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Orginal Article

Thermal and structural properties of building materials used in single-family buildings

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Abstract: All buildings, regardless of their function, should exhibit appropriate durability and aesthetics while avoiding a negative impact on the environment. The selection of building materials is increasingly crucial in this regard. Each material possesses distinct strength, technical, or production parameters. However, with regulations becoming more stringent concerning the maximum energy consumption of buildings, it is imperative to scrutinize their thermal properties and the associated thermal conductivity coefficient (λ). The article conducts an analysis of available technologies for constructing external partitions in single-family housing and their influence on energy losses within the building. Popular building materials, such as cellular concrete, ceramic hollow bricks, prefabricated expanded clay concrete walls, and a wooden frame structure, were examined.

Keywords: building materials, thermal protection of building, single-family buildings, building technologies

1. Introduction

The selection of appropriate building materials during the construction of residential buildings is a crucial aspect, impacting not only investment costs but also the ecological and energy efficiency of the structures. The materials employed significantly shape the building's environmental footprint and energy consumption. Production and transportation of building materials and components play a pivotal role in this regard [1]. Various techniques exist to minimize energy consumption in construction, with one approach being the utilization of traditional materials from local producers or those sourced through recycling or other forms of recovery. The adoption of prefabricated materials, however, results in increased production and transport costs [2]. Current national regulations stipulating minimum requirements for the thermal protection of buildings, along with pertinent acts and regulations stemming from the implementation of the Energy Performance of Buildings Directive (EPBP) [3], present new challenges to designers concerning material selection. The latest Technical Conditions [4] precisely define the technical parameters of building partitions in terms of thermal protection and specify the maximum values of the heat transfer coefficient U. This coefficient determines the amount of thermal energy penetrating individual thermal partitions in a building, allowing for the estimation of heat losses across various partitions. The lower the heat transfer coefficient U, the more effective the thermal insulation provided by a given partition. This parameter's value is influenced by:

- thermal conductivity of the material used,
- type of partition,
- partition thickness.

The parameter that governs building materials in terms of energy losses is their thermal conductivity, signifying their ability to conduct heat through the movement of molecules within the material's internal structure. This property is defined by the thermal conductivity coefficient (λ), representing the amount of heat passing through a 1-meter thick layer of material in 1 hour at a temperature difference of 1 K on both sides of the partition. Table 1 displays the values of the lambda parameter for fundamental building materials. Notably, a higher thermal conductivity coefficient indicates that the material is a more effective conductor of heat, as seen in materials like concrete. Conversely, insulators, such as polystyrene, exhibit very low lambda coefficients.

Table 1. Material table. S*ource:* [5]

Material	Thermal conductivity λ [W/m·K]
air	0.025
water	0.60
concrete	1.0-1.70
glass	0.8
brick	0.15-1.31
wood	0.16-0.4
styrofoam	0.032-0.045
steel	58
the wall made of solid silicate brick	0.90
concrete wall	0.17

Thermal conductivity is primarily influenced by the density, pore content of the material structure, and its humidity. Therefore, in determining the insulating properties of materials, it is crucial to ascertain the actual moisture content of the material [6]. The enhancement of energy efficiency in residential buildings is predominantly assessed through the utilization of suitable insulating materials. Given the substantial technological advancements in construction, attention should also be directed towards the construction materials employed for the external walls of the building. The article aims to analyze the thermal properties of popular building materials used in constructing external covers for residential buildings, contingent on the selected technology – whether traditional, frame, or prefabricated.

2. Properties of materials

2.1 Traditional technology

The majority of residential houses in Poland are constructed using traditional technology [7]. The prevalent approach involves double-layer walls with insulation typically composed of polystyrene or, less frequently, mineral wool. Adequate thermal parameters are primarily achieved through the choice of thermal insulation, with the masonry layer primarily functioning as a load-bearing component. However, it also plays a significant role in the overall thermal transmittance of the partition. A warmer wall contributes to a reduced total U-value for the insulated wall.

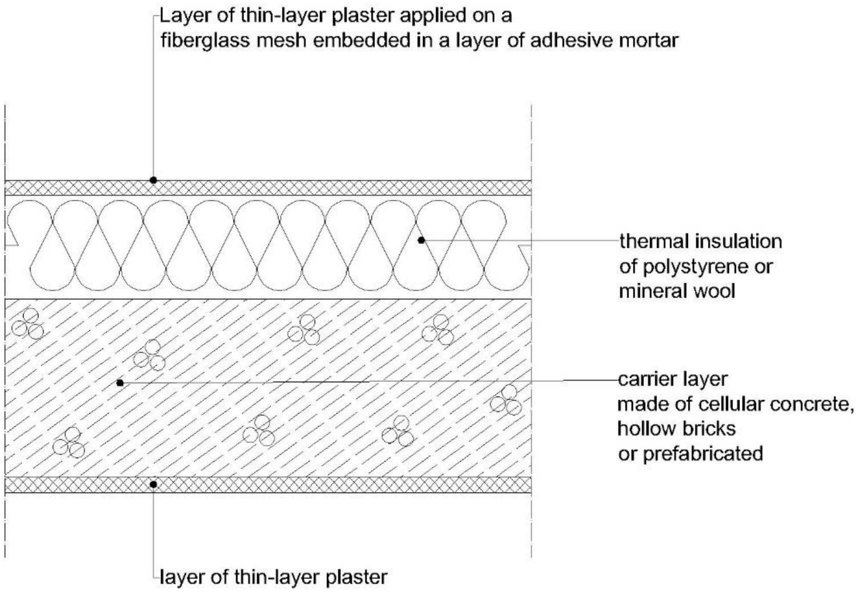

Fig. 1. Construction of a wall using the traditional two-layer technology. *Source*: own study

In traditional technology, all fundamental construction activities take place on the construction site, utilizing masonry elements as the primary construction materials. These elements must be further insulated with a layer of thermal insulation and finished, for example, with a thin-layer plaster (Fig. 1).

2.1.1 Ceramic blocks

Ceramic blocks are a commonly employed building material for constructing the structural walls of residential buildings. They exhibit high strength and low thermal conductivity owing to empty spaces filled with air, facilitating enhanced heat circulation within the block [8]. Hollow bricks in the P+W system are a standard choice in construction, featuring installation through the tongue-and-groove technology. In comparison to the traditional mortar method, this technique eliminates the need for vertical joints, expediting the construction process and minimizing heat losses and thermal bridges. Ceramic blocks demonstrate favorable thermal insulation properties, with a low thermal conductivity coefficient of 0.316 W/m·K.

2.1.2 Autoclaved aerated concrete

A distinctive feature of aerated concrete is its ratio of compressive strength to thermal conductivity coefficient, with ongoing technological progress consistently enhancing these parameters [9]. Among investors, a popular choice is the use of 24 cm wide cellular concrete blocks of type 500 or 600. An important consideration is the proper profiling of the side surfaces, with manufacturers offering two options: the tongue-and-groove system (P+W), eliminating the need to fill vertical joints with mortar, or the tongue-and-groove system (W), where mortar filling is required. Autoclaved aerated concrete blocks boast excellent thermal insulation attributed to their porous structure. The blowing agent used during production loosens the mass, creating millions of micro-pores filled with air, serving as an effective thermal buffer. Consequently, 80% of the volume of concrete blocks consists of air [10].

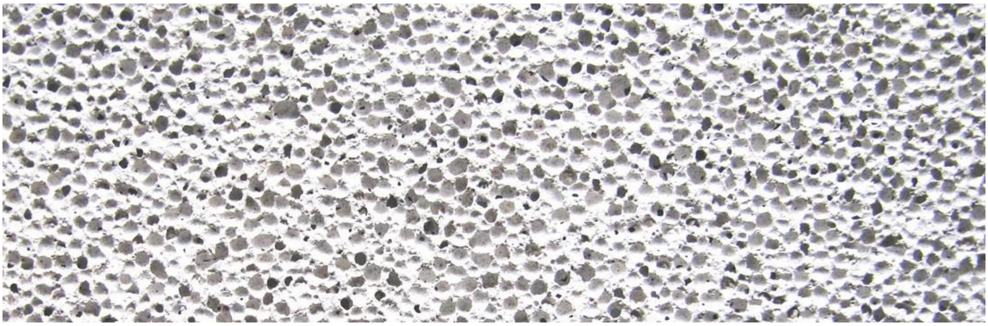

Fig. 2. Pore structure in an aerated concrete. *Source*: [11]

2.2 Wooden skeleton construction

Wood, as a natural raw material, stands as one of the oldest materials employed in residential buildings. The substantial growth in this sector has led to a departure from wood as the primary building material for residential structures, contributing to the gradual disappearance of wooden architecture from urban and increasingly rural landscapes as well [12], [13]. Presently, in Poland, wood finds predominant use in the construction of roof trusses. Over the past two decades, the construction sector's principal objective has been the development of ecological and progressively energy-efficient buildings, sparking a resurgence in wooden construction [13]. The prevalent wooden building system is frame construction. The load-bearing wall incorporates structural posts spaced every 625 mm, supported by a foundation anchored in the ground. These elements can be crafted from various types of solid or glued wood. The gaps between the posts are filled with insulating material, requiring coverage with a vapor-permeable foil externally and a vapor barrier foil internally. To finalize and reinforce the structure, the external wooden frame is clad with a covering made of gypsum-fiber boards or fiber-cement boards. Internally, plasterboards are predominantly utilized [14].

Wood possesses low heat conductivity properties, rendering it a material with excellent thermal insulation. However, it is essential to note that its thermal characteristics primarily hinge on the type of wood and its humidity (Table 1). The higher the moisture content, the greater the thermal conductivity, adversely affecting its insulating properties [15]. Only dry wood, with its porous structure, exhibits very low thermal conductivity, as all intercellular and intracellular spaces are filled with air. Consequently, it is advisable to use solely dry wood or wood with a humidity level not surpassing 20% in construction [16].

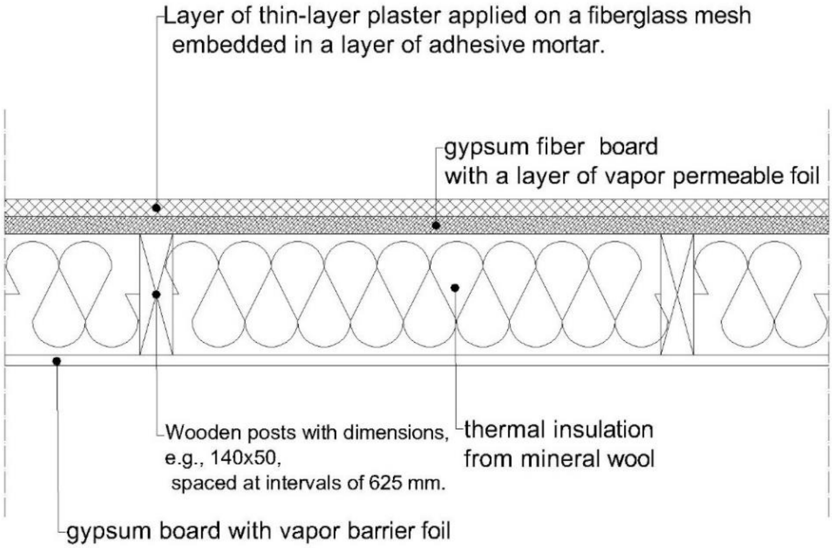

Fig. 3. An exemplary solution of an external wall of a frame building. *Source*: own study

Table 2. Physical properties of wood

No.	Type	Density 12%	Thermal conductivity	Moisture of the wood after cutting
		[kg/m^3]		[%]
1	oak	690	0.17	50
2	larch	495	0.16	82
3	beech	730	0.17	64
4	pirch	650	0.16	68-78
5	pine	510	0.13	88
6	spruce	460	0.12	91

According to Table 2, coniferous trees like pine or spruce exhibit the best thermal properties, with thermal conductivity coefficients ranging from 0.12 to 0.13 W/m·K. However, it's important to note that they also have the highest moisture content immediately after cutting. For instance, when compared to fresh oak, which has a moisture content of 50%, spruce has 91% moisture right after cutting.

2.3 Prefabricated external walls

The undeniable advantage of prefabrication lies in the shift of part of the construction process to production plants, expediting the overall implementation of the investment. The origins of concrete prefabrication trace back to the 1950s and 1960s, reaching its zenith during the development of extensive housing estates. However, due to concerns about workmanship quality and societal distrust, there was a gradual abandonment of this technology [17]. With advancements in the field and the progressively higher quality of prefabricated materials, there is a resurgence of interest in using this method for constructing residential buildings. Thanks to enhanced production processes, prefabricated walls now exhibit a higher load-bearing capacity compared to those built using traditional technology. Prefabricated walls can be composed of pure structural concrete or include additional materials such as expanded clay (LECA), polystyrene (styroconcrete), or foamed glass or polymer. For instance, the incorporation of expanded clay improves thermal properties, lightens the concrete, and enhances the material's porous structure.

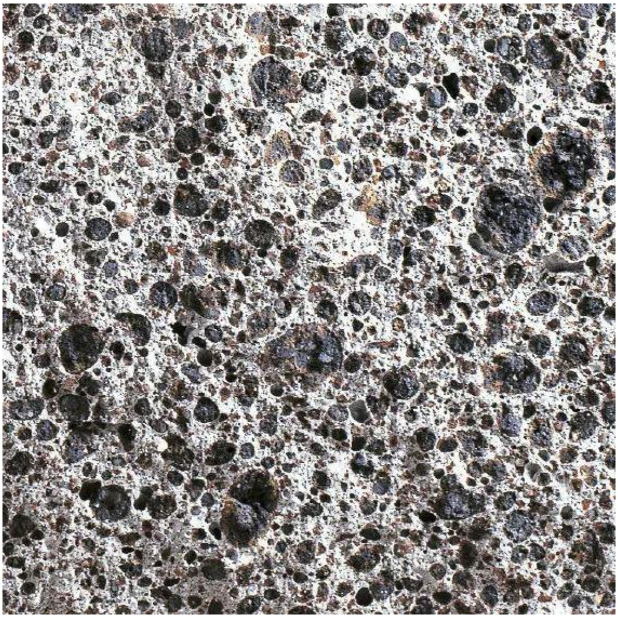

Fig. 4. Structure of expanded clay concrete. *Source:* [18]

3. Research methodology

The research aimed to analyze the U-factor for partitions constructed with different building materials. Calculations were conducted based on the PN-EN ISO 6946:1999 standard titled "Building components and building elements, Thermal resistance and heat transfer coefficient, Calculation method" [19]. The conventional approach to constructing external walls in single-family buildings involves thermally homogeneous layers. In this scenario, the U-factor is calculated using the following formula:

$$U = \frac{1}{R_{si} + \sum_j \frac{d_j}{\lambda_j} + R_{se}} \quad [\mathrm{W/m^2 \cdot K}] \tag{1}$$

where: R_{si} – the heat transfer resistance on the inner surface [(m^2 K)/W], λ_j – the heat conductivity coefficient of the glass or material layer j [W/(m K)], d_j – the thickness of the glass or material layer j [m], R_{se} – the heat transfer resistance on the external surface [(m^2 K)/W].

Due to the production technology, the wooden skeleton structure comprises one thermally heterogeneous layer. In this scenario, the U-factor is calculated using the formula below:

$$U = \frac{2}{R'_T + R''_T} \quad [\mathrm{W/m^2 \cdot K}] \tag{2}$$

where: R'_T – the upper limit of the total thermal resistance calculated according to point 6.2.3 of the PN-EN 6946 standard[1], R''_T – the lower limit of the total thermal resistance calculated according to point 6.2.4 of the PN-EN 6946 standard[2],

The research was based on calculating the U coefficient for walls constructed using the previously discussed technologies and comparing the results in terms of thermal protection. To ensure the accuracy and realism of the obtained outcomes, the actual finishing layers corresponding to the considered construction technology were considered in the calculations. As a constant element, insulation of the wall with polystyrene foam of a consistent thickness of 14 cm was assumed for all the considered variants. The material layers adopted for calculations are outlined below. Vapor barrier or vapor-permeable layers were omitted in the calculations due to their minimal impact on thermal calculations.

Table 3. List of materials for calculations in the case of external walls composed of homogeneous layers. *Source*: own study

Material	Layer thickness d	Thermal conductivity λ	Thermal resistance R
	[m]	[W/mK]	[m^{2}K/W]
R_{si}			0.13
cement-lime plaster	0.02	0.82	0.02
selected construction material	X	X	X
thermal insulation	0.14	0.038	3.68
structural plaster	0.02	0.82	0.02
R_{se}			0.04

Table 4. List of materials for calculations in the case of external walls composed of inhomogeneous layers. *Source*: own study

Material	Layer thickness d	Thermal conductivity λ	Thermal resistance R
	[m]	[W/mK]	[m^{2}K/W]
R_{si}			0.13
Plasterboard	0.02	0.82	0.02
Wooden construction 140x50	X	X	X
thermal insulation - polystyrene	0.14	0.038	3.68
Plate	0.02	0.22	
cement-lime plaster	0.0125	0.23	0.02
R_{se}			0.04

Table 5 presents the analyzed construction materials and their fundamental parameters, as defined based on catalog cards and manufacturers' information. This includes thermal coefficients and required thicknesses for layers of building partitions according to Figs 1 and 3.

[1] The upper limit of the total thermal resistance is determined by assuming one-dimensional heat flow perpendicular to the component surface.

[2] The lower limit of the total thermal resistance is determined by assuming that all surfaces parallel to the surface of the component are isothermal.

Table 5. Summary of the analyzed materials and their basic parameters. *Source*: own study

Material	Thermal conductivity λ	Layer thickness d
	[m]	[W/mK]
Aerated concrete blocks		
TYPE 500	0.127	0.24
TYPE 600	0.149	0.24
Ceramic blocks		
TYPE 25 P+W	0.316	0.25
Wooden frame construction		
Wood- pine	0.13	0.050x0.14
Prefabricated walls made of expanded clay concrete		
expanded clay concrete	0.38	

4. Research results

The conducted research enabled us to identify construction technologies with the best thermal properties. According to Chart 1, autoclaved aerated concrete stands out as the material with the best thermal properties, with a U coefficient of 0.173 W/m²K for a density of 500 and 0.181 W/m²K for a density of 600. In second place are type 25 P+W ceramic blocks with a U coefficient of 0.213 W/m²K. Both the prefabricated expanded clay concrete structure and the wooden frame structure exhibit the least favorable thermal parameters at approximately U ≈ 0.24 W/m²K.

Table 6. Summary of U-value results depending on the material. *Source*: own study

Material	Overall heat transfer coefficient U	The thickness of the outer wall
	[W/m²·K]	[m]
Aerated concrete blocks		
TYPE 500	0.173	0.42
TYPE 600	0.181	0.42
Ceramic blocks		
TYPE 25 P+W	0.213	0.43
Wooden skeleton construction		
Wood- pine	0.249	0.271
Prefabricated walls made of expanded clay concrete		
expanded clay concrete	0.243	0.33

Unlike traditional technology, prefabrication and frame construction feature smaller thicknesses for external partitions. Walls constructed with expanded clay concrete are only 33 cm thick, while frame walls are approximately 27 cm thick. The research results indicate that this difference directly affects thermal protection conditions. To comply with the relevant thermal protection regulations for buildings, the thickness of thermal insulation may need to be increased in selected cases.

Tables 7. Summary of thermal insulation thickness results. *Source*: own study

Material	Overall heat transfer coefficient U	The thickness of the outer wall	The thickness of the thermal insulation
	[W/m^2·K]	[m]	
Aerated concrete blocks			
TYPE 500	0.20	0.39	0.11
TYPE 600	0.20	0.40	0.12
Ceramic blocks			
TYPE 25 P+W	0.20	0.44	0.15
Wooden skeleton construction			
Wood- pine	0.20	0.31	0.175
Prefabricated walls made of expanded clay concrete			
expanded clay concrete	0.20	0.36	0.17

Analyzing the selected technologies in terms of meeting the maximum heat transfer coefficient U in comparison to the thickness of the external walls, the wooden frame structure emerges as the most advantageous. The condition of thermal protection is satisfied with a partition thickness of 31 cm, and the thermal insulation, in this case, must be at least 17.5 cm thick with a coefficient of $\lambda = 0.038$ m·K/W. In the case of prefabrication from expanded clay concrete, the overall external partition occupies 36 cm, with 17 cm dedicated to thermal insulation. When using aerated concrete blocks for construction, thermal insulation with a thickness of 11-12 cm would be sufficient, resulting in a total wall thickness of approximately 39-40 cm.

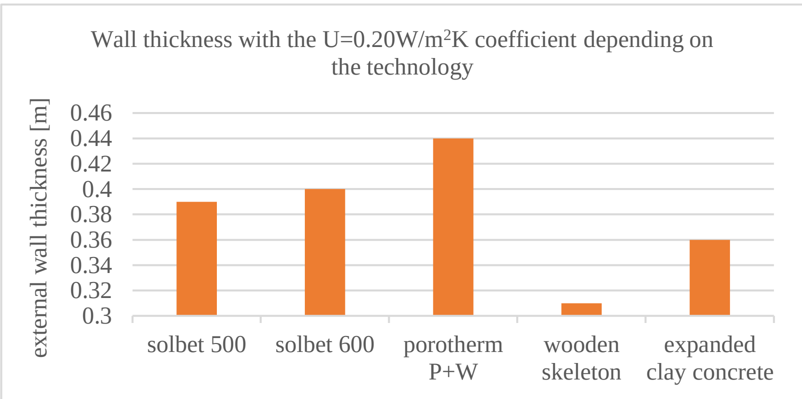

Fig. 5. Wall thickness with the U=0.20 W/m^{2}K coefficient depending on the technology. *Source*: own study

5. Conclusions

Currently, the market for building materials used in residential construction offers a diverse range of products with varying technical and thermal parameters. The use of traditional technology provides numerous possibilities, allowing for the selection of ceramic products, aerated concrete, and other mixtures that enhance their fundamental properties. Designers, armed with knowledge about the properties of specific products available in the market, can significantly influence the energy consumption of a building throughout its life cycle. An important advantage of this technology is the ability to utilize materials from demolition, recycling, or other forms of recovery, which substantially contributes to reducing gas emissions and safeguarding the natural environment. As research indicates, prefabricated and frame structures exhibit much lower thickness in their structural walls while maintaining the same level of thermal insulation as brick structures. A notable advantage is also the rapid construction of walls achieved by transferring a part of the construction process to production plants. However, it's essential to acknowledge that this technology does not align with the current principles of sustainable development included in the policies of many countries worldwide. In this context, significant actions are crucial not only to minimize the energy consumption of the building but also to ensure low energy consumption in production.

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