity of natural construction material based on straw and numerical simulation of building energy demand. Energies. 2022; https://doi. org/10.3390/en15031155.

[12] Fedorik F, Zach J, Lehto M, Kymäläinen HR, Kuisma R, Jallinoja M, IllikainenK, Alitalo S. Hygrothermal properties of advanced bio-based insulation materials. Energy and Buildings. 2021; https://doi.org/10.1016/j.enbuild. 2021.111528.

[13] Viel M, Collet F, Prétot S, Lanos C. Hemp-straw composites: Gluing study and multi-physical characterizations. Materials. 2019; https://doi. org/10.3390/ma12081199.

Przyjęto do druku: 04.06.2024 r.