Laboratory tests of external partition thermal insulation dedicated to buildings with a “nearly zero energy consumption”

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Abstract. Thermal protection regulations for the buildings change. Currently, the construction sector aims to minimize the energy consumption. Energy Performance Directives have introduced the standard of “Nearly Zero Energy Building” (NZEB). After 2021, the design of NZEB buildings will be mandatory. The parameters of NZEB buildings in Poland are very difficult to meet and concern the thermal insulation of housing structures and the non-renewable ratio of the original PE. In the article, the Authors reviewed traditional and modern thermal insulation materials that will allow meeting the thermal insulation requirements for the external walls of NZEB buildings. Another problem raised by the authors is the insulation of historic buildings. The aim of the article is to compare the parameters and prices of the thermal insulation materials such as foamed polystyrene with innovative materials such as aerogels.

1. Introduction

From 1st January 2021, the standard of buildings with nearly zero energy demand (NZEB) will become applicable in European countries. The design, implementation and construction of such buildings are challenges for architects and structural engineers. NZEB buildings are characterized by low consumption of non-renewable Primary Energy and a very low heat transfer coefficient $U$ [W/(m²K)].

The requirements for the $U$ [W/(m²K)] coefficient in force in Poland have been shown in Table 1. These requirements are mandatory for newly designed buildings as well as for renovations. The table also presents the requirements for passive buildings, which are becoming more and more popular in Europe and around the world.
Table 1. U Coefficient [W/(m²K)]

| Type of Partition | Current Requirements in Poland U [W/(m²K)] | Requirements for NZEB Buildings in Poland (from 2021) U [W/(m²K)] | Requirements for Passive Buildings U [W/(m²K)] |
|-------------------|-------------------------------------------|---------------------------------------------------------------|---------------------------------------------|
| External walls    | 0.23                                      | 0.20                                                           | 0.15                                        |
| Roofs and floors  | 0.18                                      | 0.15                                                           | 0.15                                        |
| Slab on grade     | 0.30                                      | 0.30                                                           | 0.15                                        |
| Windows           | 1.10                                      | 0.90                                                           | 0.80                                        |

Such requirements for NZEB buildings are connected with the necessity of designing external partitions with very good thermal parameters. New solutions and technologies appear on the construction materials market. Research and development laboratories carry out research on innovative products that will ensure even better thermal parameters of building partitions. Manufacturers and scientists use such phenomena as reflexivity, nanoparticles, absorption and emission of radiation to achieve better thermal parameters. In this article, the Authors will present the results of laboratory tests carried out in the modern Małopolska Laboratory of Energy Efficient Construction facility Laboratory (MLBE) (Figure 1). MLBE is a building designed for an on-site research of innovative technologies and is equipped with the highest quality research equipment.

![Figure 1. MLBE building](image-url)
The research results will concern typical and new technological material solutions. The tests will be carried out using the FOX 802 plate apparatus. The article also attempts to estimate the costs of innovative solutions in relation to standard solutions available on the construction materials market. Innovative solutions developed and tested at the MLBE are dedicated to NZEB, passive buildings and historical buildings. The test results provide guidance for the design of this type of buildings.

2. Overview of typical and innovative thermal insulation materials

To obtain the thermal insulation required by the Ordinance on the matter of Technical Conditions that are to be met by buildings and their placement [1] in most cases, the thermal insulation layer should be composed of a thermal insulation material. Thermal insulation materials can be considered as having a thermal conductivity of $\lambda < 0.2$ [W/mK] [2]. Thermal conductivity coefficients are parameters characterizing construction materials in terms of their thermal insulation. They are listed by manufacturers who commission research in accredited centers or that are listed in standards [3]. The lower the thermal conductivity coefficient, the more the material protects the partition against heat loss.

Thermal insulation materials can be divided into organic and inorganic. Organic materials consist of properly prepared parts of plants or porous plastic masses. Organic thermal insulation materials include, among others:

- Fiberboard $\lambda \approx 0.18$ [W/mK]
- Cork boards $\lambda \approx 0.18$ [W/mK]
- Straw boards $\lambda \approx 0.18$ [W/mK]
- Wood panels $\lambda \approx 0.04$ [W/mK]
- Sheep wool mats 60% modified with polyester / fibres from waste / $\lambda \approx 0.065$ [W/mK]
- Rigid plates from wood chips $\lambda = 0.043$ [W/mK]
- Hemp fiber mats $\lambda \approx 0.04$ [W/mK] (figure 2)

![Figure 2. Hemp fiber mat](image)

Inorganic thermal insulation materials are obtained from mineral raw materials (rocks, cements, glass, slags, etc.). These types of materials include, among others:

- slag wool and its derived products (which are practically out of use)
- stone wool and products from it $\lambda = 0.035 - 0.045$ [W/mK],
yarn, wool and glass wool, as well as products made from them, $\lambda \approx 0.035 - 0.045$ [W/mK]
- foam glass $\lambda \approx 0.035 - 0.045$ [W/mK],
- asbestos products, (discontinued from use!),
- termalite products,
- foamed polyurethane products (PIR and PUR foams),
- products made from expanded polystyrene, expanded polystyrenes (expanded and extruded),
- composite products

The next group includes materials of the new generation, which, thanks to special properties, improve the thermal insulation of partitions. Such thermal insulation materials include, among others:

- transparent insulation
- aerogels $\lambda \approx 0.018$ [W/mK]
- nanogels $\lambda \approx 0.013$ [W/mK]
- vacuum insulation $\lambda \approx 0.008$ [W/mK]

The most commonly used in construction is popular styrofoam. In the article a comparison was made between EPS polystyrene, XPS polystyrene and mat made from aerogel.

**EPS polystyrene** is Styrofoam Expanded polystyrene with a forward coefficient declared by producers at a level $\lambda \approx 0.035 - 0.045$ [W/mK]. It is a material obtained by foaming polystyrene granules containing a blowing agent (e.g. petroleum ether). The foaming is obtained by heating the granules, usually with steam. It consists of closed rounded cells (formed from the aforementioned granules) inside which there is a polystyrene foam (figure 3a). The styrofoam properties include: easy machining and application, low weight, a very low thermal conductivity coefficient, resistance to fungi and mold, it is a self-extinguishing material, resistant to water vapour diffusion, however, it is not resistant to organic solvents

**XPS polystyrene** (Figure 3b) is produced in a different process than EPS. The production process consists of mixing granules of polystyrene with additives that change its colour, improve resistance to fire, etc. in the machine for its production. The product is subjected to high temperature and pressure. The gas prepared in this raw material is additionally injected, which causes expansion of the polystyrene granules. The resulting mass escapes through the slots for forming outside, where it expands. Heat conductivity declared by manufacturer is at a level of $\lambda \approx 0.022 - 0.045$ [W/mK]. The properties of XPS Styrofoam include: low absorbability, easy machining and application, low weight, very low thermal conductivity coefficient, very good mechanical properties, resistance to fungi and mold, self-extinguishing material, resistant to water vapour diffusion.

**Aerogels** (Figure 3c) are a rigid foam type with extremely low density, comprised of 90-99.8% air, the rest constituting its structure (Figure 3). The properties of aerogels are low thermal conductivity declared by manufacturers: 0.018 [W/mK], high light transmission: up to 80%, good acoustic properties, resistance to UV radiation, resistance to moisture and bacterial molds etc., it is a non-combustible material, with a weight approx. 70 -200 [kg/m$^3$]. The aerogel can be in a semi-transparent form (figure 3), replacing e.g. windows or in the form of aerogel mats used as a thermal insulation layer for the building envelope.
a) EPS polystyrene  

b) XPS polystyrene  

c) Aerogels  

(semi-transparent)

**Figure 3.** a) EPS polystyrene, b) XPS polystyrene, c) Semi-transparent aerogel

3. Comparative laboratory tests of thermal properties of thermal insulation materials  
The purpose of the laboratory test was to determine the dependence of the thermal conductivity coefficient $\lambda$ on the temperature for insulating materials - aerogel mats and to compare the thermal conduction coefficient of the tested materials with the values declared by the manufacturers [4].

The research was carried out in the building of the Małopolska Laboratory of Energy Efficient Construction (figure 1) using the FOX 802 plate apparatus test equipment.

3.1. Research methodology and research equipment  
There are complex heat transfer processes in the building envelope elements through conduction, radiation, convection and mass exchange. The methodology by which the test was performed determines the total amount of heat penetrating from one surface of an object to another, for a given temperature difference, under the defined test conditions [5-7]. The test was performed in stationary conditions for one-way heat flow. The value measured in the plate apparatus was the thermal resistance $R$ [m$^2$K/W] of the thermal insulation material layer. On this basis, the heat transfer coefficient $\lambda$ [W/mK] is determined.

The test was performed with the Fox 802 plate apparatus (figure 4) in accordance with the PN-ISO 8301 standard [8]. The test was performed between January and July of 2018.

**Figure 4.** FOX 802 plate apparatus

The FOX 802 plate apparatus is equipped with sensors for measuring the temperature, heat flux density and thickness of the test object. Each panel has been equipped with a cooling and heating system containing a number of Peltier modules. Plate temperatures can be independently maintained at any
value within the range of -10 [°C] to 65 [°C] with an accuracy of ± 0.02 [K]. Transducers for measuring the heat flux density were used on the surface of each of the plates. An E-type thermocouple was mounted in the middle of each transducer. A 24-bit analog-to-digital converter converts the signal from the thermocouples and transducers into a digital signal with a resolution of 0.6 [μV], which gives a temperature measurement resolution of 0.01 [K]. The accuracy of the sample thickness reading is ± 0.025 [mm]. In order to prepare research facilities in accordance with the PN-EN 13238 standard, they have undergone a conditioning process until the samples reached an even distribution of moisture. The test was carried out at various temperature ranges set on FOX 802 apparatus plates, which have been summarized in Table 2.

**Table 2.** Comparison of the set temperatures for the test at a constant temperature difference

| Test number | Warm side [°C] | Cold side [°C] | Temperature difference between warm and cold side [K] | Average value [°C] |
|-------------|---------------|---------------|-----------------------------------------------------|-------------------|
| Test No. 1  | 10            | -10           | 20                                                   | 0                 |
| Test No. 2  | 15            | -5            | 20                                                   | 5                 |
| Test No. 3  | 20            | 0             | 20                                                   | 10                |
| Test No. 4  | 30            | 10            | 20                                                   | 20                |
| Test No. 5  | 40            | 20            | 20                                                   | 30                |
| Test No. 6  | 50            | 30            | 20                                                   | 40                |
| Test No. 7  | 54            | 34            | 20                                                   | 44                |

3.2. Description of the tested samples

The study covered aerogel mats, lintel mats, XPS polystyrene boards and XPS facade polystyrene boards. Table 3 features a list of geometry and descriptions of the tested objects.

**Table 3.** List of research objects

| Name of the research facility | Description                  | Dimensions [mm] | Nominal thickness [mm] | Measured thickness [mm] | Density [kg/m³] |
|------------------------------|------------------------------|-----------------|------------------------|-------------------------|-----------------|
| Object number 1              | White aerogel mat            | 760 x 760       | 13                     | 11,9824                 | 180             |
| Object number 2              | Gray aerogel mat             | 760 x 760       | 10                     | 8,9725                  | 146             |
| Object number 3              | Aerogel mat for lintels 13   | 760 x 760       | 13                     | 14,8717                 | 169             |
| Object number 4              | Aerogel mat for lintels 10   | 760 x 760       | 10                     | 12,3571                 | 135             |
| Object number 5              | Polystyrene XPS green plate  | 750 x 750       | 50                     | 50,1459                 | 32              |
| Object number 6              | Polystyrene XPS pink plate   | 750 x 750       | 50                     | 51,6572                 | 34              |
| Object number 7              | EPS facade polystyrene board | 750 x 750       | 50                     | 48,4378                 | 14              |

The view of the tested samples has been summarized in Table 4.
Table 4. Photographs of the tested samples

| White aerogel mat | Gray aerogel mat | Aerogel mat for lintels |
|-------------------|------------------|-------------------------|
| ![White aerogel mat](image1) | ![Gray aerogel mat](image2) | ![Aerogel mat for lintels](image3) |

| Polystyrene XPS green board | Polystyrene XPS pink board | EPS polystyrene board |
|-----------------------------|-----------------------------|-----------------------|
| ![Polystyrene XPS green board](image4) | ![Polystyrene XPS pink board](image5) | ![EPS polystyrene board](image6) |

3.3. Test results
The thermal conductivity coefficient for aerogel mats is presented in Figure 5. A summary of the results of thermal conductivity coefficients for all tested samples is presented in Figure 6.
Figure 5. The value of the $\lambda$ coefficient for the aerogel mats

Figure 6. A comparison of the values of $\lambda$ coefficients obtained from the tested aerogel mats with the values obtained for XPS extruded polystyrenes and EPS polystyrene

4. The economic aspect of the use of various thermal insulation materials

Table 5 presents the cost of constructing an external wall made using various technologies, including insulation costs, internal plaster, external plaster and labor as well as the costs of insulation materials. The materials from which the partition was made and the U heat transfer coefficient were determined. Table 6 presents the cost of 1 m² of various thermal insulation materials.
Table 5. The cost of constructing 1 m² of a single-layer exterior wall [9, 10]

| Item                                                                 | Cost of execution (gross) 1 m²          |
|---------------------------------------------------------------------|-----------------------------------------|
| The cost of constructing 1 m² of a single-layer external wall of aerated concrete with internal, external and work plaster. [10] | from 203 zł/m² (46 EUR/m²)              |

Table 6. Cost of 1 m² of thermal insulation material

| Item                                                                 | Material cost (gross) 1 m²             |
|---------------------------------------------------------------------|----------------------------------------|
| Polystyrene EPS 50 mm green (BASF 3000 CS foundation, this was tested) | 26 PLN/m², 6,0 EUR/m²                 |
| Styrofoam EPS facade 50 mm pink (Austrotherm)                        | 9,45 PLN/m², 2,2 EUR/m²               |
| Polystyrene XPS 50 mm (Dalmatian)                                   | 28,70 PLN/m², 6,7 EUR/m²              |
| Wool facade 5 cm                                                    | 18,61 PLN/m², 4,3 EUR/m²              |
| Aerogel insulation mat Porogel Optima Evergel POE 6 mm (white)      | 146,37 PLN/m², 33,9 EUR/m²            |
| Spaceloft Medium 5 mm aerogel insulation mat (gray)                 | 183,27 PLN/m², 42,6 EUR/m²            |
| Aerogel mat for lintels Porofix 10 mm                               | 631,42 PLN/m², 146,7 EUR/m²           |

For further analysis, the parameters obtained in the tests presented in item 3 were adopted. The partition meeting the requirements of thermal insulation for NZEB buildings in Poland was analyzed. The heat transfer coefficient U for Polish requirements for NZEB conditions is U = 0.2 [W/(m²K)]. Aerated autoclaved concrete masonry units with a thickness of 0.25 m variant 600 with a thermal conductivity coefficient λ = 0.21 [W/(mK)] were adopted as the structural layer of the wall. Thermal parameters for the thermal insulation materials were adopted from the tests presented in point 3 for the average value in the 10°C apparatus (Table 6). Table 6 also lists the insulation thicknesses that allow for the U-partition of 0.2 = [W/(m²K)] for the analyzed partition (table 7).
Table 7. Heat transfer coefficients obtained from tests

| Item                  | λ coefficient [W/(mK)] | Thickness of thermal insulation material [cm] |
|-----------------------|------------------------|---------------------------------------------|
| Aerogel mat           | 0,02                   | 7                                           |
| XPS (pink), XPS (green) | 0,032                 | 11                                          |
| EPS                   | 0,035                  | 12                                          |

Figure 7 presents the cost of insulating the partition with various thermal insulation materials, so that the U-value for the partition being analyzed is U = 0.2 [W/m²K] which is in line with the requirements for NZEB buildings in Poland.

Figure 7. Comparison of the costs of increasing the thermal insulation, so that the U for the partition being analyzed is U = 0.2 [W/m²K]
5. Conclusions
1. The value of the heat transfer coefficient increases with the increase of the set temperature in the test device.
2. The best thermal insulation parameters among the tested aerogels are a gray mat with an admixture of graphite.
3. The values obtained during the tests show that the thermal conductivity coefficient for aerogels varies in the range of 0.019 - 0.023 [W/mK], which is close to the values declared by manufacturers.
4. The values obtained during the tests show that the thermal conductivity coefficient for EPS polystyrene varies depending on the temperature in the range 0.034 - 0.040 [W/mK], which is consistent with the values declared by the manufacturers.
5. The values obtained during the tests show that the thermal conduction coefficient for EPS polystyrene (pink and green) varies depending on the temperature in the range 0.031 - 0.035 [W/mK], which is in line with the values declared by the manufacturers.
6. The green XPS polystyrene is characterized by the same parameters as the pink polystyrene, throughout the entire test temperature range.
7. The use of aerogels for the thermal insulation of partitions is economically unprofitable.
8. Aerogels can be used in hard to reach places or in historical buildings.

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