TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

3-B/2013

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TECHNICAL AND ECONOMIC ANALYSIS OF CERTAIN EXTERNAL WALL INSULATION SOLUTIONS IN POLAND

A b s t r a c t

This paper presents the characteristics of four types of thermal insulation, with the application of: polystyrene panels, mineral wool panels, polyurethane foam panels, and phenolic foam panels. The technical parameters, prices, and amount of labour related to wall construction technology with the application of the thermal insulation materials listed above were discussed. The goals of this article are: to compare technical parameters of certain types of thermal insulation, to provide an economic analysis of the chosen wall insulation solutions, and to choose the type of thermal insulation that is most beneficial in terms of the relationship of price to quality.

Keywords: wall insulation, thermal insulation material, technical and economic analysis

S t r e s z c z e n i e

W artykule przedstawiono charakterystyki czterech rodzajów termoizolacji: z zastosowaniem płyt styropianowych, płyt z wełny mineralnej, płyt z pianki poliuretanowej oraz płyt z pianki fenolowej. Omówiono parametry techniczne, ceny i nakłady pracy związane z technologią wykonania ścian z zastosowaniem wymienionych materiałów termoizolacyjnych. Celami artykułu są: porównanie parametrów technicznych wybranych rodzajów termoizolacji, analiza ekonomiczna wybranych rozwiązań ocieplania ścian ograniczona do wykonanycha kosztorysów i wybór rodzaju termoizolacji, który jest najkorzystniejszy ze względu na stosunek jakości do ceny.

Słowa kluczowe: ocieplanie ścian, materiał termoizolacyjny, analiza techniczno-ekonomiczna

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1. Introduction

External walls are the most important structural element of a building. They support ceilings and the roof and protect the interior of a building against external factors. At a time of rising energy prices, walls should, above all, protect a house from the escape of heat. Appropriate thermal insulation can prevent heat from escaping. A wide assortment of insulation materials in various forms is available on the market. Every manufacturer praises its product, and if it decides to compare it with a different type of thermal insulation, it does so only on the basis of those parameters which compare favourably. In addition, the thermal insulation product sector is dominated by manufacturers of conventional materials. Currently, despite increasing knowledge on the subject of profit related to energy savings, related in turn to well-made thermal insulation, the choice of thermal insulation material is mainly dependent on price. Thus, when deciding to insulate a building, an investor often chooses the product about which it has the most information and that is generally available in large quantities at a low price. However, it is possible that the selection of a more expensive material with better parameters is more advantageous due to lower costs of building use. The subject matter of thermal insulation of walls has been presented in many papers [1, 4, 5, 7, 11, 12]; however, there are very few publications that list and compare thermal insulation materials according to a series of criteria that can help e.g. an investor to make a decision.

This article presents the characteristics of four types of thermal insulation: polystyrene panels, mineral wool panels, polyurethane foam panels, and phenolic foam panels. The technical parameters, prices, amount of labour, and the technologies of wall construction required for the application of each will be discussed. These parameters are compiled in a table and compared. Economic analysis is limited to the preparation of cost estimates in which the amount of labour is determined [6, 9]. The prices of building a wall insulated with a given insulating material are determined based on cost estimates of the construction of these partitions for a single-family house that serves as an example in this paper.

The goals of this article are:

- to compare the technical parameters of certain types of thermal insulation,
- to provide economic analysis of certain wall insulation solutions,
- to select the type of thermal insulation that is most advantageous in terms of its cost-to--quality ratio.

This article can serve as a source of data and information that will be helpful when deciding on a type of external wall insulation.

Cost estimates will be made using the example of the single-family house design ‘Dom pod jarząbem 4 (G2)’ [17] in the Zuzia cost estimate program. The prices contained therein will be accepted as average prices according to the SEKOCENBUD price list for the fourth quarter of 2012 and data made available by manufacturers and contractors.

2. Comparison of the technical parameters of external wall thermal insulation solutions

2. 1. Thermal insulation parameters

Panels for insulating external walls made from 4 alternative materials were selected for analysis. The parameters of the four analysed thermal insulation materials are compiled in Table 1. Technical data concerning individual parameters was taken from standards [13–16] as well as from manufacturers. Some values are given quantitatively, while others can only be presented descriptively. In addition, numerical parameters are presented in charts (except porosity, due to very similar values, and tensile strength perpendicular to surfaces, due to a lack of data for polyurethane foam) Fig. 1–4.

The parameters which can be given only in a descriptive (qualitative) way have been determined on the basis of the adopted definitions, presented below.

Fire resistance – resistance to the destructive impact of fire during its spontaneous and uncontrolled spread over the material, in the form of changes to e.g. its structure, shape or mechanical durability [8].

Acoustic insulation – the insulation of a building partition from airborne sounds or/and impact noise, expressed as a difference between the sound in front of and behind the partition [18].

Durability – this parameter determines the impact of atmospheric factors, such as temperature, light, air, rain, ultraviolet radiation, on the properties of the material [8]

Material storage – this parameter determines the rules of material storage and the related difficulties.

Transport – this parameter determines the correct method of material protection during its transport.

Assembly – this parameter determines the degree of difficulty of work with the material.

Resistance to biological factors – the resistance of the material to the destructive activity of microorganisms, bacteria, fungi and certain insect species [8].

Resistance to chemical factors – this parameter determines the resistance of the material to various chemical substances which may cause its destruction during their contact with it.

Impact on human health – this parameter determines the impact (harmfulness) of the material on the human organism.

Ecology – this parameter determines the impact (harmfulness) of the material on the natural environment.

Method of destruction – this parameter determines the possibilities of material utilisation.

Table 1

Tabular compilation of the parameters of certain types of thermal insulation (authors' table)

Parameter	Unit	Polystyrene	Mineral Wool	Polyurethane Foam	Phenolic Foam
λ coefficient	$\frac{W}{m \cdot K}$	0.038–0.045	0.036–0.042	0.023–0.028	0.021–0.024
Bulk density	kg/m^3	15	150–180	30–35	35
Porosity	%	98	98	90–96	98
Absorbability	%	0.65–1.6	4–10	1–3	N/A

T a b l e 1 c o n .

Fire resistance	–	E	A1	E, up to 300°C	B-s1,d0
Acoustic insulation	–	low	high	medium	no data
Durability	–	high, but not resistant to UV radiation	high, but loses properties when damp	high	very high
Material storage	–	dry, covered rooms without access to flame	dry, covered rooms	dry, covered rooms without access to flame	for short-term storage – no requirements, for long-term storage – in covered rooms or with polyethylene foil covering
Transport	–	any mode of transport with safeguards	covered means of transport with safeguards	any mode of transport with safeguards	any mode of transport with safeguards
Assembly	–	easy	requires the observance of special health and safety measures, heavy panels	very easy	easy
Compression stress at 10% deformation	MPa	0.05–0.07	0.03–0.04	0.10–0.15	0.1
Tensile strength perpendicular to surfaces	MPa	0.1	0.01–0.08	not specified	0.08
Resistance to biological factors	–	resistant	resistant	resistant	resistant
Resistance to chemical factors	–	not resistant to petroleum derivatives or organic solvents	resistant	not resistant to acids with high concentrations	not resistant to acids with high concentrations
Impact on human health	–	harmless	emits dust and stings during assembly, harmless to the users of insulated rooms	emits harmful substances during a fire	harmless
Ecology	–	harmless	harmless	harmless	harmless
Method of destruction	–	burning or recycling	recycling	burning or recycling	burning or recycling

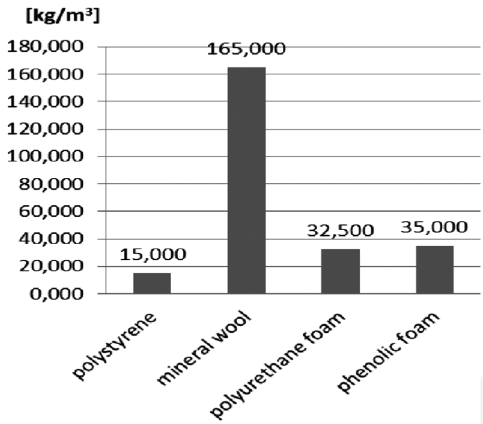

Fig. 1. Comparison of average bulk density values for 4 chosen thermal insulation materials (authors' chart)

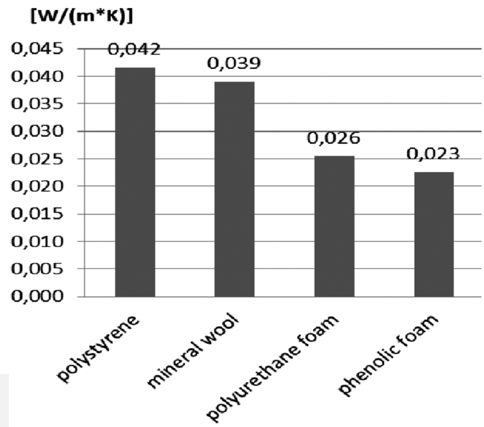

Fig. 2. Comparison of average λ coefficient values for 4 chosen materials (authors' chart)

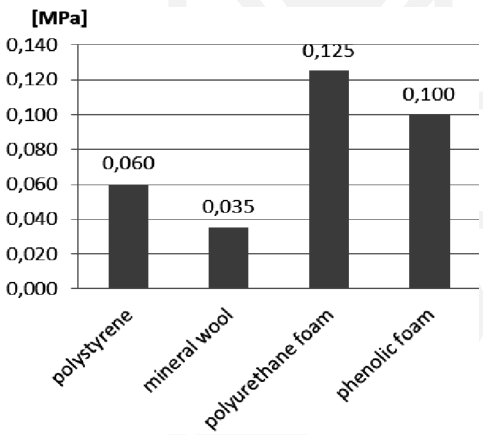

Fig. 3. Comparison of average compressive stress values at 10% deformation for 4 chosen thermal insulation materials (authors' chart)

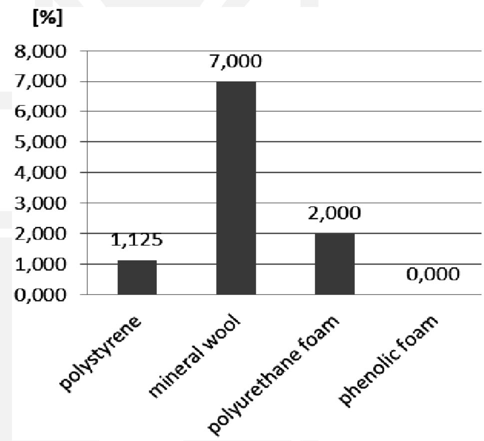

Fig. 4. Comparison of average absorbability values of 4 chosen thermal insulation materials (authors' chart)

The thermal conductivity coefficient λ for mineral wool and polystyrene is comparable, and the situation is similar for phenolic and polyurethane foam; however, the value of these foams is half that of the first two materials. Thus, when foam insulation is applied, the thickness of the material can be reduced by a(neral wool has the best resistance to fire. It is non-flammable and fully protects a building against fire. Phenolic foam has slightly inferior fire parameters: it is slow-burning. Polystyrene and polyurethane foam are classified in category *E* (self-extinguishing); however, polyurethane foam resists higher temperatures than polystyrene.

Mineral wool decidedly affords the best acoustic insulation. It is also the only material of the four that is resistant to all chemical substances. The other materials are characterised by high mechanical strength. Polystyrene has the best tensile strength perpendicular to surfaces; however, foams have better resistance to compressive stresses at 10% deformation.

In terms of absorbability, mineral wool is the most absorbent of all of the materials. Its durability, transport, and storage is related to this quality. When damp, it loses its properties, and so, in order to prevent this, it must be transported and stored appropriately. In contrast, phenolic foam, with an absorbability of zero, does not require special means of transport; it can be stored outside for a short time, and it lasts for a lifetime as long as the panel is not damaged.

Mineral wool is the heaviest material, and, because of this, the most difficult to install. Its mass may be up to 12 times greater than the mass of polystyrene. Dust and stinging from the material make mineral wool panels more difficult to install.

Porosity, impact on the natural environment, resistance to biological factors, and the method of destruction are comparable or the same for each of these insulating materials.

Table 2

Tabular compilation of the point score of parameters of certain types of thermal insulation (authors' table)

Parameter	Polystyrene	Mineral Wool	Polyurethane Foam	Phenolic Foam
λ coefficient	5	4	2	1
Bulk density	1	5	2	3
Porosity	1	1	2	1
Absorbability	2	5	3	1
Fire resistance	5	1	4	2
Acoustic insulation	4	1	2	3
Durability	4	4	2	1
Material storage	4	3	4	2
Transport	3	4	3	3
Assembly	2	3	1	2
Compression stress at 10% deformation	4	5	1	2
Tensile strength perpendicular to surfaces	1	2	3	3
Resistance to biological factors	1	1	1	1
Resistance to chemical factors	5	1	3	3
Impact on human health	1	3	3	1
Ecology	1	1	1	1
Method of destruction	1	1	1	1
TOTAL	45	45	38	31

2.2. Point scoring of thermal insulation parameters

The assessment of variants of the solutions in decision-making problems and taking into consideration multiple criteria makes use of the methods of multi-criteria analysis, e.g. TOPSIS, ELEKTRE, AHP, DEMATEL, BIPOLAR and many others [2,3,10]. Comparing measurable and non-measurable factors is usually done as non-measurable assessment by means of various methods of the so-called measure encoding, e.g. using the Peter method or standardisation [2]. The present study applies a much more simplified, practical approach to this issue. Point scoring system was used, which assigns each parameter of each material an appropriate number of points on a scale of 1–5, where: 1 – best, 2 – good, 3 – average, 4 – bad, 5 – worst.

It was assumed that every parameter has the same weight.

Based on the point scoring system, it can be stated that phenolic foam has the best technical parameters, and polystyrene and mineral wool, tied with the same number of points, have inferior properties.

3. Price and amount of labour of external wall insulation for a sample design

3.1. Design characteristics

The construction design on the basis of which cost estimates of external walls and the amount of labour will be made is 'Dom pod jarząbem 4 (G2)'. This design was developed by the ARCHON design company in Myślenice [17]. This design is a free-standing, ground-floor, single-family residential building without a basement. The house consists of 4 rooms, 1 kitchen, 1 bathroom, a pantry, boiler room, utility room, and garage. The usable area is 118.7 m^2 + garage 32.6 m^2. The walls were designed with Porotherm 30 P+W hollow bricks.
Data:

- perimeter of external walls – 68.66 m,
- wall height – 2.62 m,
- area of external walls – 179.89 m^2,
- area of openings – 41.95 m^2.

For calculations, the area reduced by the surface of openings was assumed to be 137.94 m^2.

3.2. Cost estimates, amount of labour, price

The prepared cost estimates of individual external wall insulation solutions are intended to indicate both the cheapest and the most expensive solutions. For every analysed solution, the structural wall is made of Porotherm 30 P+W hollow bricks, cleaned before insulation is laid down, and installed on a cove base. Polystyrene, mineral wool, and phenolic foam panels were glued to the walls with adhesive mortar, covered with a glass fibre mesh, and covered with a thin layer of plaster. Mineral wool and phenolic foam panels were additionally reinforced with metal connectors with a galvanised pin. Polyurethane foam panels were fastened to the walls with metal connectors with a galvanised pin and covered with a facade wall of full brick construction. The thickness of thermal insulation was calculated for a partition with a *U* coefficient of at least 0.3 W/m^{2}K.

The amount of labour determines the time necessary for the performance of all work and the composition of brigades employed at the construction site. For masonry work, a brigade composed of 2 masons, 1 carpenter, and 2 workers was assumed; for installation of thermal insulation glued to the wall, 4 plasterers and 1 worker; and for fastening, 1 plasterer and 1 worker. The following brigade was assumed for installation of thermal insulation fastened with metal connectors: 2 assembly men and 1 worker. For plaster work, 2 plasterers and 1 worker were assumed.

The price of construction of an external wall with insulation is dependent, above all, on the price of material. The cheapest among the four analysed materials is polystyrene, so it is cheapest to insulate walls with it. The mineral wool solution is not much more expensive (approximately 5,500 PLN more). In the case of foams, the situation is different. Installation of polyurethane foam panels on walls is over 4,000 PLN cheaper than installation of phenolic foam panels; however, the fact that polyurethane foam panels can only cover the facade wall makes the construction of walls insulated with polyurethane foam over 19,500 PLN more expensive than with phenolic foam. The difference between the cheapest solution (polystyrene) and the most expensive (polyurethane foam) amounts to over 27,500 PLN. Thus, if polystyrene is chosen, a building with an external wall surface of nearly twice the area can be insulated in comparison to polyurethane foam.

The time to perform the work for all solutions is very similar. Differences between solutions range from 1–2 days. The time required for raising and insulating walls with phenolic and polyurethane foams is the same. The analysed house design can be insulated the most quickly by using polystyrene panels, while mineral wool takes the longest to install.

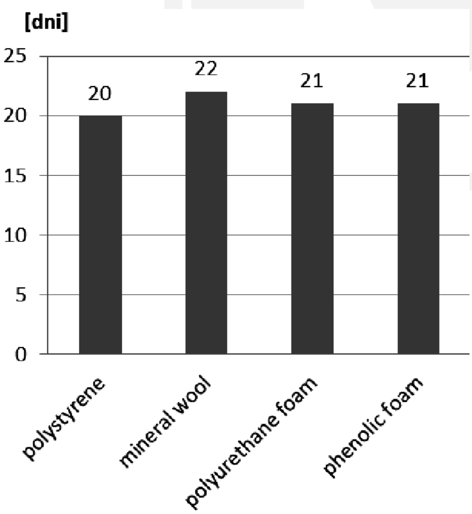

Fig. 5. Number of days required for construction of a wall insulated with one of the four chosen thermal insulation materials (authors' chart)

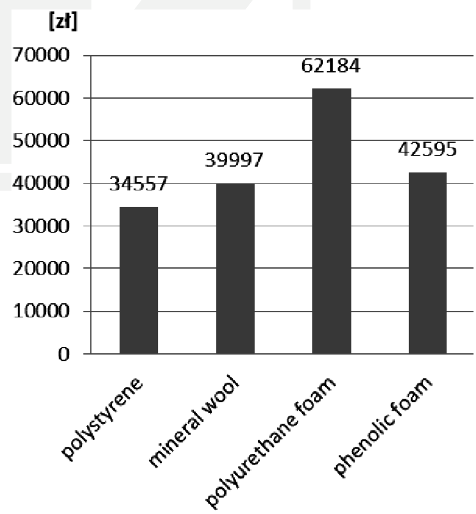

Fig. 6. Price of construction of an external wall insulated with one of the 4 chosen thermal insulation materials (authors' chart)

3.3. Point score of price and time of insulation installation

Because the price and time of insulation installation are specified using different units, it is difficult to evaluate them. In relation to this, a point scoring system was used, which assigns each wall insulation solution with the application of a given material an appropriate amount of points on a scale of 1–5 according to the price and time of installation, where 1 – best, 2 – good, 3 – average, 4 – bad, 5 – worst.

Table 3

Tabular comparison of the point scores of external wall insulation solutions according to time and price of installation (authors' table)

Parameter	Polystyrene	Mineral Wool	Polyurethane Foam	Phenolic Foam
Price	1	2	5	3
Time	1	3	2	2
TOTAL	2	5	7	5

Based on the point score, the best solution is the one with polystyrene panels and the worst with polyurethane foam, as evaluated by time and price of installation.

4. Summary of the technical and economic analysis

Based on the point scoring system, each material received an appropriate number of points in the technical and economic analysis, respectively. To compare these analyses, points were assigned on a scale of 1–4, where: 1 – first place, 2 – second place, 3 – third place, 4 – fourth place. Based on the sum of the points from the two analyses, materials were assigned places that determine which type of thermal insulation has the most advantageous price-to-quality ratio.

Table 4

Comparison of the results of technical and economic analysis and specification of the thermal insulation material with the most advantageous price-to-quality ratio (authors' table)

Analysis	Polystyrene	Mineral Wool	Polyurethane Foam	Phenolic Foam
Technical	45	45	38	31
Score	3	3	2	1
Economic	2	5	7	5
Score	1	2	3	2
Sum of points	4	5	5	3
PLACE	2	3	3	1

Phenolic foam panels took first place among the four types of thermal insulation. They mainly owe this to possession of the best technical parameters. Polystyrene panels placed second due, above all, to the lowest cost of insulation and the shortest time of installation. Mineral wool and polyurethane foam tied for third place.

5. Final conclusions

The decided majority of investors look at the price of material when selecting an insulation system, and only later consider the parameters of the system. According to the authors of this paper, this is a poor approach. The type of thermal insulation is often chosen with less precision than the house's furniture or finishing elements, even though the cost of replacement of the latter is much cheaper and less troublesome than thermal modernisation of the entire building. The analysis shows that the price of material alone does not always mean that a given solution is the cheapest, as can be seen from the example of polyurethane foam panels. In addition, the lowest cost of building insulation does not go hand in hand with low maintenance costs. Technical parameters have an impact on the future use of the building, and the better the technical parameters, the less the use-related costs. That is why it is worth paying attention to the parameters, not only the price, of a given material when choosing thermal insulation.

This paper describes and compares the technical parameters, cost, and time of construction of walls insulated with polystyrene, mineral wool, polyurethane foam, and phenolic foam. A point-scoring system was used to evaluate each analysis and to determine which thermal insulation material is the best and which is the worst among the four analysed materials. Next, both analyses were combined in order to determine which material has the best price-to-quality ratio.

It is impossible to change the mentality of people, and the materials most often used for external wall insulation will continue to be conventional materials like polystyrene and mineral wool. Investors oriented towards insulating a building at the lowest cost choose polystyrene, and, according to the conducted analysis, their decision is justified. However, those who decide to insulate a building with mineral wool should think about choosing the material that placed first according to the analysis: phenolic foam panels. The cost of insulating a building with phenolic foam panels is only 6% greater than the cost of mineral wool panels, while its technical parameters are significantly better and will enable the user to enjoy a durable, very thin, and impact-resistant facade for years.

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