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APPLICATION OF HYDRO-REMOVAL ASH IN NON-AUTOCLAVED FOAM CONCRETE TECHNOLOGY

M.A. Ermukhanbet[1], M.S. Saduakassov[2], V.A. Lapin[3*], G.G. Tokmajeshvili[2], K.T. Bayusupova[4]

[1] Kazakh National Research Technical University named after K. Satpayev, Almaty, Kazakhstan
[2] Kazakh Academy of Architecture and Construction Sciences
[3] Joint Stock Company Kazakh Research and Design Institute of Construction and Architecture
[4] International Educational Corporation (KazGASU), Almaty, Kazakhstan

*Corresponding Author, Received: 03 March 2025, Revised: 13 May 2025, Accepted: 15 May 2025

ABSTRACT: This study investigates the influence of various fillers and curing conditions on the strength development of foam concrete. It was found that conventional sand-based mixtures fail to achieve the required strength under both steaming and natural hardening conditions. Experimental results demonstrate that substituting sand with activated hydraulic ash, particularly when combined with a hardening accelerator, significantly improves the strength of non-autoclaved cellular concrete. The research also examines the effect of ash with different grinding fineness on the physical and mechanical properties of both autoclaved and non-autoclaved foam concrete. Since autoclaved curing ensures complete hydration, a comparative analysis was conducted using samples cured under atmospheric pressure in a steam chamber at 90 °C and those treated in an autoclave at 167 °C and 0.8 MPa. This approach enabled the identification of strength variations related to the content and reactivity of silicon dioxide in the ash. The novelty of this research lies in demonstrating the practical efficiency of using activated hydraulic removal ash combined with a chemical hardening accelerator to produce non-autoclaved cellular concrete with acceptable strength characteristics. The methodology emphasizes the comparative evaluation of identically composed mixtures subjected to different curing regimes, offering valuable insights into optimizing material composition and processing for sustainable and energy-efficient foam concrete production.

Keywords: Autoclaved, Non-Autoclaved, Foam Concrete, Hydraulic Removal Ash, Strength

1. INTRODUCTION

As follows from literary sources and the results of the authors' experiments, it is impossible to obtain non-autoclaved foam concrete with sufficient strength when using natural sand [1-9]. Moreover, even sand grinding does not give the expected results. This is because the quartz contained in the sand is in a crystalline state and at atmospheric pressure and temperatures up to 100 ºC it does not react with the cement minerals. Thus, according to foreign scientists, non-autoclaved foam concrete with sand filler is characterized by relatively low strength indicators [2-3]. Therefore, in the article devoted to the formulation and technological factors for improving the properties of non-autoclaved foam concrete, the following indicators were achieved: at a density of 600 kg/m^3, the compressive strength is 1.0 MPa, at 670 kg/m^3 - 1.35 MPa [2]. The same results were obtained when producing gypsum cement foam concrete: with a 926 kg/m3 density, the compressive strength is 1.8 MPa [3].

Dispersed fillers with pozzolanic properties are necessary to produce non-autoclaved foam concrete with increased strength. One such filler is thermal power plant (TPP) ash. Dry-selected thermal power plant (TPP) ash, called fly ash, is widely used in the production of cement and concrete products. The hydraulic removal of ash, which in Kazakhstan amounts to hundreds of millions of tons, is not used due to insufficient study. At the same time, their use in producing materials with low strength, for example, wall blocks made of cellular concrete of strength class B2-B5, seems effective and safe in technical terms.

Thermal power plants are among the polluters of the environment. All thermal power plants annually emit about 700 million tons of pollutants of various hazard classes [10-11]. Vast territories are occupied by their ash dumps. In particular, 430 million tons of ash and slag waste have accumulated in Kazakhstan [12].

It has been calculated that a thermal power plant with a capacity of 2.4 million kW, operating on coal, consumes (t/h): fuel - 1060, water - 3*105 and oxygen - 1060; emits into the environment (t/h): ash - 194, slag - 34.5, warm water – 28*105 [10].

The environmental load from air pollutants of thermal power plants makes the following significant changes to the atmosphere:

- The content of particles that are condensation nuclei increases by 10 times;
- Gas impurities in the air increase from 5 to 25 times;

- The number of clouds increases by 5-10%, and the Amount of fog in winter increases by 100%, in summer by 30%;
- Solar radiation decreases by 20%.

Accumulated ash and slag waste significantly impact nature with geomorphological, hydrogeological, geochemical, geothermal, engineering-geological, mineralogical, and geophysical consequences.

In developed foreign countries, fly ash from thermal power plants is almost entirely processed into commercial products, mainly in cement and concrete production. In Western Europe and Japan, ash dumps have been virtually eliminated at thermal power plants. Dry ash goes to silos built next to the main buildings of the thermal power plants.

In Germany, 3.1 million tons of cement are replaced by ash. In the USA, builders legally must use ash from thermal power plants in concrete and mortar. Thermal power plants often pay extra to consumers for ash collection. In China, ash and slag from thermal power plants are sold to consumers free of charge. In Poland, powerful economic levers are used to stimulate the use of ash and slag [10].

In foreign countries, much attention is paid to using ash in foam concrete technology [13-27]. However, an analysis of the sources indicates that only dry fly ash is used in research, while the utilization of hydraulic ash is necessary.

In recent years, the CIS countries have made great strides in using fly ash. In particular, in the new standard regulating the composition and properties of cements from 2020 (GOST 31108-2020. General construction cements), the fly ash content in composite Portland cement can be up to 20% (CEM II / A - K) and up to 35% (CEM III / B - K), and in composite cement - up to 30% (CEM V / A) and up to 49% (CEM V / B).

There are significant opportunities for using hydraulic ash in concrete production, including in cellular concrete technology. But the standard regulating the composition of cellular concrete (SN 277-80. Instructions for manufacturing products from cellular concrete. - M: Stroyizdat, 1981. - 47 p.) does not allow the use of hydraulic ash. In this regard, there is a need for experimental studies of the justification for using substandard components in the production of cellular concrete. In Almaty, a relatively large metropolis of Kazakhstan, where the pace and volume of housing construction are very high, there is no fly ash, but a lot of hydraulic ash, since all three thermal power plants in Almaty remove ash by hydraulic ash removal. But it is used not only by enterprises producing cellular concrete but also by manufacturers of ready-mixed concrete and plants of reinforced concrete products and structures. Thus, the study of the possibility of using hydro-removal ash, including through its mechanical activation, is of great practical interest.

The advantages of non-autoclaved foam concrete compared to autoclaved aerated concrete include the simplicity of the technology, including the use of natural sand in its natural state, low capital intensity of the line, and low energy intensity of production. But despite these obvious technological advantages, lines for producing autoclaved aerated concrete blocks have been widely developed worldwide, including in Kazakhstan. In Almaty alone, there are 11 factories producing autoclaved materials, mainly from German manufacturers. This situation is due to the fact that non-autoclaved foam concrete is primarily characterized by low strength, and secondly, by low line productivity, which, of course, does not suit developers.

It should be noted that manufacturers of non-autoclaved foam and aerated concrete, in particular in Almaty, use only washed river sand as a filler, which is explained by the ease of their use and the absence of dust formation. At the same time, it is known from the practice of foam concrete technology and the data of numerous studies that foam concrete made only on the basis of cement and sand does not provide the required class of concrete in terms of compressive strength according to GOST 25820-89 (Small cellular concrete wall blocks) [1-9]. According to the terms of this standard, the class of concrete in terms of compressive strength at a density of 600-700 kg/m^3 must be at least B2 (2.9 MPa), and in conditions of using non-load-bearing blocks in a seismic zone - at least B2.5 (3.3 MPa), load-bearing - at least B3.5 (4.6 MPa) [28].

At the same time, when producing foam concrete, hydraulic removal ash as a filler may solve the issue of recycling thermal power plant waste and ensuring the required strength of cellular concrete.

In several studies on obtaining foam concrete, ash is used as an additive to cement, and in small quantities, from 10 to 30% [24, 13-20]. In particular, the article provides data on adding hydraulic removal ash to the composition of foam concrete in quantities of 10 and 30% [24]. At the same time, with a foam concrete density of 700 kg/m^3, the compressive strength not only did not increase but decreased from 3.5 to 3.1-3.4 MPa. It is necessary to note the questionably high value of the strength of foam concrete, which does not agree with either the data of the authors of this article or with the data of other scientists [1-3, 4-16]. For example, in article it is noted that foam concrete with a density of 800 kg/m^3 based on sand has a strength of 1.5 MPa, and based on fly ash - 1.86 MPa; in article - with a density of 873 kg/m^3 - 1.5 MPa [25], [29]. The same results were obtained in works: 1-1.35 MPa with a foam concrete density of 600-670 kg/m3 and 1.86 MPa with a density of 926 kg/m^3 [1, 3].

This article presents the results of studies on the effect of hydraulic removal of ash of varying degrees of grinding on the physical and mechanical properties of non-autoclaved and autoclaved foam concrete. Since autoclave curing of concrete provides 100% hydration, it was assumed that by comparing the properties of samples hardened in a steam chamber at atmospheric pressure, the reasons for the low strength of foam concretes depending on the silicon dioxide content could be determined. Such comparative data can provide an answer to the objectivity of the standard requirements for cellular concrete fillers.

2. RESEARCH SIGNIFICANCE

This study presents original experimental work at the accredited "Research Institute of Building Materials and Design." Foam concrete samples were developed using a cement-ash mixture and prepared under controlled conditions using GOST-standard methods for analyzing physical, mechanical, and chemical properties. Ash was ground into a ball mill, mixing using German “Testing” equipment. Novel preparation and curing techniques—including autoclaving at 8 bar—were applied to ensure uniformity and performance. Each composition was molded twice to verify repeatability, with a 5–7% variation range. This research offers new insights into foam concrete formulation using standardized and reproducible experimental methods.

2.1 Raw Materials

The following raw materials were used: Portland cement grade M500, ash from hydraulic removal of Almaty TPP-3, Volsk quartz sand, protein foaming agent "Biofom" of Russian production, the characteristics of which are presented in Tables 1-4.

The activity of hydro-removal ash was determined using the method described in the literature, according to which the criterion for the activity of acidic mineral additives is the time (in days) after which the given additive can ensure the setting and water resistance of the dough based on the additive and slaked lime [30]. The more active the additive, the shorter the time required to ensure the setting and water resistance of the dough.

When conducting experiments, the normal consistency of the dough was first determined, after which the following composition was used: 320 g of hydro-removal ash, 80 g of slaked lime and 250 g of water. Testing of samples showed the following results: end of setting – 2 days (with the standard of no more than 7 days), water resistance meets the requirements.

Table 1 Physical and mechanical properties of Portland cement M500 of the Bukhtarma cement plant

Physical and mechanical properties						
residue on sieve 008, %	normal density, %	setting time, h-min		strength after 28 days of hardening, MPa, at		compressive strength after steaming, MPa
		start	start	bending	compression	
0,8	28	2-45	3-20	7,5	52,8	41,1

Table 2 Chemical and mineralogical composition of Portland cement M500 of the Bukhtarma cement plant

Oxide content, %						Content of essential minerals			
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	C_3S	C_2S	C_3A	C_4AF
20,85	5,62	4,22	63,52	1,53	2,09	56,29	16,62	7,28	13,14

Table 3 Granulometric composition of quartz Volsk sand with Mk = 1.86 and ash from hydraulic removal of Almaty TPP-1*

Aggregate	Partial residues, %, on sieves with a hole diameter of mm							
	2,5	1,25	0,63	0,315	0,2	0,16	0,08	Less than 0,16	Less than 0,08
quartz sand*	-	3,3	81,0	15,4	-	0,3	-	-	-
Hydro-removal ash**	-	-	3,3	2,5	6,25	-	6,5	-	81,45

*SiO2 content – 98.7%, **- 61.95%

Table 4 Chemical composition of ash from hydro-removal of Almaty CHPP-1*

Oxide content, %										p.p.p., %
Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	Fe2O3	
0,71	0,40	27,56	61,95	0,41	0,47	1,44	1,12	0,05	3,31	3,4

*Specific surface area – 2,500 cm2/g.

3. RESEARCH RESULTS

The first stage of the experimental studies included determination of the compressive strength of the solution of the additive of hydraulic removal ash. The peculiarity of these tests was the necessity to reveal the influence of the degree of activation of the ash filler on the strength of the solution. According to the experimental data of one of the authors of the article, obtained on the basis of studies on the mechanical activation of the gypsum binder, it was established that the determining influence on the structure formation of concrete is exerted not by the granulometric composition, but by the degree of reactivity of the surface of the binder grains [31]. This statement is consistent to a certain extent with the classical theory of mechanical activation, according to which the process of destruction of brittle grains is preceded by plastic deformations of the material. In particular, it was established that plastic deformation during grinding leads to a change in the crystalline structure of quartz and calcite, which causes an increase in the reactivity of the quartz powder [32-35].

The compositions of the tested samples are presented in Table 5, the test results are shown in Fig. 1.

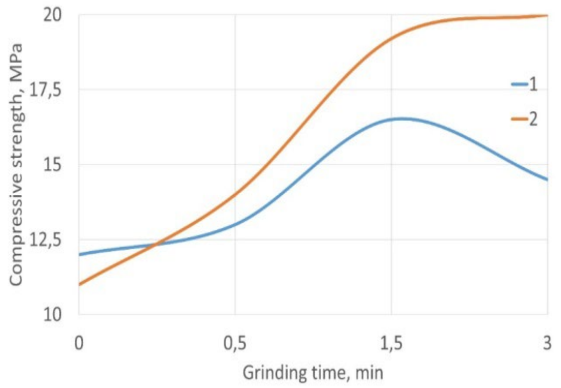

Fig. 1 Effect of the duration of grinding (activation) of hydro-removal ash on the compressive strength of the mortar after 28 days of hardening.

Ratio "cement: ash": 1 - 3:1; 2 - 7:1

On average, the density of all samples was about 2000 kg/m3. The compressive strength of the control sample (composition 1) was 15.2 MPa.

Analysis of the data in Fig. 1 shows that the introduction of unmilled hydro-removal ash into the solution leads to a significant decrease in the strength of the samples – from 15.2 MPa to 11.4-11.7 MPa, respectively. Addition of the same amount of hydro-removal ash, but already milled (activated) for 1.5-3 hours, provides a sharp increase in the strength of the samples, despite an adequate decrease in cement consumption. Of particular interest is the fact that the strength of the samples with a large amount of ash (compositions No. 6-9, curve 2) is greater than the strength of the samples with a smaller amount of ash (compositions No. 2-5, curve 1). This indicates that the ash begins to partially "work" as a binder due to a sharp increase in the pozzolanic activity of silicon dioxide.

When producing foam concrete, the hydro-removal ash was used both in its original state and after grinding for 0.5, 1, and 2 hours. The batch was prepared based on obtaining 2 liters of foam concrete mixture. Samples were molded in two standard sizes (cubes 7.07x7.07x7.07 cm and cylinders with a diameter of 4.8 cm, also 4.8 cm high.

The grinding duration (0.5, 1.5, 3 hours) was initially chosen arbitrarily, considering the ash's dispersion. Taking into account the data obtained, the grinding duration was subsequently adopted as 0.5, 1, and 2 hours.

Testing the grain composition of the ash showed that ash in its natural state consists of a fine fraction with a peak of 10 μm and a larger fraction with a peak of 100 μm. After 0.5 hours of grinding, the grain composition of the ash evens out and the particle size is within 1-80 μm. Increasing the grinding duration to 3 hours changed the overall picture of the grain composition insignificantly, apparently due to the grinding features in a ball mill.

A feature of hydro-removal ash and fly ash is that silica in the ash is in an amorphous state. Unlike crystalline quartz, the latter can interact with calcium oxide hydrate formed during the hydrolysis of tricalcium silicate and other products of binder hydration at a temperature of less than 100 °C and normal atmospheric pressure. Therefore, it is legitimate to expect foam concrete with ash filler to be stronger than when using quartz sand.

Table 5 Compositions of samples with the addition of hydraulic ash

Name of components	Compositions								
	1	2	3	4	5	6	7	8	9
portland cement M500	400	350	350	350	350	300	300	300	300
quartz sand	1200	1200	1200	1200	1200	1200	1200	1200	1200
hydro-removal ash	-	50	50	50	50	100	100	100	100
water	250	250	250	250	250	250	250	250	250

Experiments confirmed the above assumptions (Fig. 2). The grain composition graph is shown in Fig. 2, which shows that the ash in its natural state consisted of a fine fraction with a peak of 10 µm and a larger fraction with a peak of 100 µm. After 0.5 h of grinding, the grain composition of the ash evened out, and the particle size was within the range of 1-80 µm. Increasing the grinding time to 3 h changed the overall picture of the grain composition insignificantly, apparently due to the grinding features in a ball mill. The specific surface area of the ash after grinding was 3,700, 4,100, and 4,300 cm2/g, respectively.

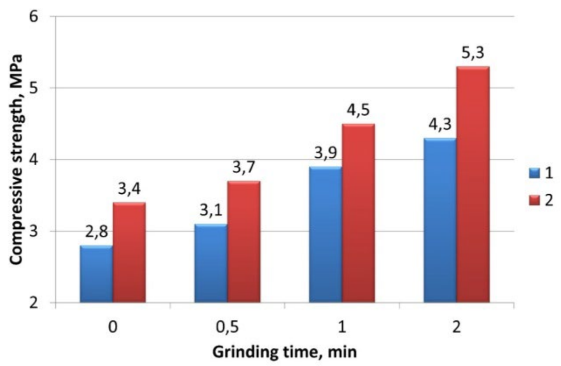

Fig. 2 Effect of the duration of milling of hydro-removal ash (activation) on the compressive strength of non-autoclaved and autoclaved foam concrete with a 700 kg/m^3 density. Heat treatment: 1 – in a steam chamber, 2 – in an autoclave

As can be seen from the experimental data, ash activation in all cases significantly increases foam concrete's strength. The compressive strength of the samples after heat treatment in a steam chamber rose from 2.8 to 4.3 MPa (53.57%), and after autoclave treatment, from 3.4 to 5.3 MPa (55.88%).

With steam treatment, the strength of concrete reaches 70% of the strength of concrete hardened in the field without steam treatment [36]. Accordingly, the design compressive strength of foam concrete manufactured in the field will be 4.3 x 100/70 = 6.1 MPa. It should be noted that the compressive strength of the control sample on quartz sand was 1.9 MPa.

Thus, it can be noted that the use of sand does not provide the required strength of foam concrete during steaming and natural hardening. Therefore, establishing the possibility of using ash from hydraulic removal as a filler for non-autoclaved cellular concrete is a significant advantage. According to the fundamental works of Russian scientists, conducted since the 60s of the last century, concrete using ash is a reasonably durable material [37-39].

To obtain foam concrete with a compressive strength class of at least B2.5, blocks that could be used to construct non-load-bearing walls in seismic zones were made with the addition of calcium chloride. Calcium chloride is a classic and well-studied additive used to accelerate hardening and simultaneously increase the strength of heavy and lightweight concrete [40]. The additive was introduced in 1-3% of the cement mass. Hydro-removal ash activated for 0.5 hour was used as a filler. The volume of the mixture was prepared based on obtaining 1.5 liters of molding mass.

The manufactured samples' compositions and the tested samples' properties are presented in Tables 6 and 7.

Table 6. Compositions of foam concrete samples with the addition of calcium chloride

Name of components	Compositions			
	1	2	3	4
Portland cement M500, g	480	480	480	480
Hydro-removal ash, g	480	480	480	480
calcium chloride, g	0	4,8	9,6	14,4
water, ml	300	300	300	300
foam, l	1	1	1	1

Table 7 Physical and mechanical properties of foam concrete with the addition of calcium chloride

Indicators	Compositions			
	1	2	3	4
dry density, kg/m3	705	695	690	700
compressive strength, MPa, after steaming	4,3	4,6	4,8	5,2
compressive strength, MPa, after 28 days of hardening	4,8	5,3	5,5	6,1
recalculation to brand strength*, MPa	3,06	3,39	3,52	3,9
brand of foam concrete	M25	M25	M35	M35
Foam concrete class by compressive strength	B2	B2,5	B2,5	B2,5

*According to GOST 12852.1-77 (Cellular concrete. Test methods).

The obtained data show that without using a hardening accelerator and without activation of hydraulic removal ash, it is impossible to obtain foam concrete with a compressive strength class of B2.5. Consequently, it can be concluded that the products of enterprises producing foam concrete blocks using non-autoclave technology, and without grinding the filler, in this case, hydraulic removal ash, do not meet the standard's requirements. At the same time, even short-term grinding for 0.5 hours allows the strength of cellular concrete to be brought to standard indicators.

Indeed, the addition of calcium chloride leads to some increase in concrete shrinkage, which is noted in the work of V. Ramachandran [40].

It can be assumed that the degree of carbonation will be less than that of concrete without adding calcium chloride. This position is based on the fact that with the addition of calcium chloride, the degree of cement hydration increases and less free Ca(OH)2 remains in the system [40]. However, in any case, carbonation is of no importance for unreinforced concrete [41].

A comparison of the microstructure of foam concrete samples with fillers made from non-autoclaved and autoclaved hydraulic removal ash shows some differences (Fig. 3-4). Visual comparison of the figures with equal scales (especially at 500 and 1000 magnification) shows that autoclave treatment provides a denser microstructure.

A dense structure characterizes the interpore partitions of autoclave-cured samples, the inner surface of the pores themselves being glossy, and also by a dense structure. The microstructure of samples of the same composition, made from the same batch with autoclave-cured samples, but heat-treated in a steam chamber at a temperature of 95 °C, shows chaotically located pores, in which the pores themselves are penetrated by pores of smaller sizes, and the interpore partitions also have a loose structure.

Analysis of the X-ray diffraction pattern shows that the reflections d = 4.92 A°; 2.63 A° and 1.93 A° inherent to portlandite Ca(OH)2 are present in the non-autoclaved sample, but are absent in the autoclaved sample, which is due to its complete binding into hydrosilicates, which ensures higher strength of the material (Fig. 5).

During non-autoclave hardening of foam concrete, the solid phase is composed of smaller, weakly crystallized calcium hydrosilicates and has a predominantly coagulation structure, especially in the initial period. This means that dispersed particles aggregated in the coagulation structure are separated from each other by thin layers of a dispersion medium containing surfactants that create a structural and mechanical barrier for contact interaction of particles.

According to theoretical views, grinding of fillers or binders leads to an increase in the surface activity of the material due to the rise in the specific surface, but to a greater extent due to the formation of uncompensated charges at the corners of the particles [31-35].

It is important to note that lightweight concretes using ash as a filler are a fairly durable material, as evidenced by the works of, among others, Russian scientists [37-39].

x50 x50

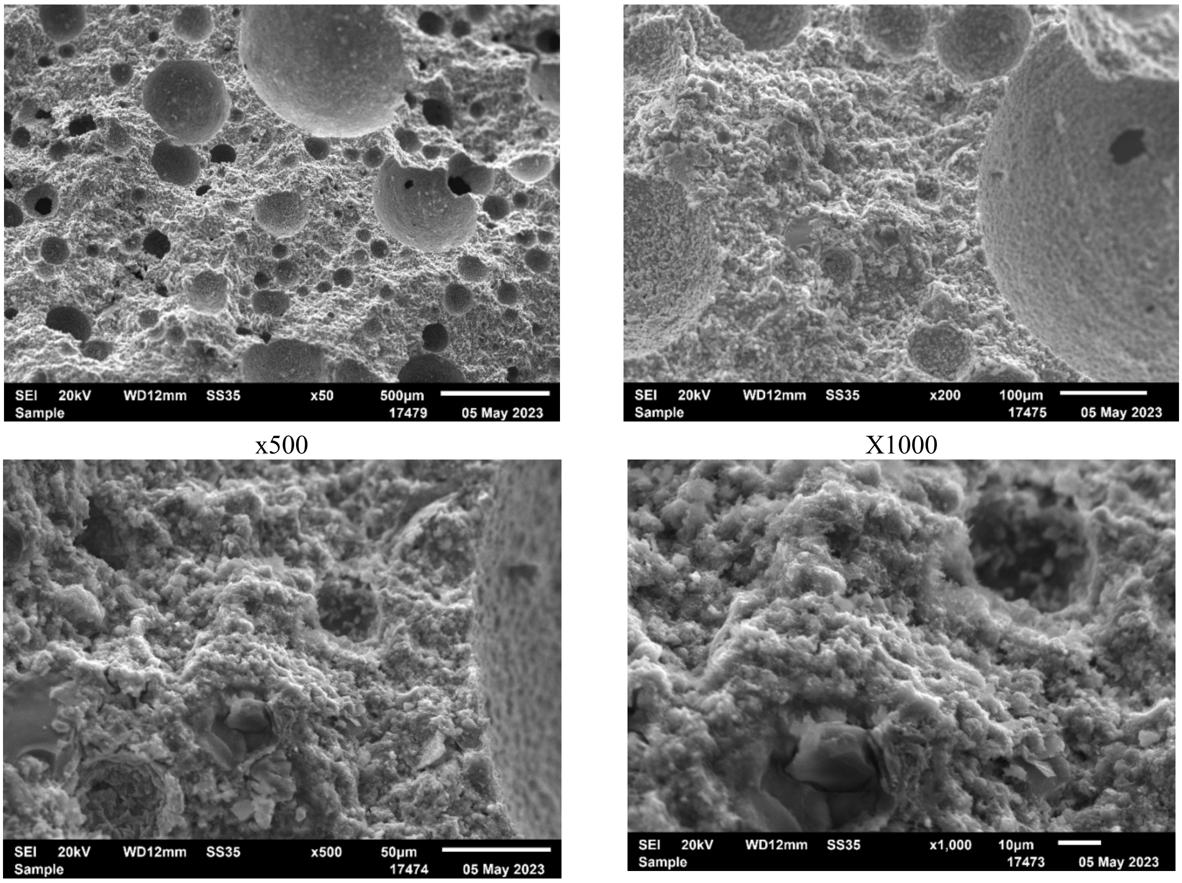

Fig. 3 Microstructure of autoclaved foam concrete samples with filler made from hydraulic ash

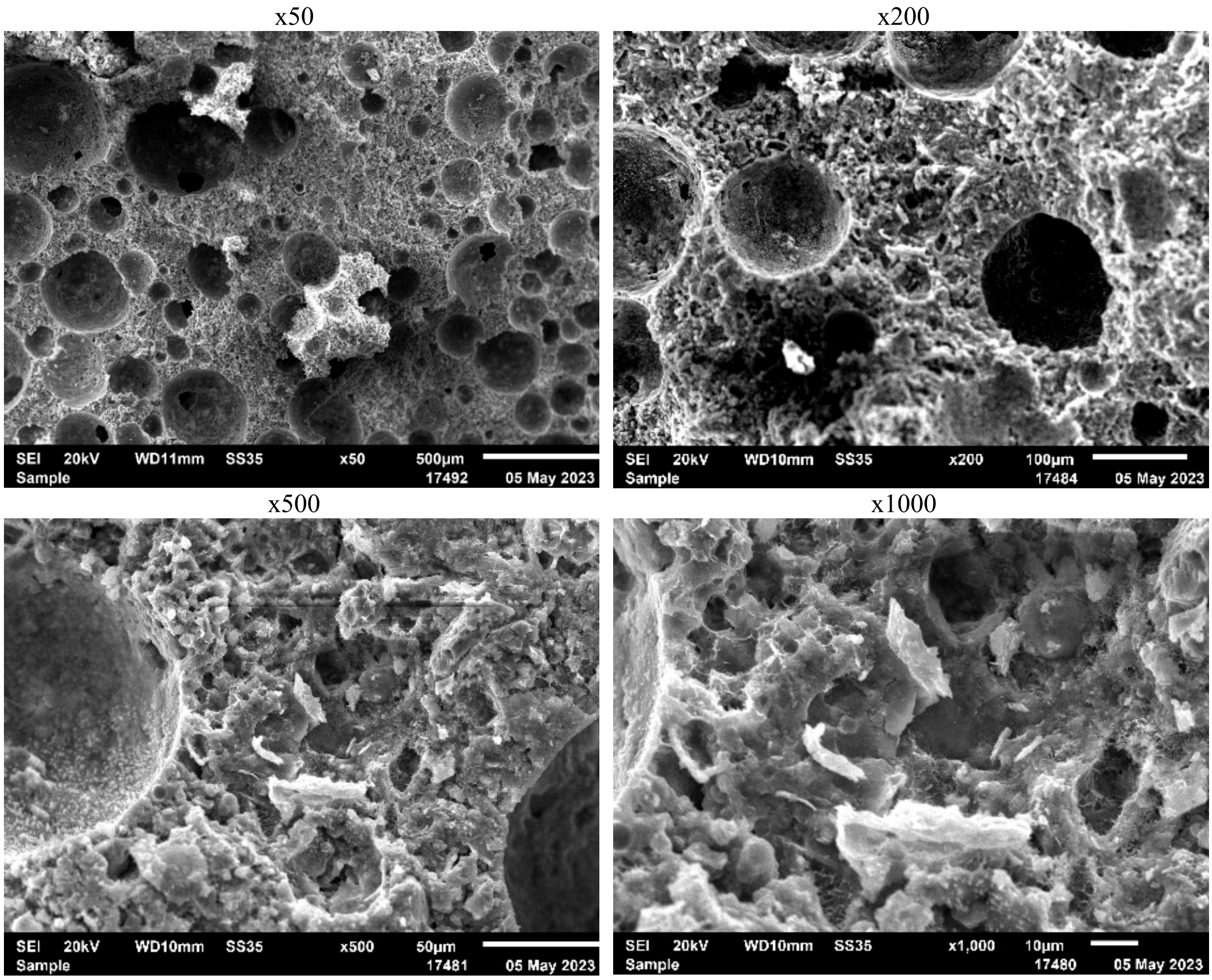

Fig. 4 Microstructure of foam concrete samples with filler made from hydraulic ash that underwent heat treatment in a steam chamber

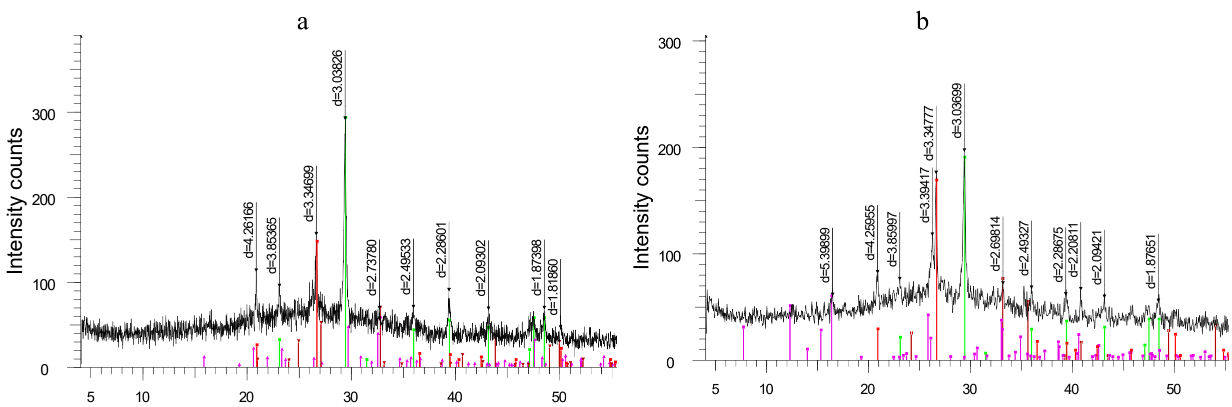

Fig. 5 X-ray diffraction patterns of foam concrete on hydro-removal ash, ground for 3 hours
a – after heat treatment in a steam chamber; b – after autoclave treatment

4. CONCLUSION

1. Using sand does not provide the required strength of foam concrete during steaming and natural hardening. Therefore, a significant advantage is establishing the possibility of using hydraulic removal ash as a filler for non-autoclaved aerated concrete.

2. It was found that replacing 50 and 100 kg of cement with untreated ash when obtaining a solution leads to a decrease in compressive strength from 15.2 MPa to 11.4 and 11.7 MPa, respectively. When introducing the same amount of ash activated for 1.5 hours into the solution with a corresponding decrease in cement consumption, strength increases from 15.2 to 16.5 and 19.1 MPa, respectively.

3. It was found that the compressive strength of foam concrete of the control composition (kg/m3): cement - 320, ash - 320, water - 200, was: after steaming - 2.8 MPa, after autoclave treatment - 3.4 MPa. When using ash activated for 0.5% for 1 and 2 hours, the compressive strength after heat treatment was 3.1, 3.9, and 4.3 MPa, after autoclave treatment, 3.7, 4.5, and 5.3 MPa.

4. It was found that the introduction of ash activated for 2 hours together with calcium chloride in the amount of 1; 2 and 3% into the composition of foam concrete makes it possible to increase the compressive strength of foam concrete after hardening for 28 days from 4.8 to 5.3; 5.5 and 6.1 MPa, respectively.

5. It was established that to obtain wall blocks with a density of 700 kg/m3 and a compressive strength class of B2.5, suitable for use in seismically hazardous zones, it is necessary to use ash activated for 0.5 h with the addition of 1% calcium chloride from the mass of cement.

6. Visual inspection of the microstructure of the samples at equal magnification (especially at 500- and 1000-times magnification) showed that autoclave treatment provides a denser microstructure than treatment in a steam chamber.

7. By analyzing the X-ray diffraction patterns of the samples, it was established that the reflexes d = 4.92 A°; 2.63 A° and 1.93 A° inherent in portlandite Ca(OH)2 are present in the non-autoclaved sample, but absent in the autoclaved one, which is due to its complete binding into hydro silicates, which ensures higher strength of the material

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