On New Approaches to the Development of Materials for External Envelope Structures of Energy-Efficient Buildings

Elena Shchipacheva1, a), Said Shaumarov1, b), Ulugbek Shermukhamedov1, c), Diyorbek Bekmirzaev2, d) and Bochao Sun3, e)

1*Tashkent State Transport University, 1 Temiryulchilar St., Tashkent 100167, Uzbekistan*2*Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbaev, Uzbekistan Academy of Sciences, Tashkent, Uzbekistan***3*Zhejiang University,*** *Zijingang Campus, 866 Yuhangtang Road, Hangzhou, Zhejiang, China*

*a) eshipacheva@mail.ru  
b) Corresponding author:* [*shoumarovss@gmail.com*](mailto:shoumarovss@gmail.com) *c)* [*ulugbekjuve@mail.ru*](mailto:ulugbekjuve@mail.ru) *d) diyorbek\_84@mail.ru  
e) sunbochao@zju.edu.cn*

**Abstract.** The current problem of modern construction science is the creation and production on an industrial scale of effective environmentally friendly structural and thermal insulation building materials that combine sufficiently high strength and thermal insulation characteristics. It seems that the most interesting and effective direction in the development of materials for external enclosing structures of buildings is the focus on establishing criteria for optimizing the properties of the material, and then studying the features of the formation of its structure with subsequent impact on it in a given direction. Theoretical prerequisites for the implementation of the proposed approach are presented, as well as the results of theoretical studies on establishing optimal criteria for assessing the thermal insulation properties of materials and determining the structure of cellular concrete with the required properties.

**Key words:** energy efficiency, energy resources, external enclosing structures, thermal insulation properties, cellular concrete, pore structure, operation

# INTRODUCTION

The activities of architects, engineers, builders, and technologists involved in the development of design and construction documentation, new building materials, structures, and technologies are inextricably linked with the general trends in the socio-economic development of society – a sustainable vector for energy conservation and energy efficiency. An important role in this is given to issues of designing energy-efficient buildings, including the development of a well-founded space-planning solution, calculation and design of external enclosing structures with increased thermal insulation properties, as well as the selection of rational and energy-efficient heating, hot water supply, ventilation, and air conditioning systems [1, 2, 3, 4, 5].

Energy-efficient buildings have become a reality of our time. And if, starting from the mid-70s of the twentieth century, they were implemented as single pilot objects, today the construction of such buildings is carried out in many countries of the world. This became possible due to the fact that the construction science and practice responded to society's demands for energy savings by updating the relevant regulatory documents, according to which the heat transfer resistance of external enclosing structures increased several times [6, 7, 8]. In turn, changes in the standards served as a powerful impetus to the development of production and widespread use of efficient thermal insulation materials and multilayer external enclosing structures based on them.

In most cases, modern external enclosing structures of energy-efficient buildings are complex systems consisting of materials with heterogeneous thermal and physical properties. When determining the thermal insulation properties of such structural elements, it is necessary to calculate two- and three-dimensional temperature fields, which is a complex mathematical problem [9, 10]. For scientific research, this is quite acceptable and is solved by developing appropriate computer programs. However, from the point of view of the practical application of such enclosing structures, many problems arise that require highly qualified specialists both at the stage of their development (or adaptation to local climatic and economic conditions) and in the process of further installation and operation. All this determines one of the most pressing problems of modern construction science - the creation and manufacture on an industrial scale of effective environmentally friendly structural and thermal insulation building materials that combine sufficiently high strength and thermal insulation characteristics. The emergence of such a material would allow for a significant rationalization of the design of external building enclosures, simplifying it to a one- to three-layer solution.

There are different approaches to developing a new effective material. But we believe that the most interesting and effective approach is to focus on establishing criteria for optimizing the properties of the material, and then studying the features of its structure formation and subsequent impact on it in a given direction.

In addition, numerous studies on the optimization of thermal parameters conducted earlier [11, 12] are limited to the consideration of specific individual cases, but do not consider the problem as a whole and do not take into account the dynamics of the modern climate.

**RELATED WORK**

Alghoul et al. conducted a study (2016) that examined the impacts of electricity cost on energy-saving measures used on building envelopes. Their research determined that cost-sensitivity models have the potential to influence greatly in thermal insulation conduct and choice of materials, such as in external walls. In relation to the agenda of making it energy efficient, the authors put emphasis on the role of policy instruments in achieving this goal, with the example of dynamic electricity pricing which can stimulate energy efficient design through the material utilisation, as well as thermal performances requirements.[1] Sustainable improvements strategies in building energy efficiency were given by Abdul-Rahman et al. (2011) using case- studies that are related to tropical climates. The study insinuates on the importance of local energy solutions, pointing out that effective thermal design and building envelope (passive) would result in enormous savings in energy. The pagination of their findings recommends tropically particular norms and cover material selections [2].

Yang et al (2008) studied the impact of climate changes in China on energy performance of building envelopes. The authors unveiled the thermal performance which has a strong dependence on regional variations in the climate and that a general solution to it does not work. This research advocates the existing envelope design of structures especially insulation and thermo mass, adapted according to the climatic regions to help in maximizing energy consumption in a project [3]. Sadrzadehrafiei et al. (2011) have examined the energy use behavior in Malaysian office buildings and found out the existence of serious potential to save energy by the means of envelope redesign. They showed that retrofitting envelopes with passive cooling measures can induce a huge saving of indoor cooling in tropical office buildings enhancing the role of selecting materials and building modeling [4].

Magrini et al. (2017) suggested an assessment model to find the appropriate integrated solutions of enhancing the envelope energy performance to prevent moisture-related issues. They combine the thermal and hygroscopic models and stress that moisture behaviour should not be neglected as it may contribute to material degradation as well as poor thermal performance and that therefore a comprehensive modelling should be used in the design of envelopes [5]. Moran et al. (2017) determined life cycle costs, energy-related costs, and global warming potentials of superinsulation compared to renewable energy planning on a comparative basis in nearly zero-energy houses. They uncovered that the long-term effect on superinsulation is more uniform in temperate climates. The paper directs the process of preprioritizing enhancement of envelopes before renewable technologies are embraced [6].

Alfarawi et al. (2022) evaluated thermal performance of different external wall systems of energy efficient buildings. The simulation tools aided in the benchmarking of wall assemblies and allowed to draw attention to the peculiarities of energy efficiency in terms of a certain assembly, insulation and cladding materials involved. Their study sustains the necessity of multi-cascaded design which could be optimized through thermal modeling [7]. Alayed et al. (2021) examined the housing envelopes in Saudi Arabia with new energy codes and concentrated on their thermal compliance and practical applicability. The findings show that there is a serious performance delta in conventional designs, and that implies suggesting code friendly inventions in term of insulation and thermal inertia. Their model of compliance is applicable to the other hot and arid areas such as Uzbekistan [8].

Tabunshchikov and Borodach (2001) introduced models that were mathematical in nature to optimize the thermic performances of buildings. This structure was used to design simulation-based thermal analysis of building envelopes to establish the foundation of the computational tools, which incorporate a real-time climate parameter, building geometry, and material properties [9]. Fedosov and Ibragimov (2006) studied unsteady heat and mass transfer in multilayer enclosing constructions, and established that external conditions (time-dependent), greatly influence the performance of the envelopes. Their results highlighted the need of dynamical simulation tools and formed a part of approaches applied in the thermal optimization of the multi-layer wall assembly [10].

The knowledge of Barabanshchikov (2005) can be characterized as fundamental knowledge of materials and structural characteristics of enclosing elements. The categorization of materials and their thermophysical behavior under different loads and conditions, as rated by him, still remains an important guide to engineers that intend to design high-performance envelopes [11]. Chikhi et al. (2013) carried out experiments on low-cost biocomposites as thermal insulation. Their emphasis was on the ability of these materials to substitute the traditional ones (in low income or resources constrained locations) without loss of thermal resistance. Their efforts advocate on the ecologically and economically viable materials on the external walls [12].

The study of Shchipacheva (2008) focused on real environmental interaction between thermal-physical states of the building envelopes. Her work pointed towards the direction of monitoring and diagnostic where the performance of envelopes cannot be assumed to be constant, and thus needs to be re-evaluated during operating conditions, which is core to the validation of simulated models [13]. Shchipacheva and Takhirov (2008) submitted a mathematical model that is applied to evaluate the thermal regime of the building and elements surrounding it. Their mechanization of thermal dynamics made it more possible to predict the temperature distribution in the envelope layers, and this is helpful in optimization of the insulation plans and structural construction [14].

Principles of structural and mechanical property conformation in asphalt concrete The principles of asphalt concrete structural and mechanical property conformation were received by Rybyev (1957), who coined the term law of alignment. The theoretical basis of porosity and strength optimization of thermal insulation materials (cellular concrete, etc.) is his hypothesis that the best material structure provides the best performance [15]. Merkin et al. (1963) have made theories in relation to the macrostructural making of cellular concrete. Their effort formed the basis of mathematical modeling methods of balancing porosity and compressive strength, and in this way directly formed the algorithms and parameters of current cellular concrete optimization research [16]. Indispensible theory of the heat and moisture transfer in the capillary-porous medium has been placed forward by Reshetin and Orlov (1998) and is extremely relevant when studying the influence of microstructure on thermophysical performance. Their differential equations are the basis of numerical simulations used in the study of the envelope materials, and vapor transport modeling in particular [19].

Adilkhodjaev et al. (2019) designed a mathematical model of cellular concrete macrostructure simulation. They would integrate some of the relationships applicable to porosity, density, and thermal conductivity into predictive software, making it possible to modify the structural parameters to achieve desired thermal characteristic [18]. Shchipacheva and Shaumarov (2020) carried out such an extension to requirements match strength and thermal conductivity requirements, providing realistic simulation data that can be used to design materials. In their work, by microstructure of the pore geometry and location, they show that mechanical robustness and thermal efficiency are directly linked and hence create a loop between the computer and the material fabricated in real life [19].

# MATERIALS AND METHODS

Let us consider the main theoretical premises for the opinion expressed.

As we have established earlier, variations in the thermal characteristics of enclosing structures depend on external climatic factors [13]. Optimum values of thermal performance indicators of enclosures (thickness, weight, multi-layer structure, etc.) were determined from the conditions of maximum heat transfer resistance and attenuation of external thermal effects under given climatic parameters. A mathematical model of the building's thermal regime was constructed for non-stationary and stationary regimes with a number of assumptions concerning the adopted homogeneity of temperature fields of internal enclosing structures, failure to take into account heat emissions due to phase transformations of moisture in the volume of individual layers of external walls, etc. Based on the above, a mathematical model of the non-stationary thermal regime of the building was presented in the form of a system of equations (1) [14].

 (1)

where

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*A*amplitude of temperature fluctuations of the enclosing surface,  - amplitude of temperature fluctuations in the enclosure layer; t – time, *Yв* heat absorption coefficient of the inner surface, *w*cyclic frequency of temperature fluctuations in the thickness of the enclosure, *w* – cyclic frequency of the temperature of the inner surface of the enclosure, phase difference (lag) between temperature fluctuations in the thickness of the enclosure and fluctuations of the driving force, ξ coefficient of attenuation of temperature fluctuations in the thickness of the enclosure,  spatial period of damped oscillations, *k*=0.013 – empirically obtained coefficient,**o – initial phase of temperature fluctuations in the thickness of the enclosure, *ϕ* phase of temperature fluctuations in the thickness of the enclosure, *Р* – fundamental period of oscillation.

In order to determine the parameters of thermal regime of the premises and the subsequent minimization of the thermal parameter of the materials of the enclosing constructions the computer program-calculation of the thermal characteristics of the building-was made, and it was applied.

Conversely, it is known using literary sources that the characteristics of building materials and, accordingly, thermal insulation materials are also defined by the condition of the structure of the substance of which they consist as well as macrostructure which is formed due to technological activities. Using the law of alignment (as I. A. Rybyev [15] says), the ideal structure appears when there is a combination of most preferable values of construction and operational quality of the conglomerate. According to the law of alignment, optimal structures of materials are found in the structures characterized by maximum values of porosity and uniform volume distribution of pores and filler. Utilizing binders, however, to acquire thermal insulation (or both structural and thermal insulation) material requires an additional criterion - that of having a continuous layer of binder with a minimal water-cement ratio.

Therefore, the distinctive property of the desired structural and heat-insulative materials on the basis of cement binder is in the porous structure that is expressed via the pore ways and which can be of different types, i.e., cellular, capillary and gel. Thus, a quasi-homogeneous medium, as an aggregate of many filled particles, and its complete physical features must be taken as the principal objects in the work of studying the properties of these materials.

In theory any collection of particles can be represented by a matrix whose elements represent the individual properties of each of the particles, including the parameters of the physical state of each of the particles. These factors of the material macrostructural parameters define the nature of the relationship the macrostructure bears with its strength and thermal parameters, which characterizes the such a matrix.

G. I. Loginov and A. P. Filin [16] offered the first theoretical explanation to the connection between the macrostructure of a material (the example of the cellular concrete is taken) and its strength. Referring to the based mathematical models of filling a unit of volume with the bodies in a form of a sphere, the researchers reached relatively rigid regularities, defining the ideal structure of the material. Nevertheless, since the strength and thermal properties of the material are related in an opposite way, the of the macrostructure in the aim of achieving increased strength and thermal properties at the same time becomes highly intricate. It seems that the answer to the optimization problem ought to be minimisation of the discovery of some golden middle. Here, the distribution density that is being sought is clearly polymodal.

The attempt to solve this problem relying on the experiment by using the method of the trial and error will involve an extremely high cost. Additionally, even an experiment carried out on the basis of some technological approach will not provide a positive value of the average density values within an area with a sufficiently broad range.

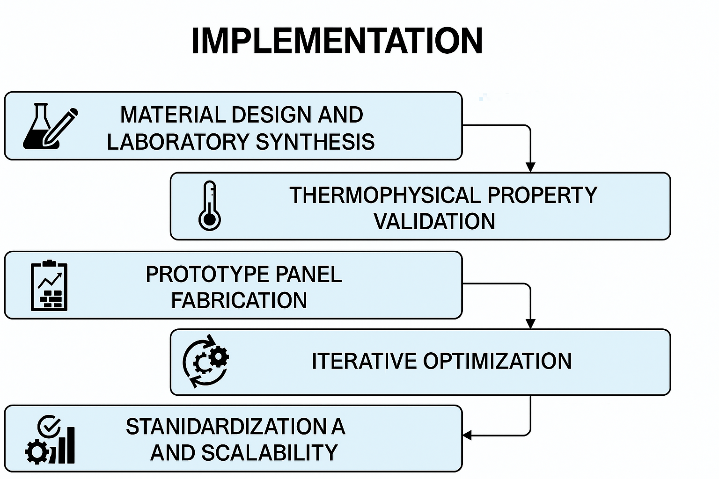
The fairest in these intentions is to implement an approach founded on the mathematical modeling because basing on a constructed physical and mathematical model, being tested and realized in the form of a software product through numerical calculations, it becomes possible to receive the needed optimal parameters of the material, which was fulfilled in the studies held. Here, the primary body of the given approach is mathematical modelization, structural optimization conceptions, and simulations.

The ability to correlate thermophysical parameters and macrostructure properties of cellular concrete allows precisely predicting and correcting the properties of the material. Having dedicated software tools, not only the simulation process is simplified, but it also becomes easier to create thermally efficient and structurally stable building materials adequate to a particular climatic regime. Such an approach has given a scientific background to rational material design and a scalable approach to improving building envelope energy performance in practical situations.

**IMPLEMENTATION**

In a bid to translate theoretical and simulation results into effective engineering results a step-by-step implementation approach has been tantamount so as to help in the development and implementation of energy efficient cellular concrete to be used in external envelope constructs as shown in Fig 1

1. **Material Design and Laboratory Synthesis** Following the simulated macrostructural schemes, the cellular concrete samples are prepared under the controlled laboratory conditions. Such parameters as size of the pore (pore size distribution), thickness of the wall between them (interpore wall thickness), total porosity is customized via the advanced pseudomorphing and curing methods. The adjustment made on the water-to-cement ratio and the additives is reflected by the desired model of the thermal conductivity and strength.



**FIGURE 1.** Implementation flowchart for developing energy-efficient cellular concrete envelope structures

1. **Thermophysical Property Validation** Thermal conductivity and correlation with heat absorption coefficient and compressive strength of the samples synthesized are stringently tested in accordance with standard ASTM and ISO tests. The simulation results are subsequently cross checked with these empirical results to ensure that the developed software tool is accurate in its predictive output.
2. **Prototype Panel Fabrication** Prototype wall panels are made (in terms of different thicknesses and construction of the layers-single-, double-, and triple-layered) based on CCGR-validated formulations. These panels also include material grading as suggested with high thermal inertia layers on areas that will be high damping areas as determined by the models of thermal oscillations.
3. **Field Performance Testing** The prototype panels are deployed in the modules under test in a real climatic environment, eg, hot-dry areas in Uzbekistan. Hygrometers, temperature sensors and heat flux meters are installed as a way to monitor the internal comfort parameters during the long term. This gives feedback on the envelope performances in situ situations.
4. **Iterative Optimization** Field tests and the trial of parameters are re-entered into simulation again and again to refine the macrostructural parameters. Indeed, optimization algorithms utilizing AI (as stated in the Future Scope) will be deployed to further improve the convergence of performance objectives with material structure.
5. **Standardization and Scalability** When benchmarks of performance are attained regularly, there is formulation of standardized guidelines and material recipe of mass production. These are custodial mixing protocols, curing procedures, and structural layout designs to be adopted in commercial construction. Polling is done with the regulatory agencies to deliberate on ways to match these materials to current or new building energy codes.
6. **Integration with Smart Systems** To enhance the usability of the envelope, the concrete modules are set up to be prepared to hybrid integration with intelligent materials, among them PCM (Phase Change Materials) or thermochromic layers, they are able to react dynamically to both the diurnal and seasonal thermal loads.

**RESULTS AND DISCUSSIONS**

To determine the optimal ratios of thermal characteristics of enclosing structures in order to ensure a comfortable microclimate, temperature fluctuations in the enclosure thickness were calculated using formula (1) taking into account the daily course of the outside air temperature. The calculation results are shown in Fig. 2. In this case, temperature fluctuations in the enclosure thickness during the day are presented in the time (Fig. 2a) and spatial domains with a main period of 0.3 m, corresponding to the enclosure thickness (Fig. 2b). When calculating Aδ, variants with different initial (t=0) amplitude values equal to the temperature of the inner surface of the enclosure at time t=0 and heat absorption coefficients of a single-layer enclosure from 6.16 to 29.08 W/ (m2 deg) corresponding to almost the entire range of materials for their manufacture were adopted.

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**FIGURE 2.** Oscillations (single-layer version) in the time domain (а) and spatial (b) temperature frequencies in the thickness of the enclosure

Analysis of the data presented in Fig. 1 shows that the small slope of the temperature fluctuation graph in the region of time frequencies and the convergence of the amplitude values at the boundary of the outer surface are explained by the influence of the daily variation of the outside air temperature and the tendency for the internal temperature of the enclosure to equalize with the outside air temperature as one approaches the outer part of the enclosure.

Given the initial data and characteristics of the material, the graph shown in Fig. 1b makes it easy to determine the layer of sharp temperature fluctuations.

Thus, based on the obtained law of temperature distribution in the thickness of the enclosing structure, it is possible to solve the inverse problem: for the required thickness of the enclosing structure, determine the thermophysical parameters of the material, or more precisely, the ratio of the thermal conductivity coefficient ** to the heat absorption coefficient of the material s. For this purpose, the areas of the corresponding operating frequencies are determined for the given basic time P and spatial P (fencing thickness) periods and a graph of the temperature distribution in the thickness of the fencing in the area of spatial frequencies is constructed using formula (1). The wavelength L and the area of sharp fluctuations d are determined using the graph and, finally, the sought ratio is determined using the formula *d* =*s*. Having a database of thermophysical characteristics, using a simple program, it is easy to find variants of thermophysical parameters that meet the given initial conditions using this ratio.

Since temperature fluctuations are intensively damped within the thickness d of the structure, it is effective to place layers with the highest thermal inertia values within the boundaries of this thickness. Considering that in dry hot climates it is necessary to provide thermal protection both in winter and in summer, and therefore consider the heat flow in two opposite directions, then in the conditions of Uzbekistan it is advisable to place such layers on both sides of the enclosing structure, which confirms the advisability of using a three-layer enclosure. Hence the need for special research on the development of building materials for the outer layers of enclosing structures that provide the required thermal inertia for dry hot climates.

The most widely used material for external enclosing structures is cellular concrete. In this regard, further studies on the structure of the material and the method of influencing it were carried out for cellular concrete.

When modeling the optimal macrostructure of cellular concrete, the relative position of the pores (type of laying), their size, and the size of the interpore partitions providing the required coefficient of thermal conductivity of the material were taken into account. To describe the process of heat and moisture transfer in porous media, a system of differential equations obtained by A. V. Lykov and described in the works of O. L. Reshetin and S. Yu. Orlov [17] was used. As a result of a number of mathematical transformations, including the introduction of the porosity parameter P as a function of moisture and steam, and also by introducing the air parameter through its concentration Wa, specific heat capacity Ca, transfer coefficient Da, thermal diffusion coefficient DTa and density ra, we obtained the final system of differential equations describing the heat transfer process at a given coefficient of thermal conductivity, depending on the macrostructure of cellular concrete, characterized by the porosity parameter P [18]:

 (2)

 (3)

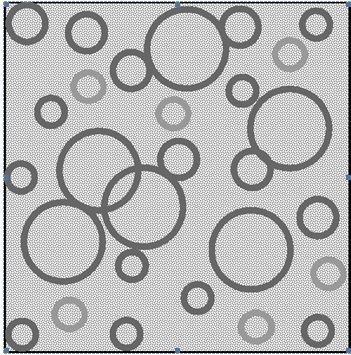
where ; ; *W=Wa* .

here: *C*∑ = *C*s + *Wl Cl* ; *Wl* , *Cl*,– respectively, the concentration and specific heat capacity of the liquid;   
*T*,  - respectively, the temperature and thermal conductivity of a wet body; *Wa -* air concentration, *C*a - specific heat capacity of air, *D*a - air transfer coefficient, *DTa* - thermal diffusion coefficient of air, *a* - air density, *v* – density of water;   operator Nabla.

Based on the obtained mathematical dependencies (2) and (3) and using modern computer modeling methods, a calculation software package “Modeling the macrostructure of cellular concrete with predetermined thermal properties” was developed, allowing one to obtain such characteristics of the material structure as the pore size, the thickness of the interpore partitions, porosity and average density corresponding to the required thermal conductivity coefficient. Using this package, numerical experiments were performed [19]. In this case, the pore size was set in the range from 0.2 to 2 mm with a step of 0.2 mm, which allowed considering the porosity of cellular concrete in the range from 10 to 90%. The variation in the percentage of porosity was carried out by changing the distance between pores of a fixed radius, representing nodes of a hexagonal and cubic lattice. The results of modeling the macrostructure of cellular concrete for a thermal conductivity coefficient specified in the range of values from 0.085 to   
0.334 W/m oC with a matrix density of 2000 kg/m3 and a “random” type of laying with a three-modal distribution density are given in Table 1, and Fig. 3 shows a model image of the macrostructure of cellular concrete corresponding to a thermal conductivity coefficient of 0.085 W/m oC.

**TABLE 1:** Results of modeling the macrostructure of cellular concrete

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| Thermal conductivity coefficient, W/m oC | Pore size, mm | Thickness of partitions, mm | Average density, kg/m3 | Strength, MPa | Porosity, % |
| 0,085 | r1=2,426  r2=1,618  r3=3,466 | 2,208 | 300 | 1 | 85 |
| 0,095 | r1=2,473  r2=1,649  r3=3,534 | 2,251 | 400 | 2 | 81 |
| 0,123 | r1=2,403  r2=1,602  r3=3,434 | 2,187 | 500 | 3 | 74 |
| 0,143 | r1=2,220  r2=1,480  r3=3,171 | 2,020 | 600 | 4 | 71 |
| 0,174 | r1=1,808  r2=1,205  r3=2,582 | 2,020 | 700 | 5 | 66 |
| 0,199 | r1=1,429  r2=0,952  r3=2,041 | 1,300 | 800 | 6 | 60 |
| 0,233 | r1=0,931  r2=0,621  r3=1,330 | 0,847 | 900 | 8 | 55 |
| 0,262 | r1=0,575  r2=0,384  r3=0,822 | 0,524 | 1000 | 10 | 52 |
| 0,314 | r1=0,161  r2=0,107  r3=0,230 | 0,147 | 1100 | 12 | 45 |
| 0,334 | r1=0,073  r2=0,049  r3=0,105 | 0,067 | 1200 | 16 | 40 |



**FIGURE 3.** Image of a model sample of the macrostructure of cellular concrete corresponding to a thermal conductivity coefficient of 0.085 W/m oC

The analysis of the influence of different pore sizes and their packing on the density and strength of cellular concrete allowed us to make a conclusion that is extremely important for practical application, namely, the properties of cellular concrete can be changed by varying the parameters that determine the structure of cellular concrete - the location (packing) and size of the pores.

Thus, the most promising method for increasing the heat-protective and strength properties of cellular concrete is to influence their pore structure, which is achieved, first of all, by special technological methods.

**CONCLUSION**

The paper introduced a pragmatic method of coming out with the best materials that can be used in the design of the external envelope of the energy efficient buildings with special emphasis at cellular concrete. Using elaborate theoretical and computational framework, it has been determined that it is possible to optimize the thermophysical behavior of building envelopes i.e., speed of thermal conductivity and coefficient of heat absorption based on their thickness as to maintain a stable and comfortable interior environment. The variations of temperature along layers of the wall were also subsequently analyzed predictively using mathematical models and simulation tools and subsequently providing best possible material arrangements. Additionally, the study emphasized the role of material macrostructure (specifically pore size, porosity and distribution) in the definition of cellular concrete thermal conductivity and strength. Using high order computer aided modeling software, a simulation package was created to effectively design and evaluate numerous pore layouts that meet thermal and mechanical performance specifications. These methods enable the originating of cellular concrete material that is thermally efficient and is also structurally sound, through data-driven design. Notably, the piece also emphasizes that fulfilling the twin agenda of energy efficiency and material strength needs to balance the co-existence of conflicting properties through sound engineer structural designs. Pore pattern should be such that it should insulate and at the same time bear the loads. The elaborated methodology therefore forms a foundation to the reasonableness of developing one to three layers wall-construction design that can be applied in different climatic conditions especially on dry and hot climatic conditions as in the case of Uzbekistan.

**FUTURE SCOPE**

Multiscale modeling frameworks which are advanced ought to be developed to simulate the interaction of effects of heat and moisture transportation among the various layers of building envelopes. These select models are able to offer a more exact picture of the behavior in a dynamic range of surroundings circumstances in the real world. The optimization of the pore configuration in cells concrete may be done with higher efficiency using artificial intelligence, especially, through the machine learning algorithms. The AI tools will be able to work out large simulation data to propose structural designs that can optimally meet the requirements of thermal performance versus strength. Custom optimization plans could be developed to suit various climatic regions, viz. hot-arid, temperate and cold-humid by changing the material parameters viz. thermal conductivity and specific heat capacity. This will enable the generation of regionalized solutions in building to enhance energy preservation and thermal comfort. Studies could be conducted on how to incorporate use of smart materials like phase change materials (PCMs), thermochromic compounds in the external envelop designs. The materials are capable of real time adaptation to the changes that occur in the environment and thus achieve greater dynamic thermal performance of the buildings.

Development of high-fidelity simulation platforms as a means of virtually testing envelope structures under different operating conditions should also be carried out. This will be a major step toward cutting down the cost of physical prototyping and speeding the process of innovation in the development of construction materials. It requires a standardized LCA framework to scrutinize the effectiveness of environmental fighters of new thermal-insulation materials. This type of framework would compare the various materials on the grounds of energy conserved, carbon emissions and reusability to ensure sustainable material decisions are made in terms of construction. It needs to perform large-scale laboratory and field tests to prove the theoretical and simulated findings. The effectiveness of the proposed materials will be proven in the form of empirical evidence that will provide feasibility to the materials in the real-world scenario. More research is also necessary in order to study the impacts of various pore shapes and distributions on the thermal inertia of cellular concrete as well as their internal structures. This comes with knowing the most effective pore morphologies in terms of weather patterns and usage environment. Thermo-Hygrometric Indoor Comfort Analysis: In the future, another investigation should be performed on how optimized envelope material will affect the long run indoor environmental quality, especially with regards to temperature control, humidity, and air quality. It is the outcome of the current study that can contribute to the emergence of novel building codes and material certification procedures promoting the application of optimized cellular concrete in energy efficient and sustainable construction processes.

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