Tech Note. Analysis of practices of layer-by-layer use of expanded polystyrene in the operation of residential buildings

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Abstract.- The purpose of this paper is to consider three aspects of the use of polystyrene as an effective heat-insulating material in three-layer load-bearing and enclosing structures of reinforced concrete residential buildings. The first aspect is related to the dependence of the enclosure heat transfer resistance degree on the method of combining expanded polystyrene with stone structural materials. For example, prefabricated expanded polystyrene concrete blocks for the construction of walls of low and medium-rise buildings and cast-in-situ expanded polystyrene concrete poured into the voids of the well brickwork in high-rise buildings. It is shown that the layer-by-layer application of pure expanded polystyrene and the concrete layers protecting it multiplies the degree of thermal insulation of the enclosing structure while retaining its strength and equal consumption of raw materials. The second aspect is associated with the fire resistance of reinforced concrete load-bearing and enclosing structures of residential buildings. A sufficient degree of fire resistance when protecting expanded polystyrene with cast-in-situ reinforced concrete layers is shown using examples. The third aspect shows the feasibility of using outer three-layer reinforced concrete walls with polystyrene insulation for panel heating of the buildings.

Keywords: expanded polystyrene; reinforced concrete; heat transfer resistance; fire resistance; panel heating.

Nota Técnica. Análisis de prácticas de capas-por-capas usadas en la expansión del poliestireno en operaciones de construcciones residenciales

Resumen.- El propósito de este artículo es considerar tres aspectos del uso de poliestireno como material aislante térmico eficaz en estructuras portantes y de cerramiento de tres capas de edificios residenciales de hormigón armado. El primer aspecto está relacionado con la dependencia del grado de resistencia a la transferencia de calor del recinto con respecto al método de combinación de poliestireno expandido con materiales estructurales de piedra, como, por ejemplo, bloques prefabricados de poliestireno expandido para la construcción de paredes de edificios de baja y media altura y hormigón de poliestireno expandido colado in situ en los huecos de los ladrillos de los pozos en edificios de gran altura. Está demostrado que la aplicación capa por capa de poliestireno expandido puro y las capas de hormigón que lo protegen multiplica el grado de aislamiento térmico de la estructura de cerramiento manteniendo su resistencia y el mismo consumo de materias primas. El segundo aspecto está asociado a la resistencia al fuego de las estructuras portantes y de cerramiento de hormigón armado de edificios residenciales. Se muestra con ejemplos un grado suficiente de resistencia al fuego al proteger poliestireno expandido con capas de hormigón armado coladas in situ. El tercer aspecto muestra la viabilidad de utilizar muros exteriores de hormigón armado de tres capas con aislamiento de poliestireno para la calefacción por paneles de los edificios.

Palabras clave: poliestireno expandido; concreto reforzado; resistencia a la transferencia de calor; resistente al fuego; panel calefactor.

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1. Introduction

The problems of using polystyrene in the structures of reinforced concrete buildings' walls have occurred due to the fact of the development of this material as a heat-insulation material [1, 2, 3]. It was used via mixing with concrete, pouring into brickwork wells, and finally, placing it as a separate

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layer in three-layer wall structures. The work in scientific and practical terms has been carried out at the Moscow State University of Civil Engineering for many years. Consequently, theses have been defended for scientific degrees, and bachelor's, as well as master's, final qualifying papers have been presented whose results are introduced into the general practice of design and construction. Today, based on the findings of scientific research, a three-layer structure of outer walls is mainly used in construction. However, the outdated approach to providing thermal insulation via other significantly less effective methods is still maintained [2, 1].

According to modern heat engineering standards [4], the required thermal resistance of the outer wall of a residential building in the second climatic zone of Russia should be about 3 units, m^2°C/W. The required resistance was about 1 unit until the end of the 20^{th} century, which was provided by a wall internally plastered with a thickness of two hollow clay bricks (a little more than 0,5 m), while modern 3 units require a wall thickness of the same brick a little less than 2,5 m. It is noted that 3 units of the required thermal insulation is provided by a wall of heavy concrete with a thickness of 6 m and light concrete – about 1 m, a wall of spruce or pine – a little over 0,5 m, and slabs of foamed plastic or mineral wool with a volumetric weight of less than 100 kg/m^3 –about 0,15 m. The last two materials are the most effective in terms of thermal insulation. With the specified volumetric weight, their thermal conductivity coefficients do not exceed 0,05 $W/m \cdot C$, even under wet operating conditions.

Nowadays, due to the exorbitant thickness, the walls from the conventional materials noted above are not built. Single-layer walls from these effective heat-insulating materials are not built due to their low strength. Therefore, modern outer enclosures should only be multi-layered, wherein the effective heat-insulating layer is protected by the bearing and facing layers, which ensure the strength, durability, and fire resistance of the structure [5, 6, 7].

2. Methods

The study presented in this article is based on theoretical and practical research conducted at the Moscow State University of Civil Engineering in 2021-2022. The authors aimed to investigate the development of effective heat-insulating and protecting structural materials in the construction of outer walls of residential buildings, particularly in the second climatic zone of Russia. The correct use of expanded polystyrene (EP) as a heat-insulating layer in three-layer reinforced concrete wall structures is shown, which ensures the regulatory fire resistance of the entire structure.

The methodology involved conducting elementary calculations to compare the thermal resistance of two different design options for enclosing structures using effective heat-insulating and structural materials.

The first option consisted of uniformly mixed concrete with expanded polystyrene (EP) granules (Figure 1), while the second option involved dividing the concrete into two plates, with the EP layer located between them (Figure 2).

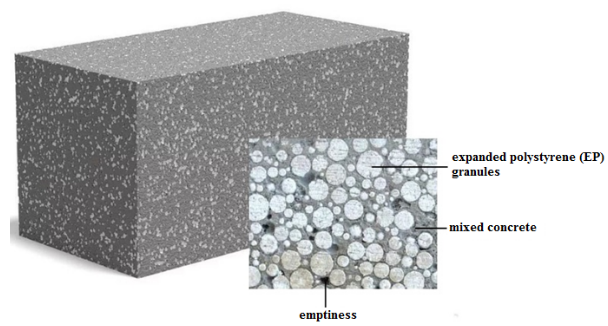


Figure 1: Concrete with expanded polystyrene (EP) granules

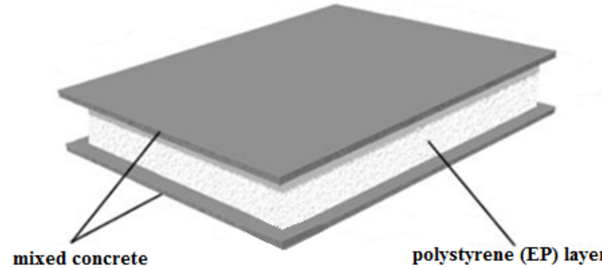
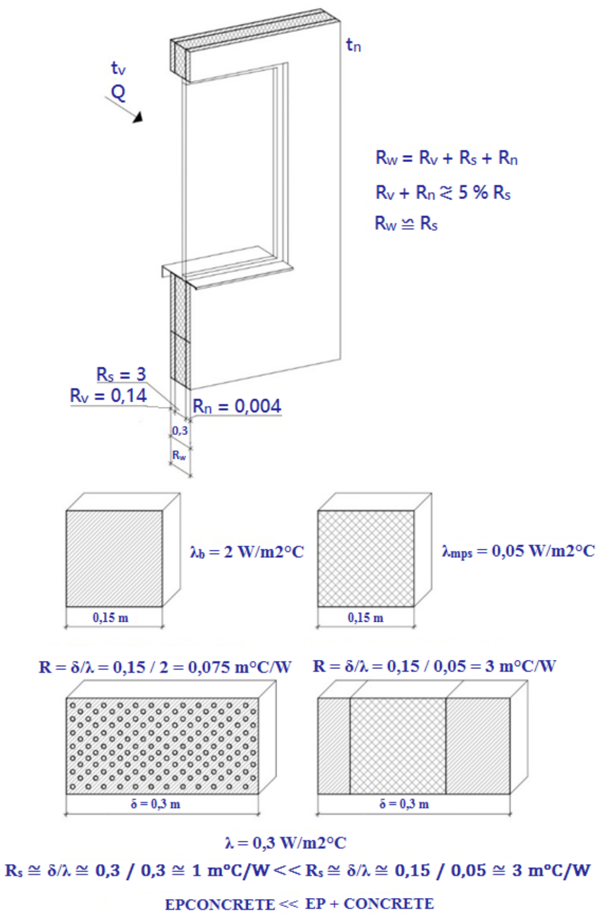


Figure 2: Concrete with EP layer located inbetween

The authors compared the thermal resistance of both options. For these two identical cubes with a side size of 0,15 m from were selected for the clarity of the experiment. This size is due to the fact that the EP layer of such a thickness provides the above-mentioned 3 units of the required thermal resistance of the wall, a fragment of which is shown in Figure 3 with a window section.



*A cube of reinforced concrete is presented in the lower half of the figure at the top left, EP is shown to the right, a mixture of reinforced concrete with EP is presented at the bottom left, and separate layers of reinforced concrete and EP are presented to the right. Symbols: λ –thermal conductivity of the material, R, R_s, and R_w –heat transfer resistance of the layer, structure, and wall, respectively.

Figure 3: Comparison of heat transfer resistance options for single-layer and three-layer walls made of the same volumes of raw materials

The cubes from these materials can be connected in two options into rectangular parallelepipeds 0,3 m long, equal to the thickness of the outer wall. Densely composed parallelepipeds form a wall uniform in terms of area, being conductor strands of the Q heat flux passing through it. In the first option, a single-layer wall consists of uniformly mixed concrete with EP granules. In the second option, the concrete cube is divided into two plates: one plate of 0,1 m thick represents the inner bearing layer of the wall; the other plate of 0,05 m thick represents the outer facing layer protecting 0,15 m thick EP layer located between the concrete plates.

3. Results and discussion

Dependence of the wall heat transfer resistance on the method of combining heat-insulating and structural material

Based on the experiment was concluded that the layer-by-layer arrangement of effective heat-insulating and protecting structural materials within the wall was necessary to maximize heat transfer resistance.

There are several rules for designing enclosing structures with effective heat-insulating materials that allow for obtaining the maximum result. The first rule follows from the consideration of two options for combining heat-insulating and structural materials. Thus, to create an energy-efficient and durable outer wall, it is enough to use two materials: EP and reinforced concrete [8].

Based in the calculations [9] presented in Figure 3, it is shown that with the same consumption of structural and heat-insulating materials, the thermal resistance of the wall made according to the second design option is three times higher than the thermal resistance of the wall made based on the first option.

The results of comparing the options demonstrate the obligatory need for the layer-by-layer arrangement of structural and heat-insulating materials within the thicknesses of the enclosing structures (first rule). This is the feature of the trend in the development of heat-insulating enclosing structures (i.e. walls and ceilings) of buildings.

Other rules refer to air voids (i.e. cavities, intermediate layers, slots, etc.) formed in the thickness of the enclosure during its construction. The number, size, and shape of the air voids depend on the materials and construction and decoration methods. They are formed when using the dry construction method, that is, installation on the bearing layer of the wall, insulation, and facing layers, consisting of piece elements (slabs, panels, sheets, etc.). If these cavities connect with the outside air through the joints of the finishing components, the heat-protective effect of the insulating layer in the cold season can be nullified, leading to the cooling of the enclosure and the premises behind it in the hot season. The described design is called a ventilated facade; it allows for effectively drying the moisture of wall materials due to ventilation [10].

If these cavities connect with the premise air through the leaks, they may form and accumulate moisture condensate from the premise air during the cold period. Undesirable processes can be avoided by placing a vapor barrier film between the bearing and insulating layers (second rule) and by placing a windproof but vapor-permeable film between the insulating and facade layers (third rule). In this case, the ventilated intermediate layers are the flame conductors of combustible heat-insulating materials. It is possible to avoid fire spreading by installing special cut-offs in the air cavities (fourth rule) and by increasing the fire resistance of heat-insulating materials by inserting flame retardants into them (fifth rule).

With the wet construction method, it is possible to perform simultaneous concrete casting of a three-layer wall or sequenced concrete casting of the bearing layer of a wall or ceiling [11], then place and strengthen the heat-insulation material and install a monolithic screed on the floor structure or wet facade plaster on the wall. The labor intensity at the construction site is higher when using this construction method, but the formation of voids is lower and there is less work regarding eliminating their negative influence.

3.1. *Fire resistance of three-layer reinforced concrete structures of residential buildings*

Occasionally, there are discussions about the fire resistance of the most common effective heat-insulating materials in the form of foamed plastics, for example, the mentioned EP and mineral wool materials, on a polymer binder (hereinafter referred to as mineral wool) [12]. Authors conclude that both materials have a variety of advantages and disadvantages in terms of technological, structural, environmental, and other indicators. However, mineral wool materials are more often put at the forefront in terms of fire resistance.

Based on the research findings, authors present arguments regarding this issue.

1. EP began to be massively used in residential construction in the Soviet Union in 1960 in the outer walls of large-panel houses of the P-32 series. There were no fire problems with the walls containing EP for the semicentennial history of their operation. Most of the largest and most famous fatal fires with EP occurred in the 70-80s, following which restrictions and bans on its use were imposed in construction, which led to a decrease in its production in the country. Today, the production of EP in the world obligatory takes place with the use of flame retardants. At present, one can observe at construction sites how splashes of molten metal melt through the adjacent heat-insulating slabs of EP without causing any inflammation while welding steel structures. As practice shows, the cause of the rare fires with EP occurring now is mainly related to the failure to comply with the technology for the application of flame retardants.
2. The flammability of a construction material depends on the weight of a combustible component contained within it. The weight of glue binding a volume unit of mineral wool fiber is close to the weight of the most popular EP slabs of the M15 grade of the same volume. Thus, there are no advantages of mineral wool over EP in terms of this flammability indicator.
3. Authors witnessed an expert assessment of the results of a cottage fire set by malevolent intruders who entered the house through a broken window in the bathhouse. The cottage was built during the initial period of development of the coniferous forest territory for the settlement. The cottage was built from cast in-situ steel-reinforced concrete with three-layer outer walls and attic flooring, in which the 15-cm middle layer was made of

the M15 grade EP. The inner, bearing layer of the outer walls and reinforced concrete floors had a thickness of 10 cm, and the outer, facade layer of the walls and the attic flooring screed had a thickness of 4 cm. The bearing layer of the outer walls contained metal-reinforced plastic heating pipes and electrical wiring.

The garret roof was covered with flat sand-cement tile, and its joints ensured air draft contributing to fire spreading during a fire, providing free ventilation of the garret floor with the attic flooring hatch open and the bathhouse window broken.

The arson of the house occurred in two spots: a bathhouse located on the first floor and the second-floor bedroom located above it. The house rooms were furnished with wooden furniture in a standard way, there was firewood in the bathhouse, and chairs from other rooms were additionally brought to the premises set on fire. The arson was committed at the beginning of the week; the fading fire was discovered by the house owners a few days later, late Friday. When opening the front door, the premises were filled with smoke and soot, the carpet was smoldering on the floors. There were no people near the site during the working week. Therefore, nobody extinguished the fire.

Inspection of the house premises showed that all the wooden objects that were in the premises with fire points were burned off, and the shower cabin in the bathhouse was destroyed. A part of its plastic burned off, and the other part froze like a griddle cake on the floor. In the bedroom, with burnt wooden furniture, a TV set kinescope exploded, the steel sections of the plastic window frame were warped, plastic was partially burned off and melted, and the glass burst and fell on the floor. The major part of the carpet on the second floor and stairs burned out, leaving a lot of soot on the walls and ceilings of the rooms. The metal-reinforced plastic heating pipes and electrical wiring were not damaged, retaining their operability. When replacing the window block of the second-floor bedroom, it turned out that the heat-insulating layer of the EP was not damaged by fire.

After repairs, the major timeshare of which was the cleaning of the premises from soot and smell (over two months), the house was brought into normal operational condition. That is how the story of the fire in a reinforced concrete house ended, the effective thermal insulation of which was made entirely of EP; the fire that no one extinguished for several days and that decayed on its own did not damage the house's thermal protection.

Possibility of panel heating arrangement

The practice of application revealed another positive quality of a three-layer wall with a 10-cm internal reinforced concrete layer and a 15-cm middle layer of EP. With a two-pipe heating system, the straight and return pipes of the floor heating circuit, laid in the window sill strip of the inner reinforced concrete layer of the outer walls with a 0.5-m gap can provide comfortable panel heating of the floor without the use of any heating devices due to the thermal conductivity of the mesh reinforcing concrete (with a cell of 150×150 mm and a wire diameter of 5 mm) [10]. The thermal inertia of the reinforced concrete window sill strip of the wall-reinforced concrete layer equalizes the temperature of the premises during sharp fluctuations in the ambient air temperature.

4. Conclusion

In conclusion, it is established that the use of layer-by-layer arrangement of effective heat-insulating and protecting structural materials within the wall is a highly effective way to improve the heat transfer resistance of three-layer walls, compared to single-layer walls made with the same materials. The semicentennial experience of residential buildings with three-layer walls, where EP is used as a heat-insulating layer protected by monolithic layers on both sides, demonstrates their reliable fire resistance. Additionally, the use of three-layer reinforced concrete outer walls with an EP heat-insulating layer allows for panel heating of premises using a two-pipe floor-by-floor outline located in the windowsill strip of the inner reinforced concrete bearing layer of the wall. These findings highlight the importance of using effective heat-insulating materials in the construction of outer walls for improved thermal efficiency, durability, and fire safety. In conclusion, the use of layer-by-layer arrangement of effective heat-insulating and protecting structural materials within the wall is a highly effective way to improve the heat transfer resistance of three-layer walls, compared to single-layer walls made with the same materials.

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