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Review article
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Enhancing performance properties and expanding the application of cellular concrete through the incorporation of industrial by-products

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ABSTRACT
Introduction. The article addresses the issues of reducing energy intensity in the production of non-autoclaved cellular concrete and enhancement its performance properties by developing new modified cements and utilizing industrial by-products and waste from energy and mining complexes. One promising approach for creating high-tech products and achieving highly functional cement systems – imparting special properties while reducing binder consumption – involves the use of modifying additives in cement compositions. These additives densify the microstructure and influence kinetics processes. In this case, industrial by-products and waste from energy and mining complexes can serve as such additives. By using industrial by-products and waste, it is possible to significantly alter the parameters of the raw material base of the Russian Federation, reduce the amount of natural traditional raw materials used, and mitigate environmental concerns. **Methods and Materials.** The study examined the influence of the type (diopside, diabase, wollastonite, and limestone), quantity, and dispersion (particle size distribution) of modifying additives. Quartz sand and acid fly ash from the Thermal Power Plant (TPP) were used as the silica components. **Results.** At the same time, a strength increase of up to 18% was observed, with the most significant enhancement achieved using diopside. When mineral additives were incorporated, the average density of aerated concrete decreases by up to 5%, while that of foam concrete decreased up to 20%. Additionally, the thermal conductivity of aerated concrete decreased from 0.14 to 0.12 W/(m•°C), and that of foam concrete decreased to 0.069–0.070 W/(m•°C). Frost resistance of modified aerated concrete increased from F50 to F75, and that of foam concrete increased from F20 to F25. The index of air noise reduction by single-layer aerated concrete enclosing structures reached 69.13 dB, exceeding the requirements set by regulatory standards. **Discussion.** The results of the studies indicate that the improved performance properties of non-autoclaved cellular concrete is associated with the changes in pore structure and the phase composition of new hydrated formations. **Conclusion.** The obtained non-autoclaved cellular concrete is structural thermal-insulating and thermal-insulating, which can be used as thermal-insulating and wall material for non-load-bearing walls and partitions or as the main wall material for low-rise construction. Reducing the time required to achieve strength significantly shortens construction timelines for projects using non-autoclaved cellular concrete, thereby lowering labor intensity and overall construction costs as a whole.

KEYWORDS: cellular concrete, modifying additive, diopside, wollastonite, limestone, diabase, energy indicator, chemical affinity, hydrate formation, performance properties, reduction of construction time and labor intensity

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CONSTRUCTION MATERIALS SCIENCE

Повышение эксплуатационных характеристик и возможностей широкого использования в строительстве ячеистых бетонов с введением техногенных продуктов

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АННОТАЦИЯ

Введение. В статье затрагиваются вопросы по уменьшению количества энергопотребления изготовления ячеистых бетонов и улучшению их эксплуатационных свойств. Данные задачи возможно решить путем применения новых модифицированных цементов отходами энергетического и горнодобывающего комплексов и использования техногенных продуктов. Применение в составе цементных композиций модифицирующих добавок, оказывающих влияние на процессы твердения и уплотняющих их микроструктуру, является инновационной технологией создания высокотехнологичной продукции и производства эффективных, обладающих улучшенными эксплуатационными свойствами, композитов на основе портландцемента. За счет использования промышленных отходов и продуктов техногенного происхождения возможно кардинально изменить параметры сырьевой базы Российской Федерации и сократить количество используемого природного традиционного сырья и снизить экологическую напряженность. **Методы и материалы.** В работе исследовалось влияние оксидного состава минеральных добавок (диопсида, диабаза, волластонита и известняка), добавляемого количества и диаметра частиц модифицирующих добавок на прочностные показатели цементной матрицы и эксплуатационные свойства модифицированных газо- и пенобетонов неавтоклавного твердения. В качестве кремнеземистого компонента использовались кварцевый песок и кислая зола-унос ТЭЦ. **Результаты.** Отмечено, что наибольшее увеличение прочности (до 18%) наблюдается при введении диопсида. При модифицировании ячеистого бетона минеральными добавками снижается средняя плотность газобетона до 5%, пенобетона – до 20% и теплопроводность у газобетона с 0,14 до 0,12 Вт/(м•°С), у пенобетона – до 0,069–0,070 Вт/(м•°С). Морозостойкость модифицированного газобетона увеличивается с F50 до F75, пенобетона с F20 до F25. Индекс изоляции воздушного шума однослойными ограждающими конструкциями из газобетона составляет 69,13 дБ, что значительно больше требуемых нормативным документом величин. **Обсуждение.** Проведенные исследования позволяют констатировать, что улучшение эксплуатационных характеристик ячеистых бетонов неавтоклавного твердения связано с изменением их поровой структуры и фазового состава гидратных новообразований. **Заключение.** Полученный ячеистый бетон неавтоклавного твердения является теплоизоляционным и конструкционно-теплоизоляционным. Его целесообразно применять как стеновой материал для ненесущих стен и перегородок или в качестве основного стенового материала для малоэтажного строительства. При этом снижается трудоёмкость и сокращаются сроки строительства.

КЛЮЧЕВЫЕ СЛОВА: неавтоклавный пено- и газобетон, минеральные добавки, диопсид, волластонит, известняк, диабаз, термодинамические характеристики, химическое сродство, гидратные новообразования, эксплуатационные характеристики, теплопроводность, сокращение сроков строительства и трудоёмкости

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Данная научная работа выполнена при поддержке Федерального государственного бюджетного образовательного учреждения высшего образования «Новосибирский государственный архитектурно-строительный университет (Сибстрин)» по плану НИР НГАСУ (Сибстрин), разделы: 6.1.4.48, 6.3.9.58.

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INTRODUCTION

The article is devoted to one of the most fundamental and highly relevant issues of modern construction materials science — reducing the energy capacity of production and enhancing the performance properties of cellular concrete by developing new modified cements utilizing industrial by-products and waste from the energy and mining complexes, thereby promoting their application in construction.

In Russia, the national project "Housing and Urban Environment" resulted in the construction of 577 million m^2 of housing between 2019 and 2024. Furthermore, the national project "Infrastructure for Life" aims to build an additional 663 million m^2 of housing by 2030 [1]. For both multi-story and private low-rise construction, a primary wall material is products made of aerated concrete.

The development and implementation of knowledge-intensive technology of cellular concretes based on modified cements using industrial by-products and waste, corresponds to the Strategy of Scientific and Technological Development of the Russian Federation (approved by Decree of the President of the Russian Federation No. 145 dated February 28, 2024). According to the Strategy of Scientific and Technological Development (further SSTD), specifically, Paragraph 18 of the Strategy emphasizes the timely creation of high technologies and products that serve the national interests of the Russian Federation and are necessary for significantly improving the population's quality of life. This work responds to a major challenge outlined in the Strategy: the exhaustion of opportunities for Russia economic growth based on the extensive exploitation of raw material resources (Item 15b, SSTD). According to SSTD, the key priority is (Paragraph 21a of SSTD) the transition to advanced technologies for creating high-tech products based on the use of new materials.

One of the most promising technologies for creating high-tech products and obtaining highly functional cement systems, giving them a number of special properties and saving binders, is the use of modifying additives in cement compositions that absorb their microstructure and influence the kinetics processes. In this case, industrial by-products and wastes from energy and mining complexes can serve as modifying additives [2–16].

Furthermore, regulatory documents of the Russian Federation require finding rational ways to use industrial waste and products of man-made origin in construction. The provisions of the Innovative Development Strategy of the Russian Federation for the period up to 2030 (approved by Order of the Government of the Russian Federation dated December 08, 2011 No. 2227-r (as amended on October 18, 2018)) and the Strategy for the Development of the Building Materials Industry for the period up to 2020 and the Future Perspective up to 2030 (approved by Order of the Government of the Russian Federation dated May 10, 2016 No. 868-r) imply the development of construction materials with the use of industrial waste. Thus, the utilization of industrial waste and by-products of man-made origin in the production of artificial cement composites is due to both the task of enhancing material quality and the requirement to dispose of multi-tonnage industrial waste [17–26].

The use of industrial waste and by-products of man-made origin has the potential to radically transform the parameters of Russia raw material base. Incorporating waste into the production of wall materials can reduce the consumption of traditional natural raw materials and reduce environmental pressure [27–31].

In Russia, more than 22 million tons of ash and slag waste are generated annually. The total accumulated volume is 1.5–1.8 billion tons, according to the forecast by 2030 this volume may exceed 2 billion tons. Ash dumps cover a total area of more than 28,000 hectares [29–32]. However, no more than 7–9% of these annual man-made products are used in the construction complex. The volume of waste from the mining industry in 2023 amounted to 7.6 billion tons, of which only about 40% is currently recycled and returned to the production cycle.

Utilizing these wastes can eliminate the costs associated with geological exploration, quarry construction, and operation, while also freeing significant land areas from the impact of negative anthropogenic factors. Moreover, nearly all basic construction materials can be extracted from waste, either in combination with or entirely replacing natural raw materials. This approach can reduce the complexity and duration of construction projects. The production of wall materials is characterized by high material consumption. Therefore, the use of industrial waste in wall materials becomes especially relevant [2–4, 13–16, 21, 24].

The current state of the research is characterized by accumulated knowledge on the theoretical foundations of cement composites production. It has been found that enhancing the performance of cement composites involves increasing the density of the cement matrix by reducing the number of macropores and increasing the number of micro- and nanopores. However, enhancing performance properties of cement composites requires a deeper understanding of the mechanism by which mineral additives of various dispersity and concentration influence the pore structure of the cement matrix, the kinetics of cement system hardening and their performance properties. It is necessary to establish a relationship between the phase composition, the microstructure of the cement matrix and the strength of the cement composites. This was the purpose of the work.

For the effective selection of mineral additives, the authors propose **a scientific hypothesis** consisting of the following five points:

1. Mineral additives can participate in the process of hydrate formation and influence the structure formation of the cement matrix. The interaction between mineral additive particles and the forming cement matrix occurs primarily at their contact surfaces. At the same time, the proximity of thermodynamic characteristics (such as enthalpy of compounds formation and their entropy) plays a crucial role in this process.

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2. The selection of additives should be based on the similarity of their chemical composition to that of the clinker minerals, and, therefore, the capability of these additives to act as substrates for the crystallization of new hydrate formations.

3. When selecting mineral additives, their hardness must be taken into account. If the hardness (and consequently, the elastic modulus) of the mineral additive exceeds that of hydrated cement, it will lead to a redistribution of stresses in the cement stone under the influence of external mechanical loads. Additionally, additives with higher hardness prevent the development of microcracks in the cement stone. The greatest reinforcement of the cement matrix can be achieved when the hardness (and therefore, the elastic modulus) of the mineral additives is higher than that of the cement matrix itself.

4. To increase the efficiency of using mineral additives, their dispersion must be carefully controlled. The greatest reinforcement of the cement matrix can be achieved when the intergranular voids between the additive particles and the binder are minimized.

5. Mineral additives with a fibrous structure can provide microreinforcement within the cement matrix of artificial composites.

6. The technological properties of the obtained materials will reduce labour costs in the construction of load-bearing and enclosing structures of buildings while accelerating project completion time.

METHODS AND MATERIALS

Portland cement (CEM I 32.5B grade) produced by Iskitimcement OJSC was used as the binding agent in this study. The cement had the following mineralogical composition (wt.%): C_3S – 67%, C_2S – 11%, C_3A – 6.4%, C_4AF – 12%. The specific surface area of the cement was 330 m^2/kg. The chemical composition of the cement is shown in Table 1.

Based on the first principle of the scientific hypothesis, diopside, diabase, wollastonite and limestone can be employed as modifying additives. Their specific thermodynamic properties are presented in Table 2.

Analysis of thermodynamic properties (Table 2) revealed close similarities in the enthalpy and entropy of formations between the selected additives and clinker minerals. This suggests that incorporating these additives into cement systems will result in good energetic compatibility of mineral additives with the cement matrix.

Thus, the following mineral additives were selected for modification: diopside from the Slyudyansk deposit (Irkutsk oblast), wollastonite from the Sinyukhinsk deposit (Altai Republic), limestone from the Iskitim deposit (Novosibirsk oblast). These minerals are by-products from mining and processing complexes. Diopside had the following mineralogical composition, wt.%: diopside – 76%, tremolite – 19%, spinel – 2%, and quartz – 2%. Mineralogical composition of wollastonite, wt.%: wollastonite – 87%, garnet – 2.8%, pyrite – 0.9%, calcite – 6.1%, quartz – 4.2%. True density, kg/m^3, diopside – 2778, wollastonite – 2455.

To validate the second principle of the scientific hypothesis, it is necessary to compare the chemical composition of Portland cement and mineral additives. The chemical composition of the additives is shown in Table 3.

Analysis of the oxide composition of cement (Table 1) and additives (Table 3) revealed their chemical similarity, as diopside and wollastonite primarily consist of calcium and silicon oxides (80–93%), while limestone contains (54.7%) calcium oxide.

To confirm the third principle of the scientific hypothesis, diabase was additionally selected as a mineral additive with high hardness (sourced from Gorny village, Novosibirsk region). The material composition of diabase

Table 1. Chemical composition of portland cement

Oxide name	SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	SO_3	Law of definite proportions
Amount of oxide, wt. %	20.65	64.20	5.44	6.04	1.58	0.97	1.12

Table 2. Specific thermodynamic properties of the compounds

Compounds name	Enthalpy of formation (ΔH°_{298}), kJ/g	Entropy of formation (S°_{298}), J/(g·K)
$3CaO \cdot SiO_2$ (tricalcium silicate)	–12.83	0.74
ß-$2CaO \cdot SiO_2$ (dicalcium silicate)	–13.40	0.74
$3CaO \cdot Al_2O_3$ (tricalcium aluminate)	–13.29	0.76
$CaO \cdot MgO \cdot 2SiO_2$ (diopside)	–14.80	0.66
$CaO \cdot SiO_2$ (wollastonite)	–14.10	0.71
$CaCO_3$ (limestone)	–12.06	0.88

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Table 3. Chemical composition of mineral additives

Rock name	Chemical composition, % mass.							
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	TiO_2	R_2O	Law of definite proportions
Limestone	54.7	0.5	0.2	0.5	0.1	–	–	40.4
Wollastonite	34.7	53.4	3.1	0.3	2.3	–	–	6.2
Diopside	26.2	53.4	0.2	17.9	0.1	0.1	0.1	1.9

(wt.%) is as follows: plagioclase albitized – 57.3; augite – 20.1; actinolite – 5.6; chlorite (hydrochlorite) – 6.2; epidote – 5.3; sericite – 2.7; sphene – 1.0; magnetite – 1.0; iron hydroxide – less than 0.8.

The hardness values of mineral additives and cement matrix are presented in Table 4.

Based on the comparison of hardness values, it can be concluded that diabase and diopside have the highest hardness (6.5–7.0 on the Mohs scale). The hardness of wollastonite (5.0) is slightly lower than that of diopside and diabase but still higher than that of new hydrated cement formations. Limestone, with the hardness of 3.0, that is lower than that of the cement matrix.

To confirm the fourth principle of the scientific hypothesis, the additives were ground to different dispersions. At the same time, the dispersion of diopside and wollastonite had the size comparable to the dispersion of Portland cement, and limestone and diabase had a dispersion (grain size) less than that of cement. Dispersion values of mineral additives are presented in Table 5.

To confirm the fifth principle of the scientific hypothesis, wollastonite with a chain structure was selected as a modifying additive (Fig.1). Wollastonite ground in a ball mill had a fibrous (acicular) structure, which was confirmed by their characteristic aspect ratio (length-to-thickness ratio) of 4:1 – 5:1 (Fig. 2).

As the silica component for foam concrete, we used the waste from the fuel and energy complex – acid fly ash from Novosibirsk. The ash particles had a spherical shape with dimensions not exceeding 130 µm. Notably, the fine ash fraction (with dimensions not exceeding 30 µm) consisted of microspheres characterized by a smooth outer surface and a sintered shell, indicating predominantly closed porosity.

Table 4. Hardness of mineral additives

Compounds	Hardness on the Mohs scale
Cement matrix	3.5–4
Diabase	7.0
$CaO \cdot MgO \cdot 2SiO_2$ (diopside)	6.5
$CaO \cdot SiO_2$ (wollastonite)	5.0
$CaCO_3$ (limestone)	3.0

Table 5. Dispersion parameters of mineral additives

Additive name	Specific surface area, m²/kg	Average grain size, µm
Wollastonite	309	28.9
Diopside	393	27.0
Limestone	470	12.3
Diabase	540	8.7

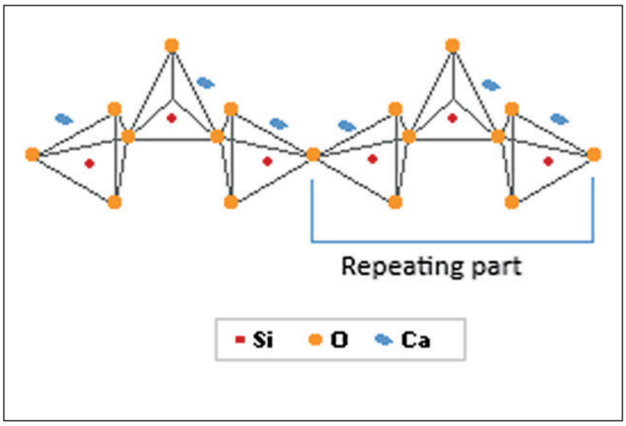

Fig. 1. Chain Structure of Wollastonite

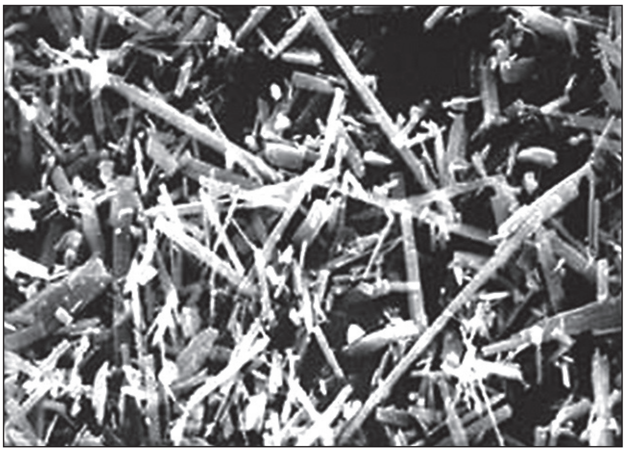

Fig. 2. Microstructure of Wollastonite (magnification ×1700)

For aerated concrete production, quartz sand from "Kamnerechensk stone quarry" OJSC in Novosibirsk was used as the silica component.

The following cellular structure-forming additives were incorporated into the mixture:

- for foam concrete – protein-based surfactants (Foamcem),
- for aerated concrete – aluminium powder of grade PAP-1 (compliant with GOST 5494).

To obtain aerated concrete, grade II lime produced by Iskitimizvest OJSC (Iskitim), which meets the requirements of GOST 9179, was employed as the second component of the mixed binder.

RESULTS

For cellular wall materials, key performance indicators include: average density, thermal conductivity, water absorption, frost resistance, and compressive strength. It is possible to achieve increased compression strength while maintaining an average density by reinforcing the inter-pore partitions. Therefore, the initial research stage focused on enhancing the cement matrix through the incorporation of dispersed mineral additives selected according to the principles of the scientific hypothesis.

Stage 1. Cement Matrix Reinforcement Using Dispersed Mineral Additives. The test additives were incorporated to Portland cement at 2-11% by weight in dry form. A normal consistency cement paste was prepared from the resulting dry mixture and then two sample series were produced. The first sample series was cured under heat-moisture treatment (HMT) conditions, the second was cured in water (W) at room temperature (20 ± 2 °C). The heat-moisture treatment regime was carried out according to the mode: 4 hours of preliminary curing, 3 hours of temperature rise up to 90 °C, 8 hours of isotherm curing at 90 °C, 2 hours of temperature decrease. The second sample series was cured for 1, 3, 7, and 28 days. The test results are presented in Table 6.

Table 6. The influence of the type and quantity of mineral additive on the strength of the cement matrix

Curing conditions and duration	Strength of cement paste, MPa, versus type and amount of additive, % by weight of Portland cement					
	0	2	5	7	9	11
Wollastonite						
HMT	49.1	56.2	59.5	60.5	62.6	58.0
WC, 1 day	15.3	17.3	18.1	18.9	19.6	16.3
WC, 3 days	31.4	34.5	35.4	36.8	38.8	35.7
WC, 7 days	46.6	52.5	55.0	55.9	59.4	54.6
WC, 28 days	62.3	70.9	74.3	76.0	79.4	73.4
Diabase						
HMT	49.1	54.5	53.5	49.4	47.2	44.7
DC, 1 day	15.3	16.5	15.7	15.2	14.4	12.8
DC, 3 days	31.4	33.4	31.8	30.5	29.2	28.1
DC, 7 days	46.6	50.9	49.4	46.1	44.7	41.9
DC, 28 days	62.3	68.7	66.8	62.1	59.8	56.6
Diopside						
HMT	49.1	59.0	66.5	71.5	65.7	57.9
DC, 1 day	15.3	17.1	19.0	20.7	19.3	15.7
DC, 3 days	31.4	36.1	41.4	44.4	41.2	37.5
DC, 7 days	46.6	53.4	62.0	68.0	63.7	56.0
DC, 28 days	62.3	73.9	84.2	92.3	85.6	74.6
Limestone						
HMT	49.1	59.1	54.9	49.9	47.5	43.9
DC, 1 day	15.3	22.1	19.5	16.7	14.4	13.2
DC, 3 days	31.4	41.8	39.3	36.6	33.1	29.9
DC, 7 days	46.6	54.7	51.7	49.6	46.9	44.0
DC, 28 days	62.3	74.7	70.9	67.6	63.5	59.2

Note: WC – water conditions, DC – dry conditions.

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The obtained concentration relationships (Fig. 3) demonstrate that during the initial hardening period, the most significant strength improvement can be achieved by adding limestone. The incorporation of

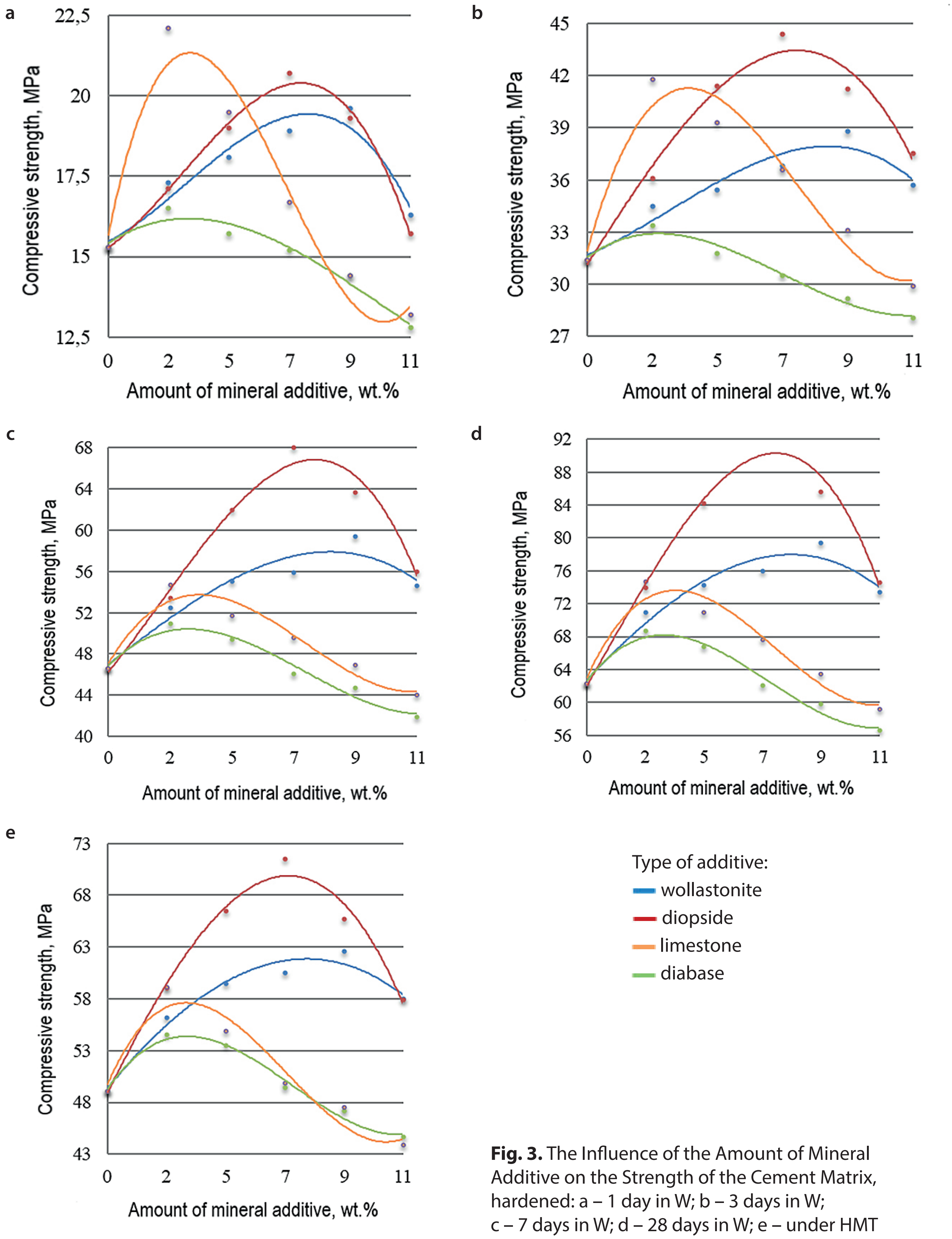

Fig. 3. The Influence of the Amount of Mineral Additive on the Strength of the Cement Matrix, hardened: a – 1 day in W; b – 3 days in W; c – 7 days in W; d – 28 days in W; e – under HMT

2% dispersed limestone results in strength enhancement of up to 20%.

During the later hardening stages, the incorporation of wollastonite and diopside show the greatest effect. At the same time, the optimal additive concentrations were found to be 9% for wollastonite, and 7% for diopside. The addition of 9% wollastonite to cement increases strength up to 27.5%, while 7% diopside produces a more substantial hardening (up to 48%). Further increasing the additive content leads to the reduction of stone strength. Notably, the addition of dispersed diabase to Portland cement did not result in significant strength improvement, with less than 10% enhancement observed throughout both initial and later hardening periods.

In the cement system structure (Fig. 4a), diopside particles appear tightly surrounded by cement crystallization products, demonstrating a strong connection between the additive and the cement stone minerals. Similarly, wollastonite (Fig. 4b) shows effective adsorption of cement hardening products on its surface.

DISCUSSION

Such a significant influence of mineral additives on the properties of the cement system can be explained through several mechanisms. When diopside ((Ca, MgO)•2SiO_2) and wollastonite (CaO•SiO_2) additives are incorporated into the dry mixture, they enhance the stability of the cellular concrete system and reduce shrinkage deformation. This allows us to state that the particles of wollastonite and diopside act as nucleation sites for new crystallization centers [34].

In contrast, calcite (the primary component of limestone flour) exhibits relatively low hardness (3 on the Mohs scale). It is lower than that of hydrated cement. Therefore, the effectiveness of the additive must be attributed to other mechanisms. The optimal content of the additive (limestone) is determined by its influence on the cement hydration process, the formation of a contact zone between the additive particles and the cement matrix. To confirm this hypothesis, comparative X-ray phase analysis was conducted on cement matrix with and without limestone addition (Fig. 5).

The influence of $CaCO_3$ will be most pronounced in the contact zone of the system due to a decrease in the intensity of portlandite reflections, an increase in the intensity of calcium hydrosilicate reflections and the appearance of reflections from hydrafed calcium carboaluminates and hydrafed calcium carbosilicates [13].

Based on L. Pauling's theory of closest packing of particles, when analyzing the influence of additive concentration on the properties of cement materials, we will assume that the particles of both Portland cement and additives have a spherical shape and similar sizes, and the additive particles are distributed uniformly throughout the volume. If the density of the additive differs from that of the cement, the optimal amount of the additive (mass fraction) can be determined by the ratio of their densities [34]:

$$n = \frac{1}{k} \cdot \frac{\rho_A}{\rho_C} = 8.3 \cdot \frac{\rho_A}{\rho_C}, \quad (1)$$

where:
n – mass fraction of additive, % by mass of cement;
ρ_A – true density of the additive, kg/m³;
ρ_C – true density of cement, kg/m³;
k – coordination number (number of cement particles surrounding an additive particle).

If the particle diameters of the additive (D_A) and cement (D_C) differ significantly, to calculate the optimal

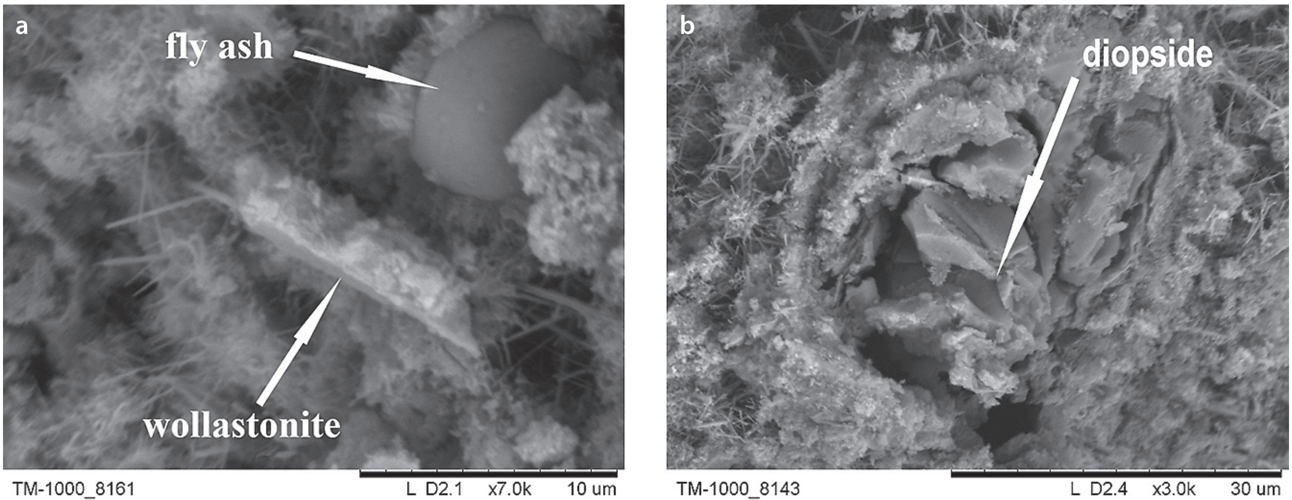

Fig. 4. Additives in the microstructure of foamed concrete after its failure: a – diopside (magnification ×3000); b – wollastonite (magnification ×7000)

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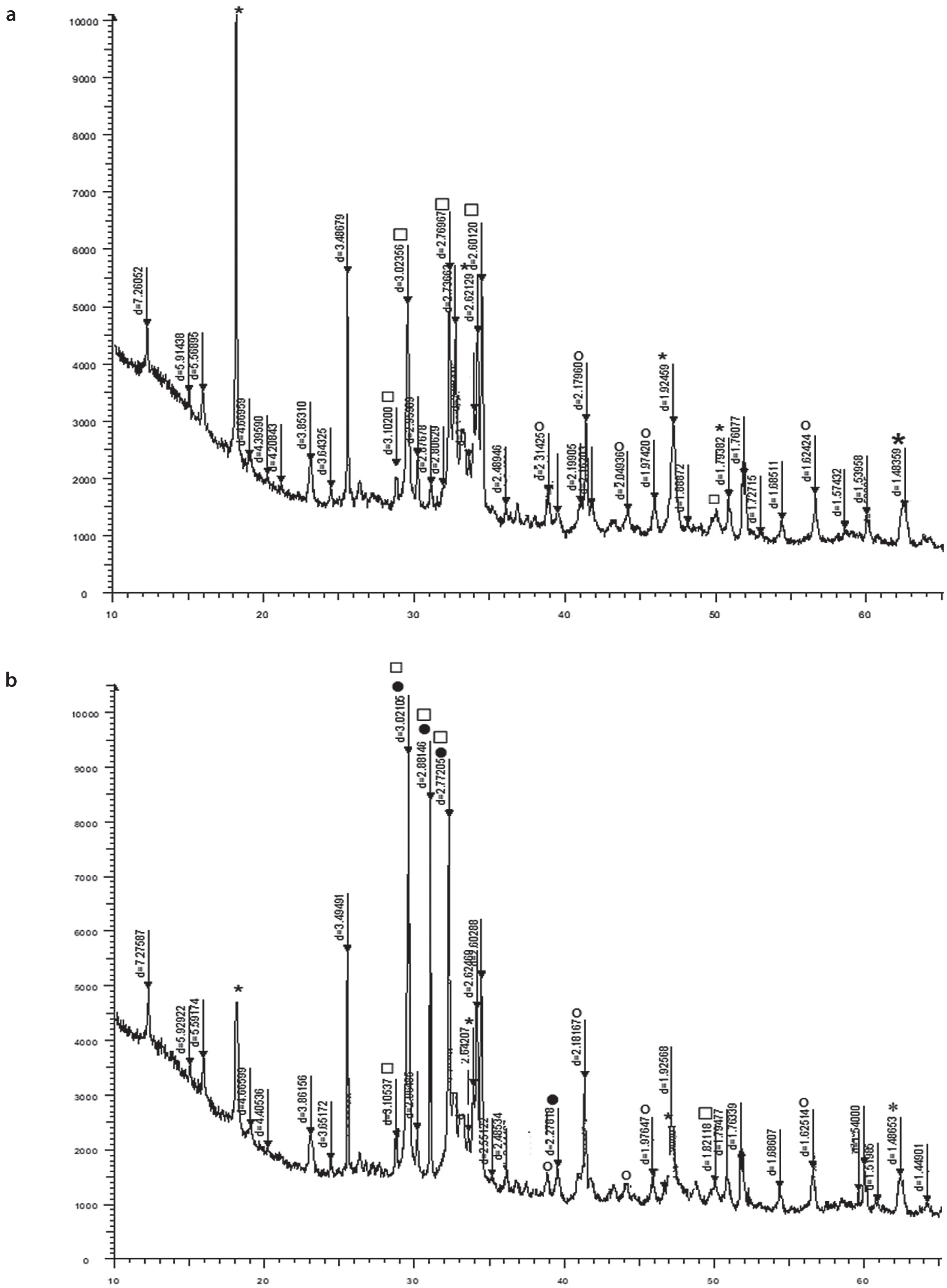

Fig. 5. Diffractogram of cement matrix: a – without additive; b – with limestone addition.
* – $Ca(OH)_2$; □ – C–S–H; ○ – C–A–H; ● – $C_3A{\cdot}CaCO_3{\cdot}12H_2O$

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proportion of the additive (n_A) the formula can be used [34]:

$$n_A = \frac{\frac{\pi \cdot D_A^3}{6} \cdot \rho_A}{k \cdot \frac{\pi \cdot D_C^3}{6} \cdot \rho_C} = \frac{1}{k} \cdot \frac{D_A^3}{D_C^3} \cdot \frac{\rho_A}{\rho_C}, \quad (2)$$

where:

n – mass fraction of additive, % by mass of cement;

ρ_A – true density of the additive, kg/m³;

ρ_C – true density of the additive, kg/m³;

k – coordination number (number of cement particles surrounding an additive particle).

The provided formulae are approximate, given that the actual shape of the additive and cement particles is not spherical. Furthermore, the particle size of both additive and Portland cement have a certain degree of variation, and the distribution of additive particles among the cement particles may also be non-uniform. Nevertheless, the quantitative and qualitative characteristics of the selected additive concentrations correspond closely to the calculated values. If the additive particle diameter is smaller than that of the cement particles, the densest packing is achieved with the lower coordination number, that is, the lower number of cement particles surrounds each additive particle.

In accordance with Formulas 1 and 2, and taking into account the density and size of cement particles and the added additives, the calculated values for the optimal additive concentration are in close agreement with the experimental data. These values are 7–8% for wollastonite and diopside, and 2–3% for limestone and diabase.

CONCLUSION

Stage 1

Thus, all the principles of the scientific hypothesis are confirmed.

1. The 20–48% increase in stone strength with the incorporation of the studied additives (limestone, wollastonite, and diopside) is due to the similarity of their thermodynamic characteristics and chemical composition to those of clinker minerals. Diabase, which differs significantly in chemical composition, results in only a minor strength increase (up to 10%).

2. The greater strengthening effect observed with the addition of diopside (up to 48%) is attributed to its higher hardness and higher modulus of elasticity compared to wollastonite and limestone, the addition of which results in strength increase of 20–27%. In contrast, the addition of diabase, which has the highest hardness (7 on the Mohs scale) of all the additives considered, led to only a minor strengthening. This is likely due to the difference in its chemical composition compared to clinker minerals and the new formations obtained during its hydration.

3. Wollastonite, which has a fibrous structure, leads to greater hardening of the stone compared to limestone and diabase due to the micro-reinforcement effect.

4. As dispersity increases, the optimal concentration of the additive that provides the maximum increase in stone strength decreases.

RESULTS

Stage 2. Performance Enhancement of Cellular Concrete Using Technogenic By-Products and Mining Waste. Since the greatest strengthening of the cement matrix was achieved by incorporating diopside and wollastonite as mineral additives, they were subsequently used to produce non-autoclaved cellular hardening materials. The optimal amount, determined in the first stage of the study, was 7% by weight of Portland cement.

The effect of modifying mineral additives on the performance properties of cellular concrete was studied using non-autoclaved gas and foam concrete. To analyze the influence of the type and quantity of mineral additives on the properties of aerated concrete, a dry mixture was prepared by co-grinding a binder, a silica component, gypsum, and the mineral additives [34]. This dry mixture was then mixed with an aluminum powder suspension and water. The aerated concrete test results are presented in Table 7.

The density of the aerated concrete varied from 580 to 610 kg/m³, while its compressive strength increased from 2.8 to 3.3 MPa. The most significant strength increase was observed with the incorporation of diopside. The density of aerated concrete containing mineral additives decreased by up to 5%, while the strength increase reached

Table 7. Properties of aerated concrete with mineral additives

Type of mineral additive	Average density, kg/m³	Thermal conductivity coefficient, W/(m·°C)	Index of air noise reduction, dB	Compressive strength, MPa	Frost resistance, cycles
Without additives	610	0.14	67.28	1.7	F50
Wollastonite	600	0.13	68.61	3.1	F75
Diopside	580	0.12	69.13	3.3	F75

18%. When modified with mineral additives, the aerated concrete exhibited a reduction in thermal conductivity from 0.14 to 0.12 W/(m • °C) and an improvement in frost resistance from F50 to F75. The index of air noise reduction of single-layer enclosing structures, calculated using design reference methods, was 69.13 dB. This value is significantly higher than that required by regulatory documents. Wall products made of non-autoclaved aerated concrete can be used for constructing walls and partitions in all types of residential and administrative buildings.

The obtained non-autoclave hardened aerated concrete is structural and thermal-insulating, making it suitable for use as a wall material for non-load-bearing walls and partitions, or as the primary wall material for low-rise construction. This application offers benefits in reduced labor costs and shorter construction times.

To determine the optimal method for incorporating mineral additives, the foam concrete mixture was prepared in three ways: diopside and wollastonite were added to the mixing water (mode I), they were added into the mortar mixture (mode II), they were blended into the dry mixture (mode III) (see Table 8).

A control mixture without any additives was used as a reference.

The best foam stability characteristics were observed in the third technological mode, when wollastonite and diopside were added to the dry mixture. Furthermore, the results of the statistical analysis of the density and compressive strength of foam concrete indicate that the addition of wollastonite and diopside to the mixture significantly reduces the coefficients of variation for both compressive strength and average density. This reduction demonstrates greater structural uniformity and more stable properties in the resulted materials.

DISCUSSION

The analysis of the experimental data on the influence of the type and quantity of mineral additives on the property of foam concrete showed that the incorporation of mineral additives increases foam stability in the mortar mixture by up to 30%.

In foam concrete mixers, the particles of mineral additives create mechanical obstacles within turbulent layers characterized by strong swirling of the mixture. This phenomenon contributes to additional air entrainment and increased stability of the foam concrete mixture. The incorporation of wollastonite and diopside additives into foam concrete mixture results in the entrainment of an additional 14–20% air. Consequently, the remaining bulk water, which transitions into a physically bound state, must also move from the interparticle space into the films. This process leads to a 13.5% increase in the mixture viscosity and enhances its aggregate stability. Based on the results of the study, the optimal foam concrete compositions were determined (see Table 9).

Table 8. Influence of the mineral additive incorporation method on foam concrete properties

Type of additive	Technological mode	Foam stability in the mortar mixture	Average density, kg/m^3	Coefficient of variation, %	Compressive strength, MPa	Coefficient of variation, %	Plastic shrinkage, mm/m
Wollastonite	I	0.84	502	5.80	1.00	10.20	6.47
	II	0.89	476	4.50	1.03	7.60	5.85
	III	0.93	435	3.30	1.19	4.10	5.03
Diopside	I	0.86	498	6.30	2.31	15.30	7.04
	II	0.89	477	5.90	0.83	14.20	6.83
	III	0.90	467	5.60	0.88	12.70	6.58
Control composition		0.74	547	6.80	1.22	17.40	7.20

Table 9. Optimal foam concrete compositions

Composition components	Type of additive		
	Without additives	Diopside	Wollastonite
Portland cement, kg	330	163	225
Fly ash, kg	200	98	135
Foaming agent, L	1.44	0.69	0.95
Water, L	267	148	205
Additive, kg	0	1.63	2.25

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Table 10 presents the physico-mechanical properties of the recommended foam concrete compositions containing the studied additives.

The largest volume of conditionally closed pores (Table 11), determined based on the water absorption of the samples, was found in the foam concrete with wollastonite and diopside additives, at 53.8% and 52.9%, respectively.

According to mercury intrusion porosimetry (MIP) data, the incorporation of wollastonite reduces 2.34 times the volume of pores larger than 0.1 μm in diameter in the foam concrete, while the incorporation of diopside reduces it by 8.2%. This enhancement can provide an increase in frost resistance up to grade F25. Due to a 1.5-fold increase in closed pores within the foam concrete structure and the predominance of uniformly distributed pores up to 2 mm in size (Fig. 6b, 6c), the thermal conductivity coefficient decreases to 0.069–0.070 W/(m•°C). This reduction is a result of diminished convective heat transfer.

According to scanning electron microscopy (SEM) data (Fig. 7), the interpore partitions of the foam concrete consist of colloidal hydration products, and rounded aggregates are visible.

As it is seen (Fig. 7) there is the presence of acicular hydrated calcium silicate crystals, which contribute to the micro-reinforcement of the foam concrete structure. Thus, it can be noted that mineral additives, possessing high chemical affinity with Portland cement hydration products, activate the crystallization processes of cement hydration products, i.e., they act as sites for crystallization.

Therefore, the enhancement in the performance properties of cellular concretes is associated with changes in their pore structure and the phase composition of new hydration products [33].

Table 10. Physico-mechanical properties of the developed foam concrete

Properties	Type of additive		
	Without additives	Wollastonite	Diopside
Average density, kg/m^3	547	345	274
Compressive strength at 28 days, MPa	1.22	1.00	0.57
Concrete strength class	B 0.75	B 0.75	B 0.5
Thermal conductivity coefficient (dry), W/(m•°C)	0.12	0.070	0.069
Thermal conductivity coefficient (equilibrium), W/(m•°C)	0.132	0.082	0.074
Frost resistance grade	F 20	F 25	F 25
Spread flow of foam concrete mixture (Suttard test), mm	185	155	170
Plastic shrinkage, mm/m	7.20	5.70	6.08
Drying shrinkage, mm/m	2.6	1.7	2.0
Water absorption, %	15.3	13.8	12.3

Table 11. Porosity of the studied foam concrete compositions

Properties	Type of additive		
	Without additives	Diopside	Wollastonite
Total pore volume, %	67.0	87.0	81.0
Volume of conditionally closed pores, %	35.9	52.9	53.8

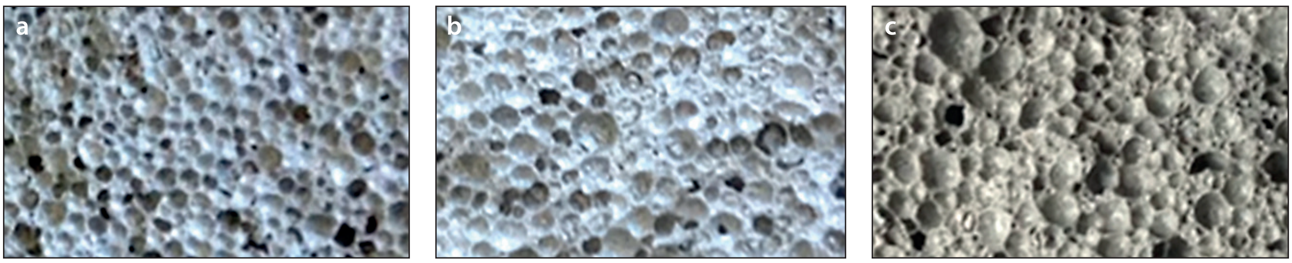

Fig. 6. Foam concrete porosity: a – with diopside; b – with wollastonite; c – without additives (magnification ×5)

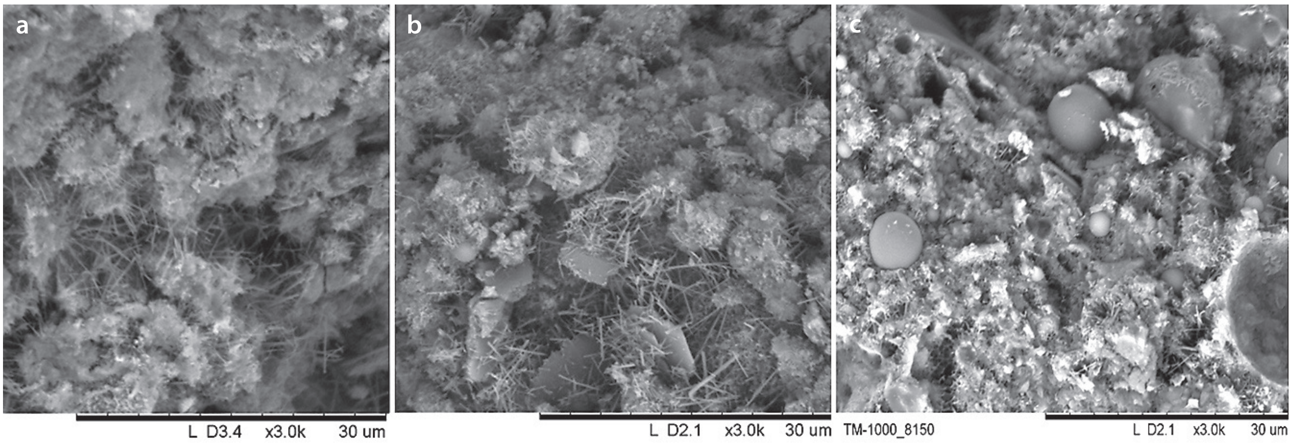

Fig. 7. Microstructure of foam concrete samples: a – without additives; b – with diopside; c – with wollastonite (magnification ×3000)

CONCLUSION

Stage 2

Thus, the enhancement in the performance properties of cellular concretes is scientifically substantiated by the principles of the scientific hypothesis proven in the first stage.

1. The enhancement of the performance properties of cellular concretes is associated with changes in their pore structure and the phase composition of new hydration products.

2. Modifying aerated concrete increases its compressive strength by 18%. The greatest strength improvement is observed with the incorporation of diopside.

3. The modification of aerated concrete with mineral additives reduces its average density by up to 5% and its thermal conductivity from 0.14 to 0.12 W/(m•°C).

4. The frost resistance of the modified aerated concrete increases from F50 to F75. The index of air noise reduction of single-layer enclosing structures made of this aerated concrete is 69.13 dB, which is significantly higher than the values required by regulatory standards.

5. The incorporation of wollastonite and diopside increases the stability of foam in the mortar mixture by up to 54%. The best foam stability results were obtained when wollastonite and diopside were added to the dry mixture.

6. The modification of the foam concrete mixture with dispersed additives (wollastonite, diopside) significantly reduces the coefficients of variation for compressive strength (from 17.4% to 3.2% and 8.4%, respectively) and for average density (from 6.8% to 2.9% and 4.8%, respectively). This indicates greater uniformity of the structure and higher stability of the properties of the obtained foam concrete.

7. The incorporation of dispersed wollastonite and diopside additives into the foam concrete mixture ensures the entrainment of an additional 14–20% of air. It is explained by the fact that particles of the mineral additives in foam concrete mixers create mechanical obstacles in turbulent layers during intense swirling of the foam concrete flows.

8. The modification of foam concrete with dispersed mineral additives leads to the change in its pore structure: the volume of closed pores increases by 1.5 times, and pores up to 2 mm in size become uniformly distributed and predominant. The incorporation of wollastonite reduces 2.34 times the volume of pores larger than 0.1 μm in diameter in the foam concrete, while the incorporation of diopside reduces it by 8.2%.

9. The change in the pore structure of the modified foam concrete results in an increase in its frost resistance and a decrease in the thermal conductivity coefficient to 0.069–0.070 W/(m•°C), due to reduced convective heat transfer.

10. The obtained non-autoclave hardened cellular concrete is thermal-insulating and structural-thermal-insulating. To reduce labor costs and construction time, it is advisable to use it as a wall material for non-load-bearing walls and partitions or as the main wall material for low-rise construction.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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CONTRIBUTION OF THE AUTHORS

Lilia V. Ilina – scientific management; research concept and methodology development, processing and analysis of experimental data, systematization of experimental data, compilation of final conclusions, literature review.

Ekaterina A. Bartenjeva – conducting the experimental part, graphical and tabular presentation of the research results, processing and analysis of experimental data using machine learning methods.

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