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Development of a 3D Modeling Method for Estimating the Thermophysical Parameters of Foam Concrete, Taking into Account Porosity

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Abstract: A theoretical study of the porosity influence on external building enclosures was conducted using ANSYS and Blender software packages. A foam concrete block with porosity up to 15% was investigated as an example of an external enclosure design. Pore content was analyzed from 1.5% to 15%. The percentage analysis of pores revealed that the thermal flow value shows a significant difference at 15% porosity, reaching up to 11.3 W/m², while porosity up to 10% indicates 12.2 W/m². Furthermore, with a difference of 1.31 times, the thermal flow value reaches 15 W/m² at 1.5% porosity. Additionally, the increase in porosity positively affects the effective thermal conductivity of the foam concrete structure and its thermal resistance. The obtained research results can be used to eliminate costly experiments and provide an accurate assessment of the thermal conductivity coefficient for external enclosures made of foam concrete blocks, taking porosity into account during residential building design

1 INTRODUCTION

Energy efficiency of building envelope structures means minimizing energy consumption while maximizing labor productivity in construction and ensuring comfortable indoor conditions. The construction industry is a primary consumer of heat and energy, annually consuming approximately 40% of extracted fuel, which leads to significant environmental pollution [1,2]. To create comfortable living environments, designers and experts develop various innovative external envelope designs, modernization programs [3-5], and regulatory documents [6-11]. Developing an energy-efficient external envelope structure requires carefully selecting materials and products with optimal thermophysical and mechanical properties [12-16], while mandatorily considering environmental and climatic parameters [17-20]. While maintaining material strength, heat-conducting properties can be manipulated through variations in internal structure — specifically, porosity or void space — which significantly influences thermal conductivity. Considering these factors, domestic and international researchers have conducted extensive studies on developing energy-efficient building blocks. For instance, in one study [21], researchers investigated porosity percentages in arbolite types and developed a methodology for assessing thermal resistance of arbolite blocks based on pore percentage. This methodology can determine thermal conductivity without experimental analysis, though it is limited to arbolite blocks. Another study [22] examined various porous structure parameters' impact on thermal conductivity of building blocks [23], establishing that average pore size and distribution are less critical than previously thought. Research by [24] explored combined slag and fly ash replacement to improve foam concrete mixtures' porous structure and corrosion resistance [25]. While showing significant

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mechanical improvements, thermal characteristics remained unexplored [26-28].

A study on open-cell foam materials [29] investigated pore size variations' effect on thermal conductivity, confirming that thermal conductivity closely correlates with porosity. However, temperature load variations were not addressed [30-34]. Research on polymer nanocomposites with carbon nanotubes [35] modeled thermal conductivity considering tube orientation using different methods. The study examined five nanocomposite concentrations (0%, 0.25%, 0.50%, 0.75%, and 1%), showing satisfactory convergence in thermal conductivity assessment across various methods. However, the research did not address the combined effect of porosity and fiber orientation, which could significantly impact thermal conductivity [36-39].

In a study using ANSYS [40], researchers calculated the effective thermal conductivity of a material at room temperature, investigating the influence of fiber placement and matrix porosity across different fiber fractions. They obtained thermal conductivity values considering both longitudinal and transverse fiber directions. The method's reliability was proven by comparing numerical and experimental data, with a relative error of less than 2%. The study's limitation was incomplete examination of large temperature differential effects on thermal conductivity and structural characteristics [41-43].

Another investigation [44] used computer modeling to examine three different carbon fiber volume fractions in natural rubber, employing eight loading scenarios to study loading conditions' impact on nanocomposites' effective thermomechanical properties. Results demonstrated that mechanical loading could improve effective thermal conductivity and increase the composite's elastic modulus [45]. However, this research did not consider pore size and structure affecting thermal conductivity. A parametric study [46] explored the influence of nanoreinforcement material morphology [47,48], volume fraction, orientation, and interphase properties on calculated effective thermal conductivity values, which corresponded with experimentally measured values.

The literature review demonstrates that research on material porosity and structure remains incomplete and requires further investigation. Appropriate porosity can lead to significant thermal energy savings in buildings, indirectly reducing operational costs for energy-producing or energy-supply infrastructure [49-53]. Therefore, this study aims to numerically model the influence of foam concrete material porosity on layer thermal conductivity using the ANSYS software package. The research results will enable accurate and efficient thermal property assessment during external envelope design, minimizing experimental expenses.

2 METHODS AND MATERIALS

In this work, foam concrete was investigated as an example (Figure 1), where the main initial thermophysical property data for further analysis were adopted according to [7].

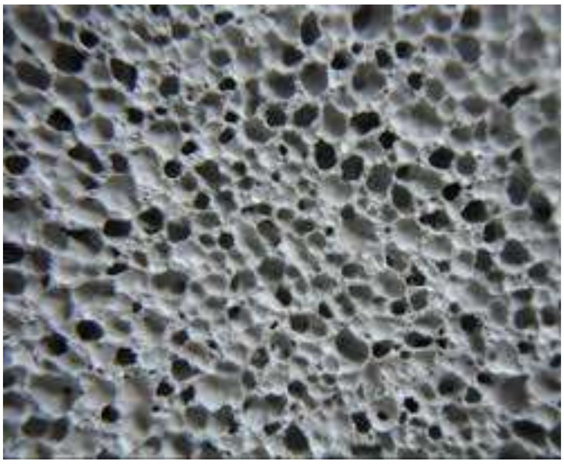

Figure 1: Foam concrete structure.

The finite element method is often applied in problems with complex body geometry, when analytical methods either cannot solve the problem or provide an approximate answer, and experiments are difficult to set up and resource-intensive.

First, let's consider solving our problem in an analytical form. In the case of a steady-state temperature regime, the law of propagation looks as follows:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) = 0 \qquad (1)$$

Assuming that in our problem the heat flow goes only in the direction of the OX axis, equation (1) takes the form:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) = 0 \qquad (2)$$

From equation (2) and Fourier's law, the effective heat transfer coefficient can be found by the formula [21,35]:

$$\lambda_e = \frac{QL}{\Delta T} \qquad (3)$$

where q – heat flow, L – distance between surfaces, ΔT – temperature difference

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At this stage, the problem of finding the heat flow magnitude arises. Usually, a coefficient determined experimentally is used to calculate it. In our case, this means that it is necessary to manufacture samples for each porosity value and conduct experiments with them, which is quite costly.

Knowing the body geometry and initial temperature on opposite walls, the heat flow can be found by numerical calculation. To determine the heat flow, the Steady-State Thermal module of the ANSYS software package was used, and the 3D model of the porous material was created in Blender (Figure 2) and prepared for numerical calculation in the ANSYS SpaceClaim module.

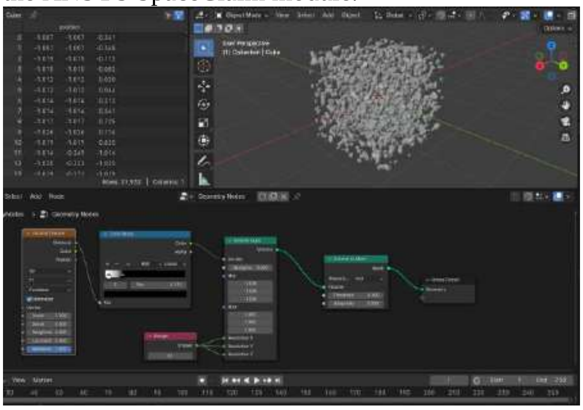
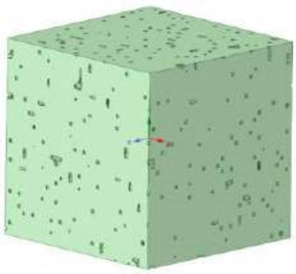


Figure 2: Algorithm for creating a porous structure in the 3D modeling program Blender.

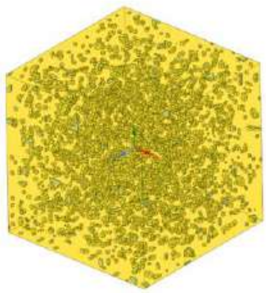
The model in the form of a cube with sides of 2 meters was divided into 600 - 2500 parts using the Voronoi Texture tool, which is based on the algorithm of dividing the volume into Voronoi cells [53]. The resulting model represented pores located inside the foam concrete.

After importing the pore model into SpaceClaim, a foam concrete model was created by subtracting the pore model from a 2-meter cube (Fig. 3). The pores in the model were filled with a volume to which the properties of air were subsequently assigned. A tetrahedral mesh was constructed taking into account the requirements for calculation accuracy. The element size was 0.05 m (Fig. 4).

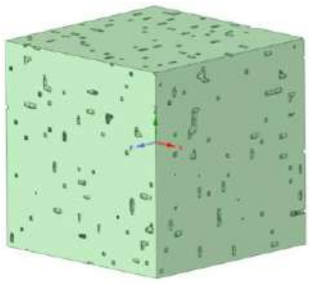
On the opposite walls located perpendicular to the OX axis, boundary conditions were set – constant temperature, -25°C on one side and 22°C on the other. The calculation was carried out to determine the amount of directed heat flow and thermal conductivity coefficient depending on the porosity of the material under consideration. The analysis considered porosity variations ranging from 5% to 15%.



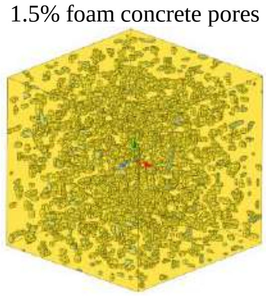
1.5% foam concrete model



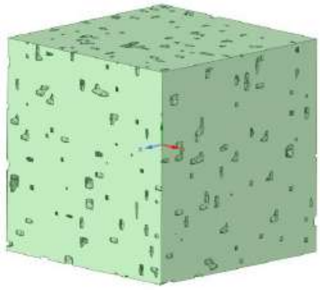
1.5% foam concrete pores



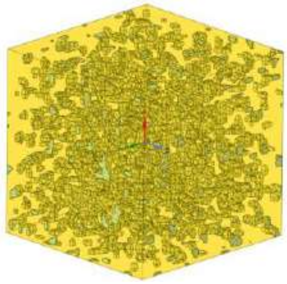
3% foam concrete model



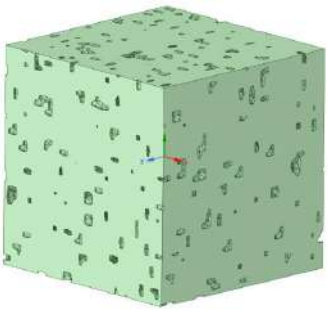
3% foam concrete pores



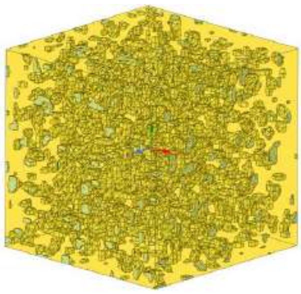
5% foam concrete model



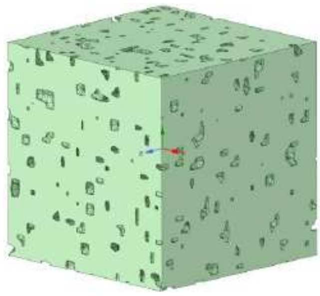
5% foam concrete pores



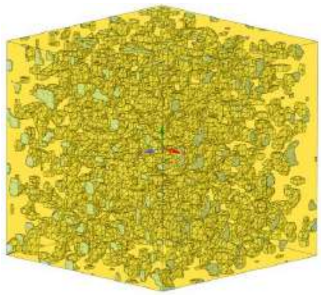
7% foam concrete model



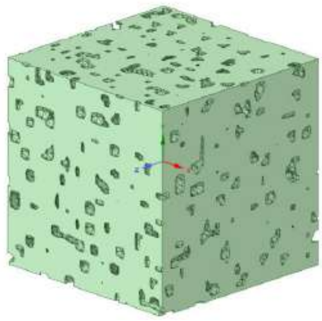
7% foam concrete pores



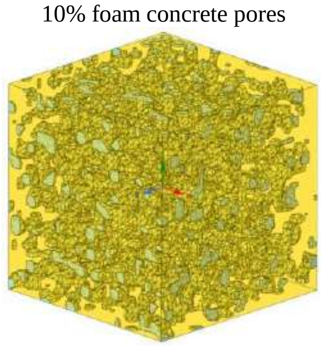
10% foam concrete model



10% foam concrete pores



15% foam concrete model



15% foam concrete pores

Figure 3: Foam concrete model and its pores.

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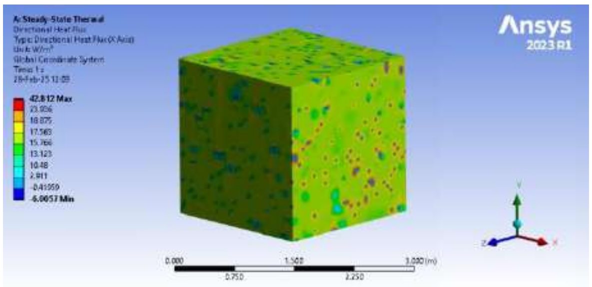
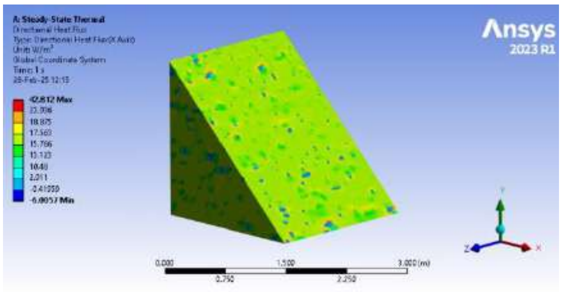
Figure 4: Finite element mesh of the foam concrete model in ANSYS program.

3 RESULTS AND DISCUSSIONS

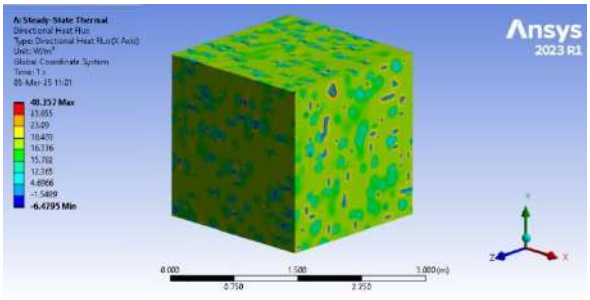
The thermal conductivity study of foam concrete according to Figure 3 was conducted in various variations in the ANSYS software complex, presented in Figure 5.



1.5%



1.5% cut



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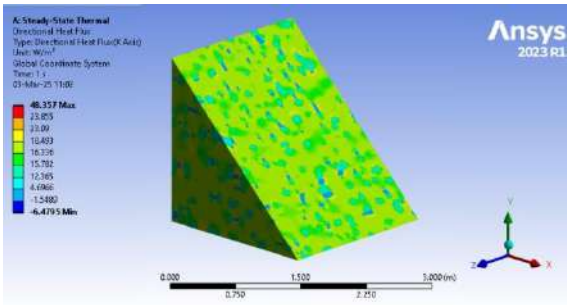

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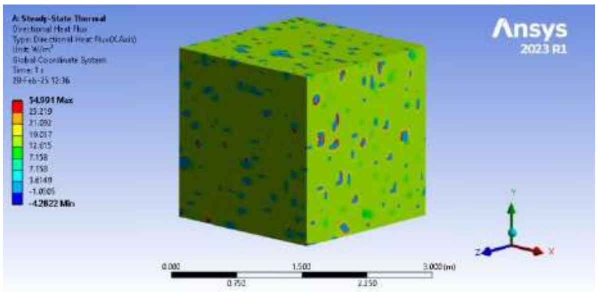
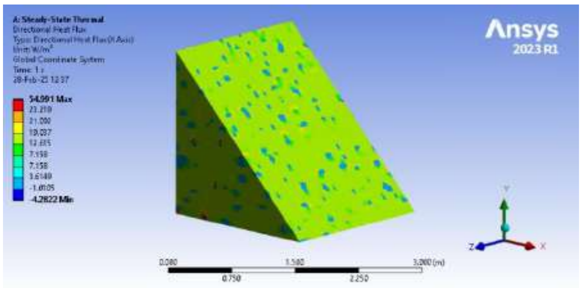


5%



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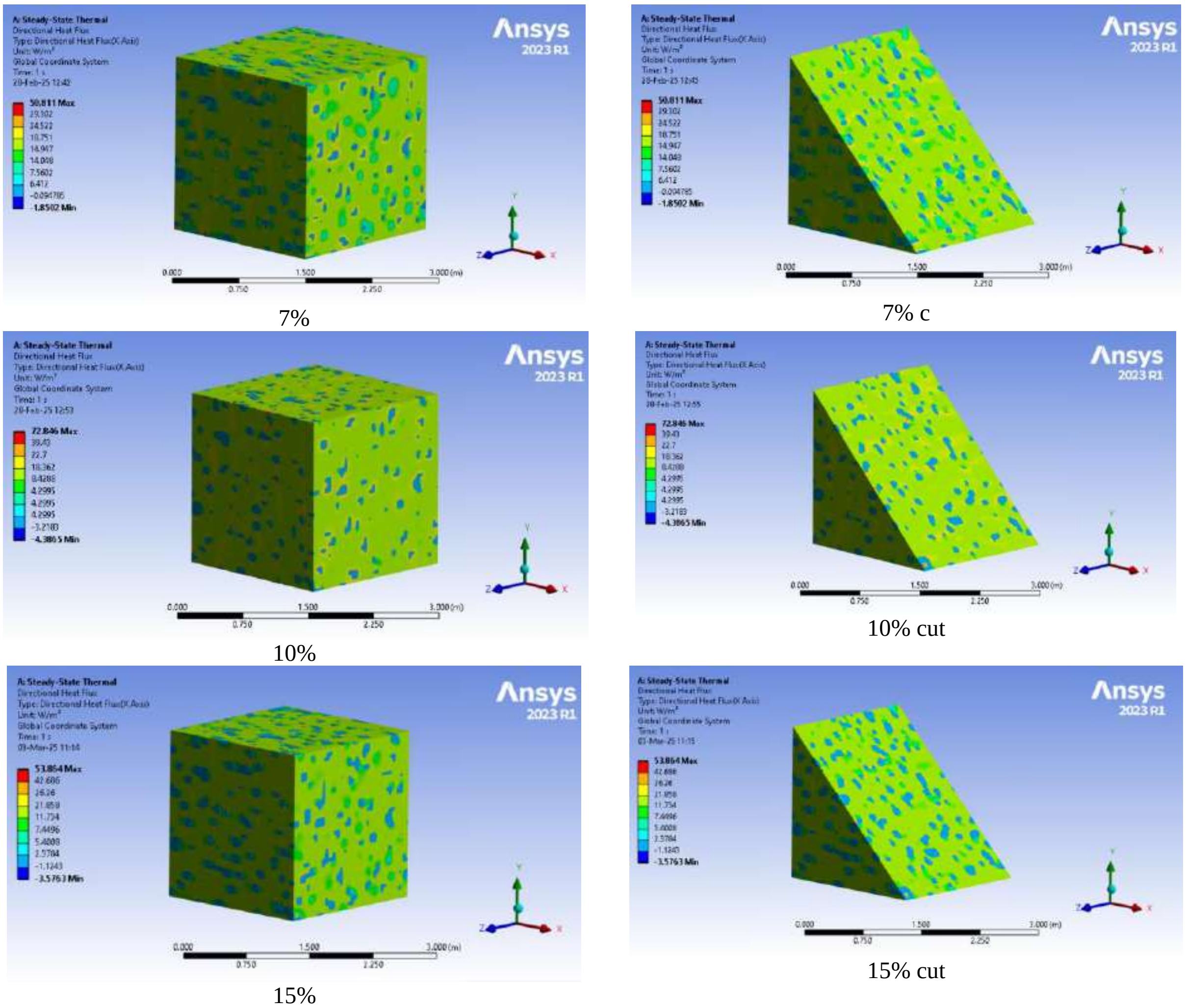

Figure 5: Analysis of foam concrete thermal conductivity in ANSYS.

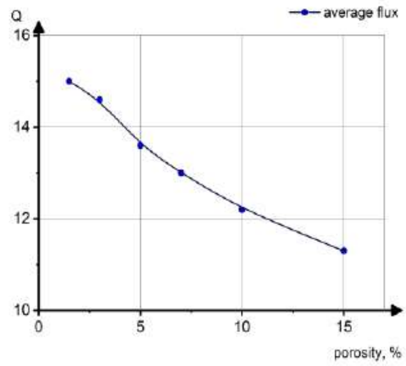

Figure 6: Diagram of average heat flow values considering porosity, W/m²: 1.5%=15; 3%=14.6; 5%=13.6; 7%=13; 10%=12.2; 15%=11.3.

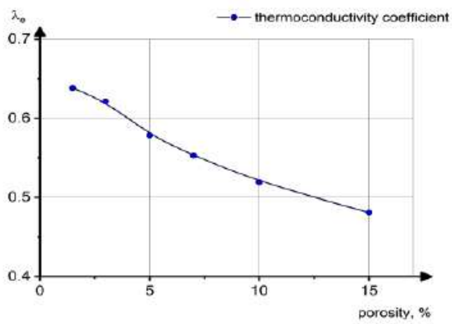

Figure 7: Dependence of effective thermal conductivity coefficient on porosity.

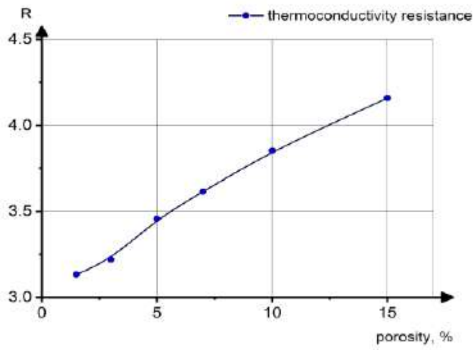

Figure 8: Dependence of thermal resistance coefficient on porosity.

Table 1 presents the values of the effective thermal conductivity coefficient (Figure 7) and thermal resistance (Figure 8) relative to the percentage of pores relative to Figure 6.

Table 1: Numerical expressions of effective thermal conductivity coefficient and thermal resistance.

Porosity	λ_e	R
1.5	0.6383	3.13333
3	0.62128	3.21918
5	0.57872	3.45588
7	0.55319	3.61538
10	0.51915	3.85246
15	0.48085	4.15929

As a result of the conducted analysis of foam concrete porosity influence in various variations (1.5%, 3%, 5%, 7%, 10%, 15%) on the effective thermal conductivity coefficient (λ_e), it was established that as the porosity value increases, the thermal conductivity coefficient (λ_e) decreases (Figure 7) in similar values to the heat flow value (Figure 6), that is, by 1.31 from 0.6383 to 0.48085 depending on the porosity index (Table 1). Moreover, the decrease in effective thermal conductivity and heat flow value favorably affects the thermal resistance (R) of the structure in similar values (Table 1).

4 CONCLUSIONS

A theoretical study of the external enclosure porosity influence was conducted in the ANSYS software complex using the Steady-State Thermal module, where the foam concrete model was developed in the BLENDER program. A foam concrete block was investigated as an example of an external enclosure structure.

The research result established that porosity of 15% has a significant influence on the heat flow dependence from the material's porosity, which was demonstrated using the example of pore content from 1.5% to 15% (Figure 3). Analysis of the percentage of pores showed that the heat flow value has a significant difference at 15% porosity, reaching up to 11.3 W/m², while at porosity up to 10% it shows 12.2 W/m². Subsequently, with a difference of 1.31 times, the heat flow value reaches 15 W/m² at 1.5% porosity. Additionally, the analysis of porosity increase also favorably affects the effective thermal conductivity of the foam concrete structure and its thermal resistance indicator.

Thus, the obtained research results can be used in the future to exclude costly experiments for accurately assessing the thermal conductivity coefficient of external enclosures made of foam concrete blocks, taking into account porosity when designing residential buildings.

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