SCIENTIFIC PAPER
Published: February 5, 2025
https://doi.org/10.13167/2025.30.2

# New energy-efficient composite wall from expanded polystyrene concrete in fixed formwork

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**Received:**
February 4, 2024

**Revised:**
August 20, 2024

**Accepted:**
September 4, 2024

**Published:**
February 5, 2025

**Citation:**
Meneylyuk, O. et al.
New energy-efficient composite wall from expanded polystyrene concrete in fixed formwork.
*Advances in Civil and Architectural Engineering*, 2025, 16 (30), pp. 24-42.
https://doi.org/10.13167/2025.30.2

**ADVANCES IN CIVIL AND ARCHITECTURAL ENGINEERING (ISSN 2975-3848)**

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**Abstract:**
This study focused on the development and verification of the effectiveness of a new energy-efficient composite wall made of polystyrene foam concrete in a fixed formwork, prepared using light steel thin-walled structures and polystyrene foam concrete as an aggregate. This research included the development of the new patented solution, a multi-criteria analysis of this solution through comparison with the most common solutions, and experimental investigations of the heat transfer resistance of the new wall. Based on the results of a multi-criteria analysis involving eight criteria, it was established that the new solution of a composite wall in a fixed formwork is more effective than 13 traditional alternatives. Experimental studies on the heat transfer resistance, conducted at the laboratory of the Scientific Research Institute of Building Structures in Kyiv, demonstrated the heat-insulating properties of the new wall. The installation of the new wall at an actual construction site confirmed the reduction in labour and material consumption owing to the new technology. Thus, for the first time, the experimental results of the heat transfer resistance of the new wall at two cross sections (maximum thickness of polystyrene foam concrete and maximum accumulation of steel elements) made it possible to substantiate the need for external insulation of the wall. Low values of the specific labour intensity, material intensity, as well as the possibility of installing wall elements with minimal use of construction equipment make it possible to use the developed solution for a wide range of construction structures.

**Keywords:**
composite wall; heat transfer resistance; expanded polystyrene concrete; light steel thin-walled structures; fixed formwork

## 1 Introduction

During the patent search, a large number of solutions for non-load-bearing composite walls were analysed, including those using expanded polystyrene concrete, fixed formwork, and light steel thin-walled structures. However, no solution was found that would combine all the specified elements. The proposed solution has significant advantages in terms of labour and material consumption. The reduction in labour intensity is achieved by reducing the number of assembly operations, which also reduces the equipment requirement to primarily a crane and inventory formwork. The reduction in material capacity involves a combination of materials with properties that improve each other. A new energy-efficient wall in a fixed formwork made of polystyrene concrete can be used as an enclosing structure for low-rise residential, industrial, and high-rise buildings. The lightness of the wall and possibility of manual assembly of the elements allow the technology to be used under special conditions, such as in difficult soil conditions, during the reconstruction or restoration of damaged elements.

A preliminary analysis showed that the existing technologies for fencing structures are less effective than the proposed solution. However, the thermophysical characteristics of the new technology must be experimentally studied. According to the normative documents of Ukraine, the main factor is heat transfer resistance, which shows the heat-insulating capacity of the enclosing structure. Considering the fact that in most cases, the developed wall in a fixed formwork is non-load-bearing, heat transfer resistance becomes the main characteristic of such walls. Experimental laboratory studies on a new wall in a fixed formwork made it possible to substantiate the optimal design of the wall to improve its thermophysical characteristics. In this case, the wall has high operational characteristics while maintaining technical and economic efficiency.

## 2 Analysis of information sources

An analysis of the information sources on the topic under consideration showed that the construction of multilayer composite fencing structures is a relevant topic. The results of compressive strength optimisation in an existing study [1] showed that polystyrene concrete can achieve a concrete strength suitable for residential purposes and can be used as a partition in high-rise buildings because of its light weight. Another study [2] reported the development of an innovative fibre-reinforced sandwich panel with polymer concrete filling, which had significantly higher strength and was intended for wall construction. The structural behaviour of an expanded polystyrene core of reinforced concrete sandwich panels under axial and plane shear loading was experimentally investigated [3]. An experimental study was conducted on samples comprising factory-made corrugated cores, welded meshes, and orthogonal shear connectors. Among the relevant publications, papers reporting the study of walls using lightweight concrete [4], a combination of steel structures and concrete [5, 6], and cement chipboards [7] were selected. The considered publications prove the effectiveness of installing a composite wall using a fixed formwork, lightweight concrete filling, and steel-bearing elements.

With the adoption of European norms for energy efficiency in Ukraine, research on the heat transfer resistance of new materials has become highly relevant. The strength and stiffness of the frame-glued concrete panel were investigated using load-displacement tests, and its thermal performance was evaluated using a hot storage apparatus [8]. The volumetric heat capacity and thermal conductivity coefficient of precast reinforced concrete walls were experimentally determined [9] in combination with a low-cement-cast lightweight concrete core under dry, hygroscopic, and superhygroscopic conditions. In [10], the specific thermal resistance, sound absorption, and vibration damping of rubber concrete were investigated. Therefore, studying the heat transfer resistance of composite frame walls remains relevant.

The following inventions were considered analogous to the proposed composite wall: ‘Multilayer panel’ [11] and ‘Building Wall’ [12].

As part of the multi-criteria analysis, various innovative and traditional technologies were considered, including Styrofoam blocks [13, 14]; Styrofoam blocks with a wall-levelling system

[15, 16]; polystyrene concrete blocks [17]; concrete blocks [18]; blocks of cement-chip material with polystyrene foam inserts [19]; large-sized polystyrene foam panels [20]; three-layer reinforced polystyrene panels [21]; cement chipboards [22]; concrete slabs with decorative coating [23]; fibre concrete slabs [24]; glass-magnesium plates [25]; and cement chipboard [26].

The Scientific Research Institute of Building Structures developed and approved an appropriate methodology for conducting the planned experimental studies. Tests to determine the heat transfer resistance of a composite wall made of expanded polystyrene concrete in a fixed formwork were carried out in accordance with the State Standard of Ukraine B V.2.6-101:2010 “Method for determining the heat transfer resistance of enclosing structures” [27]. The calculated moisture content of the materials was determined according to [28]. The freezing temperatures of the samples were set based on the temperature zone of the installed product in accordance with the values of the calculated outdoor air temperature [29]. The durations of freezing, thawing, and heating of the samples were set according to [21].

## 3 Purpose and objectives of the research

The purpose of this study was to develop and substantiate the effectiveness of a new energy-efficient composite wall made of polystyrene concrete in a fixed formwork. The relevant research objectives are as follows:

- Comparison of the existing structural and technological solutions for composite walls in a fixed formwork and development and patenting of a new energy-efficient wall made of polystyrene concrete in a fixed formwork.
- Multi-criteria analysis of the developed composite wall solution in comparison with known technologies according to the following criteria: wall thickness, heat transfer resistance, weight of 1 sq. m. of wall, area of premises with dimensions of 10 × 10 m of buildings, cost, durability, shrinkage of wall material, and resistance to mould, rotting, and destruction.
- Develop a methodology and conduct experimental studies on the heat transfer resistance of a new composite wall made of polystyrene concrete in a fixed formwork.
- Implement a new solution of a composite wall in a fixed formwork.

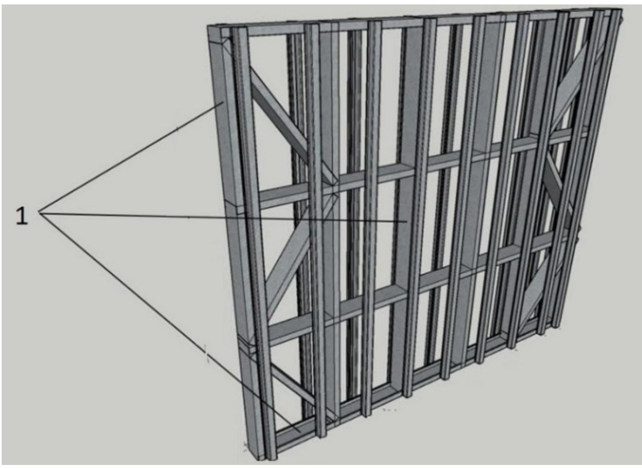
## 4 Development and patenting of a new solution

The known multilayer panel [11] consists of inner and outer layers, which are plates made of flat wood shavings. An inner insulation layer made of polystyrene foam or polyurethane foam is added between these layers. The plates and insulation layer are bonded together with glue, and the panels at the ends contain a groove for installing the load-bearing structural elements. The disadvantages of this design are the low vapour permeability of the panel material and cost of manufacturing the panels under enterprise conditions. A powerful press is also necessary; any deviation from the established technology causes the polystyrene foam structure to lose its strength.

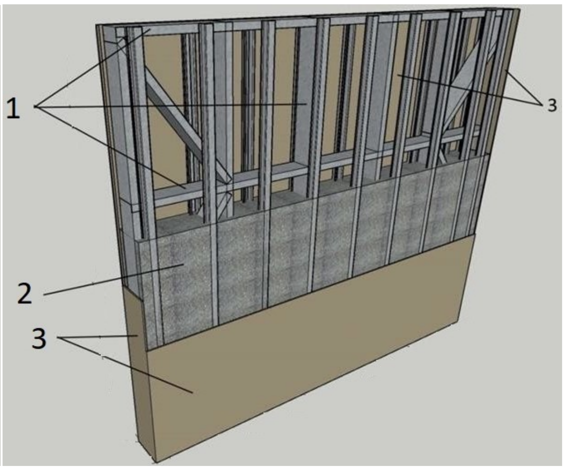
The element closest to the proposed patent is the wall of the building [12], containing the inner and outer enclosing layers; the main massif of the wall is made of polystyrene concrete and is located between the inner and outer enclosing layers. The inner and outer protective layers are composed of magnesite plates. In the upper and lower parts of the magnesite plates, depressions are made in which planar fasteners are installed on the adjacent magnesite plates, and the plane fasteners on the opposite magnesite plates are connected in pairs. However, its main drawback is the lack of a frame in the structure, resulting in inadequate stability and stiffness of the structure in seismic zones and under dynamic loads. The second disadvantage is the high cost of magnesite plates when compared with that of their analogues.

The essence of the new constructive and technological solution is as follows. The wall of the building contains internal and external enclosing layers. The main massif of the wall, made of expanded polystyrene concrete, is located between the internal and external enclosing layers

of the cement chipboards, which are connected with self-tapping screws to the supporting frame made of a metal profile, obtained as ready-to-assemble enlarged parts with a set of fasteners. The essence of the patent can be explained using the following model:
Figure 1, a depicts the metal profile frame, which serves as the load-bearing element; Figure 1, b shows the general appearance of the wall, including all layers required by the installation technology; Figure 1, c shows the transverse (horizontal) section of the wall according to the installation technology.




a)

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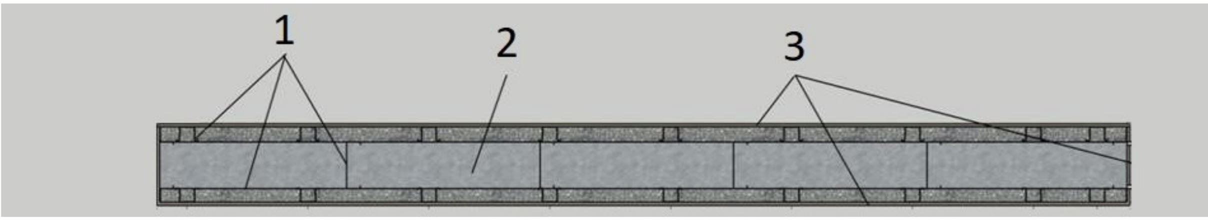



c)

**Figure 1. Schematic of a new composite wall made of expanded polystyrene concrete in a fixed formwork using light steel thin-walled structures: a) frame made of light steel thin-walled structures; b) general appearance of the wall, including all layers placed according to the arrangement technique; c) transverse (horizontal) section of the wall according to the installation technology. Conventional designations: 1 - frame with light steel thin-walled structures; 2 – expanded polystyrene concrete; 3 - cement chipboards**

The use of the patented wall made of expanded polystyrene concrete increases the manufacturability and pace of construction of load-bearing monolithic reinforced concrete walls with energy-efficient properties. This material has numerous advantageous characteristics that distinguish it from other materials for fencing structures: thermal conductivity 0,070 W/(m·K), vapour permeability coefficient 0,12 mg/(m·h·Pa), frost resistance F300, and flammability group G1 (refractory material). Simultaneously, a reduction in labour intensity, construction time, and material consumption is achieved because of the use of a frame made of metal profiles, which is not dismantled and remains in the body of the structure, thus providing rigidity and load-bearing capacity owing to the reliable combination of polystyrene foam concrete in the inner layer of the wall structure and a metal spatial frame with light steel structures (LSTWS). Because of this, monolithicity and high stability during the installation and operation of the special structure are achieved, which increases the operational reliability, heat-saving properties of the structure, service life, and economy.

## 5 Evaluation of the new solution in comparison with known ones using multi-criteria analysis

Modern structural and technological solutions for fencing structures in a fixed formwork [26, 30] and the proposed solution are presented in the form of a hierarchical classification (Figure 2) consisting of four groups of fixed formworks: blocks, panels, plates, and monolithic frame formworks with metal frame cladding. These groups were considered representative of all modern technologies in this field.

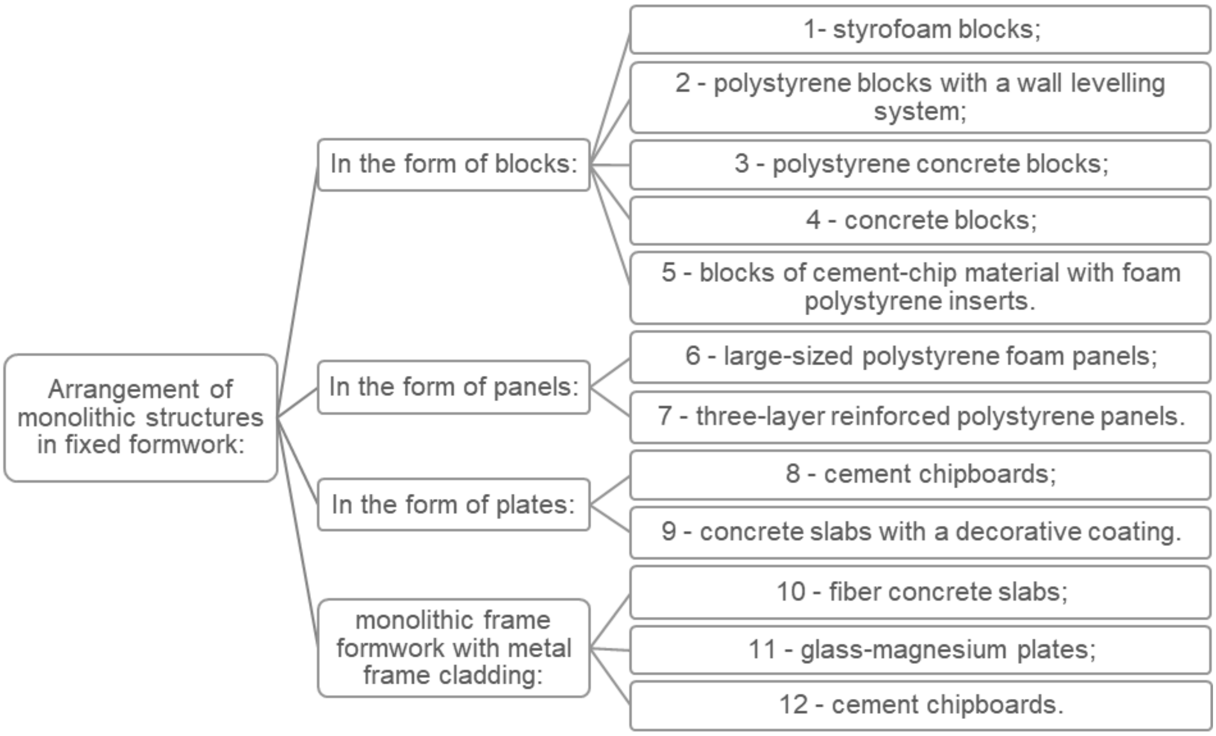



**Figure 2. Classification of monolithic structural and technological solutions in fixed formwork**

### 5.1 Determining the main criteria for comparing the selected structural and technological solutions and drawing up an analytical table

To make the optimal decision regarding the choice of structural and technological solutions for a fixed formwork, it is important to determine the main characteristics, which can be economic, technical, environmental, social, or other factors. Based on the search for relevant information about the selected technologies and to make an effective decision regarding the choice of technology, the following evaluation criteria were adopted:

- Quantitative:
  - Wall thickness: Calculated based on the thickness of all layers of the finished structure and heat transfer resistance (mm).
  - Weight of 1 sq. m. of wall, calculated based on the weight of all layers of the finished structure (kg).
  - The area of the premises when the dimensions of the buildings are 10 × 10 m is calculated based on the thickness of the protective structure ($m^2$).
  - Cost – calculated depending on constructive decision-making.
  - Durability – adopted on the basis of normative documents and literary sources (years).
  - Tendency to shrink – adopted on the basis of normative and literary sources (%).

- Qualitative: resistance to the formation of mould, rotting, and destruction.

The technologies for erecting enclosing structures according to the selected criteria were compared based on the analysis of the information sources and the presented calculations for the heat transfer resistance, thickness of the enclosing structures, and estimated calculations of the cost of erecting 1 m$^2$ of the enclosing structures [26]; the results are presented in Table 1. Quantitative evaluations of the criteria were performed from the physical units of measurement on a ten-point scale. The technologies were evaluated based on the quantitative criteria using a ten-point scale, where the least and most effective values were assigned 1 and 10 points, respectively. The remaining points were calculated using interpolation. The physically measured indicators are shown on the upper line for each technology and the respective ten-point scale values are presented on the lower line.

## 5.2 Selection of the option of fixed formwork according to the main criteria

The pivot table, implemented in Microsoft Excel, is a tool for processing the estimates for multi-criteria analysis. These along with the pivot table (Table 1) can be used to summarise, analyse, and study the data from external sources. First, a general diagram that groups the values of the quantitative criteria by technology is presented (Figure 3).

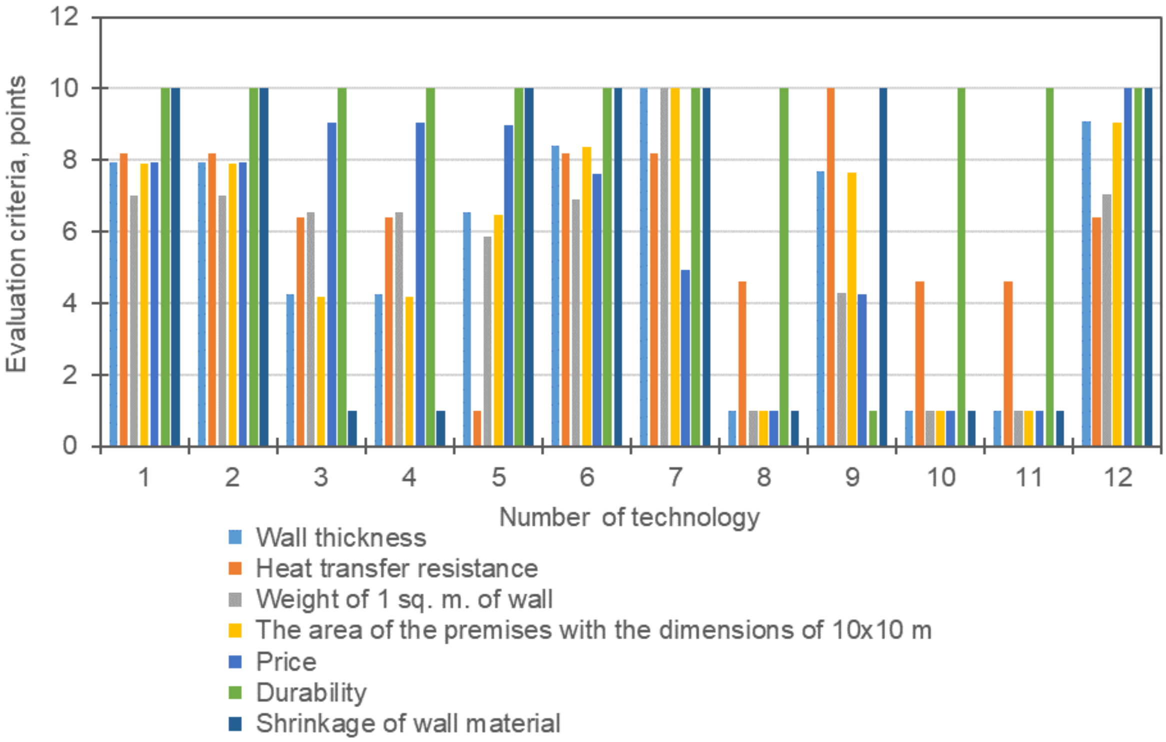



**Figure 3. Comparison of wall erection technologies by points in the pivot diagram (the technology numbers can be cross-referenced from Table 1)**

By analysing Table 1 and the pivot diagram (Figure 3) of the considered structural and technological solutions, it can be seen that heat transfer resistance satisfies the normative value set for the II temperature zone $R_{q,min}$ = 2,8 m$^2$K/W. Therefore, it was not considered further. The remaining criteria are important when choosing a technology and are used for further comparison.

Among the selected technologies in Table 1, the cement chipboard wall arrangement is the least effective, as it shows the poorest values for all indicators. The material weight increases the cost of its delivery, requires heavy equipment for unloading at the construction site, and imposes an additional load on the foundation. One of the important advantages of modern buildings is the significant increase in the useful area of the house, owing to a significant reduction in the thickness of the load-bearing walls. This advantage is especially relevant for private construction owing to the high cost of land plots. Therefore, constructive solution 8 (Table 1) can be disregarded in the future. The remaining solutions were analysed further using pivot diagrams.

**Table 1. Comparison of selected structural and technological solutions of fixed formwork walls**

| | | Evaluation criteria | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Wall thickness, mm | Heat transfer resistance, m$^2$K/W | Weight of 1 sq. m. of wall, kg | Area of the premises with dimensions of 10x10 m | Price, UAH/m$^2$ | Durability, years | Shrinkage of wall material, % | Resistance to mold rot and destruction |
| # | Technologies | the same in points, reversed | the same in points, proportionally | the same in points, reversed | the same in points, proportionally | the same in points, reversed | the same in points, proportionally | the same in points, reversed | |
| 1 | Fixed formwork "Thermod, Legod, Izod" [13, 14] | 340,00 | 3,20 | 386,00 | 86,90 | 1817,00 | 100,00 | 1,00 | Yes |
| | | 7,92 | 8,20 | 7,02 | 7,91 | 7,94 | 10,00 | 10,00 | |
| 2 | Polystyrene blocks with wall leveling system [15, 16] | 340,00 | 3,20 | 386,00 | 86,90 | 1817,00 | 100,00 | 1,00 | Yes |
| | | 7,92 | 8,20 | 7,02 | 7,91 | 7,94 | 10,00 | 10,0 | |
| 3 | Formwork from polystyrene concrete blocks [17] | 500,00 | 3,10 | 400,00 | 81,00 | 1615,00 | 100,00 | 2,00 | Yes |
| | | 4,23 | 6,40 | 6,54 | 4,17 | 9,04 | 10,00 | 1,00 | |
| 4 | Formwork from cement-chip blocks [18] | 500,00 | 3,10 | 400,00 | 81,00 | 1615,00 | 100,00 | 2,00 | Yes |
| | | 4,23 | 6,40 | 6,54 | 4,17 | 9,04 | 10,00 | 1,00 | |
| 5 | Movable modular formwork of the "U" type [19] | 400,00 | 2,80 | 420,00 | 84,60 | 1630,00 | 100,00 | 1,00 | Yes |
| | | 6,54 | 1,00 | 5,85 | 6,45 | 8,96 | 10,00 | 10,00 | |
| 6 | Fixed formwork "Plastbau" [20] | 320,00 | 3,20 | 390,00 | 87,60 | 1876,00 | 100,00 | 1,00 | Yes |
| | | 8,38 | 8,20 | 6,88 | 8,35 | 7,61 | 10,00 | 10,00 | |
| 7 | Fixed formwork "SOTA, Z-D reinforced panel" [21] | 250,00 | 3,20 | 300,00 | 90,20 | 2369,00 | 100,00 | 1,00 | Yes |
| | | 10,00 | 8,20 | 10,00 | 10,00 | 4,92 | 10,00 | 10,00 | |
| 8 | Formwork from cement chipboards [22] | 640,00 | 3,00 | 560,00 | 76,00 | 3085,00 | 100,00 | 2,00 | Yes |
| | | 1,00 | 4,60 | 1,00 | 1,00 | 1,00 | 10,00 | 1,00 | |
| 9 | Fixed formwork "Technoblock" [23] | 350,00 | 3,30 | 465,00 | 86,50 | 2492,00 | 80,00 | 1,00 | No |
| | | 7,69 | 10,00 | 4,29 | 7,65 | 4,24 | 1,00 | 10,00 | |
| 10 | Frame-monolithic formwork with cladding of cement chipboards [24] | 640,00 | 3,00 | 560,00 | 76,00 | 3085,00 | 100,00 | 2,00 | Yes |
| | | 1,00 | 4,60 | 1,00 | 1,00 | 1,00 | 10,00 | 1,00 | |
| 11 | Frame-monolithic formwork with glass magnesite cladding [25] | 640,00 | 3,00 | 560,00 | 76,00 | 3085,00 | 100 | 2,00 | Yes |
| | | 1,00 | 4,60 | 1,00 | 1,00 | 1,00 | 10,00 | 1,00 | |
| 12 | Patent UA No. 149402 "Wall of a building" [26] | 290,00 | 3,10 | 385,00 | 88,70 | 1440,00 | 100,00 | 1,00 | Yes |
| | | 9,08 | 6,40 | 7,06 | 9,05 | 10,00 | 10,00 | 10,0 | |

According to most indicators (Figure 3), the least effective technologies are formworks from cement chipboards (8), frame-monolithic formworks with cement chipboard cladding (10), and frame-monolithic formworks with glass-magnesite cladding (11). These technologies had the lowest values of the following indicators: wall thickness, weight of 1 $m^2$ of the wall, area of premises with dimensions of 10 × 10 m, price, and shrinkage of the wall material. Therefore, these were not considered further in this study.
The Fixed TECHNOBLOK formwork has moisture-resistant plywood as an internal structural element, which, owing to its physical properties, requires one-time processing of the material with special mixtures, thereby reducing its service life. In addition, the cost of 1 $m^2$ of such a wall is UAH 2492, which exceeds the average cost of the other solutions. Therefore, constructive solution 9 (Table 1) was not considered further.
Next, the technologies were analysed according to the weight and wall thickness criteria, which affect the choice of the foundation base. It can be observed that the polystyrene concrete blocks have a significant thickness of 500 mm of the finished wall structure. This results in low strength characteristics, as polystyrene is a light building material. Therefore, solution 3 was not considered further (Table 1).
The price per $m^2$ of the fencing structure is the most important among the considered criteria (Figure 4); accordingly, the remaining solutions were analysed according to this criterion. The analysis shows that the solution according to UA patent No. 149402 "Wall of the building” is the least expensive and therefore the most effective with the following indicators: price per m2 is UAH 1 440, weight is 385 kg, and thickness is 290 mm, which provides a 11 % increase in the useful area of the internal premises when compared with that of a brick wall (603 kg and 530 mm), and a weight reduction of 1,5 times. The heat transfer resistance is 3,1 $m^2K/W$, which is higher than the normatively established value of 2,8 $m^2 \cdot K/W$ for the II climate zone of Ukraine. This ensures resistance to moisture, mould, and fungal damage to the wall, providing the advantage of the possibility of construction at any time of the year. The most expensive solutions among monolithic structures in fixed formwork are ‘SOTA’, ‘Plastbau’, ‘TIBE’, and ‘Thermodom’. Therefore, solutions 10, 11, and 12 were selected (Table 1).

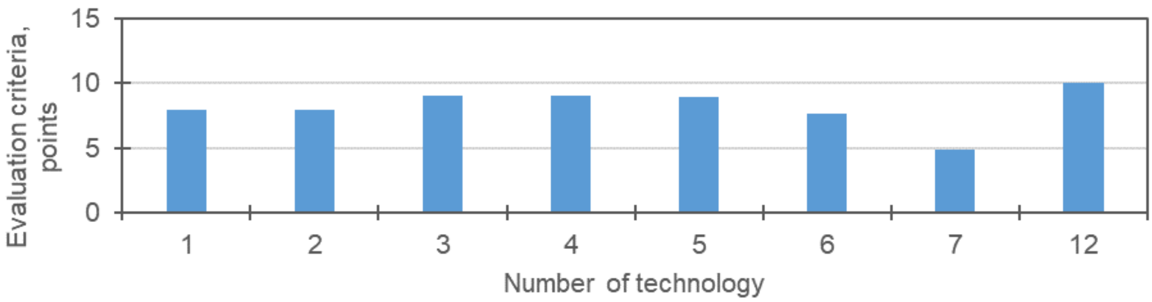



**Figure 4. Technology comparison diagram by price per $m^2$ (the technology numbers can be cross-referenced from Table 1)**

## 6 Experimental study of the patented structural and technological solutions

### 6.1 Research methodology for determining the operational properties of an enclosure structure made of expanded polystyrene in a fixed formwork

The test was conducted on samples of a fence structure made of expanded polystyrene concrete in an unchanged formwork manufactured in accordance with the technical documentation and technological regulations for these products.
Description of the tested structures: enclosing structures made of expanded polystyrene concrete in a fixed formwork for residential, public, and industrial buildings operated in temperature zones I and II of Ukraine (in accordance with [31]).
To determine the heat transfer resistance of an enclosing structure made of expanded polystyrene concrete in a fixed formwork, the following samples were prepared:

- Design solution No. 1 – 1 pc. (1200 x 800 mm),
- Design solution No. 2 – 1 pc. (1200 x 800 mm).

The types and main characteristics of the test and measuring equipment, which were used to record the parameters of the surrounding environment during the tests, are listed in Table 2. Tests to determine the thermal conductivity of the heat-insulating and structural heat-insulating materials in the initial dry state were conducted in accordance with [32] under the standard temperature condition, namely, a temperature of 283 °K (10 °C). The setup for testing the thermal conductivity at 283 °K (10 °C) is shown in Figure 5.

**Table 2. Types and characteristics of test and measuring equipment**

| Name of testing equipment and measuring equipment | Factory number | Accuracy characteristics | Measurement range |
|---|---|---|---|
| Climatic chamber KTK-3000 | No. 236103 | Dimensions of useful space, mm: 1200x1500x1650 | Temperature range, °K: -30 - +100 |
| CC climate chamber | No. 5 | Temperature setting accuracy, °K: 0,1 | Temperature range, °K: -10 to +60 |
| Agilent 34970A data acquisition system | No. MY-44051833 | Switching speed (channels/sec) 60. | Max voltage 300 V. Max. current 1 A |
| Chromel-drop thermoelectric converters, | No. 01...20 | Measurement error ± 0,2 $^0$K | Temperature range -200...+600 K |
| Psychormeter MV-4M, | No. 26431 | Measurement error: ±1% | Temperature range: -25-50 ºK. Range of relative air humidity: 10% to 100%. |
| Thermometer laboratory TL | No. 3871 | measurement error ±0,1 $^0$K | Temperature range, °K: -20...+150 |
| Measuring tape metal | No. 1 | Accuracy class: II | Tape length: 10 m |
| Calipers | No. 078538 | Measurement error 0,03 mm | Measurement range: 0 - 150 mm |
| BAMM-1 aneroid barometer | No. 101518 | Limits of permissible errors: ± 0,2 kPa | Pressure measurement range: 80 - 106 kPa |
| Non-automatic weighing device Dniproves | No. 74 | The price of division, g: 10 | Weighing limits, kg: 30-200 |
| Camera for heat treatment HPS-222 | No. 35850560 | Temperature uniformity: ±0,05 ºK at 100 ºK ±0,10 ºK at 200 ºK ±0,20 ºK at 300 ºK | Temperature range: 40-300 ºK |

**Figure 5. Installation for testing thermal conductivity at a temperature of 10 °C**

The sample prepared for testing was installed in the testing device according to the process adopted in a previous study [32]. The process ensured a close fit between the surfaces of the

test samples and those of the heater and refrigerator plates of the test device. The temperature of the heater plates and cooler of the test device were set so that the average temperature of the sample during the tests was (10 ±1) °K, and the measurements were made according to [32]. The temperature gradients of the samples during the tests did not exceed 1 °K/cm. After the measurements, the final moisture content of the sample ($w_f$, %) was determined, which influenced the obtained value of the thermal conductivity.
If the average sample temperature deviated from 10 °K by more than 1 °K, tests were carried out in the temperature range from −10 °K to 20 °K at no less than five temperature points.
The test results were recorded in the protocol.

### 6.2 Analysis of test results and error assessment

Based on the results of the temperature measurements using primary temperature transducers, the temperatures of the surfaces of the enclosing structure (internal and external) and ambient air near these surfaces (inside - $T_{surf.}^{int.}$ and outside - $T_{surf.}^{ext.}$) were determined. These temperature values (in degrees Celsius) were determined using the digital display readings of the contact and non-contact digital temperature meters.
Given the known values of the heat exchange coefficients between the surfaces of the enclosing structure and the surrounding environment, the heat transfer resistance $R_\Sigma$ of the enclosing structure is determined by formula (1). This is used to calculate the thermal resistance of the boundary layers of the environment surrounding the inner and outer surfaces of the fencing structure by applying the heat exchange coefficients inside and outside the room ($\alpha_{int.}$ and $\alpha_{ext.}$, respectively).
The heat transfer resistance of the multilayered thermally homogeneous fencing structure was calculated using the following formula:

$$R_{\Sigma}^{ml} = R_{bl}^{int.} + R_{wall}^{ml} + R_{bl}^{ext.} \tag{1}$$

where $R_{wall}^{m1}$is the thermal resistance of the multilayered thermally homogeneous fencing structure (or its sections) with known parameters for each layer, which is equal to the sum of the thermal resistance values of all layers of the multilayered fencing structure in the direction of the heat flow, calculated according to the following formula:

$$R_{wall}^{ml} = \sum_{1}^{j} R_{wall,j} \tag{2}$$

where $j$ is the number of layers of the various fencing structure materials.

### 6.3 Methodology for evaluating test results

According to [29], the fencing structure complies with the regulatory requirements if the following conditions are satisfied:

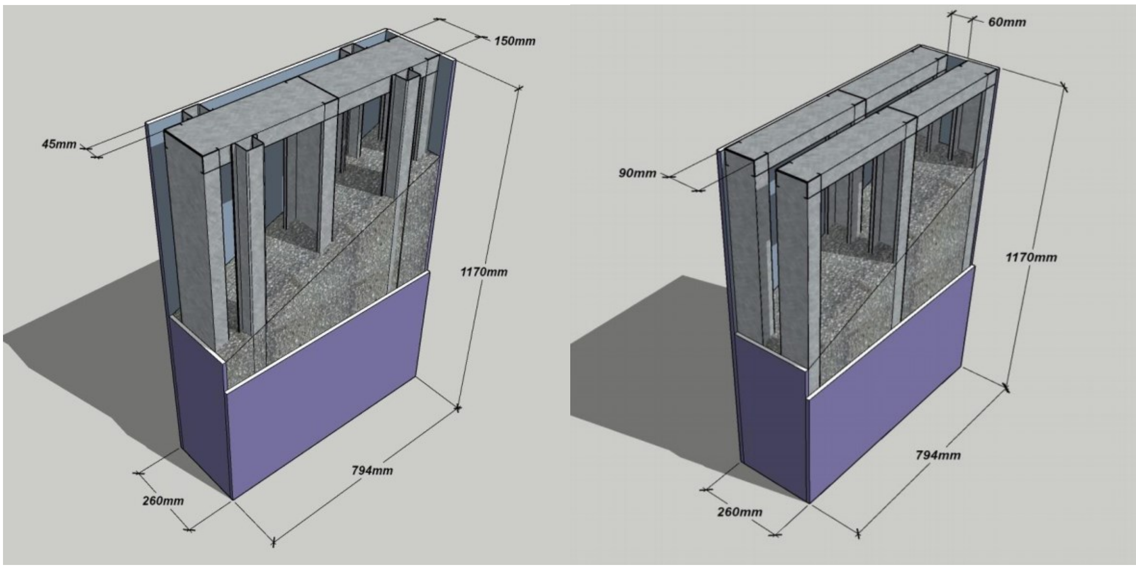
$$\begin{gathered} R_{\Sigma}^{red} \geq R_{q,min} \\ \Delta T_{dif.} \leq \Delta T_{critical} \\ T_{min}^{int.} > T_{min} \end{gathered} \tag{3}$$

Where:
$R_{\Sigma}^{red}$is the reduced heat transfer resistance of an opaque enclosing structure or an opaque part of an enclosing structure (for thermally uniform enclosing structures, the heat transfer resistance is determined) or the reduced heat transfer resistance of a translucent enclosing structure (m$^2$K/W).
$R_{q,min}$ is the minimum permissible value of the reduced heat transfer resistance of an opaque enclosing structure or an opaque part of an enclosing structure, or the minimum value of the heat transfer resistance of a translucent enclosing structure (m$^2$K/W), which is determined depending on the temperature zone of Ukraine and the purpose of the building. The minimum

permissible heat transfer resistance for residential/public buildings and for industrial buildings are listed in [29].
$\Delta T_{dif.}$ is the difference between the temperature of the internal air and the reduced temperature of the internal surface of the enclosing structure (°K).
$\Delta T_{critical}$ is the difference between the temperature of the internal air and reduced temperature $T_{\min}^{int.}$ of the inner surface of the enclosing structure, set according to sanitary and hygienic requirements (°K). The permissible temperature differences for the enclosing structures of residential, public and industrial buildings are given in [29].
is the minimum temperature of the inner surface in the heat-conducting inclusion zones of the enclosing structure (°K).
$T_{min}$ is the minimum permissible value of the internal surface temperature for the calculated internal and external air temperatures (°K).
Failure to fulfil one of the components of condition (3) indicates noncompliance of the tested structure with the regulatory requirements.

## 7 Research on determining the heat transfer resistance of an enclosing structure made of expanded polystyrene concrete in a fixed formwork

One unit of Sample No. 18-1/21 (Figure 6, a): A portion of an enclosing structure made of expanded polystyrene concrete in a fixed formwork measuring 1200 × 800 mm, 260 mm was used for the analysis. The frame, made of S220 steel, consisted of a C-profile with a section of 150 x 45 mm, metal thickness of 1,5 mm, and galvanisation density of 270 g/m$^2$. On each side, an omega profile with a section of 45 × 45 mm, thickness of 0,75 mm, and galvanisation of 270 g/m$^2$ was mounted on the frame. The cladding was 12 mm-thick moisture-resistant reinforced plasterboard. The filling was made of D250 polystyrene concrete.
One unit of Sample No. 18-2/21 (Figure 6, b): A portion of the enclosing structure made of expanded polystyrene concrete in a fixed formwork measuring 1200 × 800 mm and 260 mm was used for the analysis. The frame, made of S220 steel, consisted of two panels assembled from a C-profile with a section of 90 x 45 mm, metal thickness of 1,5 mm, and galvanising density of 270 g/m$^2$. The distance between the panels was 60 mm. The cladding was 12 mm-thick reinforced moisture-resistant plasterboard. The filling was made of D250 polystyrene concrete.




a) b)

**Figure 6. Test samples: a) Sample No. 18-1/21 b) Sample No. 18-2/21**

The moisture content of the samples during the testing was 4 %. The test conditions were as follows:

$$t_B = +(20 \pm 1)°K, t_3 = -(22 \pm 1)°K, \varphi = 51 - 54\ \%, P = 99{,}8 - 100{,}1\ kPa \quad (4)$$

where $t_в$ is the air temperature in the warm compartment, $t_з$ is the air temperature in the cold compartment, $\varphi$ is the relative humidity of the air in the warm compartment, and $P$ is the atmospheric pressure in the warm compartment.

The normative requirements for heat transfer resistance of the external walls of residential and public buildings, according to [29], are listed in Table 3. The results of determining the heat transfer resistance at the Laboratory of Construction Thermophysics and Acoustics at the State Enterprise Scientific Research Institute of Building Structures are presented in Table 4. The photographs of sample Nos. 18-1/21 and 18-2/21 during the testing are shown in Figure 7.

**Table 3. Normative heat transfer resistance (m²K/W)**

| Design purpose | Temperature zones according to [29] | |
|---|---|---|
| | I | II |
| | Purpose of the house | |
| | residential and public | residential and public |
| Outside walls | 3,3 | 2,8 |

**Table 4. Test results of reduced heat transfer resistance of the enclosing structure**

| Sample number | Indicator | Unit | Quantitative characteristic (experimental) | Normative I (II) climatic zones | Conformity |
|---|---|---|---|---|---|
| 18-1/21 | Heat transfer resistance | $m^2K/W$ | 1,81 | 3,3 (2,8) | – |
| 18-2/21 | Heat transfer resistance | $m^2K/W$ | 1,86 | 3,3 (2,8) | – |

**Figure 7. Photographs of test sample Nos. 18-1/21 and 18-2/21 during testing**

## 8 Calculation of heat transfer resistance according to the developed constructive-technological solution in fixed formwork

Normative documentation on the thermal insulation of buildings [27, 28, 29, 33, 34] establishes the requirements for the technical indicators of building enclosing structures. These requirements are mandatory in design and construction to ensure the rational use of energy resources, primarily for heating. The main task in the development of structural and technological solutions for the enclosing structures is to ensure the normative parameters of the microclimate of the premises and durability of the enclosing structures during the operation of the buildings.

It is necessary to ensure the minimum heat transfer resistance requirements of the enclosing structures of a building.

$$R_{\Sigma}^{red} \geq R_{q\ min} \quad (5)$$

According to a regulatory document [35], the minimum permissible heat transfer resistance of the opaque enclosing wall structure for temperature zone II is $R_{q,\min}$ = 2,8 m$^2$K/W. The reduced heat transfer resistance of the opaque enclosing structure is calculated according to formula 2 in accordance with [28] clauses 5.2–5.6.

$$R_{\Sigma} = \frac{1}{\propto_{int}} + \sum_{i=1}^{n} R_i + \frac{1}{\propto_{ext}} = \frac{1}{\propto_{ip}} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_{ip}} + \frac{1}{\propto_{ext}} \quad (6)$$

where $R\Sigma$ is the heat transfer resistance [m$^2$K/W]; $\alpha_{int}$, $\propto_{ext}$ are the heat transfer coefficients of the inner and outer surfaces [W/(m$^2$K)]; $R_i$ is the thermal resistance of the $i$-th layer of the structure [(m$^2$K)/W]; $\delta_i$ is the thickness of the $i$-th layer of the structure [m]; $\lambda_{ip}$ is the thermal conductivity of the material in the $i$-th layer of the structure (calculated thermal conductivity; W/(mK)); $n$ is the number of construction layers.

Appendix B of [28] sets the calculated values of the heat transfer coefficients:

- inner surface of the enclosing structure $\propto_{int}$ = 8,7 W/(m$^2$K);
- outer surface of the enclosing structure $\propto_{ext}$ = 23 W/(m$^2$K).

The calculated thermophysical characteristics of building materials that are part of the enclosing structure, in particular the thermal conductivity $\lambda p$ (W/mK), are accepted in accordance with Appendix A of [28] or [30].

A transverse (horizontal) section of the new constructive solution for the fencing structure is presented in Figure 8.

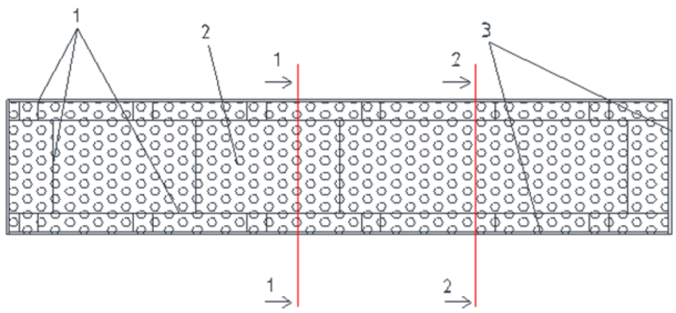



**Figure 8. Transverse (horizontal) section of the new wall-enclosing structure: 1 – a frame made of fibre-reinforced plastic; 2 – expanded polystyrene concrete 240 mm; 3 – non-removable formwork made of 10 mm chipboard**

The composition of the fencing structure with a thickness of 260 mm was as follows:

- external and internal thin-wall plastering with cement–sand solution 2 mm ($\lambda p$ = 0,7 W/mK) [36];

- external and internal cement chipboards 10 mm ($\lambda p$ = 0,26 W/mK) [36];
- expanded polystyrene concrete with density of D350 and thickness of 240 mm ($\lambda p$ = 0,12 W/mK) [36];
- LSTWS frame 4 mm ($\lambda p$ = 5,5 W/mK) [36].

Calculation of heat transfer resistance:

- in section 1-1 (Figure 8) – maximum thickness of the polystyrene foam concrete wall:

$$R_{\Sigma\text{пр}} = \frac{1}{8{,}7} + \frac{0{,}01}{0{,}26} + \frac{0{,}24}{0{,}12} + \frac{0{,}01}{0{,}26} + \frac{1}{23} = 2{,}2\ \mathrm{m^2K/W} \tag{7}$$

- in section 2-2 (Figure 8), the maximum accumulation of steel elements:

$$R_{\Sigma\text{пр}} = \frac{1}{8{,}7} + \frac{0{,}01}{0.26} + \frac{0{,}24}{5{,}5} + \frac{0{,}01}{0{,}26} + \frac{1}{23} = 0{,}27\ \mathrm{m^2K/W} \tag{8}$$

The preliminary calculation showed that the structural and technological solutions of walls made of polystyrene foam concrete do not ensure the fulfilment of the regulatory requirements: $R_{\Sigma np} \leq 2{,}8$ m²K/W.
The transverse (horizontal) section of the new constructive solution for the enclosing structure with an additional layer of heat-insulating material is shown in Figure 9.

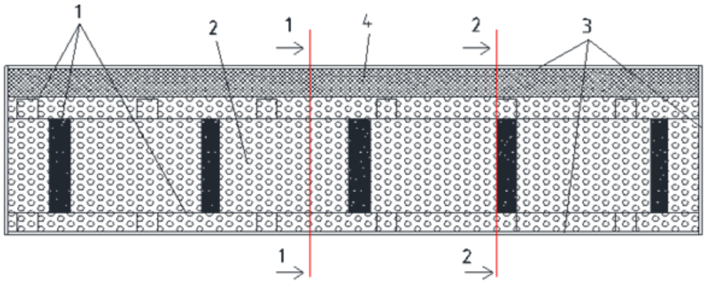



**Figure 9. Transverse (horizontal) section of the new wall-enclosing structure: 1 – frame with LSTWS; 2 – foam polystyrene concrete 240 mm; 3 – fixed formwork with 10 mm chipboard plates; 4 – mineral wool or extruded polystyrene foam (100 mm)**

The following layers were included in the finished fencing structure according to the structural and technological solutions in the patent (foam polystyrene concrete in a fixed formwork made of cement chipboards and a frame made of LSTWS), as shown in Figure 9:

- external and internal thin-wall plastering with cement–sand solution 2 mm ($\lambda p$ = 0,7 W/mK) [36];
- external and internal cement chipboards 10 mm ($\lambda p$ = 0,26 W/mK) [36];
- expanded polystyrene concrete with density of D250 and thickness of 90-240 mm ($\lambda p$ = 0,086 W/mK) [36];
- LSTWS frame 4 mm ($\lambda p$ = 5,5 W/mK) [36];
- mineral wool (100 mm; $\lambda p$ = 0,038 W/mK, material density 145 kg/m$^3$) or extruded polystyrene foam ESP 80 100 mm ($\lambda p$ = 0,034 W/mK, material density 15 kg/m$^3$) was additionally installed on the inner surface of the external cement particle boards to exclude cold bridges.

Heat transfer resistance during construction of a wall made of expanded polystyrene concrete (Figure 10 a, 10 b):

- in section 1-1 (Figure 10, a) – with mineral wool:

$$R_{\Sigma пр} = \frac{1}{8,7} + \frac{0,01}{0,.26} + \frac{0,1}{0,038} + \frac{0,24}{0,086} + \frac{0,01}{0,26} + \frac{1}{23} = 5,66\ \mathrm{m^2K/W} \quad (9)$$

- in section 2-2 (Figure 10, b) – with expanded polystyrene foam:

$$R_{\Sigma пр} = \frac{1}{8,7} + \frac{0,01}{0,26} + \frac{0,08}{0,034} + \frac{0,24}{0,086} + \frac{0,01}{0,26} + \frac{1}{23} = 6,0\ \mathrm{m^2K/W} \quad (10)$$

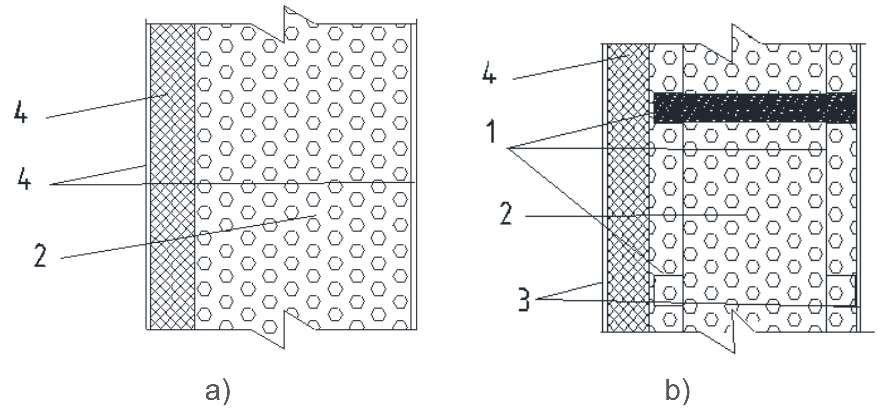



**Figure 10. Transverse (vertical) section 1-1 (a) and section 2-2 (b) of the wall: 1 – frame with LSTWS; 2 – expanded polystyrene concrete; 3 – non-removable formwork made of 10 mm chipboard; 4 – mineral wool or extruded polystyrene foam (100 mm thick)**

The structural and technological solutions of the wall made of expanded polystyrene concrete, considering an additional layer of heat-insulating material (mineral wool or expanded polystyrene with a thickness of 100 mm), ensure the fulfilment of the regulatory requirements at the places with the greatest concentration of the metal structure of the LSTWS frame along section 2-2 (Figure 10, b): $R_{\Sigma пр} \geq 2,8\ \mathrm{m^2K/W}$.

## 9 Results of the implementation of the new composite wall in fixed formwork

After confirming an effective operation period, the enclosing structure was approved for construction at the Avignon residential complex in Odesa. The process and results of the construction of the enclosing structures on the complex, consisting of 12 sections and seven stories, are shown in Figure 11.

The technology developed in this study was implemented during the construction of the residential complex "Avignon" in the city of Odesa, 91 Dacha Kovalevsky str. This technology is illustrated in Figure 11. All the enclosing structures were erected under the actual conditions at the construction site in the following sequence:

1. First, the frame of the walls/formwork made of light steel structures (LSTWS) was assembled on the assembly horizon. To accelerate the process of erecting the building, the bulk assembly of the frame from the LSTWS was performed in parallel on the site, as shown in Figure 11, a. In this case, the frame was lifted to the ceiling using a crane.
2. The frame of the wall formwork with the LSTWS was sheathed externally with cement chipboards and internally with a moisture-resistant plasterboard.
3. The space between the inner and outer elements of the fixed formwork was filled with monolithic polystyrene concrete using a special concrete pump.
4. On the outside, the walls were additionally insulated with 80 mm-thick polystyrene boards.


**Figure 11. Process of erecting the developed solution of the enclosing frame structure using expanded polystyrene concrete in a fixed formwork: a) erecting the frame from LSTWS; b) assembly nodes of the frame from LSTWS; c) sheathing the frame with cement chipboards; d) concreted wall; e) external view of the finished structure from the outside of the building; f) external view of the finished structure inside the building**

A waterproof plasterboard was used as a fixed formwork on both sides of the inner walls, which distinguished them from the outer walls. Therefore, the frame served as an element of the wall and formwork. A gypsum board and cement chipboard were used for providing a rough finish on the inner and outer surfaces of the walls, respectively. After the installation, the inner and outer walls were improved using finishing equipment. The seams were sealed with masking tape. The wall surfaces were plastered over the grid and painted. The mesh was fixed with glue, which provided additional waterproofing for the wall.

During the construction of the fencing structures, the main hypotheses laid down during its design were generally confirmed: reduced labour intensity owing to fewer assembly operations, and reduced material intensity owing to the combination of materials with appropriate properties.

## 10 Conclusions and recommendations

Structural and technological solutions for composite walls in a fixed formwork are simple and do not require the involvement of highly qualified personnel. The patented structural and technological solutions of a new wall made of polystyrene concrete in a fixed formwork (patent UA149402) differ from its closest analogue based on the five improvements given in the description of the patent.
The comparison of the new energy-efficient wall made of expanded polystyrene concrete in a fixed formwork, constructed using 13 well-known technologies and evaluated using 8 criteria in Excel's 'Pivot Tables and Charts' tools, demonstrated its advantages.
The heat transfer resistance of a portion of the new wall made of expanded polystyrene concrete in a fixed formwork with a thickness of 260 mm is $R_{\Sigma пр}$ = 1,81 ≤ 2,8 m$^2$K/W. The structural and technological solutions for the wall construction using expanded polystyrene concrete, considering an additional layer of heat-insulating material (mineral wool or expanded polystyrene with a thickness of 100 mm), ensure the fulfilment of the regulatory requirements $R_{\Sigma пр}$ ≥ 2,8 m$^2$K/W, including at places with the greatest concentration of metal structures of the light steel thin-walled structures frame.
The installation of the new composite wall in a fixed formwork using light steel thin-walled structures and expanded polystyrene concrete reduced the labour and material intensity at the construction site.

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