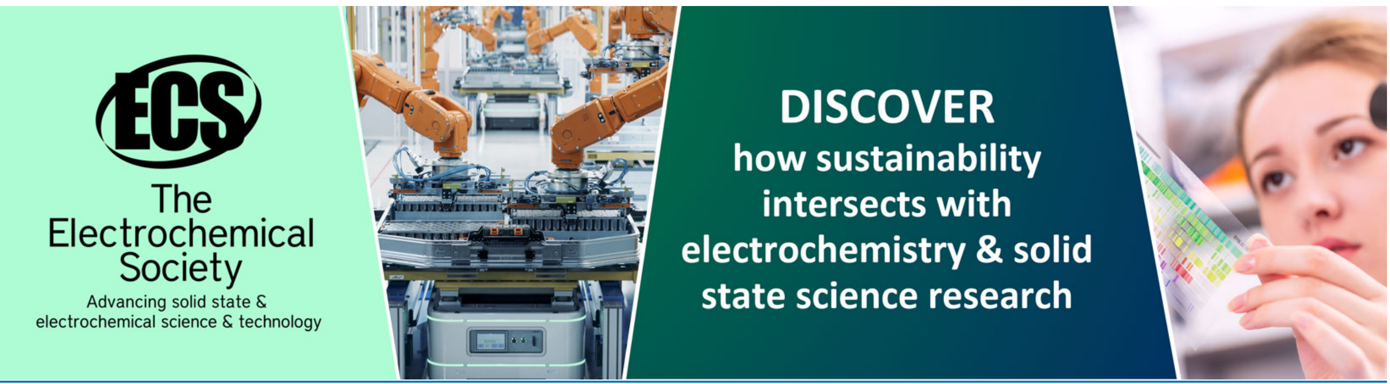
IOP Conference Series: Materials Science and Engineering

Historical Earth Architecture in Terms of Climate Change in the Temperature Climate Area (Central Europe)



Historical Earth Architecture in Terms of Climate Change in the Temperature Climate Area (Central Europe)

Izabela Kozlowska [1]

[1] Faculty of Civil Engineering and Architecture, West Pomeranian University of Technology Szczecin, ul. Zolnierska 50, 71-210 Szczecin, Poland

iza.tarka@wp.pl

Abstract. The paper deals with the earth architecture and the assessment of the impact of climatic change on its external constructions. The concept of earth architecture represents construction that uses unfired, raw soil as a building material. This material, which forms the structure of the oldest building structures, was also widely used throughout Europe until World War II. The preserved, historic earth architecture, which represents a wealth of technical solutions, creates a European cultural heritage that should be protected. Unfortunately, in modern times, structures classified as earth architecture are subject to intense interference as a result of the need to adjust their structure to thermal parameters increased as a result of climate change. According to conservation rules, the only correct action in the case of thermal upgrading in this type of structures is the introduction of insulating material from the inside of the wall. However, the thermal upgrade carried out in this way is incompatible with the principles of building physics. In addition, incompetent implementation of work or incorrect application of insulating material, ignoring the risk of inter-layer and surface condensation, can lead to the introduction of moisture in the structure, the appearance of moisture that promotes the development of mould, fungi or biological damage to the structure. The aim of the conducted research was to determine the optimal solution in the field of thermal insulation of external partitions for the two most popular earth architecture technologies found in Europe, namely: a structure made of compacted earth (French: pisé, Polish: ściany bite, ziemnościany, glinobitka) and a half-timbered structure filled with trusses or braids and then covered with ground with chaff (French: torchis, colombage), or filled with raw or burnt bricks (bolt construction).The first part of the paper defines materials for inside thermal insulation of external construction partitions, from traditional (cork boards, sheep wool, wood wool) have been collected and described by the latest, such as aerogels made of silica with nanoporous structure and vacuum insulation - VIP (Vacuum Insulated Panels). The second part presents, theoretical, exemplary calculations for selected types of walls of earth architecture from the walls made of compacted soil with a thickness of 40 cm and a half-timbered construction with 14 cm thick filled or plaited braids were carried out. The computer program WUFI Light was used to carry out the calculations. The conducted research suggests that in the case of walls made of compacted soil, the use of any insulation technology does not effect on its durability and efficiency, while for walls with a wooden structure filled with unexploded soil, available insulation materials are unsatisfactory.

1. Introduction

The concept of earth architecture represents construction that uses unfired, raw soil as a building material. This material, which forms the structure of the oldest building structures, was also widely used throughout Europe until World War II. The preserved, historic earth architecture, which represents a wealth of technical solutions, creates a European cultural heritage that should be protected. Unfortunately, in modern times, structures classified as earth architecture are subject to intense interference as a result of the need to adjust their structure to thermal parameters increased as a result of climate change. According to conservation rules, the only correct action in the case of thermal upgrading in this type of structures is the introduction of insulating material from the inside of the wall. However, the thermal upgrade carried out in this way is incompatible with the principles of building physics. In addition, incompetent implementation of work or incorrect application of insulating material, ignoring the risk of inter-layer and surface condensation, can lead to the introduction of moisture in the structure, the appearance of moisture that promotes the development of mould, fungi or biological damage to the structure.

The aim of the conducted research was to determine the optimal solution in the field of thermal insulation of the outer walls for the two most popular earth architecture technologies encountered in Europe, namely: a structure made of rammed earth (French: pisé, Polish: ściany bite, ziemnościany, glinobitka) and half-timbered construction filled with split logs or wattle (French: torchis, colombage), and then covered with soil with chaff, or filled with raw or fired brick (bolt construction).

2. Materials and methods

The assumed research method was to perform theoretical calculations that allowed to determine the heat and moisture flow. The climate parameters of Central Europe (city of Warsaw) were assumed for the study. On the basis of Polish standards PN-EN-ISO 6946 and PN-EN-ISO 12524 [1, 2], the values of heat transfer coefficient and thermal resistance for selected materials - traditional filling for a half-timbered construction, as well as for rammed earth walls, have been adopted. Polish standards are English versions of European standards and international standards with the same numbers.

Thermal insulation of outer walls is specified in the Polish Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location, where the value of heat transfer coefficient for external walls in spaces intended for human presence cannot be greater than $U_{C(max)} = 0.23$ W/(m^2·K) [3]. The parameters included in the regulation meet the European requirements in this respect.

Computational analyses were carried out for selected variants of wall insulation representing earth architecture, using the dependence in the field of building physics and the WUFI Light computer program.

3. Characteristics of selected earth architecture technologies

The technologies recommended for research represent different types of earth architecture structures. The rammed earth technology is representative of earth monolithic structures; in the case of half-timbered construction it is classified as complex structures.

The rammed earth technology consisted of making successive layers of compacted soil characterised by a sandy consistency with the addition of gravel and pebbles and clay content from 10% to 20% (soil mixed with gravel and lime up to 10%, a mixture of soil and peat was also used). The earth subjected to the process of compaction obtained consistency and stabilisation, and by reducing porosity, a wall made in this technology became resistant to moisture and had better technical parameters, such as resistance to compression. Additional advantages of this construction are: the rate of erection, low costs, wood saving, good thermal insulation, fire resistance and resistance to biological corrosion (insects). The average thickness of the walls made in the rammed earth technology ranged from 40 to 80 cm. A warming layer was added from the inside, the so-called pugging. The earth was rammed in boarding made of planks (French: pisé, Polish: ściany bite, ziemnościany, glinobitka) or without boarding (French: bauge, Polish: glinobitka) from wet earth layers. Chaff was added to this soil, which prevented the wall from breaking during drying [6] (figure 4, 5).

The half-timbered construction, the second technology chosen for the research, was made in the form of a wooden frame consisting of the following parts: ground sill, pillars, purlin (pile cap), angle braces and bolts. The ground sill, lifting the weight of the wall, evenly transferred its weight to the brick pedestal. The columns spaced from 1.5 to 2 m were connected with the ground sill and with the pile cap using pivots. The cross-sections of pillars had the following dimensions, depending on the building loads: 13x13 cm, 16x16 cm, 18x18 cm and 21x21 cm. The beams of the pile cap carried the ground sill beams and the roof. The angle braces preventing from twisting (turning) were placed in the corners of the buildings. The bolts secured the pillars against buckling while bordering the window and door openings.

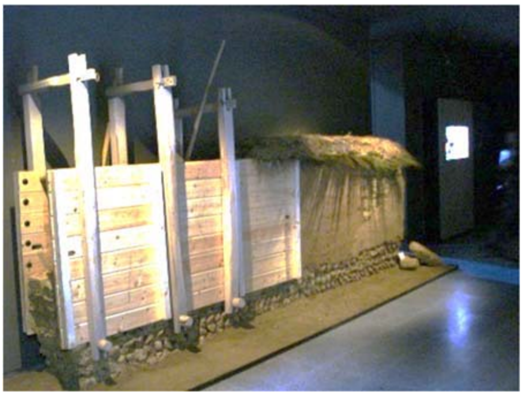


Figure 1. The technology a rammed-earth wall (pisé)

Figure 2. The fragment of the wall made in the pisé technology

The filling of the half-timbered fields varied depending on the region [6]. The oldest technique of filling the half-timbered construction (the field between the wooden structure) consisted in applying clay soil, mixed with straw or other fibres to a braid or lath (French: torchis, wattle and daub). Areas of Germany and the northern and western areas of Poland were characterised by filling of the frame with the use of straw bundles dipped in the soil and twisted around wooden slats or straw rollers fixed on rods, covered with soil (Polish: w wiązarek) [7]. Even in serious studies on the half-timbered construction, the name "Prussian wall" is incorrectly used as a replacement term (Radoń, Künzel). Meanwhile, this term is reserved for a half-timbered wall, with brick wall filling. According to the construction art, such a wall was not used in buildings with a housing function because it did not protect against "a great loss of heat" [6] (figure 3, 4).

Figures 3, 4. Examples of half-timbered construction filled with straw bundles wrapped around wooden slats (Poland, Western Pomeranian voivodship, 2017).

4. Insulation of the outer wall from the inside - materials and technologies

This chapter of the article collects and describes the materials used for the thermal insulation of outer walls from the inside, from traditional materials (cork boards, sheep wool, wood wool) to the latest ones, such as VIP (Vacuum Insulated Panels) aerogels made of silica with nonporous structure and vacuum insulation.

Introduction of insulation of the outer wall from the inside requires the use of materials that are resistant to biodegradation. An additional requirement is to design a ventilation system that ensures an adequate number of air changes and guarantees adequate humidity in the space.

In general, systems for insulating from the inside can be divided into three groups [4, 8, 9]:

1. Systems preventing the occurrence of condensation, where the diffusion-equivalent air layer thickness (Sd) is more than 1500 m. Materials used in these systems block the access of water vapour and prevent its condensation inside the wall at the interface of insulation and outer wall [4]. This type of insulation includes extruded and expanded polystyrenes (XPS, EPS), which, however, due to their moisture properties (high diffusion resistance and low water vapour

permeability expose spaces to excessive operational moisture) and fire properties is not used as internal insulation. Polyurethane panels are not used for similar reasons. The second system preventing the onset of condensation is mineral wool with a vapour-tight film layer. According to research carried out using the computer program WUFI [11], in the case of non-application of film in half-timbered constructions, the acceptable thickness of mineral wool ensuring mass humidity in wood below 20% is thickness of not more than 3 cm (moisture above 20% in longer periods leads to biological corrosion of the wooden half-timbered construction). In the case of using a vapour barrier, an optimal solution may be the use of an adaptive film, which changes its diffusion resistance depending on the ambient humidity. In the solution adopted, the permissible thickness of mineral wool insulation for half-timbered construction is maximum 5 to 6 cm [11]. It seems that in the case of the construction of rammed earth walls, the application of mineral wool insulation with a vapour barrier film on the inside with a thickness of more than 6 cm will not adversely affect the wall construction.

2. Systems minimising the occurrence of condensation, characterised by diffusion-equivalent air layer thickness (Sd) at a level between 0.5 and 1500 m. Materials of this type include lime silicates (e.g. Renovario boards) and mineral insulation boards made of light aerated concrete (e.g. Multipor boards). These materials are characterised by high capillary properties, which ensure, in the case of moisture appearing under the layer of material, its absorption and evaporation from the surface [9]. The system uses the principle of seasonal absorption and water vaporization outside and inside the room. Other materials belonging to the group of boards are: perlite boards manufactured with natural perlite with additives and foam glass SG (e.g. Calsitherm boards). In the case of historic earth architecture, the use of this type of material may be difficult, if not impossible, as a result of assembly requiring ground levelling before installing thermal insulation [10]. The boards require a smooth and even wall surface in order to be mounted on a special lightweight mortar or glue.
3. Systems allowing the occurrence of condensation with the demonstration that the condensate formed during the unfavourable period evaporates during the calculation year. Materials classified in this group are characterised the diffusion equivalent air layer thickness (Sd) of less than 0.5 m [9]. In addition, they have capillary properties and accumulate the resulting condensate in their structure without affecting the deterioration of physical properties.

Parallel to the above-mentioned commonly used thermal insulation systems, research on innovative solutions is underway. The materials belonging to this group include aerogels, silica-based products with nanoporous structure and very good thermal insulation, higher than in the case of traditional materials. Their structure is a type of rigid foam of low density, consisting of over 90% of the air. These materials are also characterised by high vapour permeability. In construction, aerogels are used in various forms, such as fibreglass-reinforced mats (e.g. Porogel Medium Spaceloft mats), aerowool – mineral wool combined with aerogel or light transmitting granulates, which are used in filling opaque panes in glass walls [12, 13]. Nanoparticles can have a negative impact on human health (e.g. nanoparticles can be absorbed into the bloodstream through the lungs), therefore the principle of careful work management when using materials from this group is recommended.

Another product that is a new proposal in the field of thermal insulation is vacuum insulation (VIP - vacuum insulated panels). Panels with a core made of pyrogenic silica or polyurethane foams have an open-chamber structure with a vacuum. The core is surrounded by a multilayer film, which has a sealing and protective function. An additional element of these structures is the dryer-absorber that ensures the absorption of water vapour and absorbs gases in order to extend the period of its operation. The thermal conduction coefficient achieved by this material is one of the lowest among materials used in thermal insulation. The most serious limitation in the use of this type of material, in addition to the limited durability and ease of damage, is the lack of processing during assembly [5, 12].

The barrier in the widespread use of new aerogels and vacuum panels is their price, which limits the universality of their use in construction.

Table 1. The table summarizing of selected thermal insulation materials used on the inside of the external barrier and their thermal-humidity and fire parameters. Sample calculation values of physical properties of materials according to PN-EN 12524 [1] and data contained in the literature [4, 9].

Material	**d [m]**	**λ W/(m·K)**	**μ**	**Reaction to fire according to DIN 13501-1**
Extruded polystyrene foam XPS	0.01-1	0.031- 0.045	100-200	E Easily ignite
Glass mineral wool	0.05-0.2	0.031-0.045	1.3-1.4	A1 Non-flamable
Autoclaved calcium silicate board (Renovario_/Calsitherm)	0.025; 0.03; 0.05	0.062	3-6	A1 Non-flamable
Mineral insulation boards (Multipor)/ Mortar	0.06-0.20/ 0.008-0.01	0.042/ 0.3	3/ 5-20	A1 Non-flamable
Perlite recover board (Ecovario)	0.05 / 0.2	0.045	5-6	A1 Non-flamable
Foam glass board SG (Foamglas)	0.04 0.18	0.038 0.050	∞ 100 000	A1 Non-flamable
Aerogel blanket (Porogel Medium Spaceloft)	0.005 0.01	0.0138 - 0.014	5	D-s1,d0 Low flammability
Aerowool	0.16-0.05	0.019	> 3	-
Vacuum Insulation Panels VIP (Proventus)	0.01-0.05	0.0043	∞ > 500 000	D-F (DIN 4102 - B2) Easily ignite or Low flammability
Cork board	0.045	0.037-0.040	25-30	E Easily ignite
Wood fibre insulation (Steico Flex 036)	0.04-0.24	0.037	≥ 5	E Easily ignite
Sheep's wool insulation (Isolenwolle)	0.08-0.30	0.0385	1	E Easily ignite
Hemp insulation panels (Vicarius Canna)	0.04-0.18	0.04	1	D-S1,d0 Low flammability
Pressed straw	-	0.035-0.045	2.5	B-s1, d0 Noninflammatory
Cellulose	0.06-0.08	0.052	2.4	D-F (DIN 4102 - B2) Easily ignite or Low flammability

A separate group of insulating materials are ecological, natural materials that have a negative impact on the natural environment. These are materials that reach for traditional technologies used in old construction. Materials belonging to this group are characterised by good thermal and moisture properties, are diffusive (vapour-permeable) and can transport moisture in the material without reducing the thermal power (high sorption capacity), which prevents the formation of water. Materials of organic origin are nowadays modified with additives that improve their fire, working and biological properties. These include: wood wool (e.g. Steico products: blow-in wood fibre insulation, thermal insulation boards made of wood wool) made of natural wood fibre from softwood; sheep wool (e.g. Isolenwolle products) from sheep fleece with very good humidity control properties; boards made of flax and hemp fibres (e.g. Vicarius Canna), coconut and cork fibres, cellulose and straw - one of the oldest building materials used for insulating buildings [12] (table 1).

Among the various groups of materials used for thermal insulation of the outer wall from the inside in historic earth architecture discussed in this chapter, the materials from the group of aerogels and ecological materials are particularly promising. Their practical application, next to theoretical calculations, requires laboratory tests and tests in the conditions of real climate impact before recommendation for general use in historic earth architecture.

5. Thermal insulation - examples of calculations for selected earth architecture technologies

In the second part of the article, examples of theoretical calculations were made for selected types of earth architecture walls made of 40 cm thick rammed earth and half-timbered construction filled with 14 cm thick split logs or wattle. The computer program WUFI Light was used to carry out the calculations. The lowest size parameters of the earth architecture walls were selected for the calculations.

The thermal resistance of homogeneous layers, with the known thermal conductivity coefficient, is calculated as follows:

$$R = \frac{\mathrm{d}}{\lambda}\ [(\mathrm{m}^2{\cdot}\mathrm{K})/\mathrm{W}] \tag{1}$$

where:

d - thickness of the material layer in the component [m];

λ - design heat transfer coefficient of the material [W/(m·K)].

The heat transfer coefficient is calculated as the inverse of the total resistance of the component according to the relationship:

$$U = \frac{1}{\mathrm{R_t}}\ [\mathrm{W}/(\mathrm{m}^2{\cdot}\mathrm{K})]\ \ [14]. \tag{2}$$

For the indicated types of walls in earth architecture, calculations were carried out in regard to their meeting the heat transfer coefficient required by the building regulations for outer walls in spaces intended for human presence. The value of the coefficient cannot be greater than $U_{C(max)}$ = 0.23 W/(m^2·K) [3]. In the case of walls in rammed earth technology, only a wall made of clay with chips or sawdust at least 80 cm thick meets modern requirements in the field of thermal protection (table 2). Rammed earth walls with a lower thickness and filled with clay and straw do not meet the above requirements (table 3). This also applies to all walls in half-timbered technology, both in terms of filling and thickness. The calculations show the need for thermal insulation of a large percentage of structures built in earth architecture (table 4) [15].

Of the thermal insulation technologies discussed in the previous chapter used from the inside of the outer wall, several groups were selected for the performance of theoretical calculations. From among thermal insulation boards, an aerated concrete mineral board was chosen as a material with thermal parameters better than boards made of sand-lime. Perlite and SG foam glass boards were grouped as materials characterised by the minimal occurrence of condensation and a similar computational thermal conduction coefficient. Another material selected for calculations was an aerogel mat. The calculations were also carried out for thermal insulation made using a VIP vacuum panel, characterised by the best thermal parameters among thermal insulation technologies. Natural materials (cork boards, wood wool, sheep wool, hemp fibre, pressed straw) were grouped as materials with a similar computational heat conduction coefficient.

Table 2. Thermal parameters of the rammed-earth wall, 40 cm thick.

Material	d [m]	λ [W/(m·K)]	R [(m²·K)/W]	U [(m²·K)/W]
Pisé wall made of clay with straw				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Clay with straw	0.4	0.5	0.8	
Outside air Rse	-	-	0.04	
Sum (Rt)			**1.07**	**0.934** > $U_{C(max)}$ = 0.23 W/(m²·K)
Pisé wall made of clay with sawdust or shavings				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Clay with sawdust or shavings	0.4	0.2-0.3	2-1.333	
Outside air Rse	-	-	0.04	
Sum (Rt)			**2.27-1.60**	**0.44-0.623** > $U_{C(max)}$ = 0.23 W/(m²·K)

Table 3. Thermal parameters of the rammed-earth wall, 40-80 cm thick.

The type of earth architecture wall	d [m]	Rt [(m²·K)/W]	U [(m²·K)/W]
Pisé wall made of clay with straw, λ = 0.5 W/(m·K)	0.4	1.07	0.934
	0.5	1.27	0.787
	0.6	1.47	0.68
	0.7	1.67	0.599
	0.8	1.87	0.534
Pisé wall made of clay with sawdust or shavings, λ = 0.2-0.3 W/(m·K)	0.4	2.27-1.60	0.44-0.623
	0.5	2.77-1.937	0.361-0.516
	0.6	3.27-2.27	0.305-0.44
	0.7	3.77-2.60	0.265-0.384
	0.8	4.27-2.936	0.234-0.34

Table 4. Thermal parameters of the half-timbered walls and of so-called "Prussian wall", 14 cm thick.

Filling material	d [m]	λ [W/(m·K)]	R [(m²·K)/W]	U [(m²·K)/W]
Half-timbered wall with clay and straw filling				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Clay with straw	0.14	0.5	0.8	
Outside air Rse	-	-	0.04	
Sum (Rt)			**0.55**	**1.818** > $U_{C(max)}$ = 0.23 W/(m²·K)
Half-timbered wall with sawdust or shavings filling				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Clay with sawdust or shavings	0.14	0.2-0.3	0.7-0.466	
Outside air Rse	-	-	0.04	
Sum (Rt)			**0.97-0.736**	**1.03-1.357**> $U_{C(max)}$ = 0.23 W/(m²·K)
Half-timbered wall with common burnt brick filling				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Common burnt brick	0.14	0.7	0.2	
Outside air Rse	-	-	0.04	
Sum (Rt)			**0.47**	**2.127** > $U_{C(max)}$ = 0.23 W/(m²·K)
Half-timbered wall with cellular concrete filling				
Indoor air Rsi	-	-	0.13	
Lime-clay mason's mortar	0.02	0.2	0.1	
Cellular concrete	0.14	0.12-0.14	1.166-1	
Outside air Rse	-	-	0.04	
Sum (Rt)			**1.436 - 1.27**	**0.696-0.787** > $U_{C(max)}$ = 0.23 W/(m²·K)

As a result of the conducted analyses, the minimum thickness of materials used for thermal insulation was determined for 40 cm thick rammed earth walls with different filling, and for 14 cm thick half-timbered walls with different filling (excluding a Prussian wall with brick filling).

In the case of insulation of the walls from their inside, analyses of the moisture increase should be carried out. Ensuring the use of thermal insulation with a very high diffusion resistance coefficient or an additional layer of vapour barrier insulation (material with an S_d slightly above 0.5 m is a diffusive/ vapour-permeable material) from the inside theoretically eliminates the internal diffusion of water vapour. According to the guidelines in the standards, it is recommended for the value of the diffusion-equivalent air layer thickness S_d of thermal insulation to exceed 1500 m [8,14, 15] (table 5).

To implement the distribution of water vapour pressure and the water vapour stream flowing through the wall, a type of medium-humid space (living space) with a humidity of 40 to 60% and partial water vapour pressure from 1060 to 1330 Pa was assumed. For this type of wall, it is recommended to use internal thermal insulation with an Sd higher than the construction layer [15, 16].

Table 5. Calculation thickness of inside insulation in the indicated technologies of earth architecture, which ensure the fulfillment of the required heat coefficient Uc (max) = 0.23 W / (m^2 · K) for the whole partition. If the S_{di}> S_{de} condition is met, the system is materially correct [1].

Material	λ [W/(m·K)]	d [m]	μ [-]	Sdi [m]
Pisé wall made of clay with straw 40 cm thick, μ=10, Sde=4 m				
Glass mineral wool	0.031	0.1	1.3	0.13
Mineral insulation boards with mortar	0.042	0.14	3	0.42
Perlite recover board	0.045	0.15	5	0.75
Foam glass board SG	0.045	0.15	100000	**15000**
Aerogel blanket	0.0138	0.045	5	0.225
Vacuum Insulation Panels VIP	0.0043	0.015	500000	**7500**
Natural materials (wood fibre, sheep's wool and hemp insulation/ pressed straw)	0.037	0.12	1 / 2.5	0.12/ 0.3
Pisé wall made of clay with sawdust or shavings 40 cm thick, μ=10, Sde=4 m				
Glass mineral wool	0.031	0.08	1.3	0.1
Mineral insulation boards with mortar	0.042	0.12	3	0.36
Perlite recover board	0.045	0.13	5	0.65
Foam glass board SG	0.045	0.13	100000	**13000**
Aerogel blanket	0.0138	0.04	5	0.2
Vacuum Insulation Panels VIP	0.0043	0.012	500000	**6000**
Natural materials (cork, wood fibre, sheep's wool and hemp insulation, pressed straw)	0.037	0.1	1 / 2.5	0.1/0.25
Half-timbered wall with clay and straw filling 14 cm thick, μ=10, Sde=1.4 m				
Glass mineral wool	0.031	0.11	1.3	0.14
Mineral insulation boards with mortar	0.042	0.16	3	0.48
Perlite recover board	0.045	0.17	5	0.85
Foam glass board SG	0.045	0.17	100000	**17000**
Aerogel blanket	0.0138	0.055	5	0.275
Vacuum Insulation Panels VIP	0.0043	0.017	500000	**8500**
Natural materials (cork, wood fibre, sheep's wool and hemp insulation, pressed straw)	0.037	0.14	1 / 2.5	1/0.35
Half-timbered wall with sawdust or shavings filling 14 cm thick, μ=10, Sde=1.4 m				
Glass mineral wool	0.031	0.11	1.3	0.14
Mineral insulation boards with mortar	0.042	0.155	3	0.465
Perlite recover board	0.045	0.165	5	0.825
Foam glass board SG	0.045	0.165	100000	**16500**
Aerogel blanket	0.0138	0.05	5	0.25
Vacuum Insulation Panels VIP	0.0043	0.016	500000	**8000**
Natural materials (cork, wood fibre, sheep's wool and hemp insulation, pressed straw)	0.037	0.135	1 / 2.5	0.135/ 0.337

6. Results and discussions

Among the buildings representing earth architecture, only the structures entered in the register of monuments are exempt from the obligation to comply with the regulations on thermal protection. However, a large percentage of buildings is outside such protection and requires an energy performance analysis in the event of adaptation to new functions or reconstruction. The conducted research shows that among two technologies representative of earth architecture (rammed earth wall and half-timbered wall) accepted for theoretical calculations, only rammed earth-type wall made of clay with chips or sawdust meets the requirements in the area of modern thermal requirements. Other structures require insulation, which can be implemented by selecting from several groups of materials.

The traditional material used in insulation from the inner side of the wall is mineral wool. In a rammed earth wall made of clay with straw, the required thickness of such insulation should be 10 cm, while in the rammed earth wall made of clay with chips or sawdust - 8 cm. In the case of a half-timbered construction, the required thickness of mineral wool is at least 11 cm. Due to the risk of moisture deteriorating the wooden structure, it is recommended to use a vapour barrier made of adaptive film. With this assumption, the maximum thickness of the wool should not exceed 6 cm [11], thus not meeting the standard thermal requirements [3].

Another group of materials subjected to the tests were thermal insulation boards panels (mineral panels made of aerated concrete) as well as perlite panels and SG foam glass panels, which have similar thermal, fire and capillary properties. In order to meet the required Umax for outer walls for a rammed earth wall made of clay with straw, the insulation thickness is 14 to 15 cm, and for a wall made of clay with chips or sawdust - from 12 to 13 cm. In the case of half-timbered construction, the thermal insulation layer must have a thickness of approximately 16 to 17 cm.

In the summary of the results of theoretical calculations, very good thermal parameters were obtained by the aerogel mat. In the earth architecture technologies studied in this paper, the thickness of the mat, from 4 to 5 cm, ensured compliance with the standard thermal requirements. A hindrance to the implementation of such thermal insulation is its harmfulness to human health during assembly work and, therefore, the need for particular care during processing.

The material achieving the best thermal parameters was the VIP vacuum panel. This material, reaching a thickness of 2 cm, meets the thermal requirements in terms of the maximum heat coefficient. However, its parameters in the field of fire reaction limit the use of this material only to housing.

Good thermal parameters are achieved by natural thermal insulating materials, which, at thicknesses from 10 to 14 cm, meet the requirements set for today's outer walls. However, their application in insulation from the inside of the wall can be limited due to fire-related causes (as in the case of extruded polystyrene XPS or VIP vacuum panels) because they belong to the group of easily inflammable, self-extinguishing materials (fire class E (cork boards, wood wool boards, sheep wool mats).

According to the regulations on buildings and their surroundings, the use of flammable materials and products for the interior finishing, whose thermal decomposition products are very toxic or intensely smoking, is prohibited. The regulations allow the use of such materials only in buildings with a residential function [3].

7. Conclusions

The conducted research suggests that in the case of walls made of rammed earth, the use of any insulation technology does not effect on its durability and efficiency, while for walls with a wooden structure filled with unfired soil, the insulation materials available are unsatisfactory.

The tests carried out in terms of humidity parameters only indicate the possibility of using the Foam glass board SG and Vacuum Insulation Panels VIP without any risk to the structure of external walls of the ground architecture.

References

[1] K. Arbeiter, "Innendämmung: Auswahl, Konstruktion, Ausführung", Interior insulation: selection, construction, execution Rudolf Mueller, Koeln, 2014.

[2] M. Bochenek, "Vacuum Insulation Panels (VIP) – properties and examples of applications in construction", *Insulation (Izolacje)*, Vol. 10/2012, pp. 16-18 ("Izolacje próżniowe (VIP) – właściwości i przykłady zastosowań w budownictwie").

[3] R.T. Bynum, "Insulation Handbook", The McGraw-Hill Companie, New York 2001.

[4] P. Harassek, "Inside insulation", *Civil Engineer* (*Inżynier budownictwa)*, Vol. 9(98)/2012, pp. 59-64, ("Izolacje od wewnątrz").

[5] A. Kaliszuk-Wietecka, "Sustainable construction. Selected problems in building physics",Wydawnictwo Naukowe PWN SA, Warszawa 2017 ("Budownictwo zrównoważone. Wybrane zagadnienia z fizyki budowli").

[6] T. Kelm, "Earth architecture. Tradition and the present day", Wydawnictwo Murator, Warszawa 1996 ("Architektura ziemi. Tradycja i współczesność").

[7] D. Krzyczkowski, "Construction: lecture popular principles of construction structures for builders, craftsmen, construction entrepreneurs and self-educators", Księgarnia Polska Bernard Połoniecki, Lwów-Warszawa 1932 ("Budownictwo: wykład popularny zasad konstrukcyj budowlanych dla budowniczych, majstrów, przedsiębiorców budowlanych i samouków").

[8] PN-EN-ISO 12524:2003, Building materials and products. Hygrothermal properties. Tabulated calculation values (Materiały i wyroby budowlane. Właściwości cieplno-wilgotnościowe. Tabelaryczne wartości obliczeń).

[9] PN-EN ISO 13788:2002, Thermal and moisture properties of building components and building elements (Cieplno-wilgotnościowe właściwości użytkowe komponentów budowlanych i

elementów budynku. Temperatura powierzchni wewnętrznej umożliwiająca uniknięcie krytycznej wilgotności powierzchni i kondensacja międzywarstwowa. Metoda obliczania).
[10] PN-EN-ISO 6946:2008, Building components and building elements (Komponenty budowlane i element budynku. Opór cieplny i współczynniki przenikania ciepła. Metoda obliczania).
[11] B. Orlik-Kożdoń, P. Krause, T. Steidl, “Rozwiązania materiałowe w dociepleniach od wewnątrz”, *Insulation (Izolacje)*, Vol. 11/12/2015, pp. 30-34.
[12] J. Radoń, H. Künzel, "Thermal and humid problems in the renovation of walls of half-timbered buildings", Acta Scientiarum Polonorum – Architektura 5 (1) 2006, pp. 45-53 (“Problemy cieplno-wilgotnościowe przy renowacji ścian budynków z muru pruskiego”).
[13] Regulation of the Minister of Infrastructure of April 12, 2002 on technical conditions that should be met by buildings and their location (Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie).
[14] T. Steidl, B. Orlik-Kożdoń, "Inside Insulation of external partitions - materials, technologies and design", *Insulation (Izolacje)*, Vol. 4/2013, pp. 43-48 (“Docieplenie przegród zewnętrznych od wewnątrz – materiały, technologie i projektowanie”).
[15] J. Szyszka, “Aerogel insulation”, *Insulation (Izolacje)*, Vol. 9/2009, pp. 34-35 (“Izolacje aerożelowe”).
[16] M. Wesołowska, "Moisture protection of the building. Selected topics", website: http://www.kup.piib.org.pl/tl_files/izba/dokumenty/szkolenia/ochrona przeciwwilgociowa budynku-dr inz-maria-wesolowska.pdf