Non-autoclave ash-filled porous concrete for bearing and enclosing structures

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Abstract. Non-autoclaved ash-porous concrete (NAAC), which is enlightened in the article facilitates the reduction of the cost of construction of large-space engineering structures and multi-storey buildings. It is possible due to eliminating the use of expensive porous aggregates, which involves using the porization effect of the concrete mixture in the manufacture of such structures, as well as using of waste from local industry. It also reveals the advantages of using cellular concrete of non-autoclaved hardening, which has a low energy consumption. Such material is showed to be of use in production of load-bearing and enclosing reinforced concrete structures.

1. Introduction
The feasibility of using light concrete in bearing structures instead of heavy concrete comes from a reduction in the load from the own weight of the structures, which saves reinforcement and the concrete itself. For large-space engineering structures and multi-storey buildings, the transition from heavy concrete to light structural concrete allows you to reduce the cost of construction of foundations [1]. At the same time, the reduction in the density of concrete for load-bearing and enclosing structures provides additional thermal protection of internal premises, facilitates the operating conditions of the structures themselves, which stipulates the relevance of the development of such materials [2].

Reducing the cost of lightweight concrete structures is possible due to eliminating the use of expensive porous aggregates and using the porization effect of the concrete mixture in the manufacture of such structures to obtain a concrete structure characterized by the presence of a number of small closed pores, which in turn determines high water and frost resistance. Methods of porizing the concrete mixture based on the use of air-entrapping additives such as neutralized air-entrapping resin, as well as foaming agents, with their relatively small consumption do not significantly reduce the density and material consumption of structures, and with a large number of additives, on the one hand, they are rather expensive (due to the high cost and scarcity of the additives themselves), and on the other hand, they differ in the complexity of making concrete (foam concrete technology).

Of late, due to the increase in the cost of energy resources, there is a profound interest in mineral construction materials with high thermal insulation properties. Such materials include non-autoclaved aerated concrete [3, 4]. Of great interest is the production of cellular concrete of non-autoclaved hardening, which has a low energy consumption, non-waste and environmental cleanliness [5]. However, the shrinkage of non-autoclaved aerated concrete during drying can reach a value of 2-3.5
mm/m. It is significantly affected by the properties of the inter-porous partition [6], which are largely hinged upon the microstructure optimized by fine mineral additives, which ultimately has a positive complex effect on the technology and properties of thermal insulation materials [7]. For example, the addition of phosphogypsum in the composition of non-autoclaved cellular concrete acts not only as a filler, but also as an activator [8]. At the same time, a decrease in the shrinkage of this material with an increase in the content of mineral additives as a part of the cement was observed [9].

Reinforcement with highly dispersed basalt fibers makes it possible to compensate for the main disadvantages of ordinary concrete, i.e. low tensile strength and brittleness (insufficient crack resistance) [10], and, apparently, to reduce shrinkage as well. In [11], the following methods of reducing the shrinkage of concrete were investigated and analyzed: the use of cement with reduced heat release, steel fibers, polypropylene fibers with their preliminary moistening, light aggregate presaturated with water. It is interesting that, in the case of using a natural light aggregate with a grain size of 2-4 mm, pre-saturated with water, the shrinkage of high-strength concrete at the age of 28 days was cut down by about 48% compared to the reference concrete, without changing the compressive strength [11].

The development of the strength of superplasticized cement stone made with an amount of superplasticizer C-3 in the range from 1.0 to 0.25% of the cement mass at a constant value of W/C, as well as 0.27%, indicates that the strength of superplasticized cement stone can be both higher and lower than that of the control mix [12]. There is a technology that does not give rise to shrinkage deformations in the production of aerated concrete wall stones based on concrete crushing waste using injection molding technologies with an average density of 650-750 kg/m$^3$ with an optimal structure [13]. In the process of drying of aerated concrete of non-autoclave hardening, the shrinkage can reach a value of 2.0-3.5 mm/m [14].

Further reduction in the cost of such structures is possible due to the use of waste from local industry and, above all, TPP ash in the composition of concrete. Gas-ash concrete in terms of performance is not inferior to brick and expanded clay concrete, and in some cases in terms of frost resistance and thermal protection are superior to them [13]. The cost of production of gas and concrete products in comparison with light concrete is 50% lower. In the conditions of increasing energy prices, the efficiency of gas-ash concrete will increase more and more in comparison with concrete on aggregates that require high-temperature treatment [15].

There is some experience in obtaining reinforced structures based on gas-ash concrete [16].

However, the use of non-autoclaved cellular concrete with a density of 900-1200 kg/m$^3$ instead of slag and expanded clay concrete with a density of 1600-1800 kg/m$^3$ is hindered by the lack of a regulatory frame structure. To date, there are no indicators of long-term deformability, data on the dynamics of strength and thermophysical indicators, information on the behavior of steel reinforcement in products made of these concretes, etc. In many cases, this makes it impossible to use non-autoclaved cellular concretes instead of concretes on firing aggregates, and in general sharply limits the scope of the former for load-bearing reinforced concrete structures [13]. The way out of this is seen in the production of a new material-non-autoclaved ash-porous concrete (NAAC) with a density of 1600-1700 kg/m$^3$ based on the use of aerated concrete technology, but with fewer gas-forming additives. The use of NAAC of the same average density as conventional light concrete on firing aggregates for reinforced load-bearing structures can be justified by the close values of the total porosity and the associated indicators of elastic and deformative properties, as well as similar working conditions of the reinforcement in these products. At the same time, in comparison with gas-ash concrete, NAAC will favorably differ in greater stability of properties during manufacture, lower consumption of gas-forming additives, and, in comparison with conventional light concrete - the absence of expensive large porous aggregates.

The use of waste from the local industry, in this work, the ash from the Tver TEC-4 hydraulic removal, the total reserves of which in the dumps amount to about 4 million tons, makes it possible to improve the environmental situation in the region, save natural raw materials. The bulk density of TEC-4 ash varies from 700 to 1300 kg/m$^3$. The specific surface area is from 800 to 1200 cm$^2$/g. The
true grain density is from 2.02 to 2.5 g/cm³. According to the classification, the ash of TEC-4 is classified as fine-grained. According to the content of CaO and MgO, as well as SO₃, the ash meets the requirements of the standards.

Conventional aerated concrete technology has certain disadvantages, in particular, an additional operation is required to cut the "hump". At the same time, a significant number of open pores – capillaries - are obtained in the structure of aerated concrete, which reduce the anticorrosive properties of concrete. Therefore, such a technological technique was used as the use of forms with lids, which can serve as the bottoms of the same forms, when they are installed on top of each other. In this case, the forms are additionally covered with film materials from above to avoid the concrete mixture sticking to the bottoms of the overlying forms. With this technology, the operation of cutting the "hump" is not required, and due to a certain compaction of the concrete structure and preventing the release of gases to the surface, the formed pores remain small and closed.

2. Models and methods
A nonlinear three-factor planned experiment B-D₁₃ was used to select the optimal composition of non-autoclaved porous ash concrete. Variable factors are the mass fraction of ash in the mixture of ash and sand A/(A+S), the amount of the gas-forming agent additive-aluminum powder in relation to the mass of cement Al and the water – cement ratio W/C, - varied within the following limits: A/(A+S) = 0-0.6; Al = 0.07-0.11 %; W/C = 0.57-0.69. The ratio of the mass of cement to the mass of aggregates (ash and sand) was constant and equal to 1:2.3. In addition, in all mixes, to increase the plasticity of the mixture during the injection molding method, an additive of the superplasticizer SP-1 was added into the mixing water in a constant amount of 1.5 % of the cement weight. To improve the gas release process, lime was added in an amount of 10 % by weight of cement. The mixing water was heated to a temperature of 60-65 °C before forming the samples. The preparation of the concrete mixture was carried out as follows: cement, previously dried and sifted through a sieve with a cell size of 5 mm, ash and sand, and mixing water were loaded into the mixing vessel. The mixture was stirred with a propeller agitator at 150-200 rpm for 2 minutes. Then the density of the non-porous concrete mixture was determined using a measuring vessel with a capacity of 1 dm³ and the fluidity of the mixture by the size (diameter) of the spread of the cake using a Suttard viscometer. Then the mixture was again discharged into the mixing vessel, the calculated amount of aluminum suspension was added and mixed for another 1 min, after which it was poured into the molds of cubes with an edge of 10 cm at about 90 % of their height. After 2 hours after pouring the mixture into the molds (the porization of the mixture usually ended after 30-40 minutes), the samples were placed in the steaming chamber. After hardening of the samples in the steaming chamber for 8 hours at an isothermal holding temperature of 85 °C, they were stripped and tested. The average density of the samples in the dry state and the compressive strength were determined.

In addition, the design quality coefficient (DQC) was calculated by the formula

\[ \text{DQC} = \frac{R_c}{\gamma_o} \]  

where \( R_c \) is the compressive strength, MPa; \( \gamma_o \) is the relative density of concrete samples (relative to the density of water), a dimensionless value.

After processing the experimental data on a computer, the coefficients of mathematical models of the dependencies of the properties of the concrete mixture and concrete on the abovementioned factors are obtained.

\[ y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3, \]

where \( x_1=3,33(A/A+S -0,3) ; x_2=50(A -0,09); x_3=16,7(W/C -0,63) \).

The coefficients of mathematical models of dependencies are given in the table 1.
Table 1. Mathematical models’ coefficients of dependences of concrete mix and ash porized concrete’s properties on composition factors.

| Parameters                                      | Coefficients |
|------------------------------------------------|--------------|
| Density of non-porous mixture, kg/m³           | B₀  B₁  B₂  B₃ B₁₁ B₂₁ B₃₁ B₁₂ B₂₂ B₃₂ B₁₃ B₂₃ |
| Diameter by the Suttard, cm                    | 2204          -28.5 -14.9 -7.5 -58.4 22.0 -109.4 -54.2 8.1 -50.6 |
| Density of concrete samples in the dry state, kg/m³ | 12.9          -4.3  -0.07  1.4  2.1  -1.7  -0.05  -0.5  -2.0  0.4 |
| Strength of concrete samples, MPa              | 1616          -66.1 -97.4 -70.0 22.0 -21.5 -42.5 -49.1 -61.6 -38.1 |
| Design quality coefficient                     | 9.6           0.13  -1.5  -1.5  -0.56 -1.15 -0.59 -0.46 -0.50 -0.54 |
|                                                | 5.91          0.26  -0.65 -0.78 -0.38 -0.71 -0.26 -0.10 -0.13 -0.30 |

3. Research results and their analysis

The dependences of the density of the NAAC samples in the dry state on the material composition factors constructed using mathematical models show that an increase in the content of aluminum powder A, the proportion of ash in the mixture of sand and ash A/(A+S), as well as the water-cement ratio B/C reduce the density of samples in the dry state. At the same time, the dependences of the compressive strength and the structural quality coefficient are more complex and are characterized by the presence of local extremes. To determine the optimal composition of the NAAC corresponding to the highest values of $R_{c}$ and DQC, the problems of optimizing these dependencies are solved. The optimal values of the variable factors corresponding to the maximum coefficient of structural quality were: $A/(A+S) = 0.465$; $Al = 0.084$%; $W/C = 0.57$. At the same time, the compressive strength of the WSPB at the age of 28 days is 15.2 MPa, the density in the dry state is 1600 kg/m³.

Based on the results of the research on the composition of the NAAC, it was decided that it was possible to use structural non-autoclaved ash-porous concrete in the manufacture of NAAC prototypes and reinforced products based on it. To study the strength and deforming properties of the optimal composition of NAAC, 40 cubes with a size of 100x100x100 mm and 40 prisms with a size of 400x100x100 mm were made. The samples were stored in their natural state at a temperature of 17-20 °C and air humidity ranging from 50 % to 75 %. To obtain data on the dynamics of changes in the cubic and prismatic strength of the NAAC, as well as the relative deformation during the compression test of prisms, depending on the time, the tests of the cubes were carried out at the age of 7, 14, 28, 45, 60, 90, 120, 150 and 200 days, and the tests of prisms - at the age of concrete 28, 90 and 200 days. The test results are shown in the table 2 and in the figure 1.

Thus, a new material was obtained as a good result of the work, namely non-autoclaved ash-porous concrete (NAAC) with a density of about 1600 kg/m³ based on the use of aerated concrete technology, but with a smaller number of gas-forming additives. The use of NAAC with the same average density as ordinary light concrete on firing aggregates for reinforced load-bearing structures can be justified by the close values of the total porosity and the associated elastic and deforming properties, as well as similar working conditions of the reinforcement in these products. At the same time, in comparison with gas-reinforced concrete, NAAC favorably differs in greater stability of properties during manufacture, lower consumption of gas-forming additives, and, in comparison with ordinary light concrete, the absence of expensive large porous aggregates. The use of wastes from the local industry,
in this work the ash from the Tver TEC-4 hydro-removal, allows us to improve the environmental situation in the region and save natural raw materials.

Table 2. Strength and deformation characteristics of concrete.

| Age of concrete $\tau$ (days) | Cubic strength $R_c$ (MPa) | Prism Strength $R_b$ (MPa) | Elasticity modulus $E_b$ (MPa) |
|-------------------------------|---------------------------|---------------------------|-------------------------------|
| 7                             | 7.7                       | -                         | -                             |
| 14                            | 11.8                      | -                         | -                             |
| 28                            | 15.2                      | 11.4                      | $2 \times 10^4$               |
| 45                            | 15.5                      | -                         | -                             |
| 60                            | 15.8                      | -                         | -                             |
| 90                            | 15.9                      | 11.9                      | $2.04 \times 10^4$            |
| 120                           | 16.1                      | -                         | -                             |
| 150                           | 16.25                     | -                         | -                             |
| 200                           | 16.4                      | 12.1                      | $2.05 \times 10^4$            |

Figure 1. The development of deformations in concrete prisms during compression tests at different ages

4. Conclusions

Based on the results of experimental and theoretical studies of the experimental samples of the NAAC and structures based on it, the following conclusions were made. The resulting concrete of class B15, with a prismatic strength of 11.4 MPa and an average density of 1600 kg/m$^3$, is an effective material for use in load-bearing and enclosing reinforced concrete structures. When using NAAC, the weight of the structure can be reduced by 40 % compared to elements made of heavy concrete.

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