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PERFORMANCES OF HIGH POROUS CELLULAR CONCRETE

Abstract: the widespread use of cellular concrete for enclosing structures forces researchers to develop ways to improve their performance and durability. Compositions of aerated and foam concrete with the use of waste heat power engineering have been developed. The optimal formulation ratios have been identified that contribute to the creation of a rigid interpore matrix and water-repellent pore protection. The regularities of the synthesis of aerated concrete and foam concrete were established, which consist in optimizing the processes of structure formation through the use of a polymineral cement-ash binder and a pore-forming agent. The mix composition intensifies the process of hydration of the system, which leads to the synthesis of a polymineral highly porous heterodispersed matrix. The increased activity and granulometry of aluminosilicates predetermine an increase in the number of contacts and mechanical adhesion between particles during compaction, strengthening the framework of the interpore partitions. The mechanism of the influence of the composition of the concrete mix on the microstructure of the composite is established. The calculated sound insulation of airborne noise shows sufficient characteristics for using aerated concrete blocks as enclosing structures. One of the main advantages of aerated concrete is its low thermal conductivity, which is especially important from the point of view of ensuring the energy efficiency of buildings and structures. Even in spite of the high values of open porosity of the developed aerated concrete, the rigid frame makes it possible to achieve almost 2 times higher frost resistance characteristics than that of the reference specimen.

Keywords: cellular concrete, porous aggregate, ash and slag mix, sound insulation, frost resistance, water absorption

Introduction

Cellular concretes are effective building materials that are widely used for the manufacture of foam and cellular blocks [1-2]. Cellular concrete blocks have good heat and sound insulation characteristics and can be used for the construction of enclosing and load-bearing wall structures [3-4]. The insulating properties of these concretes have been sufficiently investigated in the recent literature [5-7]. But such performance characteristics as frost resistance and water absorption in cellular concrete have rather low values [8-9]. This is due to the high porosity of cellular concrete, while the higher the open porosity, the worse these characteristics [10-11].

Proceeding from this, it is important to design composites with a given porous structure with the necessary characteristics of durability [12-13]. At the present stage of development of building materials science, this is possible only as a result of controlled formation of macro-, micro- and nanostructures. At the same time, a prerequisite for the scientific development of modern composites is the utilization of industrial waste with the simultaneous minimization of cement consumption, which contributes to care for the preservation of the environment [14-15].

The most important structural feature of cellular materials is open pores, in which moisture can accumulate, and in the case of alternating freezing and thawing, this leads to the destruction of the structure [16-17]. Existing ways of protecting aerated concrete enclosing structures are mainly aimed at constructive protection of the outer surface, for example, cladding. However, this causes additional money and labor costs [18-19]. Accordingly, it is necessary to create highly porous structural materials while ensuring water-repellent properties at the design stage of materials [20-21].

This can be achieved through the use of effective water repellents [22-23]. The creation of high-strength interpore partitions of cellular concrete is especially promising [24-25]. Considering that the subject of the work is aimed at creating environmentally friendly composites, it is necessary to minimize energy consumption in the production of cellular concrete, which means that high-cost autoclaving should be eliminated.

Based on the foregoing, the study outlined a working hypothesis about the possibility of developing non-autoclave durable cellular concretes as a result of the controlled formation of macro-, micro- and nanostructures through the use of polymineral systems and a water repellent.

Methods and materials

Portland cement CEM I 42.5N, quicklime and purified ash and slag mix (ASM) were used as components of the composite binder (CB). Expanded vermiculite and quartz sand (both with a fraction of 1.25 mm) from the deposits of the Russian Primorsky Krai were used as aggregates. Powder superplasticizer Pantarhit PC 160 was used to reduce the water demand of the concrete mix while maintaining its required workability. To reduce the shrinkage deformations of cellular concretes, polypropylene fiber manufactured by Universum-DV LLC (Primorsky Krai) was used. The Etalon foaming agent and PAP-1 aluminum powder were used as blowing agents. To regulate the setting time of the aerated concrete mass, two-water gypsum was introduced, obtained by grinding gypsum stone. Calcium chloride has also been used to control the rate of outgassing and setting rate. To reduce water absorption of highly porous concrete, an AMSR-3 water repellent was used.

The particle size distribution of powdery substances was carried out on a laser diffraction particle size analyzer "Analysette 22" (Germany). The determination of the specific surface area of raw materials was carried out on a PSKh-11 device. The study of the microstructure of raw materials and synthesized composites was carried out on a scanning electron microscope TESCAN MIRA3 (Czech Republic). The compressive strength was measured on cubic specimens $100 \times 100 \times 100$ mm in size. The compressive strength of an individual specimen was calculated by dividing the value of the breaking load by the working area of the plate. The arithmetic mean of the compressive strength was calculated for the four largest results of the study of the six test cubes. The average density of concrete samples was determined as follows: 3 cube samples with an edge of 70 mm, identical in terms of hardening conditions, were weighed with an accuracy of 0.5% and the dimensions of the faces were measured with a caliper (average of 3 measurements – two parallel faces on one side and a height middle of this side). The average density was calculated by dividing the measured mass by the calculated volume. The water absorption of the synthesized composites was investigated on specimens with dimensions $70 \times 70 \times 70$ mm at the age of 28 days. The study of frost resistance was carried out according to the first basic F1 method in accordance with the Russian standard GOST 10060 on specimens of $100 \times 100 \times 100$ mm. The samples were immersed in water, first at 1/3 of the height for a day, then at 2/3 of the height for a day, and then completely immersed in water for two days. Then the specimens were placed in a Polair CV-105S freezer at a temperature of -18°C . Each freezing cycle lasted 4 hours, the thawing cycle at a temperature of 20°C – 2 hours, which meets the requirements for lightweight concrete. The frost resistance grade was evaluated by the value of the compressive strength after a certain number of freeze-thaw cycles. The thermal conductivity of the specimens was evaluated using the hot disk transition plane method in accordance with ISO 22007-2 [26]. The Hot Disk TPS 2200 (Sweden) device consists of two main parts: the main Hot Disk device and the temperature sensor. Thermal properties can be calculated from the change in temperature during the measurement period [27-28]. Due to the high sensitivity to moisture content of the material, the specimens were oven dried and cooled to room temperature under zero humidity conditions. For measurements, cubic specimens with an edge length of 40 mm were used.

Results and discussion

To control the structure formation of the cement composite, it is necessary to use new raw materials. Taking into account that huge dumps of hydro-removed ash-and-slag mix have been accumulated in Russia, the authors have developed a technology for their four-stage purification followed by the production of an aluminosilicate additive (AD), as mentioned earlier [29]. With the use of AD, as well as two types of aggregates, compositions of insulating, structural-insulating, and structural cellular concrete were developed (Table 1). Compositions 1, 3, 5, 7, 9, 11 were used to make foam concrete, and compositions 2, 4, 6, 8, 10 and 12 were used for aerated concrete. Dispersed reinforcement was used for compositions 3, 4, 7, 8, 11, 12. As an object of comparison, a reference composition was made from traditional aerated concrete grade D300.

Quicklime is a component of the binder and can increase the efficiency of the blowing agent. Calcium chloride and gypsum dihydrate are used to control the rate of outgassing and setting rate.

Foam concrete mixes were prepared as follows. First, the cement, ASM and aggregate were mixed in a laboratory mixer for 10 minutes. Then, water and superplasticizer were gradually added to the dry mix with continued stirring. Once the mixture became liquid and began to show adequate consistency, the polypropylene fiber (if present) and the pre-made foam were added to the mixer and mixed for another five minutes to evenly distribute the fibers. The mix was then poured into molds without a seal. The cast samples were covered with plastic sheets and held at 18°C for 24 hours,

after which they were removed from the molds. Then the specimens were cured up to the age of 28 days in laboratory conditions.

The aerated concrete mix was prepared using the following technology. The original dry components were loaded into the mixer and mixed for 5 minutes, and then water was added and mixed for another 3 minutes. Aluminum powder and lime react with an alkaline cement slurry, and this chemical process produces calcium salts (aluminates) and hydrogen gas, which forms pores. The water temperature was 45°C, which is necessary to regulate the process of cement hydration. The mixture was poured into a previously prepared mold (cleaned and greased) with a size of 400 × 400 × 400 mm. The volume of the poured mix was taken taking into account the swelling by 1/3. After pouring the aerated concrete mass, its intensive swelling began, which lasted 10-15 minutes. In order to avoid the formation of a hump, which leads to material loss, the autofrettage technology was used (the form was covered with a lid). In order to avoid possible subsidence of the massif and to ensure its plastic strength, the mold was placed in a heat holding chamber at 40-60°C for 8 hours.

The absorption of water from the concrete mix by vermiculite aggregates during preparation and pouring into molds leads to a decrease in workability. Moreover, the higher the roughness and specific surface area of the porous filler, the more the workability decreases. The creation of equally mobile mixtures was achieved by varying the amount of mixing water and polycarboxylate superplasticizer.

Table 1

Developed compositions of cellular concrete

Components, kg/m³	Mix ID												Ref
	Insulating composites				Structural and insulating composites				Structural composites				
	1	2	3	4	5	6	7	8	9	10	11	12	
Portland cement	150	105	125	85	192	130	160	110	240	170	200	140	125
Quicklime	-	45	-	40	-	62	-	50	-	70	-	60	50
ASM	100	100	125	125	128	128	160	160	160	160	200	200	-
Water	100	100	112.5	112,5	128	128	144	144	150	150	180	180	98
Foaming agent	0,8	-	0,8	-	1	-	1	-	1,2	-	1,2	-	-
Aluminum powder	-	0.5	-	0.5	-	0.5	-	0.5	-	0.5	-	0.5	0.5
Gypsum dihydrate	-	2.5	-	2.1	-	3.2	-	2.7	-	4	-	3.5	2.5
Calcium chloride	-	1.5	-	1,3	-	2	-	1.7	-	2.5	-	2.2	1.5
Superplasticizer	1.1	1.1	1.1	1.1	1.5	1.5	1.5	1.5	2	2	2	2	-
Water repellent AMSR-3	0.25	0.25	0.25	0.25	0.32	0.32	0.32	0.32	0.4	0.4	0.4	0.4	-
Expanded vermiculite	35	35	35	35	20	20	20	20	-	-	-	-	-
Quartz sand	-	-	-	-	180	180	180	180	335	335	335	335	205
Polypropylene fiber	-	-	12	12	-	-	12	12	-	-	12	12	-
Water / binder ratio	0.4	0.4	0.45	0.45	0.4	0.4	0.45	0.45	0.4	0.4	0.45	0.45	0.56

Fig. 1 and 2 show the values of compressive strength and density for all investigated developed compositions according to Table 1 (13 compositions of 6 specimens each), where there is a direct relationship between the compressive strength and the density of cellular concrete

Fig. 1. Compressive strength of developed compositions

Fig. 2. Density of developed compositions

It should be noted that aerated concrete specimens show the lowest both compressive strength and density. The addition of polypropylene fiber to concrete is an effective means of increasing strength characteristics with little effect on density. In addition, although replacing vermiculite with quartz sand increases the compressive strength, the density also increases due to the improved packing of particles, which will obviously have a negative effect on the sound and heat protection characteristics.

The calculation of airborne noise insulation was carried out for external walls made of aerated concrete blocks of the developed composition 4 with a density of 329 kg/m^3 and a thickness of 600 mm. The airborne sound insulation, which depends on the surface density, was calculated according to the Russian standard GOST R 56769-2015, which is a modified version of ISO 717-1: 2013. It should be noted that the one-number parameter of airborne noise insulation according to the standard is calculated for a frequency of 500 Hz. This parameter is the airborne noise insulation index R_w , which is calculated by the elements of the enclosing structures of buildings and structures in accordance with the requirements of the Russian standards GOST R ISO 10140-2-2012 and GOST 27296-2012. Also, additional terms of spectral adaptation are taken into account, which make it possible to expand the range of the studied frequencies to 50-5000 Hz.

According to the Russian standard SP 23-103-2003, the airborne noise insulation index for single-layer structures is calculated based on the calculated frequency response. The frequency response is depicted as a broken line ABCD. Here, A is the corrected reference sound pressure level. The coordinates of point B are determined according to the reference data of SP 23-103-2003, depending on the density of the material of the enclosing structure and its thickness. Frequency corresponding to point B:

$$f_B = \frac{40000}{h} = \frac{40000}{600} = 67 \text{ Hz}$$

This value is rounded to the geometric mean one-third octave range, within which the found frequency is located (63 Hz). The surface density of the fence is calculated as the product of its thickness and the density $m = 329 \times 0.6 = 197 \text{ kg/m}^2$. According to the tabular data of the Russian standard SP 23-103-2003, in accordance with the surface density and strength class (B5), it was found the coefficient K equal to 1.7. Accordingly, the equivalent value of the areal density is $197 \times 1.7 = 336 \text{ kg/m}^2$, and the value $R_B = 20 \log 336 - 12 = 39 \text{ dB}$. To the right side of point B, drawn a segment with a slope of 6 dB per octave to point C with a coordinate on the ordinate axis is 65 dB. Thus, it was obtained a graph of the dependence of the airborne noise insulation index on the frequency range, shown in Fig. 3.

Fig. 3. The graph of the dependence of the airborne sound insulation index on the frequency range (specimen 4)

For comparison, similar graphs were also built for the structural, and structural and insulating composition. Structural and insulating composition of foam concrete 7 has the same frequency corresponding to point B at 63 Hz. However, the surface density will be: $m = 602 \times 0.6 = 361 \text{ kg / m}^3$. The equivalent value of the areal density is $361 \times 1.7 = 614 \text{ kg / m}^3$, and the value $R_B = 20\lg 614 - 12 = 44 \text{ dB}$. The graph of the dependence of the airborne noise insulation index on the frequency range is shown in Fig. 4.

Fig. 4. The graph of the dependence of the airborne sound insulation index on the frequency range (specimen 7)

For a specimen of aerated concrete of composition 12, the frequency corresponding to point B:

$$f_B = \frac{40000}{h} = \frac{39000}{600} = 65 \text{ Hz}$$

This value is rounded to the geometric mean one-third octave range, within which the found frequency is located (63 Hz). The surface density of the fence is calculated as the product of its thickness and the density $m = 834 \times 0.6 = 500 \text{ kg / m}^3$. According to the tabular data of the Russian standard SP 23-103-2003, in accordance with the density of cellular concrete, it was found the coefficient K equal to 1.6. Accordingly, the equivalent value of the areal density is $500 \times 1.6 = 800 \text{ kg / m}^3$, and the value $R_B = 20\lg 800 - 12 = 46 \text{ dB}$. To the right of point B, drawn a segment with a slope of 6 dB per octave to point C with a coordinate along the ordinate at 65 dB. Thus, we obtain a graph of the dependence of the airborne noise insulation index on the frequency range, shown in Fig. 5.

Fig. 5. The graph of the dependence of the airborne sound insulation index on the frequency range (specimen 12)

One of the main advantages of cellular concrete is its low thermal conductivity, which is especially important from the point of view of ensuring the energy efficiency of buildings and structures. The low density achieved in the developed cellular concrete compositions will obviously contribute to the achievement of low thermal conductivity. Fig. 6 shows the results of a study of the thermal conductivity coefficient of the specimens, measured using the method of the transient sensor with a Hot Disk. According to these results, all aerated concrete samples had a thermal conductivity below $0.175 \text{ W / (m} \cdot \text{K)}$, which means that they can be considered good thermal insulation materials compared to traditional concrete. The thermal conductivity of cellular concrete specimens increases with raising density. The thermal conductivity of specimens with practically the same density was also almost equal.

Fig. 6. Thermal conductivity coefficients of the developed cellular concrete

The results confirm the well-known statement that the thermal conductivity of the specimens strongly depends on the density of the material, regardless of the type of blowing agent used (foaming agent or aluminum powder) [12, 30].

The frost resistance of the developed compositions was assessed by the change in the compressive strength of the specimens after a different number of freeze-thaw cycles (Table 2). The analysis of the variation in the strength parameters and the mass of the specimens relative to the initial characteristics is presented in Table 3.

Table 2

Change in the compressive strength of cellular concrete when tested for frost resistance

Mix ID	Compressive strength (MPa) after the number of freeze-thaw cycles					
	0	25	50	75	100	125
Insulating composites						
1	1.1	1.0	0.9	0.8	0.7	-
2	1.1	1.0	0.9	0.8	0.7	-
3	1.5	1.3	1.1	0.9	0.8	-
4	1.0	1.0	0.9	0.8	0.7	-
Structural and insulating composites						
5	4.0	3.6	3.2	2.9	1.9	-
6	4.3	4.2	3.8	3.2	2.2	1.6
7	4.9	4.6	4.1	3.3	2.2	1.5
8	4.0	3.7	3.3	2.7	1.8	-
Structural composites						
9	7.6	7.0	6.5	6.0	5.1	4.4
10	7.5	6.8	6.4	5.8	4.7	4.2
11	7.8	7.1	6.7	6.1	5.3	4.4
12	7.6	6.9	6.5	5.9	5.3	4.3
Ref	1.0	0.8	0.5	0.3	-	-

Table 3

**Change in the properties of cellular concrete during testing for frost resistance
(in% of the initial value)**

Mix ID	Change in compressive strength after the number of freeze-thaw cycles,%					Change in weight after the number of freeze-thaw cycles,%					Frost resistance grade
	25	50	75	100	125	25	50	75	100	125	
Insulating composites											
1	-10	-10	-12	-15	-	-1.0	-1.7	-2.0	-2.4	-	F75
2	-10	-10	-12	-15	-	-0.8	-1.6	-1.9	-2.3	-	F75
3	-11	-20	-19	-14	-	-1.0	-1.4	-1.7	-2.3	-	F75
4	-2	-10	-16	-16	-	-1.1	-1.5	-1.8	-2.4	-	F75
Structural and insulating composites											
5	-10	-10	-13	-33	-	-1.2	-1.5	-1.7	-2.2	-	F75
6	-5	-10	-17	-34	-37	-0.7	-1.1	-1.4	-1.9	-2.4	F100
7	-6	-12	-20	-29	-41	-0.7	-1.0	-1.3	-1.7	-2.3	F100
8	-8	-13	-22	-29	-	-1.2	-1.5	-2.0	-2.6	-	F75
Structural composites											
9	-8	-14	-21	-33	-42	-0.8	-1.2	-1.5	-1.9	-2.5	F100
10	-9	-15	-23	-37	-44	-0.9	-1.3	-1.7	-2.0	-2.4	F100
11	-9	-14	-22	-32	-44	-0.6	-1.0	-1.4	-1.8	-2.3	F100
12	-9	-14	-22	-30	-43		-1.1	-1.5	-1.9	-2.4	F100
Ref	-20	-29	-38	-	-	-1.6	-2.0	-2.3	-	-	F50

Analyzing the experimental data given in Tables 2 and 3, it was came to the conclusion that even in spite of the high values of open porosity of the developed cellular concrete, the rigid frame makes it possible to achieve almost 2 times higher frost resistance characteristics than that of the reference specimen. The use of the water-repelling additive AMSR-3, which is a 30% solution of sodium methylaluminosiliconates, according to the declared technical characteristics, 5 times reduces the water absorption of the hardened concrete composite by 28 days. The mechanism of operation of the additive in the concrete mixture is based on the settling of sodium methylaluminosilicate particles on the inner surfaces of the capillaries during chemical interaction during the hydration of clinker minerals. This forms microscopic water-repellent coatings. During interaction with hydration products, these films take a reciprocal angle, and, accordingly, surface tension forces push the liquid out of the pore space to the surface. Accordingly, this makes it possible to count on the increased durability of the developed foam and aerated concrete.

The density of cellular concrete, as well as its porosity and water absorption are closely related to each other. With a decrease in density and an increase in porosity, water absorption increases. The water absorption of cellular concrete is shown as a function of density in Fig. 7.

Fig. 7. The relationship between the density of cellular concrete and its water absorption

There is a good relationship between water absorption and density. It was evident that the lower density mixtures absorbed a significantly higher percentage of water than the higher density mixes. This property requires further study as it may be related to its durability. For example, when cellular concrete specimens are exposed to moisture in freeze-thaw cyclic conditions, the absorbed water inside the specimen can freeze and cause damage to the concrete. However, as shown by the experimental results given in Tables 2-3, due to prescription resources, high frost resistance characteristics were obtained.

The porosity of cellular concrete is the sum of macro- and micropores (including capillary and gel pores) inside the concrete. Water in larger capillary pores and air bubbles is critical and more susceptible to frost. Fig. 8 shows the relationship between water absorption and open porosity of aerated concrete. The increase in porosity has led to an increase in water absorption. It should be noted that the absorption values in Fig. 8 are based only on the volume of open accessible pores that have been exposed to water (the water content of a saturated specimen is expressed as a percentage of its mass).

Fig. 8. The relationship between the open porosity of cellular concrete and its water absorption

Thus, comprehensive studies of performances make it possible to judge the durability of the developed materials. The material during operation, obviously, will not undergo significant moistening (due to the formulation of the composition). Accordingly, indicators such as water absorption, frost resistance (which depends on water absorption) and thermal conductivity (which also depends on humidity) are optimized.

Conclusions

A technological solution has been substantiated and experimentally confirmed, which ensures the production of non-autoclave aerated and foam concretes with improved performances due to the use of a composite binder containing purified aluminosilicates obtained from ash and slag mix, as well as expanded vermiculite. It has been established that cellular concrete has a sufficient degree of durability, which is especially important for operation in areas with high humidity. The relationship between the components of the binder, the ratio of porous and dense fine aggregate and the processes of structure formation has been revealed, which can significantly increase the performances.

- it was revealed that the use of an ash-and-slag mixture previously purified from impurities, replacing Portland cement by 40-50%, as well as expanded vermiculite, optimizes the microstructure of the cellular composite, while the use of a water repellent in the mix makes it possible to reduce water absorption and, accordingly, to increase frost resistance and durability of non-autoclaved cellular concrete;

- the parameter "aggregate ratio" has the maximum effect on the dynamics of the compressive strength and density of the composite. At the same time, an increase in the content of expanded vermiculite leads to a decrease in density, and an increase in the content of quartz sand contributes to the strengthening of concrete;

- a wide range of cellular concretes based on the developed composite binder has been developed, providing the specified strength and performances. Rational compositions were designed on the basis of certain natural and man-made resources of the Primorsky Krai, which have high adhesion to the cement matrix, while simultaneously providing highly porous structures, in addition, they are characterized by a reduced consumption of cement using an aluminosilicate additive and a complex of modifiers, which makes it possible to obtain wall products with grades according to density D300 – D900 and strength classes B1 – B5.

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