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LONG-TERM THERMAL PRODUCTIVITY OF POLYSTYRENE CONCRETE IN A NEW COMPOSITE WALL IN A FIXED FORMWORK

Purpose. Determination of the term of long-term thermal productivity of expanded polystyrene concrete in a new composite frame wall in a fixed formwork.

Methodology. Methods of analysis and synthesis were used to conduct a patent search and develop a research methodology. The search was conducted using the patent database of Ukrainian Institute of Scientific and Technical Expertise and Information. Experimental studies were carried out in accordance with State Standard of Ukraine B V.2.7-38-95. The essence of the experiment consisted in reproducing the natural conditions of the "freeze-thaw-heat" cycle and measuring the thermal insulation characteristics of the main insulating material – polystyrene concrete – before and after the tests. Based on this, a conclusion was made about the long-term thermal productivity of the expanded polystyrene concrete in a new composite wall in the fixed formwork. The calculation of the dependence of thermal productivity on the number of cycles was carried out by arithmetic means using standard methods and programs such as Microsoft Excel.

Findings. New technical solution of a composite wall made of expanded polystyrene concrete in a fixed formwork using light steel thin-walled structures has been created. A methodology for researching the long-term thermal productivity of this composite wall has been developed. An experimental study was conducted to research the influence of cyclic temperature changes ("freeze-thaw-heat") on the long-term thermal productivity of the main heat-insulating element of the composite wall – expanded polystyrene concrete. An appropriate analytical model of the dependence of long-term thermal productivity of expanded polystyrene concrete samples on the number of "freeze-thaw-heat" cycles was calculated. The possibility of effective operation of the structure was confirmed by checking the normative values of the resource index and the factor of climatic destruction influence of materials during operation on their long-term thermal productivity. Implementation of a new composite wall solution in construction was conducted.

Originality. For the first time, the dependence of cyclic temperature effects on the long-term thermal productivity of expanded polystyrene concrete in a new composite wall made in a fixed formwork using light steel thin-walled structures was determined, which made it possible to establish its effective operation life. This scientific result makes it possible to reduce material consumption, ensure economy, increase operational reliability and energy-efficient properties, and increase the service life of the composite wall.

Practical value. New solution for installing a composite wall made of expanded polystyrene concrete in a fixed formwork using light steel thin-walled structures was developed and its effective thermal operation within the legally established term was substantiated. The period of effective exploitation of expanded polystyrene concrete as the least durable component of a composite wall is substantiated. Approbation of this design was carried out by installing it on a real construction site, which showed an increase in the manufacturability of construction processes compared to traditional enclosing structures.

Keywords: *composite wall, operating life, expanded polystyrene concrete, light steel thin-walled structures, fixed formwork*

Introduction. Previously, many variants of non-load-bearing composite walls were developed, including the use of fixed formwork and light steel thin-walled structures. However, during the search, no wall was found that would combine all the specified elements. The main advantages of these constructive and technological solutions are the reduction of labor intensity due to the lowing of assembly operations and material intensity – as a result of the combination of materials with appropriate properties. A composite wall made of expanded polystyrene concrete in a fixed formwork can be used for the construction of low-rise buildings of the most diverse purpose. These are villas and farm cottages, warehouses and special purpose buildings, such as industrial refrigerators or port terminals. They are light, do not create much pressure on the soil. This makes it possible to erect such buildings in difficult soil conditions, for example, on sedimentary or loose soils. The wall contains a metal frame made of a thin-walled bent galvanized profile. It consists of ready-to-assemble enlarged parts with a set of fasteners. The inner layer of the wall is made of expanded polystyrene concrete. The outer layers are a fixed formwork made of cement chipboards. They are attached to the frame through special patented elements. Due to the fact that both cement chipboard and polystyrene are vulnerable to adverse weather conditions, it is necessary to carry out studies on the period of effective operation. The inner layer of the wall is made of expanded polystyrene concrete. The outer layers are a fixed formwork made of cement chipboards. They are attached to the frame through special patented elements. Due to the fact that both cement chipboard and polystyrene are vulnerable to adverse weather conditions, it is necessary to carry out studies on the period of effective operation. The inner layer of the wall is made of expanded polystyrene concrete. The outer layers are a fixed formwork made of cement chipboards. They are attached to the frame through special patented elements. Due to the fact that both cement chipboard and polystyrene are vulnerable to adverse weather conditions, it is necessary to carry out studies on the period of effective operation.

As a result of the use of the patented design and method for erecting the wall, the manufacturability and pace of construction increases. At the same time, a reduction in labor and material consumption is achieved. Thanks to the reliable combination of expanded polystyrene concrete in the inner layer of the wall structure with a metal space frame made of light metal profiles, rigidity and load-bearing capacity are ensured. Due to this, monolithicity and high stability of the structure during installation and performance of special works are achieved. This leads to increased operational reliability, energy-efficient properties, increased service life and cost-effectiveness.

The peculiarity of the patented structure and construction technology is the installation, which is carried out easily and quickly, allowing one to reduce the time and cost of construction, excluding the use of special machinery and equipment. The cost of transporting elements of the metal frame is reduced due to the lightness of the structures and the linear shape of the parts in comparison with traditional fittings, which enables compact packaging. For this reason, wall constructions with a light steel frame have gained extreme popularity in the construction of prefab buildings all over the world.

Literature review. The analysis of information sources on the topic under consideration showed that the construction of multi-layer composite fencing structures is relevant. Results on the optimization of compressive strength [1] show that expanded polystyrene concrete can achieve concrete strength suitable for residential purposes and can also be used as a partition in high-rise buildings due to its light weight. The article [2] reports on the development of an innovative sandwich panel reinforced with fiber concrete with a polymer concrete filling, which has significantly higher strength, intended for the construction of walls. The structural behavior of the expanded polystyrene core of reinforced concrete sandwich panels under axial and plane shear loading was experimentally studied [3]. The experimental study was carried out on samples consisting of a factory-made corrugated core, welded mesh and orthogonal shear connectors. Among the relevant publications, works can be noted on the study of walls using lightweight concrete [4], a combination of steel structures and concrete [5, 6], cement chipboards [7]. The considered publications prove the effectiveness of the technology of installing a composite wall from fixed formwork, lightweight concrete filling and steel bearing elements.

Most of the reviewed publications on the analysis of long-term effects are concerned with mechanical loads. The bearing capacity, displacement profiles, and crack structure of reinforced wall panel with expanded polystyrene concrete were analyzed and discussed [8]. Experimental results [9] of multi-year tests conducted on six samples, one wood-concrete composite beam with threaded screw connections and one wooden beam were presented. The effect of an external composite wall made of fiber cement panels on the seismic characteristics of a steel frame was investigated, a test for alternating sign load was carried out, and a method of numerical modeling of an external composite wall was proposed [10]. The strength and stiffness of the frame-glued concrete panel were investigated using load-displacement tests, and the thermal performance was evaluated using a hot storage apparatus [11]. The volumetric heat capacity and long-term thermal productivity coefficient were determined experimentally [12] for precast reinforced concrete walls in combination with a low-cement cast lightweight concrete core in dry, hygroscopic and super hygroscopic conditions. Research work [13] on specific thermal resistance, sound absorption and vibration damping of rubber concrete was considered. The quality of presentation, the depth of carbonation and the amount of rebound of ordinary concrete in 120 days were observed and tested in the article [14]. Thus, it can be noted that the study of the term of effective thermal exploitation of composite frame walls remains relevant.

The following inventions were used as the main analogs of the proposed composite wall: "Multilayer panel" [15] and "Building Wall" [16].

The Research Institute of Building Structures has developed and normatively approved the appropriate methodology for conducting 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 requirements [17, 18]. Tests to determine the term of effective operation of expanded polystyrene concrete were carried out in accordance with the requirements of next documents [19, 20]. The calculated value of the moisture content of the material was determined on the basis of the data in Table A1 in accordance with [21]. The freezing temperature of the samples was set depending on the temperature zone of product operation in accordance with the values of the calculated outdoor air temperature in accordance with [22]. The duration of freezing, thawing and heating of samples was set according to table A1 [21]. The measuring devices used in the study met the requirements [23, 24], as well as other normative documents.

Unsolved aspects of the problem. The proposed composite wall provides the possibility of simplifying the structure, increasing the manufacturability of its erection, stability and load-bearing capacity while maintaining operational characteristics. Analysis of known inventions revealed the following.

In the patent [15] there is considered a multi-layer construction of the wall, consisting of chipboard, an internal insulating layer of polystyrene foam or polyurethane foam. The elements are glued together. There are grooves for installing load-bearing structural elements at the ends of the wall element. Among the disadvantages, the following can be noted: low vapor permeability; additional costs for design, equipment adjustment and transportation in the manufacture of individual elements; the need for a powerful press; loss of strength of expanded polystyrene with deviations from the technology.

The patent [16] considers a wall consisting of a main array of expanded polystyrene concrete, located between the inner and outer enclosing layers of magnesite plates. Magnesite plates with bending strength of 5.5–7.0 MPa and thermal productivity of 0.2–0.3 $W/m^2 \cdot K$ are used. Planar fasteners connecting the plates to each other are laid on the top and bottom of the magnesite plates. The main drawback of the proposed solution is the lack of a supporting frame, which makes it impossible to ensure proper stability and rigidity of the structure in seismic zones and under dynamic loads. In addition, the cost of magnesite plates is much higher than possible analogues.

Thus, there is a need to create a new structural and technological solution of the composite wall, which should take into account the structural and technological drawbacks mentioned above. It is necessary to establish the period of effective operation of the new structure, taking into account that the developed technical solution must use metal and cement chip elements that can deteriorate under the influence of weather factors.

Purpose. The main goal of the study is to determine the term of effective thermal productivity of expanded polystyrene concrete in a new composite frame wall in fixed formwork. Research objectives:

1. To justify the relevance of developing a new structural and technological solution of a composite wall in a fixed formwork, as well as methods for researching the long-term thermal productivity.
2. To analyze existing structural and technological solutions of composite walls in fixed formwork and develop a new solution using a frame made of light steel structures and expanded polystyrene concrete.
3. To choose the necessary method for researching the term of effective operation of the developed composite wall.
4. To conduct experimental research on the long-term thermal productivity of a new composite wall in a fixed formwork.
5. To put a new solution of a composite wall in a fixed formwork into production.

Development of a new composite wall using fixed formwork, light steel thin-walled structures and expanded polystyrene concrete. The proposed new technical solution is a wall structure consisting of: cement chipboards forming fixed formwork, the main massif of the wall made of expanded polystyrene concrete, a frame made of light steel thin-walled structures.

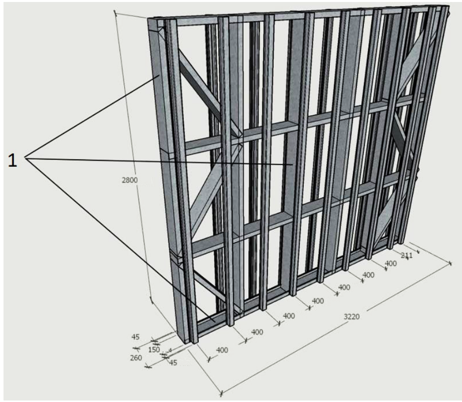
The main tasks in the development of a new technical solution were: ensuring the possibility of simplifying the structure, increasing the manufacturability of its construction, stability and load-bearing capacity while maintaining operational characteristics. These problems are solved due to a new approach to construction. The frame from the light steel thin-walled profiles is a load-bearing element of the wall structure. The frame consists of ready-to-assemble enlarged parts with a set of fasteners. The inner and outer enclosing layers are made of cement chipboards of fixed formwork, which are fixed to the frame with the help of special U-shaped profiles, excluding the formation of "cold bridges". The main body of the wall is made of expanded polystyrene concrete with a density of 258 to 375 kg/m^3 and thermal productivity from 0.052 to 0.1 $W/m^2 \cdot K$.

The peculiarity of the proposed composite wall is the installation, which is carried out easily and quickly, allowing one to shorten the construction period, excluding the use of special equipment and equipment, which allows reducing the cost of construction. Also, the cost of transportation of frame elements is reduced due to the lightness of structures and the linear shape of light steel thin-walled parts compared to traditional fittings, which enables compact packaging. For this reason, wall constructions with a frame made of light steel thin-walled structures have gained extreme popularity in the construction of quickly assembled buildings, both abroad and in our country.

The main advantage of the proposed composite wall is that the inner layer of the wall structure has a spatial frame of light steel thin-walled structures, which serves as a load-bearing element of the fixed formwork. In addition, together with expanded polystyrene concrete with a density of 258 to 375 kg/m^3 and a thermal productivity of 0.052 to 0.1 W/m$^2 \cdot$ K the frame will carry and receive the main operational loads, thanks to which additional reinforced layers can be avoided with traditional reinforcement, which leads to an increase in the time for the wall reinforcement process. The frame technology allows building a house in an accelerated time with the use of a minimum number of workers. The metal frame is assembled from thin-walled steel profiles. For corrosion resistance, the profiles are covered with a layer of zinc and are delivered to the construction site in finished sizes and with holes for installation. A shallow foundation is laid under such a structure, because the weight of the building will be small, so there is no need to build a large deep foundation. Expanded polystyrene concrete with a density of 258 to 375 kg/m^3 and thermal productivity from 0.052 to 0.1 W/m$^2 \cdot$ K acts as an effective heat-insulating material. This is a light version of the traditional classic cement mortar, in which the heavy sand filler is replaced by a light polymer, as a result of which not only the weight of concrete structures is significantly lightened, but also an excellent thermal insulation material is created. It has high thermal productivity (depending on the brand of the mixture, it ranges from 0.052 to 0.1 W/m$^2 \cdot$ K) and sound insulation (13 dB at 20,500 Hz and a thickness of 5 cm) and sufficient vapor permeability (μ 8.5). Thermal insulation with expanded polystyrene concrete in the conditions of the current energy crisis is an outstanding achievement in the field of energy-saving technologies and construction. Fixed formwork is an alternative construction method that does not involve the presence of waste from disassembling the formwork. It has many advantages, as there is no need to spend time on dismantling. In addition, the formwork creates a single structure with the monolith, giving it additional strength, reducing heat loss and providing protection against moisture. Simplicity and speed of work execution ensures a reduction in terms and complexity of construction, as well as the absence of the need for lifting mechanisms. Cement chipboards are successfully used as a material for fixed formwork because it provides a number of advantages. The cement in the composition makes it possible to keep the shape and provides rigidity under compression, and the wood shavings prevent the slab from bending. Cement chipboards have the ability to retain hardness, which ensures ideal preservation of shape even with significant pressure of the concrete solution. The material is resistant to temperature changes, ignition, it is not a breeding ground for fungi and insects. Cement chipboard can be subjected to any treatment, it can be plastered and painted or faced with any material. Thanks to the materials used and the constructive and technological solutions offered (Fig. 1), zones of increased heat leakage are excluded. They are formed in elements with high thermal productivity that pass along the entire cross-section of the wall, and thus significantly reduce the effectiveness of thermal protection of the building, as well as freezing of the inner surface of the wall and the formation of condensate.

As a result of the use of an enclosing structure, in the form of a wall made of expanded polystyrene concrete, the manufacturability and speed of construction of load-bearing monolithic reinforced concrete walls with energy-efficient properties increases. At the same time, a reduction in labor intensity, construction time and material consumption is achieved due to the use of a frame made of metal profiles, which will remain in the body of the structure without their subsequent dismantling, and provide rigidity and load-bearing capacity due to the reliable combination of expanded polystyrene concrete in the inner layer of the wall structure. Due to this, monolithicity and high stability of the structure during installation are achieved, which leads to increasing operational reliability, heat-saving properties of the structure, service life and ensuring cost-effectiveness.

The method of arrangement of the proposed wall is carried out as follows. Building a wall (Fig. 1) begins with the assembly of the light steel thin-walled frame *1*; the assembly of light steel thin-walled frame is performed with the help of bolts, self-tapping screws, and screwdrivers. Next, a fixed formwork of cement chipboards *3* is mounted, by fixing with self-tapping screws from the outside and inside to the light steel thin-walled



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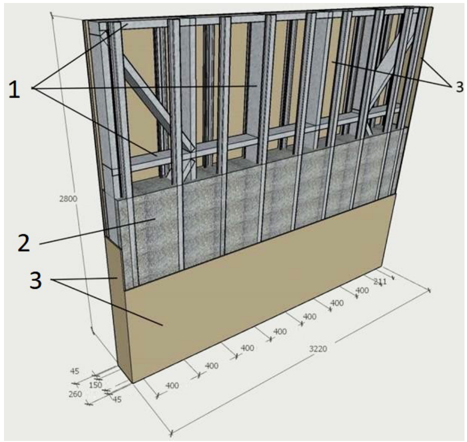

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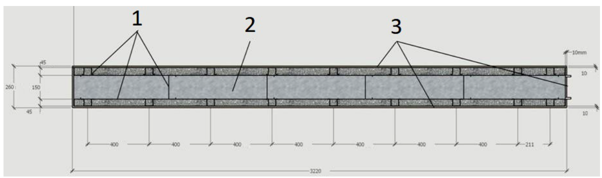

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Fig. 1. Schematic diagram of a new composite wall made of expanded polystyrene concrete in a fixed formwork using light steel thin-walled structures:

a — light steel thin-walled frame; b — general appearance of the wall including all layers according to the arrangement technology; c — transverse (horizontal) section of the wall according to the installation technology. Conventional designations: 1 — light steel thin-walled frame; 2 — expanded polystyrene concrete; 3 — cement chipboards frame *1* with the help of special U-shaped profile elements. When all the elements of the fixed formwork *3* are completely installed, the connections with the light steel thin-walled frame *1* are made, the inner space formed is ready for the further arrangement of the supporting layer of expanded polystyrene concrete *2*. Thanks to the plasticity of the expanded polystyrene concrete *2*, it is possible to concrete the structure walls for the entire floor at one time, without additional technological operations to compact the concrete mixture.

Description of methods and equipment for the study on the period of effective operation. The main climatic parameters of the impact on the composite wall are: air temperature, humid climatic influences on structures, solar radiation and the number of probable temperature transitions through 0 °C. For further experimental assessment of the influence of sign-changing temperature on long-term thermal productivity of a composite wall made of expanded polystyrene concrete in a fixed formwork, a study was conducted to research the physical, mechanical and thermal properties before and after the climatic influences.

The tests were carried out on samples of a composite wall made of expanded polystyrene concrete, manufactured in accordance with the technical documentation and technological regulations for these products. Expanded polystyrene concrete was selected for testing as the least durable composite wall material. It is assumed that with the presence of fixed formwork as a protective cladding, the long-term thermal productivity of the composite wall will not be lower than that of expanded polystyrene concrete. For laboratory studies on the period of effective operation under the influence of cyclic climatic influences, 48 samples were made: 300 × 300 × 50 mm.

The brand of expanded polystyrene concrete that is used most often due to their physical and mechanical parameters is listed below. Table 1 presents the main thermophysical characteristics of expanded polystyrene.

Table 1

Basic thermophysical characteristics of polystyrene foam of 20/80 brand

Brand 20/80: 200 kg of cement, 800 l of polystyrene foam, 1 l of additives, water	
Bulk density of fresh solution	0.4 ± 5 % g/cm^3 (0.25 g/cm^3 in dry state)
Thermal productivity coefficient	λ = 0.07 W/m · K
Compressive strength	≥ 0.4 MPa
Bending strength	≥ 0.15 MPa
Adhesion with concrete base	> 0.1 MPa
Setting time	up to 12 hours

Table 2 shows the type and characteristics of the equipment and measuring equipment used during the tests. All devices have been calibrated and have certificates from SE "Ukrmetrteststandart".

In order to estimate the long-term thermal productivity, it is necessary to subject the tested material to cyclical climatic influences. These influences simulate changes in the thermal characteristics of the material during the operation of the material in the enclosing structures.

According to the results of the decrease in the thermal characteristics of the material, its long-term thermal productivity is evaluated. The long-term thermal productivity was estimated by the change in thermal productivity under standard test conditions.

Expanded polystyrene concrete was chosen as the test object, as it is the least stable of the elements of the composite wall. It was assumed that the composite wall will withstand no fewer cycles of changes in ambient temperature than expanded polystyrene concrete, taking into account the longer period of effective operation of other materials.

Samples were selected in random order. The density of the samples was equal to the average density of the material within ± 1 % deviation. At least 10 samples of the same type were selected. Three of them were used as standards, that is, to determine the thermal characteristics of the material at the beginning of the tests.

Figs. 2–3 show the installation for forced moistening of the material. It consists of:

- low-intensity steam generator, which includes heat-insulated heater and metal container with water;
- support frame with a wire grid made of 1 mm diameter with a cell 20 × 20 mm, on which the test sample is located;
- rames for fixing the experimental sample and the refrigerator;
- thermal electric refrigerator based on Peltier elements, which includes: metal refrigerator plate, Peltier elements, refrigerator radiator, refrigerator fan, and side thermal insulation;
- rubber seals for sealing the test sample around the perimeter and creating a wind gap between the surface of the sample and the refrigerator plate;
- heater and refrigerator temperature control system, which includes temperature sensors and controller. The temperature of the heater should be maintained automatically in the range from 30 to 60 °C, that of the refrigerator – in the range from –20 to 0 °C.

The samples were dried in laboratory drying cabinets to a constant mass at a temperature that excluded the possibility of

Table 2

Type and characteristics of testing and measuring equipment

Name of testing and measuring equipment	Factory number	Certificate number	Calibration date	
			The last	The next one
Climatic camera KTK-3000	Factory No. 236103	UA/24/200618/2917	06.2021	06.2022
Climate chamber	Factory No. 5	UA/24/200618/2912	06.2021	06.2022
Agilent 34970A data collection system	Factory No. MY440518 33	UA/24/191024/8442	10.2021	10.2022
Thermal electric chromel-drop converters, THK, according to State Standard of Ukraine EN 60584÷1:2016, measurement error ± 0.2 °C	Factory No. 01–20	UA/24/19 0717/2803	07.2021	07.2022
Psychormeter MV-4M, measurement error ± 1 %	26431	UA/24/19 0717/2826	07.2021	07.2022
Thermometer laboratory error of measurements ± 0.1 °C	3871	UA/24/19 0717/2829	07.2021	07.2022
Measuring metal tape	1	UA/23/20 0206/000265	02.2021	02.2022
Calipers	078538	UA/23/19 0711/001282	07.2021	07.2022
BAMM-1 aneroid barometer	101518	UA/39/200 03/0149	02.2021	02.2022
Non-automatic weighing device Dneproves	74	UA/35/200 23/7223	01.2021	01.2022
Camera for heat treatment HPS-222	35850560	UA/24/20 0618/2919	06.2021	06.2022

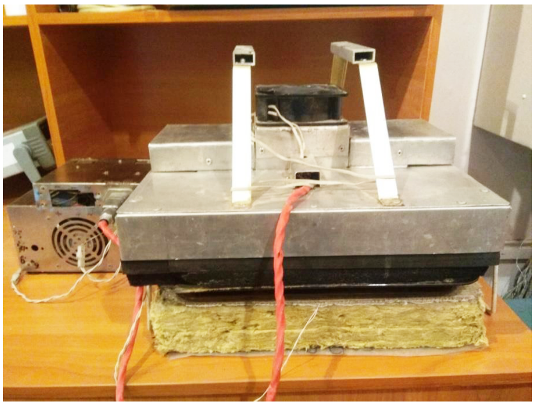

Fig. 2. Installation for moistening the material

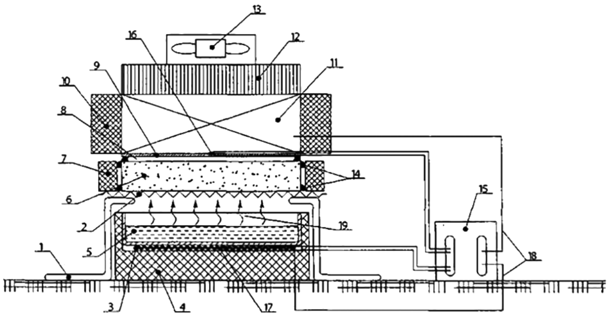

Fig. 3. Scheme of the experimental installation for forced moistening of the material with water vapor:

1 – support frame; 2 – metal grid; 3 – electric heater; 4 – thermal insulation of the heater; 5 – metal container with water; 6 – sample; 7 – fixing frame; 8 – air gap; 9 – refrigerator plate; 10 – thermal insulation of the refrigerator; 11 – thermal electric refrigerator based on Peltier elements; 12 – refrigerator radiator; 13 – refrigerator fan; 14 – rubber seals; 15 – heater and refrigerator temperature regulator (controller); 16 – refrigerator temperature sensor; 17 – heater temperature sensor; 18 – control channels; 19 – couple

chemical or phase destruction of the material skeleton. The sample was considered dried to a constant mass if the difference between two consecutive mass measurements after the next weighing did not exceed 0.5 % for a period of at least 0.5 h. The sample was kept in a desiccator with a relative humidity of up to 20 % before testing.

The mass of each sample, m_{0i}, kg, and the material density ρ_{0i}, kg/m^3, were determined in the dry state. The density was calculated according to the formula

$$\rho_0 = \frac{\sum_{n-1}^{N} \rho_{0i}}{N} + \varepsilon_\rho,$$

where N is the number of tested samples; ε_ρ is the total confidence limit of the random error of the density measurement results, kg/m$^{3.}$

Experimental determination of the characteristics of calculated humidity w_a and w_b was carried out by sorption moistening of material samples successively at a relative air humidity of 80 and 95 %, respectively. After determining the values of *wa* (at 80 % relative air humidity) and w_b (at 95 % relative air humidity), the sample was moistened to values close to w_a, w_b (hereinafter calculated values of humidity w_p).

The term of effective service of the material at the moisture content of the test samples was calculated according to the formula

$$[(w_b + \Delta w_b) \pm 2] = (w \pm 2) = w, \qquad (1)$$

where Δw_b is a possible excess of material humidity during operation above the calculated value, $\Delta w_b = 0.5 w_b$ is accepted, but in all cases not less than 4 %;

$$w_p = w_b + \Delta w_b.$$

An experimental setup was used to moisten the samples: the sample *6* (Fig. 3) was installed in the fixation frame *7* and was placed in a horizontal position on the metal grid *2* and the support frame *1*. Thermal electric refrigerator *11* was arranged above the test sample with the formation of an air gap *8*. In the lower part of the support frame *1*, a steam generator *3, 4* was installed, into which water is poured *5*. The temperature sensors of the heater and refrigerator *16, 17* were connected to the controller *15*. The temperature of the heater and refrigerator was set for automatic maintenance. The humidification procedure, depending on the material of the test sample, was from 30 to 240 min. The wetting procedure was repeated by inverting the sample to obtain a mass m_{wp} close to the required value.

The mass to which it is necessary to moisten the sample m_{wp}, corresponding to w_p or $\hat{w}_p$, was determined by the formula

$$m_{wp} = m_0(1 + 0.01 w_p).$$

Humidification was performed for the entire sample as follows. After reaching the required humidity value, the sample was wrapped in polyethylene film and placed on a horizontal surface. After that, the sample was turned every hour for 4 hours, after which the sample was installed vertically and kept in this position for at least 10 days. Test samples were considered prepared for testing after the following conditions were met

$$W_m = [(w_p \;\; or \;\; \hat{w}_p) \pm 2],$$

where i is the serial number of the test sample; w_p, $\hat{w}_p$ are the same as in formula (1).

Determination of indicators of long-term thermal productivity of a new composite wall. To ensure air movement, the samples were placed in a climate chamber with gaps evenly across the working volume of the chamber. After that, the samples were subjected to cyclical temperature effects "freeze-thaw-heat".

The freezing temperature of the samples was set according to the values of the calculated temperature of the outside air tf. The cooling rate of samples should be 20 °C/h in the range from 18 to 0 °C and 10 °C/h in the range from 0 to 3 °C, but not less than 3 hours. At the same time, the duration of thawing was 4 hours at an air temperature of 18 to 22 °C. Samples were heated in a climate chamber under forced conditions convection during 6 hours at temperature $t_h = (60 \pm 1)$ °C.

The relative humidity of the air in the climatic chamber was kept constant at the level of $\varphi = (95 \pm 5)$ %. The number of test cycles was 60. 3 samples of materials were selected from among the tested every ten test cycles. The selected samples were dried to test thermal characteristics.

The final number of test cycles was set depending on the nature of the change in the operational thermal parameter. The tests were completed when a non-linear section of the change appeared thermal parameter, which is established based on the test results of at least three experimental points after a linear section, but no more than 60 test cycles.

The climate chamber for durability testing is shown in Fig. 4. The general appearance of the tested samples is shown in Fig. 5.

The tight fit of the surface of the test samples was provided to the surface of the heater and refrigerator plates of the test device. The temperature of the plates of the heater and the refrigerator of the test device was set so that the average temperature of the sample during the tests was (10 ± 1) °C and measurement was carried out. After measurements, the final moisture content of the sample w_k, %, was determined, to which the obtained value of thermal productivity was related.

The average declared value was set according to the results of measurements of the operational thermal parameter according to the formula

$$y_0 = \hat{y} \pm \varepsilon,$$

where $\hat{y}$ is the average arithmetic value of the parameter according to the test results; ε is the confidence limit of the random error of measurement results, which is determined by the formula

$$\varepsilon = tS(\hat{y}),$$

where t is the Student's coefficient, which depends on the confidence probability P and the number of observation results n; $S(\hat{y})$ is estimate of the mean square deviation of the measurement result, which is calculated according to the formula

$$S(\hat{y}) = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y)}{n(n-1)}},$$

where y_i is the i^{th} observation result; n is the overall number of observation results.

To process experimental data, methods of regression analysis and mathematical statistics were used, on the basis of which the following dependence was obtained

$$y = y_0 + bx \pm \varepsilon,$$

where y is the numerical value of the parameter; x is the number of test cycles; ε is the confidence limit of the random error of measurement results for a 95 % confidence level; b is the regression coefficient.

For each of the operating thermal parameters, the numerical value of the resource indicator is set for the security level of 0.95, which is calculated according to the formula

$$r = bx^* \pm \varepsilon, \quad (2)$$

where x^* is the largest value of the number of cycles corresponding to the linear section of the change in the operating thermal parameter; b is the tangent of the angle of inclination of the dependence $\lambda(z)$; ε is the confidence limit of the random error of the measurement results for the 95 % reliability level.

When determining the resource index of the change in thermal productivity r_λ of heat-insulating and structural heat-insulating materials, the confidence limit in (2) has a "+" sign. When determining the resource index x^*, $x^* = 60$ can be accepted, if after 60 test cycles no nonlinear section of the change in the thermal parameter is recorded.

The long-term thermal productivity for heat-insulating and structural-heat-insulating materials was assumed to be at least 25 years, if after 60 cycles the condition is met

$$\frac{r}{\lambda_0} k_z \le 0.2, \quad (3)$$

where k_z is a scaling factor that takes into account the compliance of the experimental cycles with the thermal and moisture conditions of use of the material in the structure. $k_z = 5$ for structures of external walls with facade thermal insulation and for structures with a protective furnishing layer located between the thermal insulation layer and the outside air; λ_0 – thermal productivity in standard conditions, W/(m · K), at $T_c = +25 \pm 1$ °C.

The factor taking into account the influence of climatic destruction of materials during operation on their thermal productivity was determined by the formula

$$K_k = 1 + \frac{r}{\lambda_0} k_z.$$

The scaling factor increases by the value of $60/x^*$ when non-linear section of operational thermal parameter changes occurs after the number of cycles $x < 60$.

Conducting research on determining the long-term thermal productivity of a composite wall. The samples to be tested were moistened to a moisture content of $[(w_b + 5) \pm 2]$ % (which is 7 %) and sealed in polyethylene bags.

The samples were subjected to cyclic temperature effects of "freeze-thaw-heat": $t_f = -22 \pm 1$ °C; $\tau_f = 3$ h; $t_t = +20 \pm 2$ °C; $\tau_t = 4$ hours; $t_h = +60 \pm 1$°C, $\tau_h = 16$ h; t_f, m_t, m_h are freezing, thawing and heating temperatures of the samples, respectively; τ_f, τ_t, τ_h are duration of freezing, thawing and heating of samples.

Based on the results of the tests, a graph of the dependence of thermal productivity on the number of cycles $\lambda(z)$ was constructed. The numerical value of the resource indicator was determined by (2).

It was established that the appearance of expanded polystyrene concrete samples does not change after 60 cycles of "freeze-thaw-heat" climatic effects. The change in the geometric dimensions of the samples was within the limits of permissible values, no visual changes in the color and structure of the material were detected.

The graph of the dependence of thermal productivity of products on the number of cycles is shown in Table 3 and in Fig. 6.

The dependence of thermal productivity of expanded polystyrene concrete samples on the number of "freeze-thaw-heat" cycles is determined by the formula

$$\lambda(z) = 0.1344 + 0.0003z. \quad (4)$$

The resource indicator determined by (2) is r = 0.003. The condition is checked according to (3)

$$\frac{r}{\lambda_0} k_z = \frac{0.003}{0.1311} 5 \le 0.2.$$

The factor of climatic destruction influence of materials during operation on their long-term thermal productivity is determined by (4)

$$K_k = 1 + \frac{0.003}{0.1311} 5 = 1.11.$$

Therefore, the condition according to (3) is fulfilled, that is, the period of effective operation of the products is at least 25 years.

Fig. 4. Climatic chamber for testing the term of effective material use

Fig. 5. General view of the experimental samples

Table 3

Thermal productivity of expanded polystyrene concrete samples during tests

Cycle number	Sample number	Density, kg/m^3	Average density, kg/m^3	Thermal productivity 1 W/m · K	The average value of thermal productivity, 1 W/m · K
0	53-11/21	405.92	401.87	0.1281	0.1311
	53-15/21	369.62		0.1195	
	53-12/21	430.00		0.1406	
	53-8/21	430.00		0.1364	
10	53-1/21	409.62	427.96	0.1296	0.1403
	53-2/21	442.59		0.1397	
	53-3/21	431.85		0.1573	
	53-4/21	425.92		0.1347	
20	53-25/21	396.30	412.87	0.1398	0.1417
	53-33/21	436.30		0.1428	
	53-20/21	394.81		0.1396	
	53-27/21	424.07		0.1446	
30	53-9/21	380.74	378.02	0.1405	0.1434
	53-10/21	367.77		0.1482	
	53-28/21	385.55		0.1417	
40	53-13/21	434.07	421.7	0.1380	0.1463
	53-24/21	435.55		0.1499	
	53-29/21	397.40		0.1601	
	53-6/21	420.74		0.1417	
	53-6a/21	420.74		0.1419	
50	53-22/21	434.44	406.14	0.1616	0.1494
	53-7/21	357.03		0.1322	
	53-23/21	396.66		0.1338	
	53-14/21	442.59		0.1630	
	53-16/21	400.00		0.1565	
60	53-26/21	445.18	460.00	0.1535	0.1513
	53-18/21	491.48		0.1470	
	53-19/21	443.33		0.1536	

The results of the introduction into production of a new composite wall in fixed formwork. After confirmation of the period of effective operation, the enclosing structure was accepted for construction at the Avignon residential complex in Odesa. The process and results of the construction of the enclosing structures on the 12-section, 7-story complex are shown in Fig. 7.

The technology presented in the work was implemented during the construction of the residential complex "Avignon" in the city of Odesa, str. Dacha Kovalevsky, 91. The technology is illustrated in Fig. 7. All enclosing structures were erected in the conditions of the construction site in the following sequence:

1. First, the light steel thin-walled frame of walls/formwork was assembled on the assembly horizon. Sometimes, in order to speed up the process of erecting the building, the bulk assembly of the light steel thin-walled frame was carried out in parallel on the site, which can be seen in Fig. 7, *a*. In this case, the frame was lifted to the ceiling by a crane.

2. The light steel thin-walled frame of the wall formwork was sheathed externally with cement chipboards, and internally with moisture-resistant plasterboard.

3. Then, the space between the inner and outer elements of the fixed formwork was filled with monolithic expanded polystyrene concrete with the help of a special concrete pump.

4. On the outside, the walls were additionally insulated with 80 mm thick polystyrene boards.

The inner walls differ from the outer ones in that waterproof plasterboard was used as a fixed formwork on both sides. Thus, the frame served as an element of the wall and formwork. Gypsum board was used as a rough finish on the inside of the walls, and cement-chipboard was used as a rough finish on the outside of the walls. After the assembly work, the inner and outer walls were subjected to finishing equipment: the seams were sealed with masking tape. The surface of the walls was plastered over the grid and painted. The mesh was fixed with glue, which is an additional waterproofing of the wall.

During the construction of the fencing structures, the main hypotheses laid down during its design were generally confirmed: reduction of labor intensity due to reduction of assembly operations and material intensity – due to the combination of materials with appropriate properties.

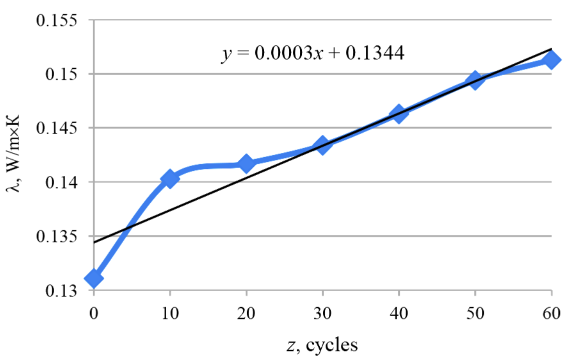

Fig. 6. Dependence of thermal productivity on cyclic influences

Conclusions.

1. The analysis of the information sources showed the relevance of the study on composite frame walls, in particular

Fig. 7. The process of erecting the developed solution of the enclosing frame structure from expanded polystyrene concrete in a fixed formwork:

a – erecting the light steel thin-walled frame; b – assembly nodes of the light steel thin-walled frame; 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

with the use of light concrete, light steel thin-walled structures and fixed formwork. The results of studies on structures with such a technical solution were not found. Most studies on long-term impacts are concerned with mechanical resistance rather than climate change. State standard of Ukraine B V.2.6-101:2010 is devoted to the method of research of the long-term thermal productivity.

2. The results of patent research allowed developing a new structural and technological solution of composite walls in fixed formwork using light steel thin-walled frame and expanded polystyrene concrete.

3. The chosen method of research on the long-term thermal productivity is based on the requirements of current regulatory documents and allows the necessary research to be carried out.

4. Experimental studies on the term of effective operation conducted for the first time made it possible to obtain the dependence of cyclic temperature effects on the thermal productivity of expanded polystyrene concrete in a new composite wall in a fixed formwork. This made it possible to prove the compliance of the thermal characteristics of such a wall with regulatory requirements for 25 conditional years. In this way, the thermal efficiency of using a new wall solution in residential buildings has been proven.

5. The installation of a new composite wall in a fixed formwork with the use of light steel thin-walled frame and expanded polystyrene concrete proved a reduction in labor and material consumption in the conditions of the construction site.

References.

1. Ubi Stanley, E., Okafor, F. O., & Mama, B. O. (2020). Optimization of Compressive Strength of Polystyrene Lightweight Concrete Using Scheffe"s Pseudo and Component Proportion Models. *SSRG International Journal of Civil Engineering, 7*(6), 21-35. https://doi.org/10.14445/23488352/IJCE-V7I6P103.

2. Wattick, J. A., & Chen, A. (2017). Development of a prototype fiber Reinforced Polymer – Concrete Filled wall panel. *Engineering Structures, 147*, 297-308. https://doi.org/10.1016/j.engstruct.2017.05.053.

3. Ahmad, A., & Singh, Yo. (2021). In-plane behaviour of expanded polystyrene core reinforced concrete sandwich panels. *Construction and Building Materials, 269*, 121804. https://doi.org/10.1016/j.conbuildmat.2020.121804.

4. Rassouli, B., Soheil Shafaei, S., Ayazi, A., & Farahbod, F. (2016). Experimental and numerical study on steel-concrete composite shear wall using light-weight concrete. *Journal of Constructional Steel Research, 126*, 117-128. https://doi.org/10.1016/j.jcsr.2016.07.016.

5. Tong, J.-Zh., Pan, W. H., & Shen, M.-H. (2020). Performance of double-skin composite walls with re-entrant profiled faceplates under eccentric compression. *Journal of Building Engineering, 28*. https://doi.org/10.1016/j.jobe.2019.101010.

6. Wang, K., Su, M.-N., Wang, Yu.-H., Tan, J.-K., Zhang, H.-B., & Jun Guo (2022). Behaviour of buckling-restrained steel plate shear wall with concrete-filled L-shaped built-up section tube composite frame. *Journal of Building Engineering, 50*, 104217. https://doi.org/10.1016/j.jobe.2022.104217.

7. Liu, C., Mao, X., He, L., Chen, X., Yang, Y., & Yuan, J. (2022). A new demountable light-gauge steel framed wall: Flexural behavior, thermal performance and life cycle assessment. *Journal of Building Engineering, 47*, 103856. https://doi.org/10.1016/j.jobe.2021.103856.

8. Mamat, R., Abd Rahim, J., & Hamzah, S. R. (2015). Behaviour of unreinforced expanded polystyrene lightweight concrete (EPS-LWC) wall panel enhanced with steel fiber. *Journal of Engineering Science and Technology, 10*(12), 1600-1614.

9. Shi, B., Liu, W., Yang, H., & Ling, X. (2020). Long-term performance of timber-concrete composite systems with notch-screw con-

nections. *Engineering Structures, 213*, 110585. https://doi.org/10.1016/j.engstruct.2020.110585.
10. Zhou, B., Si, Q., Zong, L., & Wang, B. (2022). Seismic performance analysis of steel frames with FCP composite external wall. *Structures, 39*, 86-97. https://doi.org/10.1016/j.istruc.2022.02.076.
11. Boscato, G., Dalla Mora, T., Peron, F., Russo, S., & Romagnoni, P. (2018). A new concrete-glulam prefabricated composite wall system: Thermal behavior, life cycle assessment and structural response. *Journal of Building Engineering, 19*, 384-401. https://doi.org/10.1016/j.jobe.2018.05.027.
12. Glória Gomes, M., Moret Rodrigues, A., Bogas, J.A., & Freitas, A. (2021). Thermophysical properties under different hygroscopic conditions of an innovative composite concrete pre-walls system. *Construction and Building Materials, 307*, 124938. https://doi.org/10.1016/j.conbuildmat.2021.124938.
13. Bala, A., & Gupta, S. (2021). Thermal resistivity, sound absorption and vibration damping of concrete composite doped with waste tire Rubber: A review. *Construction and Building Materials, 299*, 123939. https://doi.org/10.1016/j.conbuildmat.2021.123939.
14. Guo, B., Yu, Ch., Yu Han, Y., & Zhu, J. (2012). Long-term Performance of Concrete Suffered Infant Age Freezing. *Advanced Building Materials and Sustainable Architecture, PTS 1-4*, 174-177, 524. https://doi.org/10.4028/www.scientific.net/AMM.174-177.524.
15. LLC "Building company "SERVUS" (2007). *Multi-Layer Panel.* (Ukrainian Patent No. 24051). Kyiv: Ukraine. Retrieved from https://base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=106308&chapter=biblio.
16. Sopelnyk, V., Sopelnyk, K., Taran, R., & Taran, V. (2009). *Wall of the Building.* (Ukrainian Patent No. 38504). Kyiv: Ukraine. Retrieved from https://uapatents.com/5-38504-stina-budivli.html.
17. Ministry of Regional Development and Construction of Ukraine (2010). *State Standard B V.2.6-101:2010 Method for determining the heat transfer resistance of enclosing structures*. Kyiv. Retrieved from http://uas.org.ua/wp-content/uploads/2019/01/dstu_b_v.2.6-101_2010.pdf.
18. Ministry of Regional Development and Construction of Ukraine (2010). *State Standard B V.2.7-61:2008 Brick and stone ceramic ordinary and front*. Kyiv. Retrieved from http://keraterm-ua.com/dsty.pdf.
19. Interstate Scientific and Technical Commission for Standardization, Technical Standardization and Certification in Construction (2001). *State Standard B V.2.7-105-2000 Construction materials and products. Method for determining thermal conductivity and thermal resistance under stationary thermal regime*. Kyiv. Retrieved from https://ukrsmeta.ua/wp-content/uploads/files/DSTU/33.DOC.
20. Ministry of Regional Development of Ukraine (2009). *State Standard B V.2.7-182:2009 Building materials. Methods for determining the term of effective operation and thermal conductivity of building insulation materials in design and standard conditions*. Kyiv. Retrieved from https://issuu.com/maxwell3249/docs/dstu_b_v_2_7-182_2009__stroitel_nye.
21. Ministry of Regional Development of Ukraine (2014). *State Standard B V.2.6-189 Methods of selection of heat-insulating material for warming of buildings*. Kyiv. Retrieved from https://eurobud.ua/wp-content/uploads/2020/09/dstu-b-v_2_6-189-2013.pdf.
22. Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine (2017). *State Building Code V.2.6-31 Thermal insulation of buildings*. Kyiv. Retrieved from https://www.minregion.gov.ua/wp-content/uploads/2016/01/DBN-V.2.6-31-2016-Teplova-izolyatsiya-budivel.pdf.
23. Ukrainian Research Institute of Standardization, Certification and Informatics (2003). *State Standard 4179-2003 Roulettes measuring metal. Specifications*. Kyiv. Retrieved from http://online.budstandart.com/ua/catalog/doc-page?id_doc=50212.
24. SE "Ukrainian Research and Training Center for Standardization, Certification and Quality" (2019). *State Standard EN 13190:2018 Thermometers with scale (EN 13190:2001, IDT)*. Kyiv. Retrieved from http://online.budstandart.com/ru/catalog/doc-page?id_doc=79229.

Термін ефективної теплової експлуатації пінополістиролбетону в новій композитній стіні в незнімній опалубці

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Мета. Визначення терміну ефективної теплової експлуатації пінополістиролбетону в новій композитній каркасній стіні в незнімній опалубці.

Методика. Для проведення патентного пошуку й розробки методики дослідження використовувалися методи аналізу й синтезу. Пошук проводився за патентною базою УкрІНТЕІ. Проведення експериментальних досліджень виконувалось у відповідності до ДСТУ Б В.2.7-38-95. Сутність випробувань полягала у відтворенні природних умов циклу «заморожування–відтавання–нагрівання» та вимірах теплоізоляційних характеристик основного ізолюючого матеріалу – полістиролбетону – до й після випробувань. На основі цього робився висновок щодо терміну ефективної експлуатації нової композитної стіні в незнімній опалубці. Розрахунок залежності теплопровідності від кількості циклів проводився арифметичними засобами з використанням нормативних методик і програм типу Microsoft Excel.

Результати. Створено нове технічне рішення композитної стіни з пінополістиролбетону в незнімній опалубці з використанням легких сталевих тонкостінних конструкцій. Розроблена методика дослідження терміну ефективної теплової експлуатації цієї композитної стіни. Проведене експериментальне дослідження впливу циклічних змін температури («заморожування–відтавання–нагрівання») на теплопровідність основного теплоізолюючого елементу композитної стіни – пінополістиролбетону. Розрахована відповідна аналітична модель залежності теплопровідності зразків пінополістиролбетону від кількості циклів «заморожування–відтавання–нагрівання». Підтверджена можливість ефективної експлуатації конструкції шляхом перевірки нормативних значень показника ресурсу й коефіцієнта урахування впливу кліматичної деструкції матеріалів у процесі експлуатації на їх теплопровідність. Виконане впровадження нового рішення влаштування композитної стіни в будівництво.

Наукова новизна. Уперше визначена залежність циклічних температурних впливів на теплопровідність нової композитної стіни з пінополістиролбетону в незнімній опалубці з використанням легких сталевих тонкостінних конструкцій, що дозволило встановити її термін ефективної експлуатації. Цей науковий результат дозволяє знизити матеріалоємність, забезпечити економічність, підвищити експлуатаційну надійність і енергоефективні властивості, збільшити термін служби композитної стіни.

Практична значимість. Розроблене нове рішення влаштування композитної стіни з пінополістиролбетону в незнімній опалубці з використанням легких сталевих тонкостінних конструкцій та обґрунтована її ефективна теплова експлуатація протягом нормативно встановленого терміну. Обґрунтовано термін ефективної експлуатації пінополістиролбетону як найменш довговічного компоненту композитної стіни. Проведена апробація цієї конструкції шляхом облаштування її на реальному об'єкті будівництва, що показала підвищення технологічності будівельних процесів у порівнянні із традиційними огороджуючими конструкціями.

Ключові слова: *композитна стіна, термін експлуатації, пінополістиролбетон, легкі сталеві конструкції, незнімна опалубка*

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