

Article

Numerical Simulation and Thermal Efficiency Assessment of Variatropic-Type Multi-Layer Exterior Wall Panels

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Abstract

This study presents a theoretical analysis of the effectiveness of the use of variatropic concretes in multi-layer panel structures of buildings in terms of heat transfer. Theoretical analysis was performed with the aid of the modern numerical modeling software package ELCUT 6.6 and the computer algebra system Maple, which helped improve the reliability of the calculations. The results of this study of the thermophysical parameters of multi-layer panels using variatropic concrete showed that an increase in the degree of variatropy contributes to a rise in the temperature on the inner surface of the panel from 17.94 °C (traditional panel) to 18.87 °C (the most variatropic panel, Scheme 4), which improves indoor comfort conditions and reduces the risk of condensation. Additionally, it is possible to reduce the thickness of the insulation layer without compromising thermal efficiency. The high thermal inertia ($D > 7$) of variatropic panels ensures the accumulation and retention of heat, which has a positive effect on energy consumption during the heating season. The moisture regime of the studied structures meets regulatory criteria for preventing moisture accumulation, thereby increasing panel durability and eliminating conditions for mold formation or structural degradation. The air permeability performance of the panels also complies with the standards, while the dense outer concrete layers provide additional protection against air infiltration, stabilizing both thermal and moisture balance. The calculated thermal resistance of variatropic panels (Schemes 3 and 4) exceeded the standard requirement ($3.20 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$) by 1.2 and 1.74 times, respectively. Thus, it was established that the application of the variatropic principle in panel design ensures a more rational distribution of temperature fields, which results in reduced heat losses and improved thermal stability of exterior enclosures. This approach develops new design solutions focused on improving the energy efficiency of buildings and reducing material costs, which is consistent with current trends in Functionally Graded Design (FGD).

Keywords: multi-layer panel; thermophysical parameters; variatropy; modeling; energy efficiency



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1. Introduction

In the context of contemporary global climate change and the increasing demand for energy, the issue of energy conservation in construction has become particularly significant.

The construction sector is recognized as one of the largest energy consumers, with buildings and structures accounting for, on average, up to 40% of total global energy consumption [1–3]. A considerable share of this energy is utilized inefficiently, resulting in higher operational costs, increased greenhouse gas emissions, and greater anthropogenic pressure on the environment. Given these circumstances, energy efficiency in construction is regarded by the international community as one of the key priorities for sustainable development.

Countries around the world are introducing new energy efficiency standards and developing building certification systems [4–6], which provide an objective basis for assessing the energy performance of facilities [7,8]. Among the most authoritative certification frameworks are LEED (USA), BREEAM (United Kingdom), and DGNB (Germany). These systems encompass a wide range of criteria, extending from energy efficiency and indoor environmental quality to the sustainability of construction materials. Such standards increasingly serve as benchmarks for national building codes and regulations, thereby contributing to the advancement of global practices in “green” construction.

Particular emphasis is placed on innovative materials, advanced engineering systems, and the integration of “smart” building management technologies [9–11]. Such solutions not only enable a substantial reduction in energy consumption [12,13] but also ensure a high level of comfort, safety, and building durability [14]. Developed countries have demonstrated that investments in energy-efficient technologies are justified by reductions in operating costs, increases in real estate market value, and mitigation of negative environmental impacts [15–17].

One of the most promising approaches to enhancing energy efficiency in construction is the use of multi-layer envelope structures, particularly energy-efficient panels for external walls [18–20]. These panels combine load-bearing, thermal insulation, and finishing functions, thereby significantly reducing heat losses in buildings, lowering heating and cooling costs, and accelerating the construction process [21,22]. In global practice, multi-layer panels have gained wide application in residential, public, and industrial construction alike [23,24]. Their composition includes advanced thermal insulation materials (such as mineral wool boards, expanded polystyrene, polyurethane foam, PIR, and others), which are characterized by low thermal conductivity, high mechanical strength, and long-term durability. The external layers of such panels provide resistance to mechanical and climatic influences, while the inner layers maintain a favorable thermal regime and prevent condensation [25].

In recent years, particular attention has been directed toward the use of variatropic materials, which provide new prospects for enhancing the energy efficiency and durability of building envelopes [26–28]. In the presented study, variatropy is realized through the gradient distribution of concrete density in multi-layer panels, which ensures an optimal combination of the bearing capacity of the outer layers and the thermal insulation characteristics of the inner layers in a single structure. Variatropic multi-layer panels are characterized by the combination of materials with distinct thermophysical and mechanical properties integrated into a unified structure. This design ensures optimal distribution of mechanical loads, increased resistance to thermal deformations, reduced heat losses, and improved long-term performance. By adjusting the arrangement and thickness of individual layers, it becomes possible to achieve target operational characteristics that are unattainable with conventional panels [26].

Despite the obvious potential, there is a significant gap in comprehensive studies devoted to quantifying the effect of the degree of variatropy on key thermophysical parameters of multi-layer panels in harsh climatic conditions. In particular, insufficient attention was paid to how the gradient change in concrete density inside the panel structure affects the distribution of temperature fields, humidity conditions, and overall thermal resistance

while maintaining a constant overall thickness of the structure. Most existing studies have focused on the mechanical properties of variotropic concretes, with limited attention on their integrated energy efficiency when used in multi-layer enclosing structures.

Thus, the use of variotropic structures in external walls demonstrates considerable potential for improving the energy efficiency of buildings. This approach is particularly relevant for Kazakhstan, where the heating season extends over 6–7 months annually, and winter temperatures in some regions drop below $-30\text{ }^{\circ}\text{C}$. The severe climatic conditions necessitate innovative solutions aimed at minimizing heat losses, reducing operating expenditures for heating, and ensuring a comfortable indoor microclimate. The implementation of energy-efficient structures under such conditions not only contributes to energy conservation but also carries significant environmental importance, as it is directly associated with the reduction of carbon dioxide emissions and the mitigation of anthropogenic impacts on the environment [29].

In this regard, the purpose of the present study is to conduct a theoretical investigation of the application of the variotropic principle in multi-layer panels and carry out a comparative analysis with traditional panel systems in terms of their thermophysical characteristics. The use of exclusively computer modeling in the study is due to the fact that the purpose of the work was to obtain a detailed quantitative assessment of thermophysical parameters for further validation with experimental studies.

It should be emphasized that the further development of the study previously conducted by the authors [25] using variotropic-type concrete could provide a strong impetus for the widespread implementation of variotropic concrete structures in construction practice in Kazakhstan. The scientific novelty of this study lies in the complex numerical modeling and comparative analysis of a series of multi-layer wall panels with varying degrees of variability but constant overall thickness, which has not been studied at this scale before. For the first time, the effect of gradient changes in the density of concrete layers on the thermophysical characteristics of fencing, including temperature fields, humidity, and air conditions, under the harsh climate of Central Kazakhstan, was quantified. Such an approach will enhance the energy efficiency, environmental sustainability, and operational reliability of buildings, while also contributing to the development of scientifically grounded recommendations for the design of modern energy-efficient building envelopes that comply with both national and international standards of sustainable construction. At the same time, the use of variotropic materials directly corresponds to the principles of Functionally Graded Design (FGD), where the properties of the material and structure are purposefully changed to optimally meet heterogeneous requirements.

2. Materials and Methods

This study examines four new design solutions for variotropic-type, multi-layer panels in comparison to a traditional configuration, which had previously been developed and analyzed by the authors in [25]. To assess energy efficiency, the following key parameters were considered: thermal resistance, temperature fields, moisture regime, and air permeability. In determining the geometric parameters of the investigated structures, the minimum requirements were adopted in accordance with the standards [30–32]. The principal thermophysical parameters were taken from normative data, while the thermal conductivity of concrete was calculated as a function of its density using the Nekrasov Formula (1) [33]. The overall thermal resistance of the structures was then determined according to Expression (2) [4].

$$\lambda = 1.16\sqrt{0.0196 + 0.22d^2} - 0.16 \quad (1)$$

where d is the relative density of the material, expressed in g/cm^3 (numerically: $d = \rho/1000$, if the density ρ is given in kg/m^3).

$$R = \frac{1}{a_{int}} + \sum R_i + \frac{1}{a_{ext}} \quad (2)$$

where a_{int} and a_{ext} are the heat transfer coefficients of the internal and external surfaces, respectively; R_i denotes the thermal resistance of the i -th layer.

According to the standards [30–32], a single concrete element may be subdivided into several layers with different density values under specific conditions. Taking these provisions into account, the analysis of the effectiveness of variatropic concretes was carried out by examining the division of all layers within the structure.

This study focused on a curtain-type panel with a width and height of 3 m, where the remaining minimum geometric parameters were adopted in accordance with the standard [30]. The thickness of all panel variations was assumed to be identical, equal to 460 mm. The principal geometric and thermophysical parameters of the investigated structures are presented in Figure 1 and Table 1. The analysis considered four design types (schemes), one of which had been previously investigated by the authors and is referred to in the present study as the traditional (reference) configuration.

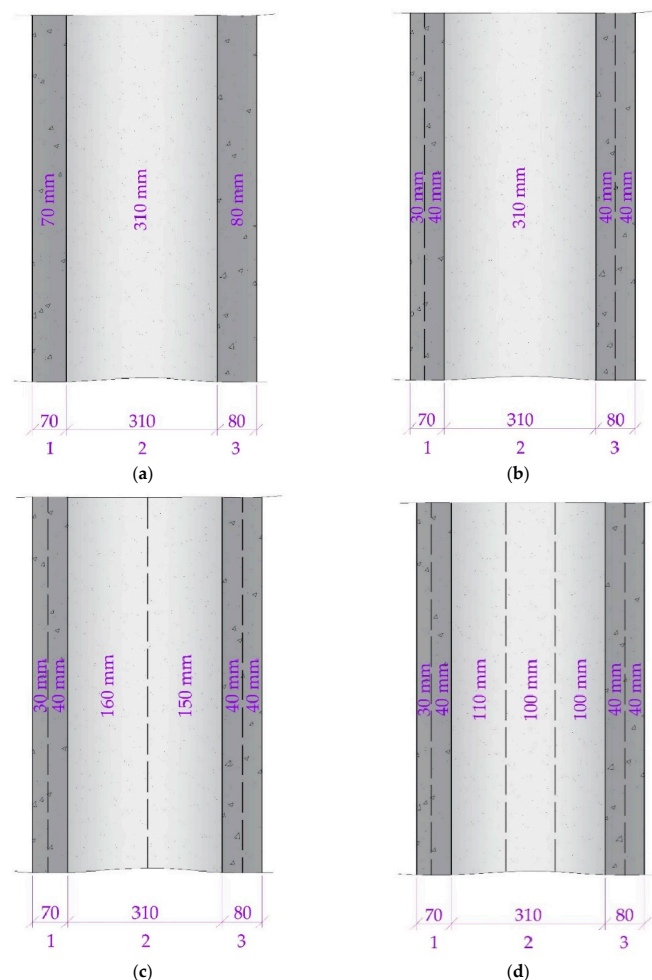


Figure 1. Panel design variants (Scheme 1, Scheme 2, Scheme 3 and Scheme 4) for analyzing the effectiveness of variatropic concretes: (a). Traditional configuration; (b). Variatropic concrete in layers 1 and 3; (c). Variatropic concrete in layers 1, 2 (two sub-layers), and 3; (d). Variatropic concrete in layers 1, 2 (three sub-layers), and 3.

Table 1. Thermophysical parameters of the investigated structures (Schemes 1–4) [4,30–32].

Layer No.	Layer Type	Concrete Type	Thickness, mm	Density ρ , kg/m ³	Thermal Conductivity λ , W/(m·°C)	Thermal Absorption Coefficient s , W/(m ² ·°C)	Vapor Permeability μ , mg/ (m·h·Pa)
Scheme 1							
1	External layer	Heavyweight concrete	70	2400	1.156	16.77	0.03
2	Insulating layer	Highly porous polystyrene concrete	310	400	0.112	2.07	0.085
3	Internal layer	Heavyweight concrete	80	2400	1.156	16.77	0.03
Scheme 2							
1	External layer	Heavyweight concrete	30	2400	1.156	16.77	0.03
			40	2000	0.940	13.5	0.06
2	Insulating layer	Highly porous polystyrene concrete	310	400	0.112	2.07	0.085
3	Internal layer	Heavyweight concrete	40	2400	1.156	16.77	0.03
			40	1800	0.833	9.6	0.09
Scheme 3							
1	External layer	Heavyweight concrete	30	2400	1.156	16.77	0.03
			40	2000	0.940	13.5	0.06
2	Insulating layer	Highly porous polystyrene concrete	160	400	0.112	2.07	0.085
			150	300	0.070	1.55	0.10
3	Internal layer	Heavyweight concrete	40	2400	1.156	16.77	0.03
			40	1800	0.833	9.6	0.09
Scheme 4							
1	External layer	Heavyweight concrete	30	2400	1.156	16.77	0.03
			40	2000	0.940	13.5	0.06
2	Insulating layer	Highly porous polystyrene concrete	110	400	0.112	2.05	0.085
			100	300	0.070	1.55	0.10
			100	200	0.035	1.12	0.12
3	Internal layer	Heavyweight concrete	40	2400	1.156	16.77	0.03
			40	1800	0.833	9.6	0.09

The arrangement of layers within the panel structure is not arbitrary: the outer layers are made of denser concrete to provide protection against external impacts (precipitation, wind, and mechanical loads), whereas the inner layers are composed of lower-density concrete varieties, which reduce heat losses and enhance the energy efficiency of the structure. This design choice aligns with contemporary practices in the use of multi-layer panels in both international and domestic construction industries, where the optimal balance between structural strength and thermal insulation is achieved precisely through variations in layer density.

At the same time, the evolution of structures from Scheme 2 to Scheme 4 demonstrates the consistent implementation of the principles of functional gradient design, where each subsequent option provides improved thermal performance due to a more rational distribution of material with variable density.

The boundary conditions for the climatic parameters of the study area were adopted in accordance with standards [33,34] and are presented in Table 2.

Table 2. Boundary conditions for climatic parameters [33,34].

№	Indicator	Value
1	Study area	Karaganda, Republic of Kazakhstan
2	Indoor humidity regime	Normal
3	Humidity zone	Dry
4	Operating condition of enclosing structures	A
5	Air temperature of the coldest days, with a probability of 0.92	−34.7 (°C)
6	Mean relative humidity of the coldest month (January)	79 (%)
7	Duration of the heating season	207 (days)
8	Indoor temperature in winter	20 (°C)
9	Indoor relative humidity	55 (%)
10	Mean daily temperature during the heating period	−4.8 (°C)
11	Required design resistance according to the degree-days of the heating period	3.20 (W/m ² ·°C)

To determine the temperature field distribution in multi-layer panels, the specialized software package ELCUT 6.6 [34–36] was employed, which has been proven to be an effective tool for solving problems related to heat conduction and conducting thermal analysis of building structures. The verification of the correctness and reliability of the finite element mesh used in the calculations was previously carried out by the authors and presented in an earlier published work [25]. In this study, the simulation results were compared to an analytical method for calculating temperature values at the boundaries of multi-layer wall structures, which showed satisfactory convergence of the results obtained, confirming the adequacy of the chosen technique.

At the same time, to determine other thermophysical characteristics of the panels under investigation (such as the heat transfer coefficient, thermal resistance, and others), calculation methods regulated by national building standards [4,33] were applied. These calculations were carried out using the Maple-2020.0 software package, which is designed for solving systems of algebraic equations and performing numerical experiments.

The developed analytical framework, ensuring a comprehensive combination of numerical modeling in ELCUT and analytical–normative calculations in Maple, is presented in Figure 2 [4,33,36].

The integrated workflow of ELCUT-Maple consisted of sequentially performing finite element modeling of thermal fields in ELCUT, followed by analytical processing of the results in Maple. The data were transmitted through text files containing temperature distributions, which were used in Maple to calculate heat transfer resistance, humidity, and air conditions. Verification was carried out by comparing the ELCUT results with analytical calculations according to the standards, which showed satisfactory convergence, confirming the reliability of the methodology.

The proposed method for evaluating the effectiveness of variotropic concrete application in panel structures possesses significant practical and scientific potential. Its further use will make it possible not only to identify the most rational engineering solutions for specific design conditions but also ensure the optimal selection of structural parameters, taking into account operational requirements, climatic characteristics of regions, and economic feasibility.

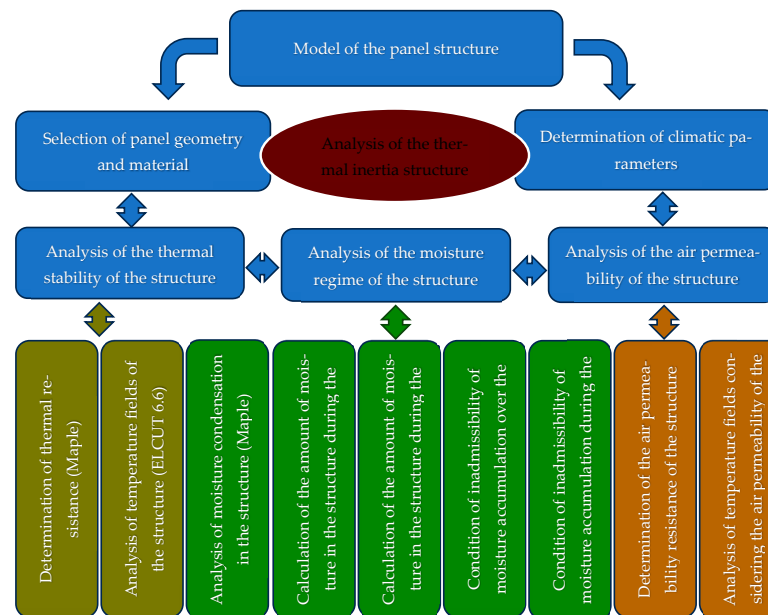


Figure 2. Algorithm of the method for analyzing the thermophysical parameters of the studied panel structure.

In addition, the methodology opens up opportunities for the comprehensive optimization of the thermophysical characteristics of multi-layer enclosing structures, which contributes to enhancing their energy efficiency, durability, and resistance to external impacts. The implementation of this approach in design and construction practice will enable the development of structures that meet modern requirements of energy-efficient construction and sustainable development, while also reducing operating costs and improving environmental safety.

3. Results and Discussion

3.1. Actual Heat Transfer Resistance of Multi-Layer Panel Structures in Comparison to the Required Value

Figure 3 presents the results of the analysis of the actual heat transfer resistance of all types of panel structures shown in Figure 1, compared to the required values (Table 2). The required values were determined based on the normative parameters corresponding to the climatic conditions of the region, in accordance with [4,33].

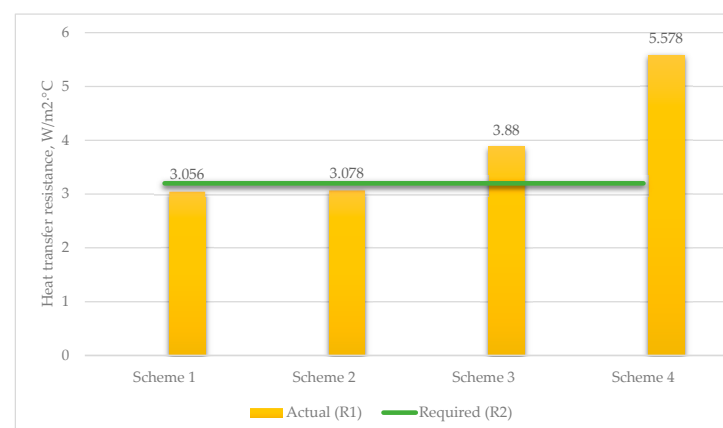


Figure 3. Actual (R₁) and required (R₂) thermal resistance values of multi-layer panel structures: Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers.

3.2. Analysis of Temperature Fields in Multi-Layer Variotropic Panel Structures

Figure 4 presents an analysis of the temperature fields in multi-layer variotropic panels, simulated using the ELCUT 6.6 software package [25,36].

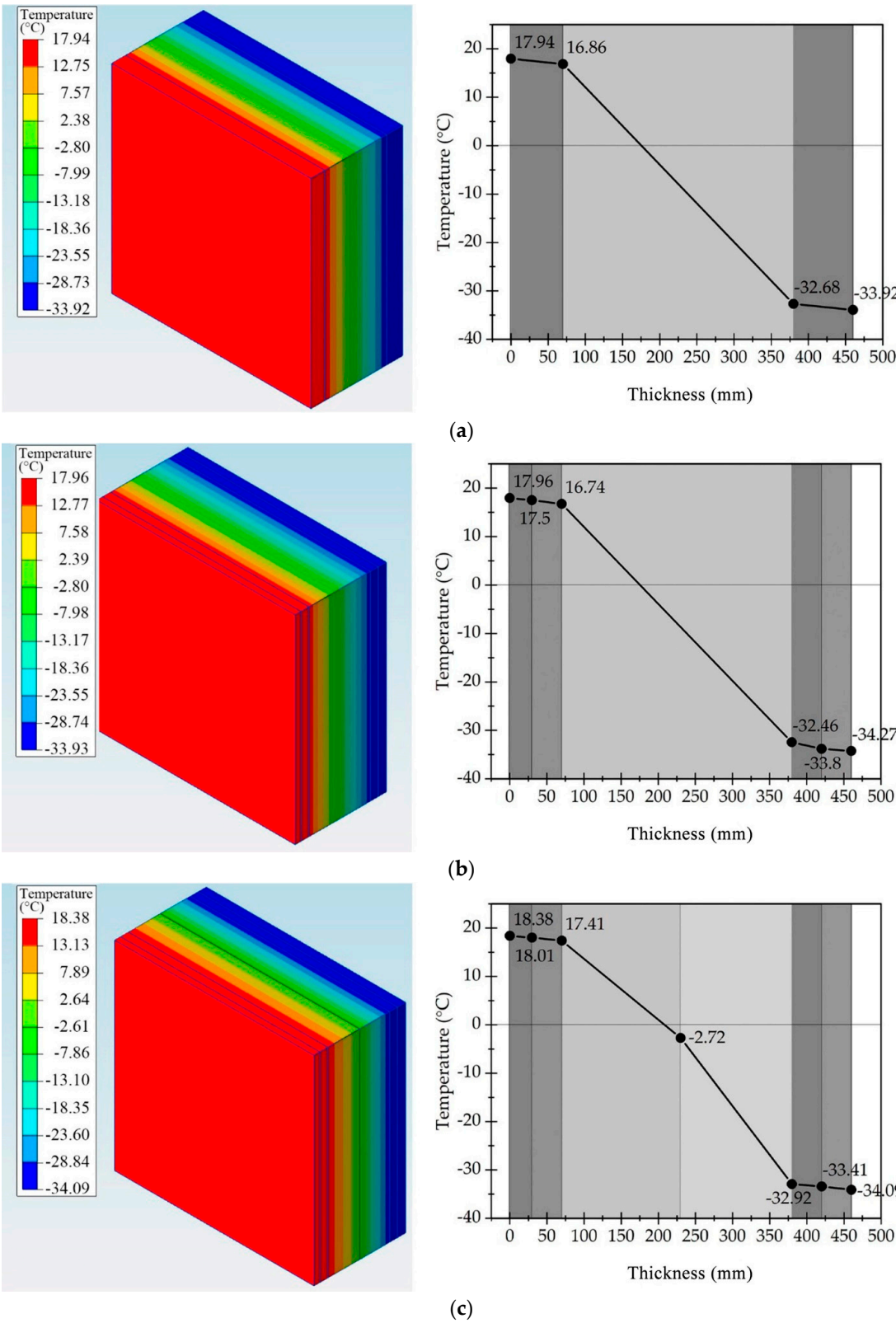


Figure 4. Cont.

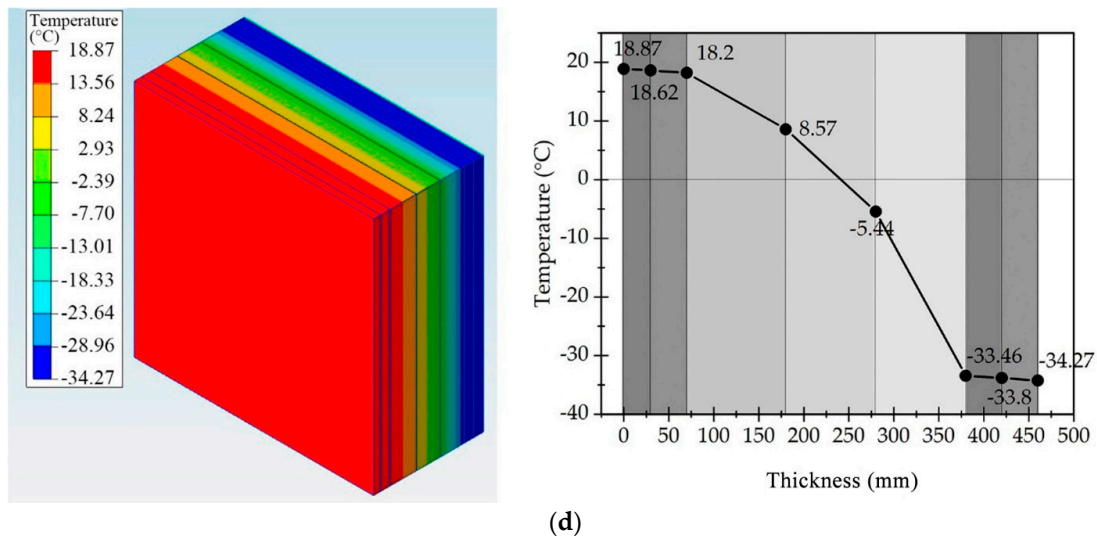


Figure 4. Analysis of temperature fields in multi-layer variotropic panels: (a). Traditional type (Scheme 1); (b). Variotropic concrete in 1 and 3 layers (Scheme 2); (c). Variotropic concrete in 1, 2 (two layers), and 3 layers (Scheme 3); (d). Variotropic concrete in 1, 2 (three layers), and 3 layers (Scheme 4).

3.3. Analysis of Thermal Inertia in Multi-Layer Variotropic Panel Structures

Figure 5 presents the results of the analysis of thermal inertia values for multi-layer variotropic panel structures.

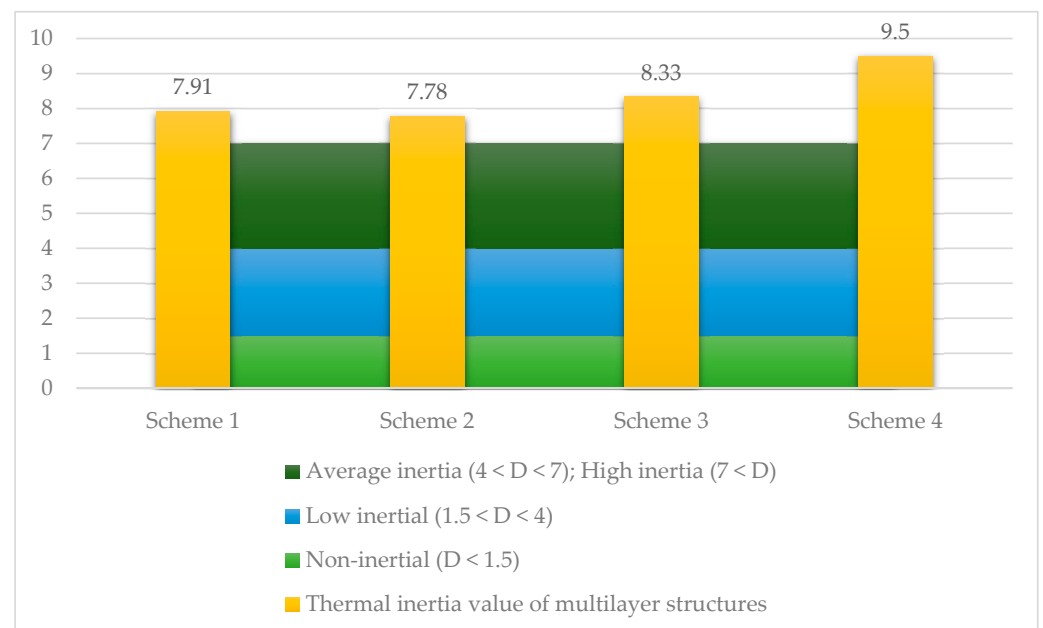


Figure 5. Thermal inertia values of multi-layer variotropic panel structures: (Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers).

3.4. Analysis of Moisture Regime in Multi-Layer Variotropic Panel Structures

3.4.1. Analysis of Moisture Condensation in Multi-Layer Variotropic Panels

Figure 6 presents the results of the analysis of moisture condensation in multi-layer variotropic panel structures.

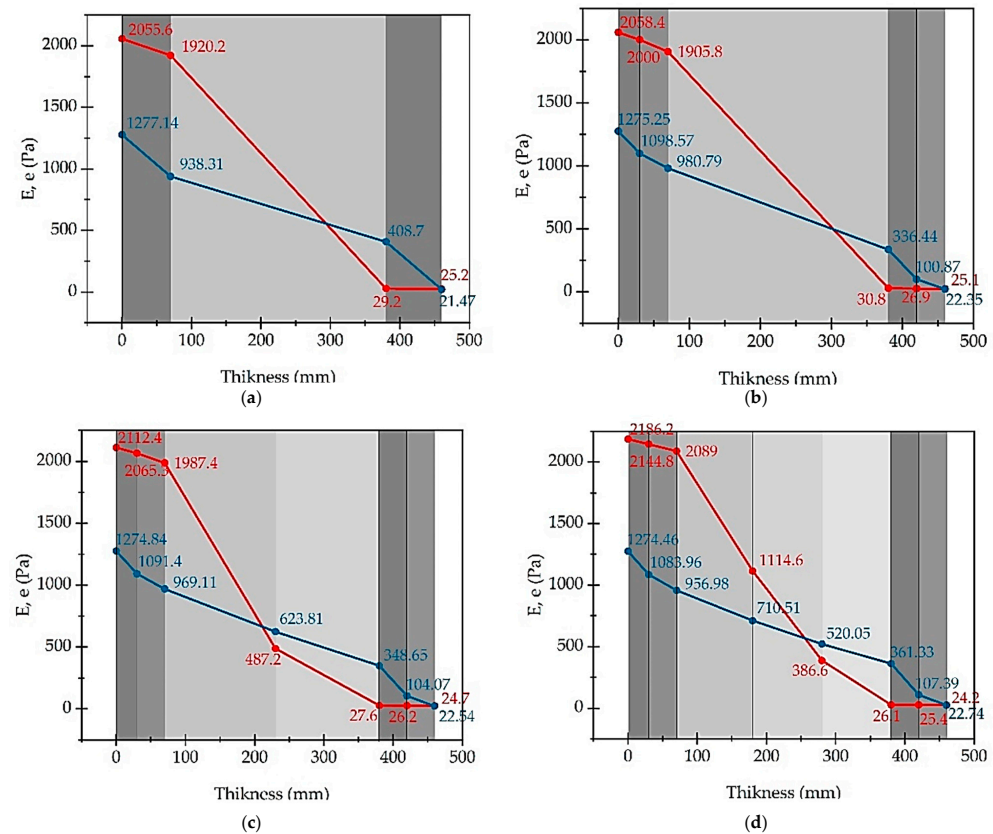


Figure 6. Moisture condensation values in multi-layer variotropic panel structures: (a). Traditional type (Scheme 1); (b). Variotropic concrete in 1 and 3 layers (Scheme 2); (c). Variotropic concrete in 1, 2 (two layers), and 3 layers (Scheme 3); (d). Variotropic concrete in 1, 2 (three layers), and 3 layers (Scheme 4).

3.4.2. Analysis of the Amount of Moisture Condensing in Multi-Layer Variotropic Panel Structures During the Moisture Accumulation Period

Figure 7 presents the results of the analysis of the amount of moisture condensing in multi-layer variotropic panel structures during the moisture accumulation period.

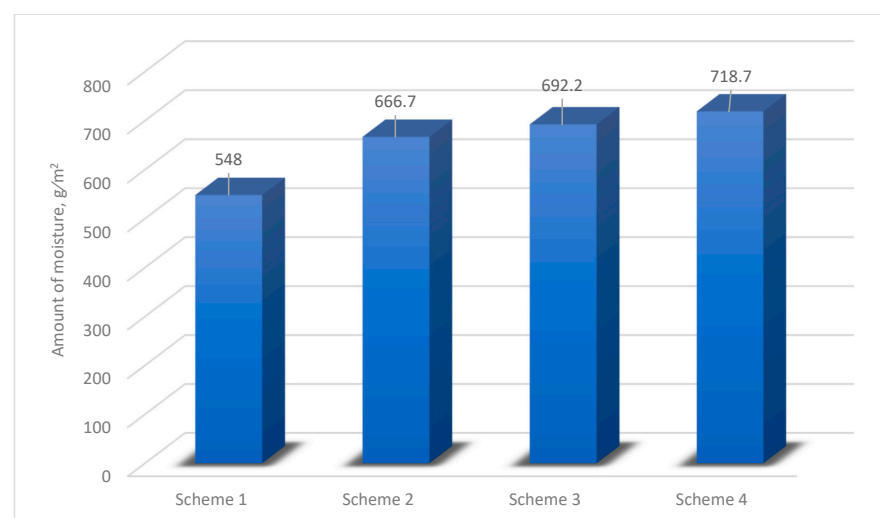


Figure 7. Amount of moisture condensing in multi-layer variotropic panel structures during the moisture accumulation period: Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers.

3.4.3. Analysis of the Amount of Moisture Evaporating from Multi-Layer Variotropic Panel Structures During the Drying Period

Figure 8 presents the results of the analysis of the amount of moisture evaporating from multi-layer variotropic panel structures during the drying period.

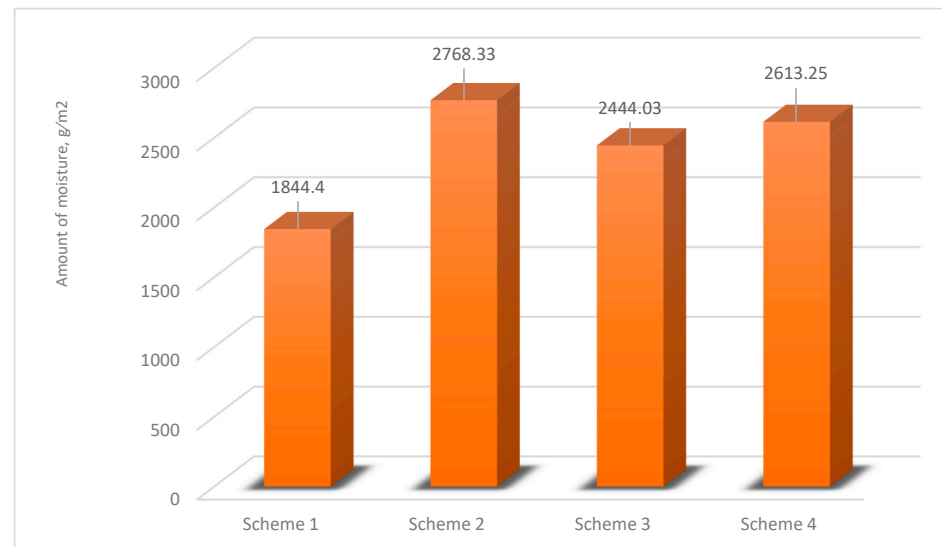


Figure 8. Amount of moisture evaporating from multi-layer variotropic panel structures during the drying period: Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers.

3.4.4. Conditions for the Unacceptability of Moisture Accumulation in Variotropic Panel Structures over an Annual Service Period ($R_{vpc}^f \geq R_{vpc}^{req}$)

Figure 9 presents the results of the analysis of the unacceptability of moisture accumulation in multi-layer variotropic panel structures over an annual service period.

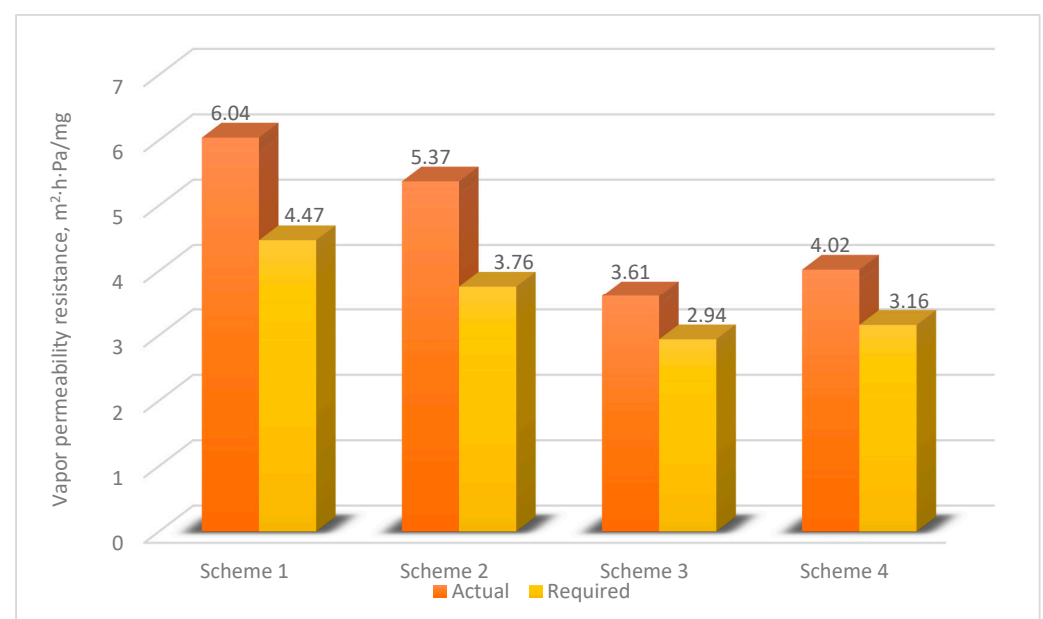


Figure 9. Condition for the unacceptability of moisture accumulation in multi-layer variotropic panel structures over an annual service period: Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers.

3.4.5. Conditions for the Unacceptability of Moisture Accumulation in Multi-Layer Variotropic Panel Structures During the Moisture Accumulation Period ($R_{vpc}^f \geq R_{vpc}^{req}$)

Figure 10 presents the results of the calculation of moisture accumulation unacceptability values in multi-layer exterior panel structures during the moisture accumulation period.

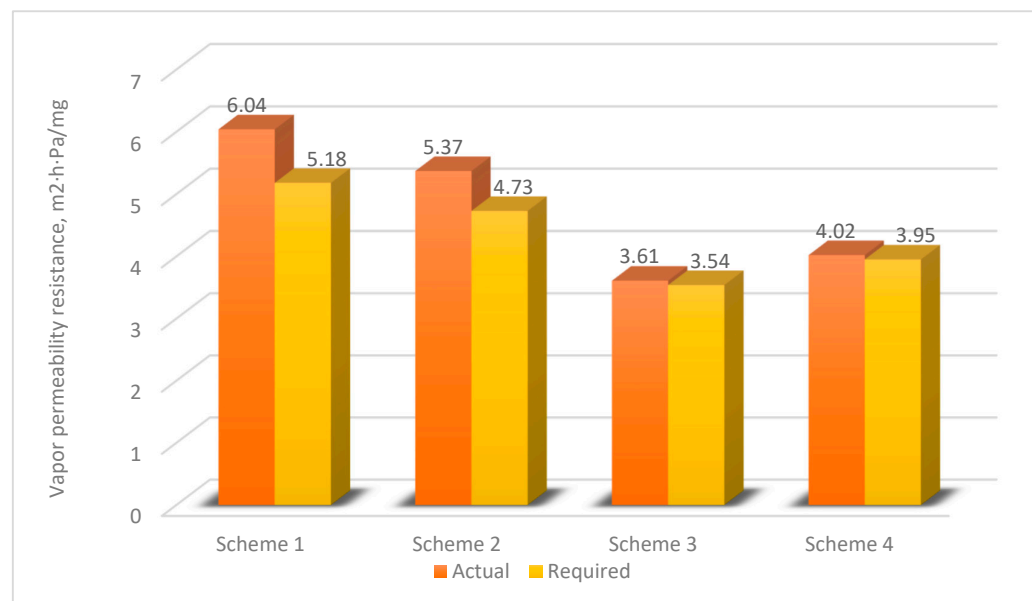


Figure 10. Condition for the unacceptability of moisture accumulation in multi-layer variotropic panel structures during the moisture accumulation period: Scheme 1—Traditional type; Scheme 2—Variotropic concrete in 1 and 3 layers; Scheme 3—Variotropic concrete in 1, 2 (two layers), and 3 layers; Scheme 4—Variotropic concrete in 1, 2 (three layers), and 3 layers.

In conclusion, it is noted that the combination of materials with different densities and vapor permeability creates conditions for the natural circulation of moisture vapor. During periods of high humidity, the inner layers with higher vapor permeability temporarily accumulate excess moisture, which is then effectively removed during periods with more favorable conditions, which is confirmed by the drying coefficient exceeding the moisture accumulation by 3.3–4.1 times.

Thus, the improvement of the moisture resistance of variotropic panels is a consequence of the purposeful design of the gradient of material properties, which provides a synergistic effect in controlling the humidity regime of the enclosing structure.

3.5. Analysis of Airflow Regime in Multi-Layer Exterior Panel Structures ($R_u^{req} \leq R_u^f$)

3.5.1. Analysis of Air Permeability Resistance in Multi-Layer Variotropic Panel Structures

Table 3 presents the results of the analysis of the required and actual air permeability resistance of multi-layer variotropic panel structures.

Table 3. Required and actual air permeability resistance values of multi-layer variotropic panel structures.

№	Schemes	Required Air Permeability Resistance, for Building Height, H = 27 m	Actual Air Permeability Resistance	Condition Fulfilled
1	Variant—1	59.28	29,802	Fulfilled
2	Variant—2	59.28	26,304	Fulfilled
3	Variant—3	59.28	26,259	Fulfilled
4	Variant—4	59.28	26,214	Fulfilled

The results obtained demonstrate that the air regime of all the studied panels meets the regulatory requirements for air permeability, while the dense outer layers of concrete provide additional protection against air infiltration, helping to stabilize the thermal and humidity balance. However, achieving high airtightness requires addressing certain design aspects. Sealing of mounting seams and junctions, as well as the development of fastening units with thermal breaks and sealing elements to preserve the integrity of the air barrier, is of key importance.

At the same time, high airtightness also has certain drawbacks. The main one is the need to organize balanced supply and exhaust ventilation with heat recovery, since natural infiltration through enclosing structures becomes minimal. Without an effective ventilation system, there is a risk of increased humidity in the premises, which can negatively affect the microclimate. Thus, the use of variotropic panels with increased airtightness requires an integrated approach to the design of the building as a whole.

3.5.2. Study of Temperature Distribution at the Boundaries of Multi-Layer Variotropic Panel Structures Considering Air Filtration

Table 4 presents the results of the analysis of temperature distribution at the boundaries of multi-layer variotropic panel structures, taking air filtration into account.

Table 4. Temperature distribution values at the boundaries of multi-layer variotropic panel structures.

Condition	τ	Schemes			
		1	2	3	4
Without Air Filtration, °C (According to Figure 3)	τ_{int}	20.00	20.00	20.00	20.00
	τ_1	17.94	17.96	18.38	18.87
	τ_2	16.86	17.50	18.01	18.62
	τ_3	−32.68	16.74	17.41	18.20
	τ_4	−33.92	−32.46	−2.72	8.57
	τ_5	-	−33.07	−32.92	−5.44
	τ_6	-	−33.93	−33.41	−33.46
	τ_7	-	-	−34.09	−33.80
	τ_8	-	-	-	−34.27
	τ_{ext}	−34.7	34.7	34.7	34.7
With Air Filtration, °C	τ_{int}	20.00	20.00	20.00	20.00
	τ_1	17.94	17.95	18.37	18.87
	τ_2	16.85	17.49	18.01	18.61
	τ_3	−32.69	16.73	17.40	18.19
	τ_4	−33.92	−32.46	−2.78	8.51
	τ_5	-	−33.08	−32.93	−5.53
	τ_6	-	−33.93	−33.41	−33.47
	τ_7	-	-	−34.09	−33.81
	τ_8	-	-	-	−34.28
	τ_{ext}	−34.7	34.7	34.7	34.7
Difference	%				

This study presents a comprehensive theoretical investigation of the effectiveness of using variotropic concretes in multi-layer building panel structures (Figure 1b–d) in comparison to the previously studied traditional three-layer panel (Figure 1a) [24].

Within the framework of the study, the thermophysical parameters of the structures were analyzed, including thermal performance (thermal resistance, temperature field distribution, and thermal inertia), and moisture and airflow regimes. The theoretical analysis was carried out using the modern numerical modeling software package ELCUT 6.6 [25,35–37] and the computer algebra system Maple, which enhanced the reliability of the calculations.

For the modeling of multi-layer panels, appropriate types of concrete were selected, and their thermophysical properties are presented in Table 1. The geometric dimensions

of the structures were chosen such that the overall thickness of all four panel variants remained the same, while the configuration of the internal layers varied. The study was conducted for a climatic region with severe winter conditions (Table 2), where the temperature of the coldest days with a probability of 0.92 is -34.7°C . Based on these data, the parameters of the heating period (degree-days) were determined, which are necessary for the subsequent analysis.

The analysis of thermal performance showed that the required thermal resistance (Rt) for the selected region is $3.2 \text{ m}^2 \cdot ^{\circ}\text{C}/\text{W}$ [4,25]. A comparison of this normative value with the actual thermal resistances (R) of the studied structures (Figure 3) revealed that the first two panel variants do not meet the minimum Rt requirements. At the same time, Scheme 3 and Scheme 4 demonstrated exceedances of the normative value by 1.2 and 1.74 times, respectively. This confirms that increasing the degree of material variatropy enhances the effectiveness of the building envelope structures in terms of thermal resistance.

The analysis of temperature fields (Figure 4) showed that increasing the variatropy of the layers contributes to a rise in the temperature on the inner surface of the panel: from 17.94°C for the traditional structure (Scheme 1) to 18.87°C for the variant with more pronounced variatropy. Scheme 3 and Scheme 4 thus demonstrate higher energy efficiency compared to the traditional three-layer panel (Scheme 1) and the less variotropic variant (Scheme 2). This is explained by the physical nature of the density distribution of the concrete within the panel structure: the use of a gradient density variation creates a sequential transition from denser outer layers to less dense inner layers. As a result, the effective thermal conductivity of the panel decreases, the influence of thermal bridges is reduced, and a more uniform temperature distribution across the panel thickness is formed. This approach minimizes local zones of reduced temperature on the inner surface of the wall, thereby enhancing thermal comfort in indoor spaces and reducing the risk of moisture condensation.

The study of thermal inertia (D) confirmed that all structures fall into the high-inertia category ($D > 7$). Moreover, with an increase in the degree of variatropy, the thermal inertia value exhibits an additional positive effect, enhancing the ability of the building envelope to smooth out temperature fluctuations (Figure 5).

The analysis of the moisture regime (Figure 6) showed that, at the second stage of the study, all multi-layer panel structures demonstrated moisture accumulation. The calculation of the accumulated moisture (Figure 7) revealed that, in the traditional three-layer structure (Scheme 1), the moisture accumulation values are lower, on average, compared to the variotropic panels, by 1.21–1.31 times depending on the panel scheme. However, the results of the moisture exchange analysis during the drying period (Figure 8) indicated that the balance between moisture accumulation and drying is positive. The drying coefficient of the structures exceeds the moisture accumulation values by 3.3–4.1 times, confirming the panels' capability for self-regulation of their moisture state.

In all the studied structures, the condition for the unacceptability of moisture accumulation ($R_{vpc}^1 \geq R_{vpc}^2$) is satisfied both over the annual cycle and during the moisture accumulation period (Figures 9 and 10). This highlights the positive effect of using variotropic concretes in exterior building envelope structures, despite significant differences in layer thicknesses compared to traditional solutions.

The analysis of the airflow regime revealed that, in all multi-layer structures, the condition for compliance between the required and actual air permeability resistance ($R_u^2 \leq R_u^1$) is met with a considerable margin (Table 3). This result is explained by the design features of the panels: the presence of dense outer concrete layers significantly limits air filtration through the envelope, while the variotropic structure further inhibits through-transfer. For comparison, according to current regulations [4], the minimum required air permeability re-

sistance for exterior walls is considerably lower (in the order of hundreds), so the calculated values obtained exceed the normative level many times over. This emphasizes that the studied structures not only meet the requirements but also possess a substantial safety margin in this regard, ensuring high airtightness and resistance to air infiltration. At the same time, the traditional three-layer structure (Scheme 1) exhibits the highest air permeability resistance, exceeding that of the variotropic panels (Scheme 2, Scheme 3 and Scheme 4) by an average of 10%. Additionally, the analysis of temperature distribution at the panel boundaries, considering air filtration (Table 4), showed only minor temperature fluctuations, which can be attributed to the positive effect of the dense outer concrete layers limiting the intensity of filtration processes.

This study on the effectiveness of using variotropic concretes in panel structures is part of the authors' broader theoretical and experimental research [25]. The obtained results confirmed that incorporating variatropy into panel design provides significant advantages in terms of thermal performance, including energy savings and reduced material consumption through the rational selection of concrete types. This approach opens opportunities for the development of new structural solutions aimed at enhancing building energy efficiency and reducing material costs. It aligns with current trends in Functionally Graded Design, where the combination of different materials within a single structure allows the creation of constructions with improved operational characteristics.

This research clearly demonstrates the significant potential of using variotropic concretes in multi-layer enclosing structures. The obtained results require a deep understanding of the context of existing scientific research and current trends in building thermophysics [25,38,39].

The prospects for further research in this area are associated with extending the theoretical results through experimental verification of the obtained data under real operating conditions of the panels. Particular attention should be given to accounting for the concrete heterogeneity coefficient, which may influence stress distribution and heat transfer in variotropic structures. Furthermore, an important stage of future work involves conducting a techno-economic analysis to assess the feasibility of large-scale implementation of variotropic panels in construction practice, taking into account production costs and operational benefits under the severe climatic conditions of Kazakhstan.

At the same time, the obtained results can serve as scientifically grounded recommendations for design organizations and research centers in the development of energy-efficient multi-layer exterior wall structures. Moreover, they can complement the catalog of modern construction solutions and contribute to the adoption of innovative technologies in construction practice.

4. Conclusions

As a result of this comprehensive theoretical study of the thermophysical parameters of multi-layer panels using variotropic concrete, the following conclusions were drawn:

- The scientific novelty of this study is that it established quantitative relationships between the degree of variability of the structure and its key thermophysical characteristics. It proved that the application of the variotropic principle provides not just an improvement, but a qualitative transformation of the thermal regime due to a more rational distribution of temperature fields. This leads to a decrease in heat loss and an increase in the thermal stability of exterior fences, which is especially important for building operations in regions with harsh climatic conditions.
- The quantitative results of calculations of heat transfer resistance showed that the variatropic-type panels (Scheme 3 and Scheme 4) not only meet regulatory requirements but also significantly exceed them by 1.2 and 1.74 times, respectively. This

allows us to consider such structures as an effective alternative to traditional three-layer panels in the construction of buildings in the cold zones of Kazakhstan.

- An increase in the degree of variability was found to contribute to a temperature increase on the inner surface of the panel from 17.94 °C (Scheme 1) to 18.87 °C (Scheme 4), which improves the comfortable operating conditions of the premises and reduces the risk of condensation. Additionally, it is possible to reduce the thickness of the insulation layer without reducing heat efficiency.
- All structures are confirmed to have high thermal inertia ($D > 7$), while with increasing variability, the ability of panels to accumulate and store heat increases, which has a positive effect on energy consumption during the heating period.
- The humidity regime of the studied structures, despite the increase in moisture accumulation, meets the regulatory criteria for preventing moisture accumulation by exceeding the drying coefficient over the moisture accumulation coefficient by 3.3–4.1 times. This increases the durability of the panels and eliminates the conditions for mold formation or destruction of the structure.
- The air regime of the panels exceeds the requirements for air permeability by a significant margin (with the actual values exceeding the requirements hundreds of times), and the dense outer layers of concrete provide additional protection against air infiltration, stabilizing the thermal and humidity balance.

Thus, the scientific, technical, and economic feasibility of using variotropic concrete in multi-layer panels has been proven, which opens up practical prospects for the construction of energy-efficient and durable buildings in Kazakhstan. The implementation of such solutions will reduce operating costs, increase comfort, and reduce the material consumption of structures, conforming to the principles of functional gradient design and “green” construction.

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