International Journal of GEOMATE, Sept. 2022, Vol.23, Issue 97, pp.131-138
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.97.3334
Geotechnique, Construction Materials, and Environment

MODIFIED AERATED CONCRETE BASED ON MAN-MADE WASTE

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*Corresponding Author, Received: 01 April 2022, Revised: 13 May 2022, Accepted: 02 Aug. 2022

ABSTRACT: This article presents the results of experimental studies on aerated concrete based on industrial waste with improved operational, physical, chemical and mechanical properties; modified homogeneous structures are obtained in this material as a result of its compaction and hardening. The structure of the modified aerated concrete and its influence on the physical, mechanical and hydrophysical properties are studied in detail. Aluminium powder is used as a foaming agent. The content of active aluminium is 82%. To give the powder hydrophilic properties, it is treated with an aqueous solution of surfactants. The use of complex organometal modifiers in products made of modified and non-autoclaved aerated concrete with industrial waste, such as phosphogypsum, significantly increases the likelihood of obtaining high-quality products by controlling the processes of gas evolution and structure formation under the impact of the organometal modifier.

Keywords: Aerated concrete, Coremaking, Thermal insulation, Energy conservation, Industrial waste, Environmental safety, Structure formation.

1. INTRODUCTION

Cellular concretes are known to have low thermal conductivity, so the heat of binder hydration is not sufficient for an accelerated gain in structural strength. Under these conditions, the hydration of cement, from the point of view of thermokinetics, is a slow process with weak thermal effects and does not provide intensive structural formation. However, efficient activation can be facilitated by not only binders but also solid powdery wastes, in particular phosphogypsum, as well as the use of multicomponent chemical additives. These include man-made waste from alcohol production (post-alcohol stillage, hydrophobic) and milk production waste (whey, hydrophobic). The combination of such dissimilar substances can be achieved with an emulsification process to obtain a direct oil-in-water emulsion.

Cement, lime, ground blast furnace slag with hardening activators (lime and gypsum), and nepheline cement are used as binders for the production of cellular concrete. Ground quartz sand, fly ash from thermal power plants, and ground blast furnace slag is used as siliceous components. The introduction of a siliceous component can reduce binder consumption and improve the quality indicators of aerated concrete. Normal quartz sand should contain at least 80% silicon dioxide SiO_2 and no more than 0.5% mica and 0.3% silt and clay particles. To increase reactivity, the sand is subjected to wet grinding to a specific surface area of 2000-3000 cm^2/g. Ground granulated blast furnace slag and fly ash from thermal power plants are also widely used industrial wastes. Fly ash must contain at least 40% silicon dioxide SiO_2, no more than 30% aluminium oxide Al_2O_3, no more than 15% ferric oxide Fe_2O_3, no more than 3% magnesium oxide MgO, and no more than 2-3% compounds with sulfur (in terms of sulfur trioxide SO_3). When introduced into the concrete mixture, they interact with its components and release gas (hydrogen, oxygen, carbon dioxide), which increases the volume of the aerated concrete mixture.

For the production of aerated concrete, aluminium powder is used as a blowing agent and is preliminarily activated by treatment with an aqueous solution of surfactants (sulfite-alcohol barge, rosin oil, sulfonic acid, etc.). Aerated concrete is cellular concrete and is used for the thermal insulation of pipelines, building materials and products [1-4].

However, when surface-active substances (surfactants) are adsorbed on cement grains, the formation of structures in cement-water-surfactant systems is delayed. Therefore, it is necessary to introduce a hardening accelerator of cement stone into the composition of the complex additive. The use of a complex of technical methods, such as activation of a binder and solid powdered waste (phosphogypsum) followed by their combination with the direct emulsion of the water-repellent agent in an aqueous solution of the water-repellent agent with salts of inorganic acids, should enhance the effect the multicomponent additive components on cement systems. This ensures the production of aerated concrete products based on industrial waste with improved construction and technical properties [5-8].

To regulate the setting and hardening time, some additives are introduced into the composition of cellular concrete mixtures: natural gypsum, potassium carbonate K_2CO_3 potash, water glass, sulfite-alcohol stillage, etc.

Manufacturing products of cellular concrete have been predominantly developed in CIS countries. Cellular concrete is produced at factories using injection technology. This technology facilitates the formation of products in the form of liquid mixtures containing dry components, with up to 50-60% water by weight. The production process includes the addition of a binder, a silica component, aluminium powder in the form of a paste, additives and water, mixing them within 3-5 minutes and pouring the prepared mixture into metal moulds. The mixture is not added to the top of expansion moulds. A part of the mixture bulges over the top of the mould and forms a hump. To accelerate gas evolution and solidification of the mass after expansion, the temperature of the mixture during pouring should be approximately 40 °C. After 3-6 hours, the hump is cut off with a string or saw, and the mass is cut into separate blocks. When the mass is cut into side blocks, the moulds are tilted. After that, the products in moulds are sent for heat treatment [9, 10].

For this reason, the vibrocompression process was developed. With this technology, in the course of mixing in the mixer and foaming in the mould, the mixture is subjected to vibration, which causes it to liquefy. This makes it possible to reduce the amount of mixing water by 25-30% without losing full expansion, and with increases in the concentration and temperature of the mixture, the process of gas evolution and expansion is completed within 3-5 minutes (instead of 15-50 minutes with the use of the injection technology). After vibration stops, the mixture quickly loses its mobility, and its strength rapidly increases. This allows the material to be cut into blocks within 0.5-1.5 hours. The autoclaving time is also reduced. As a result, the existing plant productivity can be increased by 25-30%, and the cost of production can be reduced by 5-10%, while its quality is improved. The introduction of this technology does not require a radical reconstruction of the existing lines for the production of cellular concrete. The use of vibration technology is currently the most promising method.

The use of vibration technology such as periodic vibration, vibration treatment with shield braking, step changing the vibration frequency, and Vibro forming mixtures that are removed during mixing can have positive effects. A certain effect is also achieved when using sands with different particle-size distributions, which makes it possible to obtain denser and stronger intergranular partitions [11, 12, 13].

At the Department of Building Materials of the MECI, a new technology for manufacturing cellular aerated concrete using cold mixes (t = 18-22 °C) with surfactant additives and a small amount of mixing water was developed. The use of cold mixes makes it possible to reduce the amount of mixing water by 25-30% without compromising the workability of mixes in the course of mixing. Blistering in the mixer does not occur at lower temperatures since the binder setting and the gas release in the mixture are significantly delayed. When the mixture is placed in the mould, it vibrates and heats up in the electromagnetic field of an inductor. These processes are sharply accelerated, and the mixture quickly swells and hardens. This allows the process of aerated concrete forming to be controlled, which is very important for improving product quality. Cold mixes can be mixed not in special aerated concrete mixers but conventional forced-action mixers. After moulding, the products do not have a hump and have sufficient strength for them to be cut into blocks [14, 15].

In world practice, aerated concrete is used in the reconstruction of old buildings when additional insulation in enclosing structures and increasing the number of floors in the building are required while maintaining the existing foundations. In individual cottage houses, cellular concrete is used from the basement to the roof, including in bathrooms. There is substantial opportunity for the use of cellular concrete of a low average density when insulating old buildings [7]. Products have a "tongue-and-groove" system and various special profiles for assembly and mounting [9-12].

Effective aerated concrete products are produced using chemical modifiers and heat and moisture treatments [16-19].

2. RESEARCH SIGNIFICANCE

There are several ways to improve the physical, chemical and mechanical properties of aerated concrete, and they have advantages and disadvantages. In the search for environmentally friendly solutions and green technologies in the development of new building materials, taking into account the economic aspect of production, there is an urgent need to develop and implement a new composition of aerated concrete using man-made industrial waste.

3. MATERIALS AND METHODS

Aerated concrete is a building material with unique properties. It is an artificial stone with a porous structure. It consists of cement, sand, lime, gypsum and aluminium powder (a gas former). To manufacture modified aerated concrete, Portland cement was used as a binder. Quartz sand and glass were used as the siliceous components.

Aluminium powder was used as a blowing agent, complying with the requirements of SS 5494-95 "Aluminium powder. Specifications". The content of active aluminium is 82%. The aluminium powder was ground to a fineness of 5000 cm^2/g. The factory aluminium powder was covered with a thin film of paraffin and therefore was not wetted by water. To give the powder hydrophilic properties, it was treated with an aqueous solution of surfactants.

For manufacturing aerated concrete based on man-made waste, the following components were used:

- phosphogypsum: waste products of phosphoric acid production;
- post-alcohol stillage: waste from the production of ethyl alcohol;
- whey: dairy production waste;
- water-repellent modifier – post-alcohol stillage - phosphogypsum plus sodium thiosulfate (WM-PS-PhG-STS);
- salts of inorganic acids: chemical production wastes.

The method of manufacturing aerated concrete blocks based on industrial waste has a closed cycle and includes the following main steps:

- preliminary mixing of the components dosed by weight: sand, cement with water and phosphogypsum in an aerated concrete mixer within 3-5 minutes;
- preparing an aluminium suspension in an aqueous solution of a surfactant (organometal modifier) to remove wax from the surface of aluminium powder in the mixer;
- mixing the resulting suspension of aluminium in an aqueous solution of the modifier with the main components of the aerated concrete mixture in an aerated concrete mixer within 1-3 min;
- pouring thoroughly mixed aerated concrete mixture into moulds at an air temperature of +18 to 20 °C in the shop;
- allowing the aerated concrete mass to swell in stationary form within 30-50 minutes;
- cutting the "hump" and cutting the mass into blocks by a special cutting machine with metal strings that perform reciprocating and rotational movements;
- grinding the cut "hump", i.e., the upper part of the mass and returning it to the mixer for mixing with the main components of the mixture;
- heat treating the cut blocks in a chamber with a heat-insulating casing. The hood reduces energy consumption compared to that heat treatment in autoclaves. Strengthening occurs within 5-6 hours. The use of the heat-insulating casing protects aerated concrete products against drafts and heat loss, which makes it possible to obtain a stable quality of blocks;
- laying and packaging finished blocks and shipping finished products to the warehouse;
- sending rejected products to the grinder and returning to the mixer for mixing with the components of the mixture. Rejected products are returned to the production process.

The control composition is shown in Table 1. The working components of the prescribed mixture are shown in Table 2.

Table 1 – Control composition of aerated concrete mixture

Cement	Sand	Aluminium powder
245	250	0,35

Table 2 – Working composition of aerated concrete mixture

Consumption of materials per 1 m^3 of aerated concrete, kg				
Cement	Sand	Aluminium powder	Phosphogypsum	Phosphogypsum WM-PS-PhG-STS
245	300	0,35	50	5

For the microstructural analysis of samples of the obtained modified aerated concrete, an FEI Quanta 200 SEM scanning electron microscope (manufactured in Switzerland) was used.

Not only microstructural but also X-ray phase studies were carried out. The results of the X-ray phase studies are shown in Figures 5 and 6.

The studies were carried out to identify the effect of the modified cellular concrete structure on its frost resistance (State Standard 10060-2012 "Concrete. Methods of determining frost resistance"). For comparison, cellular concrete was made using traditional techniques. The average density of cellular concrete was 700 kg/m3. The criteria of concrete frost resistance state that the compressive strength of concrete Rcp after the test cycles can be reduced by no more than 15%, and the weight loss of the samples can be no more than 5%. The coefficient of thermal conductivity of the obtained aerated concrete was determined in the dried state and for materials with different humidities according to SS 7076-99 "Materials and building products. Methods of determining thermal conductivity”.

Water resistance is known to be determined by the softening coefficient, and the softening coefficient is equal to the ratio of the strength in the water-saturated state to the strength in the dry state. The vapour permeability of aerated concrete was studied by SS 25898-2012 "Building materials and products. Methods of determining vapour permeability". Samples sized 100x100x20 mm were used for the experiment. Their side faces were isolated with paraffin-ozone mastic to exclude capillary absorption of water. Then, the samples were placed in a vessel above the water so that the sample did not touch it.

Tests were carried out for water absorption and capillary absorption (State Standard 12730.3-78 "Concrete. Methods of determining water absorption").

4. RESULTS

In the course of this work, concrete mixtures were prepared with a cake spread diameter of 14 cm according to the Suttard viscometer. The properties of modified aerated concrete with non-autoclave hardening at the age of 28 days are presented in Table 3.

Table 3 – Modified aerated concrete properties

Concrete type	W/S ratio	Density grade	Compression ultimate strength, MPa	Concrete strength grade 1
Control (traditional)	0.7	D700	3.3	B2.5
Modified	0.6	D700	4.5	B3.5

The analysis of the obtained results shows that the compressive strength of the modified cellular concrete is 36% higher than that of the control (traditional) composition. This occurs due to the organometal modifier, which makes it possible to reduce the W/S ratio by 14% and to strengthen the cement matrix of the interpore partitions of cellular concrete.

The capillary absorption of water by modified cellular concrete (18%) and traditional cellular concrete (24%) was determined by the known method. The results of testing cellular concrete for water absorption and capillary suction are shown in Figures 1 and 2.

The analysis of the obtained results shows that modified aerated concrete has better water absorption and capillary suction characteristics: the water absorption and capillary absorption of modified cellular concrete are reduced by 52 and 26%, respectively.

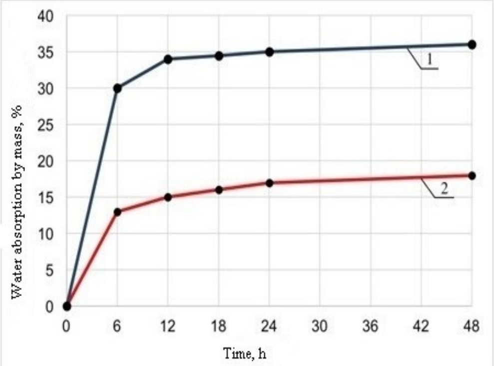

Fig. 1 Water absorption kinetics of modified and traditional cellular concrete: 1 – traditional aerated concrete; 2 – modified cellular concrete

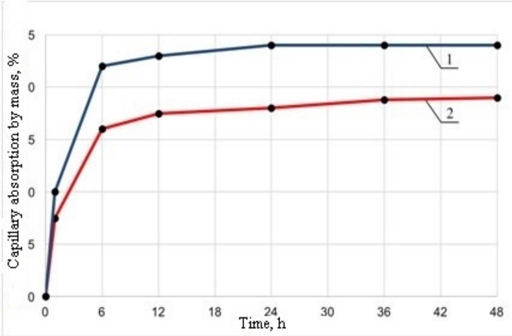

Fig. 2 - Kinetics of cellular concrete capillary suction

1 - Aerated concrete control; 2- modified cellular concrete

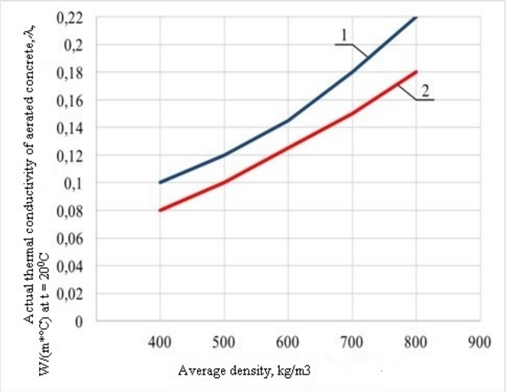

Fig. 3 - Actual thermal conductivity of aerated concrete:

1 - control aerated concrete; 2 - modified aerated concrete. Figure 3 shows that the thermal conductivity coefficient of modified aerated concrete is 0.142 W/(m*°C), which is 22% lower than that of traditional aerated concrete (0.178 W/m*°C) at the same average density of 700 kg/m3. Thus, the experiments show that modifying the aerated concrete structure with water-repellent additives yields positive results. This is expressed by a decrease in thermal conductivity of 25% in comparison with the thermal conductivity of traditional aerated concrete.

The results of the microstructural analysis of samples of the obtained modified aerated concrete are presented in Figure 4.

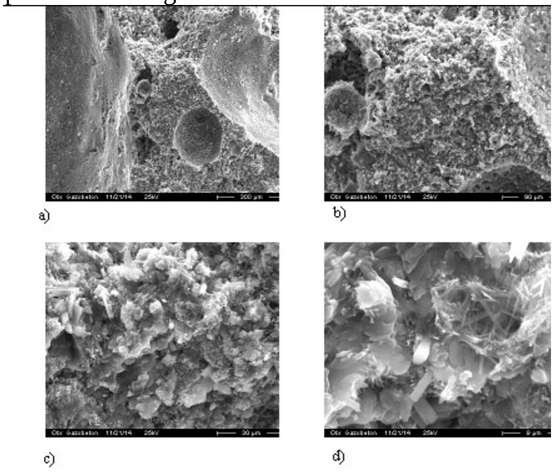

Fig. 4 - Structure of the modified aerated concrete: a - macrostructure; b, c - microstructure

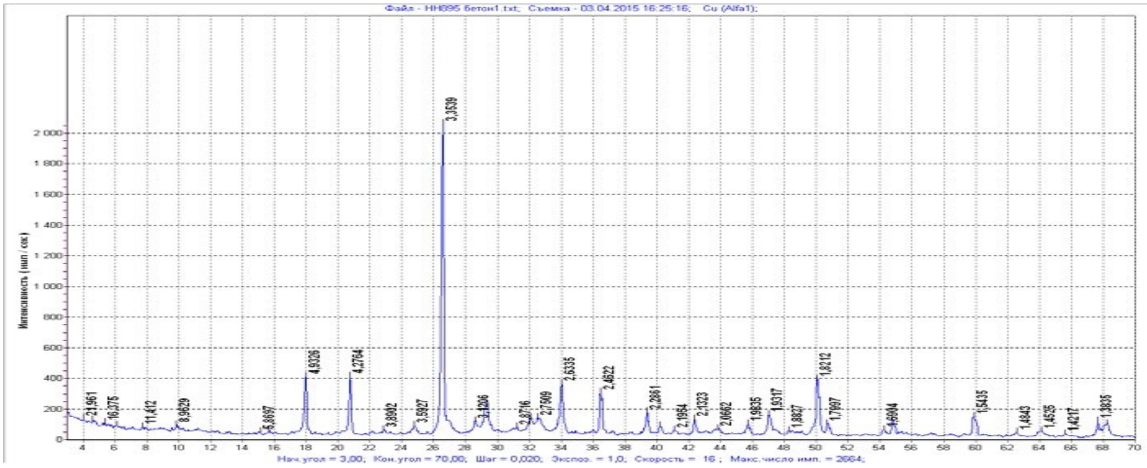

Fig. 5 - X-ray pattern of control (traditional) aerated concrete

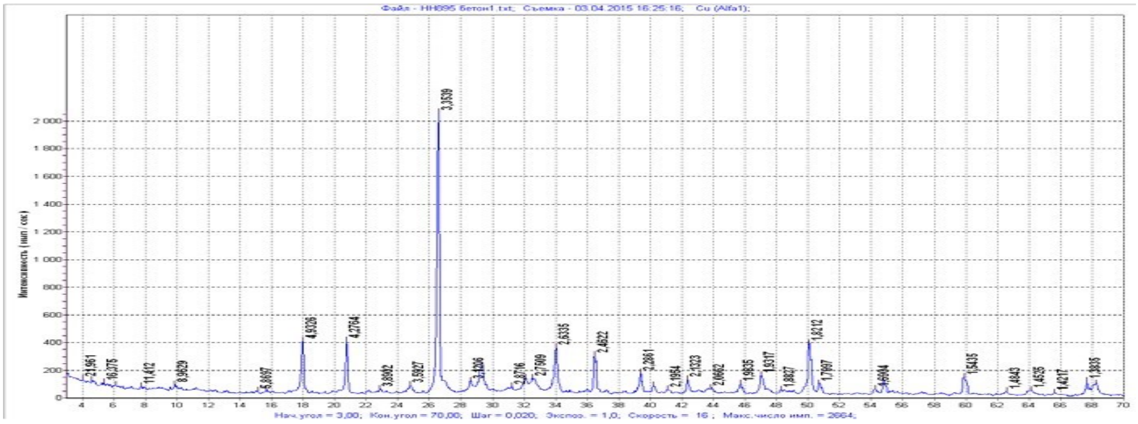

Fig. 6 - X-ray pattern of modified non-autoclaved aerated concrete

The photographs show that the modified aerated concrete differs from the control concrete, showing a more developed and homogeneous finely porous structure. The diameter of even gas pores does not exceed 1 mm. The nature and size distribution of pores in modified aerated concrete obtained by the proposed technology are shown in Table 7. The very noticeable decrease in pore volume due to air entrainment in the cellular mass (almost twofold) can be explained by the positive effect of the hydrophobic modifier, which reduces the energy adsorption of air on the mineral components of the aerated concrete mixture. The spatial frame of aerated concrete is formed by successively filling the volume of concrete with relatively small pores (no more than 1 mm in diameter). The maximum porosity of aerated concrete with an interpore space thickness of 80-100 microns and a pore diameter of no more than 0.8-1.0 mm reaches 75-80%. This porous structure formed by pores of different sizes with hydrophobic partitions significantly reduces the likelihood of pore aggregation and provides increased stability to the system; i.e., the aerated concrete mix does not shrink. Activation of the binder (cement) with phosphogypsum and an organometal modifier makes it possible to control the process of gas formation.

The results of the X-ray phase studies are presented in Figures 5 and 6.

The following compounds were identified from comparison to previous works through analysis of the X-ray patterns in Figures 5 and 6 [20-24]:

- elite C3S with interplanar spacing d=(3.03; 2.78; 2.75; 2.61; 2.18; 1.76; 1.49, etc.)· 10-10 m. Peak d=1.76 characterizes the degree of cement hydration. For the modified aerated concrete, the degree is 91%, and for the aerated concrete of the control or traditional composition, it is 67%. Therefore, the strength of the first concrete is higher, and the other properties are better than those of the second concrete;
- tricalcium aluminate C3A with d= (4.23; 4.08; 2.05; 1.91)· 10-10 m,
- belite βL-C2Sc d= (2.748; 2.609; 2.189; 2.047; 1.98; 1.696)· 10-10 m;
- four-calcium aluminium ferrite C4AFd = (7.32; 2.67; 2.04; 1.92; 1.81; 1.39) 10-10 m;
- quartz: β-SiO2c d =(4.26; 3.35; 1.82; 1.54)· 10-10 m.

According to peak d=3.35, the intensity of this peak in modified aerated concrete is 40% lower than that of the traditional composition. This suggests that quartz sand in the modified aerated concrete was included in the matrix of interpore partitions, strengthened them and reduced shrinkage;

- natural gypsum CaSO4·2H2Oc d = (7.56; 4.26; 1.99; 1.66)·10-10 m;
- calcite CaCO3c d = (3.828; 3.04...3.06; 2.511; 2.301; 1.88)·10-10 m.
- CSH(I) partially crystallized calcium silicate hydrate c d = (12.5; 3.07; 2.8; 1.83)·10-10 m,
- CSH(II)cd = (9.8; 3.07; 2.8; 2.0; 1.83; 1.56)·10-10 m;
- Portland cement Ca(OH)2cd = (4.93; 3.11; 2.63; 1.78-1.79; 1.315)·10-10 m.

Portlandite is a weak link between cementitious materials and corrosion. According to the peak d=4.93, modified aerated concrete contains almost 7 times less portlandite than traditional aerated concrete. It is known to be a soluble substance that can leach out of the material;

- ettringite 3CaO·Al2O3·3CaSO4·32H2Ocd =(9.73; 5.65; 4.704; 3.88; 2.56; 2.21)·10-10 m.

The optimal spatial frame of aerated concrete consists of a cement-sand matrix filled with small pores (no more than 0.8 mm in diameter). The maximum porosity of aerated concrete with an interpore partition thickness of 80-100 microns and a pore diameter of no more than 0.8 mm reaches 76-83%. The use of complex organometal modifiers of the water-repellent type in modified non-autoclaved aerated concrete products with industrial waste significantly increases the likelihood of obtaining high-quality products by controlling the processes of gas release and structure formation due to the organometal modifier.

5. DISCUSSION

The porosity of aerated concrete determines its water absorption, water resistance and capillary absorption during operation. The operational properties of aerated concrete largely depend on the size, shape and surface quality of the pores.

To assess the cellular concrete strength, water absorption, and water resistance, the degree of filling of the pores with water and the rate of capillary absorption were determined.

The analysis of the results shows that the modified aerated concrete has better water absorption and capillary absorption characteristics: the water absorption and capillary absorption of modified cellular concrete are reduced by 52 and 26%, respectively. This is caused not only by the hydrophobic properties of modified aerated concrete but also by the formation of closed pores with a smaller diameter in their volume. The positive results obtained allow us to conclude that modified cellular concrete has the best hydrophysical properties, which, in the course of operation of buildings built with these materials, ensure the environmental safety of people, indoor comfort and high thermal protection of the premises [25].

Another important hydrophysical property is the frost resistance of building materials. It is one of the main factors determining their durability and an integral part of reliability in design. The main reason for the destruction of building structures during alternating freezing and thawing cycles is the formation of ice in the pores of the material. It is known that when water becomes ice, its volume increases, resulting in large tensile stresses in the products.

By changing the pore structure by imparting hydrophobic properties to the material, i.e., modification, it is possible to increase cellular concrete frost resistance. The cellular concrete frost resistance of the modified material is good due to its optimal pore structure. In addition to a large number of gas pores, it also has a significant number of smaller pores, such as air-bearing and capillary pores. Changing the relative humidity of the ambient air combined with the temperature fluctuations leads to the loosening of the structure of the cement-sand matrix and the formation of cracks. The number of various defects also increases, and accordingly, the water absorption, capillary absorption and heat conductivity of aerated concrete increase. Increasing thermal conductivity, as already noted, leads to heat transfer through the walls and increases the greenhouse effect. Therefore, increasing the frost resistance grade increases the environmental safety of aerated concrete during the operation of a building and the entire service life of the material.

On the one hand, capillary porosity and air intake porosity reduce the frost resistance of water-saturated aerated concrete. On the other hand, air intake porosity and cellular porosity with pore size greater than 1 mm increase heat conductivity. Additionally, heat losses through the walls occur due to increasing heat conductivity due to the convective method of heat transfer through the walls during the heating season.

Consequently, decreasing gel and capillary porosity reduces the risks of the destruction of aerated concrete walls during variable freezing and thawing. Reducing the diameter of the cellular porosity reduces heat loss through the walls.

Thus, the use of modified non autoclaved aerated concrete based on industrial waste will ensure environmental safety by significantly reducing heat loss through the walls of buildings during cracking under the impact of frost and the inhomogeneous porous structure of the control aerated concrete.

6. CONCLUSIONS

A new composition of aerated concrete based on man-made waste was obtained. The use of production waste made it possible to reduce the amount of soluble and corroded Portlandite by a factor of 7 compared to that of the control aerated concrete. It was established that the use of industrial waste and an organometal modifier in modified aerated concrete significantly increases the ecological safety of the environment by strengthening the structure and increasing its uniformity and heat-shielding properties.

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