Aerated concrete with predetermined pore parameters for the exterior walls of energy efficient buildings

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Abstract. This article presents the results of theoretical and experimental studies on the development of aerated concrete with predetermined pore structure parameters. Investigations of the physical-mechanical and heat-engineering properties of external wall fences made of cellular concrete are given and the optimal parameters of the porosity of the material structure are established. The testing results were tested in the factory and the main properties of aerated concrete with an improved pore structure were determined.

1. Introduction
One of the urgent problems in the design of energy-efficient buildings is the development of external enclosing structures with the required strength and heat-shielding properties, as well as the efficiency and simplicity of technology. Leading research centers and higher educational institutions of the world, including Bundesverband Betonbauteile Deutschland, University of Exeter, American Concrete Institute, International Federation for Structural Concrete, International Union of Laboratories and Experts in Construction Materials, International Council for Building conduct extensive research on the development new and improvement of existing technologies of cellular concrete, methods of optimal design of their compositions and structure [1-2].

Scientific research in the field of development of effective wall structures and products from aerated concrete with high mechanical, thermal and operational performance is developing in the following priority areas: development of aerated concrete dispersed reinforced with non-metallic fibers; improvement of methods for the optimal design of the compositions of aerated concrete mixtures with various mineral and chemical additives; development of new methods of mathematical planning of experiments, allowing to ensure optimal indicators of the structure and properties of cellular concrete at the micro level; development of techniques for optimizing the structure and properties of aerated concrete at the macrolevel using methods of structural simulation; development of methodological foundations for optimal design of the composition of cellular concrete at various structural levels.

B.P. Danilov and A.A. Bagdanov [3] showed the technological possibility of manufacturing enclosing structures from aerated concrete of variable density. The thermal conductivity of the compacted layer of aerated concrete by 7-10% made it possible to protect the walls from the side of its inner surface...
from evaporating operational moisture from the room. In the studies of L.A. Suleimanova, N.A. Sapelin, A.N. Khakhardin [4-5] showed that the strength of aerated concrete is greatly influenced not only by the porosity itself, but also by its structure. To increase the density of the solid phase A.P. Merkin, A.M. Filin [6] propose to select the optimal granulometric composition of solid components that make up aerated concrete.

The works of H. Weber are devoted to scientific research on the development of technology for obtaining effective aerated concrete, H. Hullmann, M. Schlaich, A. Lagoaz, P. Szymanski, P. Walczak, N.I. Levin [7-10] and others. In these studies, the mechanisms for obtaining enclosing structures from aerated concrete with various densities and strengths through the use of mineral and organic additives, superplasticizers were disclosed, the issues of optimizing the structure of heat-insulating and structural-heat-insulating cellular concrete were considered. At the same time, the dependences of the strength and heat-shielding properties of cellular concrete on their pore structure have not been fully studied, which requires special theoretical and experimental studies.

2. Methods

In the course of experimental studies, both generally accepted methods of laboratory testing of materials, set forth in the relevant standards, and non-standard methods developed by specialists from leading foreign research institutes were used. The pore structure of aerated concrete blocks was studied using a Thermo Scientific Pascal 240 EVO mercury porosimeter (Fig. 1).

![Figure 1. Thermo Scientific Pascal 240 EVO Mercury Porosimeter](image)

After the analysis is completed, the computer automatically generates the following diagrams: cumulative mercury penetration; generated drawing of pore volume versus pressure; total pore volume.

Tests to determine the compressive strength during splitting of aerated concrete samples were carried out in accordance with GOST 10180-2012 “Concrete. Methods for determining the strength of control samples "using a hydraulic press" CD-2000 ".

To determine the optimal pore structure of aerated concrete with specified heat-shielding properties, the authors used the software package “Program for modeling the macrostructure of cellular concrete with predetermined thermal properties” [11-12].

To determine the required values of the thermal conductivity coefficients of the material of the walls of energy-efficient civil buildings for various climatic conditions of the Republic of Uzbekistan, a standard technique was used, implemented in the computer program "Base". The results of experimental studies were processed by methods of mathematical statistics.
3. Investigation of the physical, mechanical and thermal properties of external wall fences made of cellular concrete and the establishment of criterion parameters for the porosity of the material structure

Aerated concrete blocks of grades D500 and D700 were selected for research. From the formed aerated concrete blocks, 2 series of samples of each brand with dimensions of 100x100x100 mm were made (Fig. 2).

Figure 2. Photos of the surface of aerated concrete samples grades D500 (1, 2) and D700 (3, 4)

Samples of non-autoclaved aerated concrete of factory production were studied using the developed photo-optical method and the computer program based on it "Determination of the properties of aerated concrete based on image analysis" [11-12]. The results of determining the characteristics of aerated concrete samples and calculating their fractal dimension D according to the proposed photo-optical method are presented in table. 1

| №  | Average density, kg / m³ | Compressive strength R_YB, MPa | Porosity P, % | Fractal dimension D |
|----|--------------------------|-------------------------------|--------------|---------------------|
| 1  | 540                      | 0,915                         | 70,0         | 1,627               |
| 2  | 554                      | 0,975                         | 68,8         | 1,631               |
| 3  | 650                      | 1,57                          | 63,9         | 1,648               |
| 4  | 710                      | 1,63                          | 62,3         | 1,650               |

Then the tests of the same samples were carried out in accordance with GOST 10180-2012 “Concrete. Methods for determining the strength of control samples. ” The results are presented in table. 2.

| №  | Average density, kg / m³ | Humidity, % | Compressive strength, MPa | Matrix density, kg / m³ | Porosity, % |
|----|--------------------------|------------|---------------------------|-------------------------|-------------|
| 1  | 546                      | 5,4        | 0,821                     | 2000                    | 69,8        |
| 2  | 567                      | 5,8        | 0,897                     | 2000                    | 69,4        |
| 3  | 661                      | 14,2       | 1,486                     | 2200                    | 65,2        |
| 4  | 689                      | 14,7       | 1,516                     | 2200                    | 64,8        |

Comparison of indicators of average density, compressive strength and porosity of non-autoclaved aerated concrete samples, determined by the proposed photo-optical and standard methods, showed
that the difference in average density is (1-3)%; compressive strength - (7.5 - 11.4)%; by porosity - (2 - 3.8%). The competence of using the developed photo-optical method for assessing the quality of non-autoclave aerated concrete has also been confirmed on prefabricated products [13]. At the same time, the obtained results of strength tests showed that the actual compressive strength of D500 non-autoclaved aerated concrete is (18-25)% lower than stated in the passport, and D700 brands are (5-7)% lower.

Based on the initial formulation of the research problem, further efforts were aimed at solving the problem of improving the pore structure of cellular concrete. For this, taking into account the close relationship between thermal conductivity and strength, with the help of the developed computer program "Modeling the macrostructure of aerated concrete with predetermined thermal properties", studies were carried out to model the optimal structure to ensure the necessary complex of properties of the developed composite.

In fig. 3 shows a modeled (within the developed software package) image of aerated concrete with ideal hexagonal and cubic packings with superimposed grid images with squares, which were used to determine the fractal dimension of model samples in accordance with the «Box Counting» algorithm.

![Figure 3](image)

**Figure 3.** Model representation of aerated concrete with an ideal maximum dense packing of hexagonal (a) and cubic (b) types with a square grid for the implementation of the "Box Counting" algorithm for calculating fractal dimensions

Then, using the developed software package, the characteristics of the pore space were calculated for aerated concrete grades D500 and D700 [11-13]. The calculation results allow us to determine the optimal parameters of the pore space in order to increase both the strength and heat-shielding properties of the material are presented in Table 3.

**Table 3.** Results of modeling the macrostructure of aerated concrete

| Coefficient thermal conductivity, W/m°C | Average matrix density, kg/m³ | The size since then, mm | Thickness partition, mm | Average density of aerated concrete, kg/m³ | Compressive strength, MPa | Porosity, % |
|----------------------------------------|-----------------------------|-------------------------|-------------------------|-------------------------------------------|----------------------------|-------------|
| 0.123                                  | 2000                        |                         |                         | 2.249                                     | 500                        | 1.8         | 75          |
|                                        |                             | r₁=2.571                |                         |                                           |                            |             |
|                                        |                             | r₂=1.748                |                         |                                           |                            |             |
|                                        |                             | r₃=3.631                |                         |                                           |                            |             |
| 0.174                                  | 2200                        |                         |                         | 1.631                                     | 700                        | 3.6         | 66          |
|                                        |                             | r₁=1.793                |                         |                                           |                            |             |
|                                        |                             | r₂=1.195                |                         |                                           |                            |             |
|                                        |                             | r₃=2.561                |                         |                                           |                            |             |

Analysis of the table. 3 shows that in the case of achieving the optimal pore structure of concrete, a significant increase in strength and heat-shielding properties can be provided. At the same time, non-autoclaved aerated concrete D700 can, both in terms of strength and thermal conductivity, be used for
external walls 400 mm thick in buildings with III level of thermal protection located on the territory of Uzbekistan.

To obtain a real practical result for optimizing the pore structure of aerated concrete, based on a number of theoretical assumptions and analysis of literature sources, appropriate technological methods were developed that are successfully used in production conditions.

4. Testing the results of research in the factory and determining the main properties of aerated concrete with an improved pore structure

The developed technology for the manufacture of non-autoclaved aerated concrete was tested in the conditions of the production of wall blocks on the technological line of the plant. For this, the compositions D500 and D700 were mixed according to the developed technology. The samples were photographed for their use in assessing the properties of the developed photo-optical method (Fig. 4) [10-13].

![Figure 4. Photos of surfaces of non-autoclaved aerated concrete samples D500 (a) and D700 (b)](image)

Samples from each series were investigated using the developed photo-optical method, the results obtained are presented in table. 4.

**Table 4. Results of determining the characteristics of aerated concrete samples by the photo-optical method**

| №  | Average density, kg / m³ | Compressive strength $R_{VII}$, MPa | Porosity P, % |
|----|--------------------------|------------------------------------|--------------|
| 1  | 515                      | 1.08                               | 72.4         |
| 2  | 532                      | 1.19                               | 71.5         |
| 3  | 509                      | 0.98                               | 73.2         |
| 4  | 698                      | 1.84                               | 66.7         |
| 5  | 720                      | 1.96                               | 64.9         |
| 6  | 706                      | 1.91                               | 65.3         |

The same samples were also tested to determine the average density and strength by standard methods. The results are presented in table. 5.

**Table 5. Results of determining the characteristics of aerated concrete samples according to GOST 10180-2012**

| №  | Average density, kg / m³ | Humidity, % | Compressive strength, MPa |
|----|--------------------------|-------------|---------------------------|
| 1  | 509                      | 5.3         | 1.00                      |
| 2  | 524                      | 5.8         | 1.12                      |
| 3  | 501                      | 5.1         | 0.95                      |
| 4  | 690                      | 14.2        | 1.72                      |
The pore structure of the samples was investigated using a mercury porosimeter. For this study, samples were selected that showed the best strength indicators - No. 2 and No. 5. The results of experimental studies are shown in Figs. 5 and 6. As can be seen from the graphs, D700 aerated concrete is characterized by the presence of a large number of evenly distributed small pores and an insignificant content of large pores 0.5-2 mm in size, while D500 aerated concrete has a pronounced positive asymmetry: a significant difference between the average porosity, there is a large number of large pores larger than 1.5-3.5 mm. According to the results of studies on a porosimeter, the total porosity of aerated concrete samples D500 was 72.4%, and D700 - 67.3%.

![Figure 5. Histogram of pore size distribution for aerated concrete D500 (sample 2).](image1)

![Figure 6. Histogram of pore size distribution for aerated concrete D700 (sample No. 5).](image2)

5. Discussion

Comparison of the results of the study of the obtained aerated concrete by the proposed photo-optical method and standard techniques confirmed the possibility of using the photo-optical method and the software complex “Determination of the properties of aerated concrete based on image analysis” developed on its basis to assess the quality of non-autoclave aerated concrete. Comparison of indicators of average density, compressive strength and porosity of the samples showed that the discrepancy in average density is (1-3)%; compressive strength - (7.5 - 11.4)%; in porosity - (2 - 3.8)%.

Table 6. Indicators of properties of non-autoclave-hardened cellular concrete obtained under different conditions and using different technologies

| Composition, manufacturing conditions, technology | Aerated concrete grade |
|-------------------------------------------------|------------------------|
|                                                  | D500      | D700      |
| **Characteristics of aerated concrete**          |           |           |
| Compressive strength, MPa                       |           |           |
| Porosity, %                                     |           |           |
| Compressive strength, MPa                       | 0.86      | 1.50      |
| Porosity, %                                     | 71.1      | 65.0      |
| Compressive strength, MPa                       | 1.20      | 1.90      |
| Porosity, %                                     | 73.5      | 68.2      |
| Factory composition, in factory conditions, according to factory technology | 0.86 | 1.50 |
| The proposed composition, laboratory conditions, according to the proposed | 1.20 | 1.90 |
The proposed composition, factory conditions, according to the proposed technology

|                | 1.06 | 72.4 | 1.80 | 67.3 |

The analysis of the results of the performed studies of the properties of cellular concrete in laboratory and factory conditions showed that a directed effect on the structure of the pore space of a material can significantly improve its strength and heat-shielding properties. At the same time, in the factory conditions, cellular concretes made according to the proposed recipe and technology have strength indicators higher by (20 -23)%, and porosity by (3.2 -3.6)%. And although we were unable to achieve results in strength and thermal conductivity close to the calculated ones with an ideal arrangement of pores and their sizes, which were determined using the developed program "Modeling the macrostructure of cellular concrete with predetermined thermal properties", which, in principle, was quite predictable, but, at the same time, it was possible to prove that the developed method of obtaining aerated concrete with the desired properties is correct. And obtaining higher quality indicators of aerated concrete is only a process of further improvement of technological methods for optimizing the pore structure of the material.

6. Conclusion
1. The results of field experiments proved the competence of using the developed photo-optical method and the software complex "Determination of the properties of aerated concrete based on image analysis" developed on its basis for assessing the quality of non-autoclaved aerated concrete. Comparison of indicators of average density, compressive strength and porosity of non-autoclaved aerated concrete samples, determined by the proposed photo-optical and standard methods, showed that the difference in average density is (1-3)%; compressive strength - (7.5 - 11.4)%; by porosity - (2 - 3.8%).
2. An improved technology for producing aerated concrete of non-autoclave hardening with predetermined properties for an enterprise for the production of aerated concrete products is proposed. The developed compositions of aerated concrete D500 and D700, as well as the materials manufactured according to the proposed technology, made it possible to increase the strength of aerated concrete by 20-23%, porosity - by 3.2-3.6%.
3. Experimental studies in laboratory and factory conditions have proven the effectiveness of the developed technique for improving the pore structure of cellular concrete for external walls of buildings using the developed software package "Modeling the macrostructure of cellular concrete that meets a given thermal conductivity" for the purposeful development of technological methods for producing concrete with predetermined properties.

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