UDC 691.327.32
IRSTI 67.09
RESEARCH ARTICLE

LIGHTWEIGHT CONCRETE COMPOSITIONS FOR MULTILAYER ENCLOSING STRUCTURES

O.A. Miryuk[1], N.Zh. Zhanabay[2], G.M. Rakhimova[3], M.A. Rakhimov[3], T.Yu. Samoilova[3], K.K. Maikotova[3,*], R.B. Zakaria[4]

[1]Rudny Industrial University, 111500, Rudny, Kazakhstan
[2]Mukhtar Auezov South Kazakhstan Research University, 160012, Shymkent, Kazakhstan
[3]Abylkas Saginov Karaganda Technical University, 100027, Karaganda, Kazakhstan
[4]Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

Abstract. *Lightweight concretes are widely used in construction, however, achieving an optimal balance between thermal insulation and strength characteristics remains an urgent scientific and technical task. The purpose of this study is to develop multilayer lightweight concrete with a variotropic structure based on expanded polystyrene fillers and adjustable porosity of cement stone using air-entrapping additives. Experimental studies of the effect of the composition of the mixture, the content of expanded polystyrene and the porization parameters on the density, compressive strength and thermal conductivity of the material were carried out. It was found that an increase in porosity of up to 4.5% due to the use of air-entrapping additives allows maintaining strength at the required level (up to 2.8 MPa for thermal insulation layers and up to 39.0 MPa for structural layers) while reducing the coefficient of thermal conductivity to 0.095 W/(m·°C), which is 15-30% lower compared with traditional lightweight concrete. The scientific novelty of the research lies in the development of a variotropic multilayer structure with a controlled distribution of density and porosity over the thickness of the material, providing a targeted combination of strength and thermal characteristics. The proposed approach makes it possible to reduce the average density of the material, increase the energy efficiency of enclosing structures and can be used in the design of energy-efficient buildings.*

Keywords: *lightweight concrete, variotropic structure, polystyrene concrete, thermal conductivity, enclosing structures, strength, energy efficiency.*

***Corresponding author**
Kamilya Maikotova, e-mail: k.maykotova@ktu.edu.kz

https://doi.org/10.51488/1680-080X/2026.1-27
Received 18 February 2026; Revised 10 March 2026; Accepted 25 March 2026

ӘОЖ 691.327.32
ҒТАМР 67.09
ҒЫЛЫМИ МАҚАЛА

КӨП ҚАБАТТЫ ҚОРШАУ ҚҰРЫЛЫМДАРЫНА АРНАЛҒАН ЖЕҢІЛ БЕТОН

О.А. Мирюк[1], Н.Ж. Жанабай[2], Г.М. Рахимова[3], М.А. Рахимов[3], Т.Ю. Самойлова[3], К.К. Майкотова[3,*], Р.Б. Закария[4]

[1]Рудный индустриялық университеті, 111500, Рудный, Қазақстан
[2]Мұқтар Әуезов атындағы Оңтүстік Қазақстан зерттеу университеті, 160012, Шымкент, Қазақстан
[3]Әбілқас Сағынов атындағы Қарағанды техникалық университеті, 100027, Қарағанды, Қазақстан
[4]Малайзия технологиялық университеті, 81310 UTM Скудай, Джохор, Малайзия

Аңдатпа. *Жеңіл бетондар құрылыста кеңінен қолданылады, бірақ жылу оқшаулау және беріктік сипаттамалары арасындағы оңтайлы тепе-теңдікке қол жеткізу өзекті ғылыми-техникалық міндет болып қала береді. Осы зерттеудің мақсаты ауа өткізгіш қоспаларды пайдалана отырып, стирофам толтырғыштары мен реттелетін цемент тас кеуектілігі негізінде вариатропты құрылымы бар көп қабатты жеңіл бетонды әзірлеу болып табылады. Жұмыс барысында қоспаның құрамының, полистирол көбігінің құрамының және поризация параметрлерінің материалдың тығыздығына, қысу беріктігіне және жылу өткізгіштігіне әсері бойынша эксперименттік зерттеулер жүргізілді. Ауа өткізгіш қоспаларды қолдану арқылы кеуектіліктің 4,5% - ға дейін артуы жылу өткізгіштік коэффициентін 0,095 Вт/(м·°С) дейін төмендете отырып, беріктікті қажетті деңгейде(жылу оқшаулағыш қабаттар үшін 2,8 МПа-ға дейін және құрылымдық қабаттар үшін 39,0 МПа-ға дейін) сақтауға мүмкіндік беретіні анықталды, бұл дәстүрлі өкпемен салыстырғанда 15-30% - ға төмен бетондармен. Зерттеудің ғылыми жаңалығы беріктік пен жылу сипаттамаларының мақсатты үйлесімін қамтамасыз ететін материалдың қалыңдығы бойынша тығыздық пен кеуектіліктің басқарылатын таралуы бар вариатропты көп қабатты құрылымды әзірлеу болып табылады. Ұсынылған тәсіл материалдың орташа тығыздығын төмендетуге, қоршау құрылымдарының энергия тиімділігін арттыруға мүмкіндік береді және энергияны үнемдейтін ғимараттарды жобалауда қолдануға болады.*

Түйін сөздер: *жеңіл бетон, вариатропты құрылым, полистиролбетон, жылу өткізгіштік, қоршау құрылымдары, беріктік, энергия тиімділігі.*

***Автор-корреспондент**
Камиля Майкотова, e-mail: k.maykotova@ktu.edu.kz

https://doi.org/10.51488/1680-080X/2026.1-27
Алынды 18 ақпан 2026; Қайта қаралды 10 наурыз 2026; Қабылданды 25 наурыз 2026

УДК 691.327.32
МРНТИ 67.09
НАУЧНАЯ СТАТЬЯ

ЛЕГКИЙ БЕТОН ДЛЯ МНОГОСЛОЙНЫХ ОГРАЖДАЮЩИХ КОНСТРУКЦИЙ

О.А. Мирюк[1], Н.Ж. Жанабай[2], Г.М. Рахимова[3], М.А. Рахимов[3], Т.Ю. Самойлова[3], К.К. Майкотова[3,*], Р.Б. Закария[4]

[1]Рудненский индустриальный университет, 111500, Рудный, Казахстан
[2]Южно-Казахстанский исследовательский университет имени Мухтара Ауэзова, 160012, Шымкент, Казахстан
[3]Карагандинский технический университет имени Абылкаса Сагинова, 100027, Караганда, Казахстан
[4]Малайзийский технологический университет, 81310 UTM Скудай, Джохор, Малайзия

Аннотация. *Лёгкие бетоны широко применяются в строительстве, однако достижение оптимального баланса между теплоизоляционными и прочностными характеристиками остаётся актуальной научно-технической задачей. Целью настоящего исследования является разработка многослойного лёгкого бетона с вариатропной структурой на основе пенополистирольных заполнителей и регулируемой пористости цементного камня с использованием воздухововлекающих добавок. В рамках работы проведены экспериментальные исследования влияния состава смеси, содержания пенополистирола и параметров поризации на плотность, прочность при сжатии и теплопроводность материала. Установлено, что увеличение пористости до 4,5% за счёт применения воздухововлекающих добавок позволяет сохранять прочность на требуемом уровне (до 2,8 МПа для теплоизоляционных слоёв и до 39,0 МПа для конструкционных слоёв) при одновременном снижении коэффициента теплопроводности до 0,095 Вт/(м·°С), что на 15–30% ниже по сравнению с традиционными лёгкими бетонами. Научная новизна исследования заключается в разработке вариатропной многослойной структуры с управляемым распределением плотности и пористости по толщине материала, обеспечивающей целенаправленное сочетание прочностных и теплотехнических характеристик. Предложенный подход позволяет снизить среднюю плотность материала, повысить энергоэффективность ограждающих конструкций и может быть использован при проектировании энергоэффективных зданий.*

Ключевые слова: *легкий бетон, вариатропная структура, полистиролбетон, теплопроводность, ограждающие конструкции, прочность, энергоэффективность.*

***Автор-корреспондент**
Камиля Майкотова, e-mail: k.maykotova@ktu.edu.kz

https://doi.org/10.51488/1680-080X/2026.1-27
Поступила 18 февраля 2026; Пересмотрено 10 марта 2026; Принято 25 марта 2026

ACKNOWLEDGEMENTS/ FUNDING SOURCE

The research was conducted within the grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan AP26199493 “Development of Multilayer Concretes with Improved Technological and Operational Properties for Wall Products”.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

When preparing this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің AP26199493 "Қабырға бұйымдары үшін жақсартылған технологиялық және пайдалану қасиеттері бар көп қабатты бетондарды әзірлеу" гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан AP26199493 “Разработка многослойных бетонов с улучшенными технологическими и эксплуатационными свойствами для стеновых изделий”.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The external enclosing structures of most buildings in the Republic of Kazakhstan are characterized by low energy efficiency or economically unjustified indicators, which does not meet modern international requirements and leads to extra consumption of thermal energy **(Resolution of the Government of the Republic of Kazakhstan, 2023; Sadyrov, 2022)**. This is due to the fact that there were no energy-saving technologies at the construction stage of these houses. To reduce heat loss and adapt such apartment buildings to the standard of a low-energy building, it is necessary to significantly improve the energy efficiency of the building. The structure of heat losses in apartment buildings includes: through the exterior walls 20-30%, through the ventilation system 30-40%, through windows and entrance doors12-25%, through the roof 10-20% and through the basement 3-6% **(Gonçalves et al., 2020; Tuktamisheva & Adilova, 2025).**

In this regard, a significant role is played by the development of new solutions in creating new energy-efficient enclosing structures. One approach to solving this issue is the use of multilayer lightweight concrete with a variable structure for the enclosing structures of residential buildings. The following features characterize multilayer lightweight concrete with a variotropic structure:

- smooth change in average density between layers;
- change in the pore structure of concrete layers from the periphery to the center of the product;
- varying the ratio of layer thicknesses to control the properties of multilayer lightweight concrete (strength, average density, thermal conductivity).

Despite the extensive body of research on lightweight concrete and polystyrene-based materials, most existing studies focus on homogeneous structures with fixed porosity and density parameters. These approaches, while effective in improving either thermal or mechanical properties, often fail to ensure their optimal combination **(Estemesova et al., 2023)**.

Modern foreign studies also confirm the high potential of lightweight concretes and multilayer enclosing systems to improve the energy efficiency of buildings. The works **Haller et al. (2024); Lee et al. (2021); Shi (2025)** show that the use of lightweight composites and styrofoam-based materials helps to reduce heat loss and increase the thermal efficiency of external enclosing structures.

Furthermore, the majority of previous works do not consider the possibility of controlled variation of material properties across the cross-section of enclosing structures **(Zhangabay et al., 2023)**.

Therefore, there is a clear research gap in the development of multilayer lightweight concrete with a variotropic structure, enabling the regulation of density and porosity distribution within a single structural element.

The present study aims to address this gap by developing and experimentally validating multilayer lightweight concrete compositions with controlled structural heterogeneity.

The hypothesis of the study is that the formation of a variotropic structure of multilayer lightweight concrete using polystyrene aggregates allows the simultaneous increase in thermal insulation properties and the provision of the required strength of the material due to the rational distribution of density across the cross-section of the structure.

The scientific novelty of the research lies in the development of a method for forming a variotropic structure of multilayer lightweight concrete with an adjustable porosity of the cement matrix. The dependences between the degree of porization, the content of polystyrene filler and the physical and mechanical characteristics of the material have been established.

Despite numerous studies of lightweight concretes, most of the existing solutions are based on homogeneous materials with fixed porosity, which limits the ability to simultaneously provide the required strength and energy efficiency.

The aim of this study is to develop and experimentally validate compositions of multilayer lightweight concrete with a variotropic structure based on expanded polystyrene aggregates, as well as to determine the influence of mixture composition and porosity parameters on the physical, mechanical, and thermal properties of the material.

2 MATERIALS AND METHODS

The experimental program was designed to investigate the influence of mixture composition and structural configuration on the physical, mechanical, and thermal properties of lightweight concrete.

The main variables of the study included:

- the content of polystyrene aggregates (kg/m³ of mixture);
- the use of air-entraining additives;
- curing conditions (normal curing and heat treatment);
- the structural configuration of multilayer concrete.

All experimental procedures were carried out in accordance with standard testing methods. Compressive strength was determined according to GOST 10180-2012, density was measured in accordance with GOST 12730.1-2020, and thermal conductivity was evaluated following GOST 7076-99. As part of the experimental program, 10 samples of highly porous polystyrene concrete with different porosity parameters and the composition of the mixture were produced. To ensure the reliability of the results, the tests were carried out on at least three parallel samples for each composition under the same laboratory conditions. The obtained values were averaged, and the deviations between individual measurements did not exceed 5%, which ensured reproducibility and reliability of experimental data. Statistical processing of the results was performed by calculating the average values and relative deviations of experimental parameters.

Preliminary tests were conducted on the following lightweight aggregates as components for various layers of multilayer lightweight concrete: expanded polystyrene, foam glass, perlite, vermiculite, granulated slag, expanded clay, and glass microspheres.

Polystyrene, expanded clay, and blast furnace slag are the most suitable aggregates due to their availability on the raw material market and ease of use.

The selection of materials was based on their availability, low density, and suitability for producing lightweight concrete with enhanced thermal insulation properties. In particular, expanded polystyrene was selected due to its extremely low density and its ability to significantly reduce the thermal conductivity of the material.

Blast furnace slag was used as a mineral additive to improve durability and reduce cement consumption, while also contributing to sustainability through the use of industrial waste **(Akmalayuly & Toleuov, 2022).**

The first step in producing multilayer concrete was the development of a highly porous polystyrene for use as a thermal insulation layer in three-layer enclosing panels in residential buildings.

Polystyrene concrete is an effective and relatively inexpensive thermal insulation material that is widely used in construction. Depending on its composition, this concrete can be used as thermal and sound insulation or as a structural material **(Samoilova et al., 2024).**

Polystyrene-based concrete can be used for all parts of a building (structural and non-structural) as a very lightweight material by varying the percentage of its aggregates. Changing the polystyrene ratio in concrete also changes its intended use. Unlike lightweight industrial aggregates, polystyrene is widely available **(Gernay, 2018).**

An analysis of existing approaches indicates that the use of polystyrene granules in lightweight concrete represents an efficient solution for several reasons. Firstly, due to their low density, polystyrene granules increase the porosity of the concrete matrix, thereby improving its thermal insulation performance. Secondly, polystyrene is an industrial by-product, which contributes to reducing the overall cost of the material. Finally, the utilization of industrial waste provides additional environmental benefits, supporting sustainable construction practices.

The fundamental difference between polystyrene concrete and its closest comparable material, cellular concrete, is its increased tensile and compressive strength (approximately 12% higher), as well as greater resistance to moisture and steam.

While polystyrene concrete has many advantages, it also has its disadvantages, namely low strength and shrinkage. These disadvantages can be minimized with additives and proper manufacturing technology. To solve this issue, a number of studies were conducted, including examining the effects of various additives on the properties of polystyrene concrete, the use of modified cements, and different aggregate fractions.

A number of authors emphasize that materials containing lightweight aggregates are less resistant to frost, but have sufficient frost resistance for use in wall structures. The frost resistance of lightweight concrete decreases significantly with increasing polystyrene content and the size of the aggregates themselves.

It is also worth noting that the frost resistance of lightweight concrete is primarily determined by the product porosity. The resistance of concrete to freezing is determined not only by the air gaps in the product, but also by the bonds between the aggregate and the matrix. To improve the frost resistance of materials containing lightweight aggregates, it is not necessary to increase the density (as is the case with heavyweight concrete), but either to reduce the open porosity or increase the density of the cement paste. Sufficient frost resistance is achieved by using porous aggregate or an air-entraining additive in the cement paste. The frost resistance of these materials can be enhanced by using hydrophobic additives **(Samoilova et al., 2024).**

The feasibility of using industrial waste as an economically and environmentally beneficial solution was also proved. Numerous studies have focused on the use of ash and slag in the production of building structures **(Samoilova et al., 2024).**

The use of slag as a composite binder has several advantages:

- it is used for the construction of massive structures; however, in winter concreting conditions using slag binders, heating is recommended;
- it increases the initial and final setting time, which leads to the preservation of the concrete mix workability;
- it increases resistance to aggressive environments (sulfate attack, alkali resistance, acid resistance, etc.);
- it increases the frost resistance and water resistance of products.

The concrete mix was prepared using the following materials:

- I 42.5 B cement, with a specific effective activity of natural radionuclides for raw materials equal to 57 Bq/kg;
- blast furnace slag, ground in a ball mill;
- expanded polystyrene gravel, 2.5-5 mm fraction;
- water;
- air-entraining additives (MasterAir 200) and superplasticizer (Master Rheobuild 270W). The composition of the concrete mix is shown in **Table 1**. The appearance of polystyrene concrete samples is shown in **Figure 1**.

The chemical composition of cement and slag is shown in **Table 2**. The use of slag as a mineral additive to cement is due to the desire to increase corrosion resistance and reduce the proportion of an expensive component in the concrete mix. Blast furnace slag is a chemically active waste from the metallurgical industry, and reacts with cement and additives. Due to the high content of calcium, silicon and aluminum oxides (SiO_2, Al_2O_3, CaO), concrete with blast furnace slag content becomes more resistant to aggressive media (alkalis, salts and acids).

Air-entraining additive in combination with steaming allows to increase porosity up to 4,5% without strength decrease.

Table 1
Composition of highly porous polystyrene concrete

№	CEM I 42,5H, kg/m^3	Blast furnace slag, kg/m^3	Polystyrene, kg/m^3	Air-entraining modifier Master Air 200, %	Superplasticizer Master Rheobuild 270, %
1	240	160	20	0.7	0.7

Figure 1 – Polystyrene concrete samples with a water-binding ratio (W/B) = 0,45 (author's material)

Table 2
Density of polystyrene concrete

Concrete hardening conditions	Standard density, kg/m^3	Actual density, kg/m^3
Heat treatment	350-400	370
Normal conditions	350-400	398

The studies were conducted according to the following hardening modes:

- natural hardening. The samples were tested for durability at the ages of 3, 7, 14 and 28 days. The samples were stored in a specialized cabinet under a film with sawdust. The average temperature for 28 days in the laboratory room is t = 23°C and W = 75%.
- hardening under heat treatment conditions.

In the process of heat treatment, accelerated hydration of cement stone occurs and the time for gaining final strength decreases. It is important to note that polystyrene granules are "sensitive" to temperatures above 80 °C. For this reason, it is important to ensure a balance between accelerating hydration processes and preserving polystyrene granules. According to the heating technology, there are three stages: preheating, isothermal exposure, and gradual cooling. For highly ionized polystyrene concrete, the temperature limit is regulated by 60-70°C, as well as a relative humidity of at least 90%. Such parameters will ensure the hydration processes without destructive effects on the polymer.

The stages of heat treatment are shown in **Figure 2**:

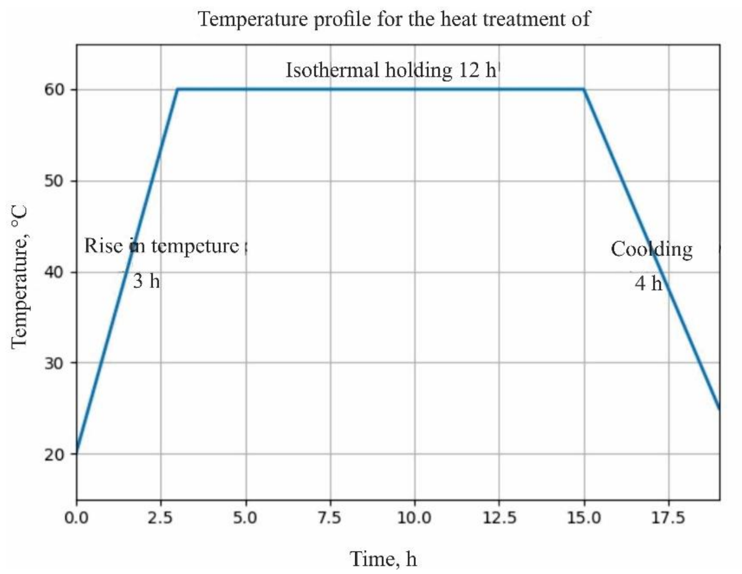

Figure 2 – Stages of heat treatment of three-layer wall panels

Stages of heat treatment of three–layer wall panels:

Heating to a temperature of 60°C - 3 hours: the purpose of this stage is to evenly distribute the temperature throughout the entire volume of the product to prevent thermal shock, as well as to activate the initial stage of binder hydration (C_2S and C_3S).

The duration of the first stage usually does not exceed 2-3 hours, and the heating rate is 15-20°C/h. At this stage, the heat released during the cement hydration combines with the external thermal effect, thereby building a smooth temperature gradient across the product section. Also, at this stage, C_3S hydration increases, crystallization begins (C-S-H(I)), and free H_2O binding in the gel begins.

1) Isothermal exposure of products at a temperature of 60°-12 hours. The purpose of this stage is to achieve maximum hydration of the cement stone. During isothermal exposure, concrete reaches about 80% of its design strength. Hydrosilicates and calcium hydroaluminates are actively formed here, which are a fundamental factor in the concrete structuring. The processes that occur with concrete in an autoclave are subject to thermophysical laws that affect its structure.

The next step requires gradual cooling.

2) The products are kept in the chamber at a reduced temperature for 4 hours. The main focus at this stage is on removing thermal stresses in concrete, preventing cracking and shrinkage. The temperature decreases gradually (10-150°C/h). The temperature dependence is expressed by the following equation:

During the pressure reduction process, it is important to control the rate of pressure reduction to prevent damage to the concrete. Cooling is slow due to low heat transfer. A sharp decrease in temperature leads to the formation of cracks at the boundary of the cement stone/ polystyrene granules.

The positive side of heat treatment also manifests itself in its environmental benefits, as the removal of the blowing agent (isopentane) from the mixture toward the edges of the mold improves the environmental friendliness of the material.

The intensive development of industry in the Republic of Kazakhstan is aimed at improving the quality of domestic products and their competitiveness in the marketplace of alternatives offered by other countries. The primary factors influencing the quality of finished products include their production process, including the materials used and the manufacturing technology.

Taking into account the sharply continental climate prevailing in Kazakhstan, the most fundamental requirements for thermal insulation materials are resistance to fluctuating low temperatures, high operational reliability coefficient, durability, as well as environmental and fire safety. The expanded polystyrene concrete (EPSC) being developed and studied by us must possess all of the abovementioned properties while maintaining an economic component that affects the cost of the final product **(Samoilova et al., 2024; Rakhimov et al., 2024).**

Polystyrene aggregates in concrete have been studied since the late 20th century, and the results indicate that the water-cement ratio is a key factor determining the strength, deformation, and performance characteristics of the material. Based on experimental data, relationships were proposed that make it possible to predict the modulus of elasticity from the material strength.

Modern research confirms the effectiveness of polystyrene in enclosing building structures both in hot and cold climates. It has been established that the use of polystyrene materials reduces operating energy costs, life-cycle costs, and carbon dioxide emissions, and also provides environmental benefits through the recycling of hard-to-decompose waste.

At the same time, most studies consider materials with a homogeneous structure and fixed porosity parameters, which limits the possibilities for optimizing their properties. Therefore, it is actual to develop compositions with controlled porosity, including through the use of various additives that enhance thermal insulation properties and reduce the material density.

However, increasing porosity, despite improving thermal performance, is accompanied by a decrease in strength, that requires finding the optimal balance between energy efficiency and material mechanical properties in accordance with regulatory documents.

Based on the proposed composition of highly porous expanded polystyrene concrete an energy-efficient three-layer panel was developed.

The following materials were used to manufacture the wall panel:

- Portland cement I 42.5B (M500D0), with specific effective activity of natural radionuclides for raw materials: A_{eff}(cement)=57 Bq/kg from *Central Asia Cement JSC*;
- blast furnace slag as a composite binder for cement;
- air-entraining additive;
- superplasticizer with water-reducing properties;
- crushed stone of fraction 5-20 (Keregetass quarry);
- sand and gravel mixture (Shakhan quarry);
- gauging water.

The technology for the production of three-layer wall panels with a HPEPC (Highly Porous Expanded Polystyrene Concrete) layer has been developed based on existing technology, but the cost of products is significantly lower, in addition, less time is spent on production. The technology of manufacturing wall panels using a heat-insulating layer of polystyrene concrete:

1. A reinforcing mesh is installed on a form with a formwork, after that a mixture of heavy concrete is supplied.
2. After laying, the mixture is compacted for 30 seconds.
3. Then the pallet moves off into the pre-hardening chamber for 10 minutes before the concrete mixture sets, and a new pallet takes its place.
4. After 10 minutes, a mixture of light HPEPC is laid on the newly gripped mixture of heavy concrete.
5. After laying two layers of concrete, the pallet is sent back to the pre-hardening chamber to set the light concrete for 10 minutes.
6. A reinforcement frame is installed on the gripped mixture of light concrete and a second layer of heavy concrete is poured in the same way as the first layer.
7. The second layer of heavy concrete is compacted using an immersion vibrator.
8. The finished wall panel is sent to the heat and humidity treatment chamber for 12 hours, where all stages of isothermal heating take place.

The chemical composition of cement and slag is given in **Table 3**. Blast furnace slag is a chemically active waste product of the metallurgical industry and reacts with cement and additives.

Table 3
Chemical composition of Portland cement and blast furnace slag

Binder	SiO_2	Al_2O_3	CaO	MgO	Cl
Portland cement M500D0	23.37	4.98	60.38	1.13	0.003
Blast furnace slag	36.5	13.95	38.74	9.47	0.038

Due to the high content of calcium, silicon and aluminum oxides (SiO_2, Al_2O_3, CaO), concrete containing blast furnace slag becomes more resistant to aggressive environments (alkalis, salts and acids).

Figure 3 shows a diagram of the structure of an energy-efficient three-layer panel. The surface layers of the panel are made of heavy concrete. The central part of the wall panel is heat-insulating and is made of highly porous expanded polystyrene concrete.

The mechanical and thermal characteristics of all layers of the proposed panel were tested in an accredited laboratory and have the following indicators **(Table 4):**

Table 4
Characteristics of three-layer wall panel concretes

Property	Internal layer	Highly porous expanded polystyrene concrete	External layer
Thermal conductivity, W/(m·°C)	1.74	0.095	1.74
Vapor permeability, mg/(m·h·Pa)	0.03	0.087	0.03
Compressive strength grade	B30	B1.5	B30

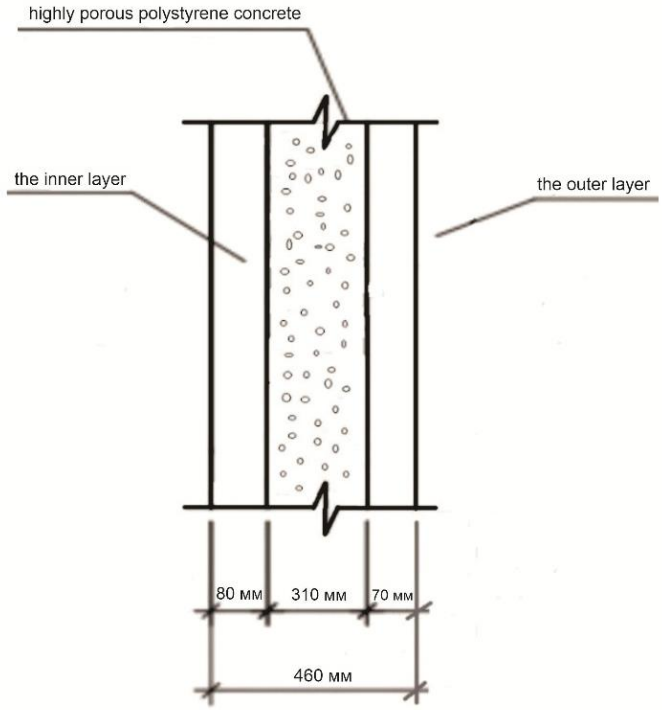

Figure 3 – Wall panel with heat insulation layer of highly porous expanded polystyrene concrete (author's material)

Actual results of samples studied comply with the standards of regulatory documentation.

The produced panels use highly porous polystyrene concrete as the thermal insulation layer. This means that in addition to the polystyrene in its composition, additional pores in the cement paste are created by an additive. Concrete aeration occurs through chemical reactions that create air bubbles in the concrete mixture **(Figure 4).**

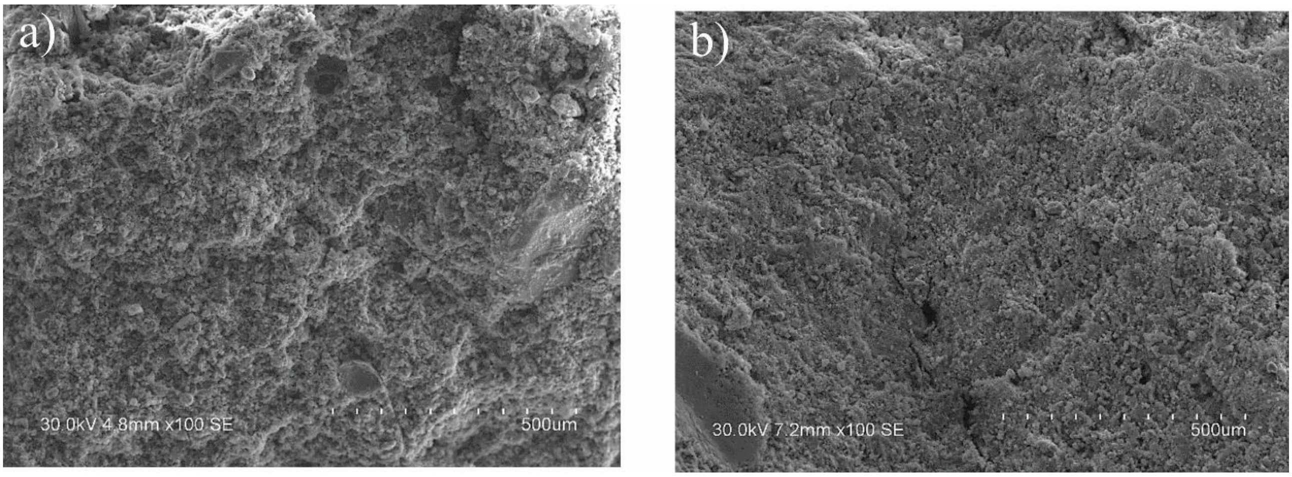

Figure 4 – Micrographs at ×100 magnification of cement paste samples without air-entraining additive (a) and with it (b) (author's material)

Figure 5 clearly shows the even distribution of closed pores formed after the introduction of the air-entraining additive. Its addition to the concrete mix will enhance the thermal insulation properties of the concrete, as well as its noise and sound insulation.

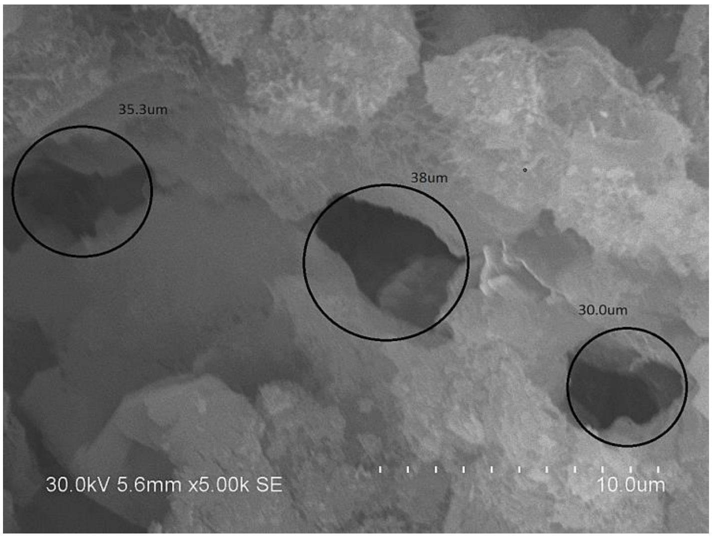

Figure 5 – Micrographs in ×5000 magnification of cement paste samples with pore sizes (author's material)

It was practically established that the use of an air-entraining additive allows increasing the entrained air volume by almost 1.5%. It was also established in the study **(Meddage et al., 2022).** that steam curing of concrete makes it possible to increase its porosity by almost 3%. An increase in the volume of entrained air by more than 5% results in a significant reduction in concrete strength.

Experiments in laboratory conditions showed that the amount of water can be reduced using a plasticizer by more than 10%.

Using a scanning electron microscope Prisna E SEM, photographs were taken of the adhesion of polystyrene granules to the cement paste, where it is seen that the granules are completely drawn into the cement paste pores **(Figure 6):**

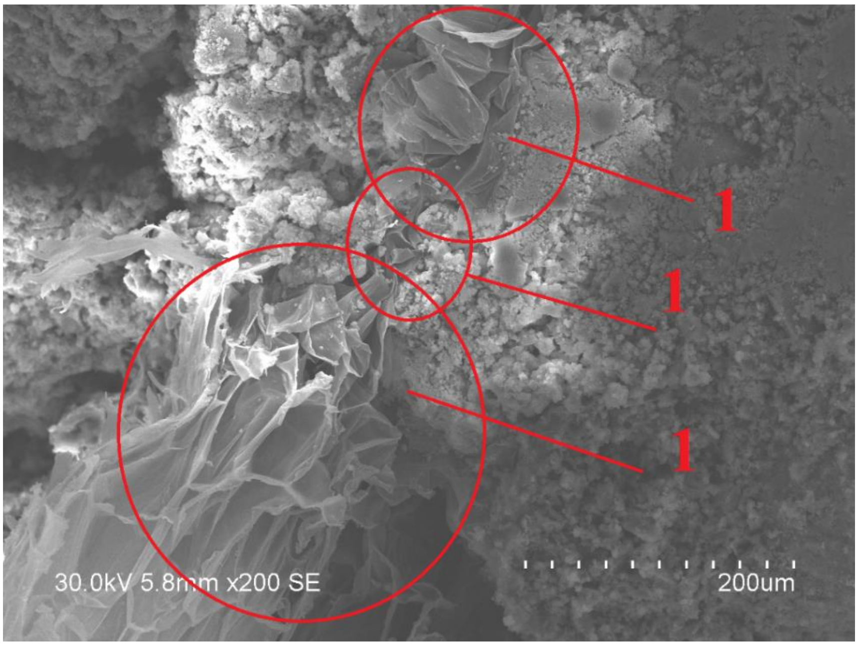

Figure 6 – Adhesion of polystyrene to the cement paste (1- polystyrene granules) (author's material)

An EDX (electron-dispersive X-ray) analysis of two cement paste compositions (the proposed composition with additional porosity and the control sample) gave results with approximately identical chemical compositions. Moreover, the thermal insulation properties of the proposed composition were superior to those of the control sample due to the additional porosity of the cement paste.

The layer of thermal insulation polystyrene concrete is not flammable, while the polystyrene board is a combustible material.

Thus, the resulting highly porous polystyrene concrete meets its characteristics as one of the layers for the further development of multilayer lightweight concrete with a variotropic structure.

The methodological novelty of this study lies in the combined use of multilayer structuring and controlled porosity formation through air-entraining additives. Unlike conventional approaches focused on homogeneous materials, the proposed method enables the regulation of material properties across the thickness of the structure.

3 RESULTS AND DISCUSSION

The use of multilayer concrete with a variotropic structure results in a reduction in thermal conductivity of enclosing structures by 10–15%, which is associated with the redistribution of density and pore structure across the thickness of the material. Unlike homogeneous lightweight concretes, where porosity is uniformly distributed, the proposed approach allows concentrating low-density, highly porous layers in the thermal insulation zone while maintaining denser structural layers. This leads to a decrease in heat transfer without a proportional loss of mechanical strength.

The obtained results confirm that the increase in porosity up to 4.5% due to the use of air-entraining additives contributes to the formation of a system of closed pores, which effectively reduces thermal conductivity to 0.095 W/(m·°C). At the same time, compressive strength remains at a sufficient level (2.8 MPa for the insulating layer and 39.0 MPa for structural layers), which indicates a successful balance between thermal and mechanical properties.

These results are consistent with previous studies **(Meddage et al., 2022; Estemesova et al., 2023),** which report a decrease in thermal conductivity with increasing porosity; however, in those works, an increase in porosity was accompanied by a significant reduction in strength. In contrast, the proposed variotropic structure mitigates this limitation by separating functional layers according to their performance requirements.

Compared to conventional polystyrene concrete, where thermal conductivity typically ranges from 0.11 to 0.14 W/(m·°C), the developed material demonstrates a reduction of approximately 15 – 30%, which confirms the efficiency of controlled porosity and multilayer structuring. Furthermore, the achieved compressive strength values exceed those reported for similar density materials in earlier studies **(Gernay, 2018; Samoilova et al., 2024),** indicating improved structural performance.

Similar trends have been noted in foreign studies. Thus, **Wibowo et al. (2024)** found that the use of lightweight concrete based on expanded polystyrene helps to reduce thermal conductivity and increase energy efficiency of building structures. **Lee et al. (2021)** also note that the use of lightweight composites reduces the operational heat loss of buildings, but with increasing porosity, the mechanical characteristics of the material deteriorate. In contrast to these studies, the variotropic approach proposed in this paper provides a reduction in thermal conductivity while maintaining the required strength of the structural layers.

The optimal number of layers for variotropic concrete was determined to be four, which ensures a gradual transition of density and minimizes interlayer stress concentrations. The use of Portland cement as a common binder for all layers improves adhesion between layers and enhances the overall integrity of the structure.

The introduction of granulated blast furnace slag as part of the composite binder contributes not only to improved durability and resistance to aggressive environments but also to resource efficiency through the utilization of industrial waste. This aligns with current trends in sustainable construction materials.

Thus, the proposed approach demonstrates that the combination of multilayer structuring and controlled porosity formation provides a more effective solution compared to traditional homogeneous lightweight concretes, ensuring both reduced thermal conductivity and sufficient mechanical strength.

Quantitative analysis showed that the developed highly porous polystyrene concrete has a lower thermal conductivity compared to traditional lightweight concretes based on expanded clay and homogeneous polystyrene concrete, for which the coefficient of thermal conductivity is usually 0.11–0.14 W/(m·°C). In the proposed composition, this indicator was reduced to 0.095 W/(m·°C), which provides an increase in thermal insulation efficiency by 15-30%.

An additional advantage of the developed composition is the possibility of maintaining strength characteristics with increased porosity due to the combined use of air-entrapping additives and multilayer structuring. In traditional lightweight concretes, an increase in porosity is usually accompanied by a significant decrease in strength, whereas in the proposed system, the strength of the structural layers reached 39 MPa, which meets the requirements for enclosing structures of residential buildings.

In addition, the use of blast furnace slag as a component of a composite binder reduces cement consumption and increases the material resistance to aggressive media, which further increases the operational efficiency of the developed material.

4 CONCLUSION

1. It has been established that the use of multilayer lightweight concrete with a variotropic structure reduces thermal conductivity of enclosing structures by 10–15% compared to conventional homogeneous lightweight concrete. This effect is achieved due to the controlled redistribution of density and pore structure across the thickness of the material, ensuring an optimal combination of thermal insulation and mechanical performance.

2. Experimental results showed that an increase in porosity up to 4.5% leads to a decrease in thermal conductivity to 0.095 W/(m·°C), while maintaining sufficient compressive strength (up to 39.0 MPa for structural layers). The optimal number of layers (four) provides a smooth transition of properties and minimizes internal stresses.

3. The scientific novelty of the research lies in the development and experimental substantiation of a method for forming a variotropic structure of multilayer lightweight concrete with an adjustable distribution of density and porosity over the thickness of the structure. For the first time, the combined use of air-entrapping additives and multilayer structuring was proposed, which reduces thermal conductivity while maintaining the required strength characteristics of the material.

4. The practical significance of the research lies in the possibility of using the developed multilayer lightweight concrete in the production of energy-efficient exterior wall panels and enclosing structures of residential and public buildings. The use of the developed composition makes it possible to reduce the heat loss of buildings, increase the energy efficiency of construction sites and reduce cement consumption by using blast furnace slag as a component of a composite binder.

5. The prospects for further research are related to studying the durability of variotropic multilayer concretes under cyclic freezing and thawing conditions, as well as optimizing the structure of the material for various climatic operating conditions.

REFERENCES

1. **Zhangabay, N., Kudabayev, R., Mizamov, N., Imanaliyev, K., Kolesnikov, A., Moldagaliyev, A., Umbitaliyev, A., Kopzhassarov, B., Fediuk, R. & Merekeyeva, A.** (2023). Study of the Model of the Phase Transition Envelope Taking into account the Process of Thermal Storage under Natural Draft and by Air Injection. Case studies in Construction Materials. – 2023. - e02050. DOI: https://doi.org/10.1016/j.cscm.2023.e02050
2. **Sadyrov, R.K., Beksultanova, N.N.** (2022). Formation of methodological foundations for the organization of construction production of energy-efficient buildings // Bulletin of Kazakh Leading Academy of Architecture and Construction, 2(84), 279-284. [Formirovanie metodologicheskikh osnov organizatsii stroitel'nogo proizvodstva energoeffektivnykh zdaniy]. https://doi.org/10.51488/1680-080X/2022.2-30 (in Russ.)

3. **Haller, T., Beutner, N., Thienel, K.-Chr.** (2024). Optimized Building Envelope: Lightweight Concrete with Integrated Steel Profiles // Materials, 17(6), 1278. https://doi.org/10.3390/ma17061278
4. **Akmalayuly, K., Toleuov, E.** (2022). Development of technological parameters of thermal insulation material with improved properties based on industrial waste // Bulletin of Kazakh Leading Academy of Architecture and Construction, 2(84), 146-156. [Razrabotka tehnologicheskikh parametrov teploizolyatsionnogo materiala s uluchshennymi svoystvami na osnove promyshlennykh othodov]. https://doi.org/10.51488/1680-080X/2022.2-16 (in Russ.)
5. **Shi, Sh.** (2025). Research on the design application and effect of lightweight concrete materials in improving the thermal insulation performance of housing buildings // Applied Mathematics and Nonlinear Sciences, 10(1), 1-15. https://doi.org/10.2478/amns-2025-0682
6. **Meddage, D. P. P., Jayasinghe, M. T. R.** (2022). Use of EPS Based Light-Weight Concrete Panels as a Roof Insulation Material for NERD Slab System. ICSBE 2020, Singapore. 375–384. https://doi.org/10.1007/978–981-16–4412-2_28
7. **Al-Alusi, M. R. M., Abdullah, A.** (2024). Freeze–thaw performance of lightweight concrete with EPS and recycled fibers // Construction and Building Materials, 390.
8. **Wibowo, A.P., Saidani, M., Khorami, M.** (2024). Enhancing Sustainability in Construction: Investigating the Thermal Advantages of Fly Ash-Coated Expanded Polystyrene Lightweight Concrete // Journal of Composite Science, 8(4), 157. https://doi.org/10.3390/jcs8040157
9. **Samoilova, T., Rakhimov, M., Rakhimova, G., Zhangabay, N.** (2024). Effect of Heat Treatment of Expanded Polystyrene Concrete on its Compressive Strength. Technobius, 4(2). https://doi.org/10.54355/tbus/4.2.2024.0059
10. **Gernay, T.** (2018). Fire behavior of lightweight concretes with polymer-based aggregates // Fire Safety Journal, 100, 82–95.
11. **Samoilova, T. Yu., Rakhimov, M. A., Rakhimova, G. M.** (2024). Raw material mixture for thermal insulation products. Patent of the Republic of Kazakhstan for utility model No. 9341, registered in the State Register of Utility models of the Republic of Kazakhstan on 11/29/2024.
12. **Rakhimov, M. A., Rakhimova, G. M., Samoilova, T. Yu., Akhmetzhanov, T. B.** (2024). Investigation of physical and technical properties lightweight concretes based on porous expanded polystyrene concrete. Proceedings of the University, 4 (97). 168–174.
13. **Hasanzadeh, R., Azdast, T., Doniavi, A., Eungkee, Lee R.** (2019). Multi-objective optimization of heat transfer mechanisms of microcellular polymeric foams from thermal-insulation point of view. Therm. Sci. Eng. Prog. 21–29. https://doi.org/10.54355/tbus/4.2.2024.0059
14. **Estemesova, A.S., Altaeva, Z.N., Yesselbaeva, A.G.** (2023). Energy-efficient lightweight concrete for green construction_// Bulletin of Kazakh Leading Academy of Architecture and Construction, 2(88), 153-161. [Energoeffektivnyy legkiy beton dlya zelenogo stroitel'stva]. https://doi.org/10.51488/1680-080X/2023.2-17 (in Russ.)
15. **Meddage, D. P. P., Chadee, A., Jayasinghe, M. T. R., Rathnayake, U.** (2022). Exploring the applicability of expanded polystyrene (EPS) based concrete panels as roof slab insulation in the tropics. Case Studies in Construction Materials. https://doi.org/10.1016/j.cscm.2022.e01361
16. **Zhangabay, N., Giyasov, A., Ybray, S., Tursunkululy, T., Kolesnikov, A.** (2024). Field thermovision study of external enclosing for multi-storey residential building under climatic conditions of Northern Kazakhstan. Construction Materials and Products, 7 (1). https://doi.org/10.58224/2618-7183-2024-7-1-1
17. **Zhanabai, N., Buganova, S., Baydilla, I., Tagybaev, A.** (2023). Modeling of thermal resistance of the developed external enclosing structures with an air layer // Bulletin of Kazakh Leading Academy of Architecture and Construction, 2(88), 178-191. [Modelirovanie teplovogo soprotivleniya razrabotannykh naruzhnykh ograzhdayushchikh konstruktsiy]. https://doi.org/10.51488/1680-080X/2023.2-19 (in Russ.)
18. **Zheng, Ch., Chen, Ch., Hong, X., Zhang, W., Yang, R., Shi, F.** (2024). Experimental evaluation of the thermal, lighting, and energy performances of a mechanically ventilated

double-skin façade with Venetian blinds and a light shelf. Energy and Buildings. 2024, 306. https://doi.org/10.1016/j.enbuild.2024.113947

19. **Tukhtamisheva, A.Z., Adilova, D.A.** (2025). Study of properties of multilayer reflective thermal insulation materials for improving energy efficiency of buildings // Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 1(95), 222-235.
20. **Samoilova, T. Yu.** (2026). Development of technology for the production of highly porous polystyrene concrete for heat-efficient exterior wall panels (PhD dissertation, Abylkas Saginov Karaganda Technical University). https://www.kstu.kz/wp-content/uploads/2026/02/Dissertatsiya-Samojlovoj-Tatyany-YUrevny.pdf
21. **Zaragoza-Benzal, A., Ferrández, D., Santos, P., Atanes-Sánchez, E.** (2025). Lightweight gypsum composite material to improve energy efficiency: Assessment of physico-chemical, mechanical, thermal and fire performance properties // Materiales de Construcción 75 (358) April-June 2025, e377 ISSN-L: 0465-2746, eISSN: 1988-3226. https://doi.org/10.3989/mc.2025.395824
22. **Lee, Y.H., Chua, N., Amran, M. Lee, Y.Y., Kueh, A.B.H., Fediuk, R., Vatin, N., Vasilev, Y.** (2021). Thermal Performance of Structural Lightweight Concrete Composites for Potential Energy Saving // Crystals 2021, 11(5), 461. https://doi.org/10.3390/cryst11050461