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*Article*

# Prediction of compressive strength and density of aerated ash concrete

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**Abstract.** The article presents the results of studies on forecasting the compressive strength and density of aerated ash concrete. A theoretical review was conducted on the variability of strength and density of cellular concretes when selecting their compositions. A series of experiments was conducted to study the dynamics of changes in the compressive strength and density of non-autoclaved gas-ash concrete during the initial stages of hardening under natural conditions and after thermal treatment to select a composition of the specified quality. It was revealed that it is possible to control both the strength and the density at the early stages of hardening to forecast these parameters at the design age of 28 days. It was established that the compressive strength of aerated ash concrete samples hardening under natural conditions increased by an average of 42.62% at the design age compared to the strength at 7 days, while the density decreased on average by 19.19%. For aerated ash concrete samples that underwent thermal treatment (steaming), the increase in strength averaged 34.67%, and the decrease in density was 11.07%. The obtained results are of practical value for scientists and engineers engaged in the development of cellular concrete compositions.
**Keywords:** cellular concrete, aerated concrete tests, ash and slag waste, compressive strength, density.

## 1. Introduction

The use of cellular concrete in construction, both in monolithic housing construction and for the manufacture of individual products, does not lose its relevance, including due to several advantages in contrast to other types of concrete and such a traditional material as ceramic brick [1], [2]. Cellular concrete has excellent heat and sound insulation properties, and products made from it are easy to process. At the same time, cellular concrete is more "capricious" when selecting a composition of a certain specified quality. The structure formation of cellular concrete is influenced by such factors as the type of raw material, the ratio between the components, the water-solid ratio (W/S), the type and amount of foaming agent, the mode of heat and moisture treatment, and others [2].

The main standardized characteristics of cellular concrete are the concrete grade by average density and the corresponding values of concrete classes by compressive strength [3]. Therefore, when developing compositions for cellular concretes and blocks made from them, it is important to monitor both the strength and density of the concrete [4].

Many studies are devoted to the development of cellular concrete compositions, both foam and aerated concrete of autoclaved and non-autoclaved hardening, including the use of industrial waste.

In the work [5], the authors investigated the effect of a complex modifier based on graphene oxide and lignosulfonate on the physical and mechanical properties of non-autoclaved aerated concrete, such as compressive and flexural strength. Portland cement M500, sand, slaked construction carbonate-lime flour, and aluminum powder were used as raw materials. It was found that the complex additive of graphene oxide provides the greatest increase in compressive strength by 54% and flexural strength by 45%. The disadvantage of this study is that density control was not carried out.

The authors of the study [6] determined the effect of various components, such as the water-cement ratio, NaOH content, polycarboxylate superplasticizer, aluminum powder, and calcium stearate, on the strength and density of non-autoclaved aerated concrete based on sulfoaluminate cement. The strength of the samples was determined at the ages of 7 and 28 days, and the density only at the design age of 28 days. At the same time, the values of compressive strength at the age of 28 days were consistently higher than the values of compressive strength at the age of 7 days for all the studied components in different percentage ratios. The dynamics of density in samples with different curing periods were not studied.

A literature review [7] examines the use of additives such as fly ash, crushed granulated blast-furnace slag, and waste such as quarry dust, rubber particles, rice husk ash, plastic waste, glass powder, and others on the properties of aerated and foam concrete. Their influence was assessed based on such properties as workability, elastic modulus, compressive strength, flexural strength, and microstructural characteristics. Unfortunately, the study missed the data on the dynamics of density for samples with different curing periods.

The study [8] related to the selection of autoclaved cellular concrete compositions focused on replacing part of the sand with waste from its production; there is also a lack of data on the dynamics of changes in strength and density at different curing periods.

The work [9] was devoted to the selection and optimization of the composition of non-autoclaved aerated concrete. The study compared the properties of autoclaved and non-autoclaved aerated concrete with the introduction of metakaolinite, microsilica, and rice husk in the amount of 7% into the mixture. The comparison was carried out according to compressive strength, flexural strength, and splitting strength. The results of the study confirmed the classical patterns of strength gain for autoclaved and non-autoclaved aerated concrete. For non-autoclaved concrete, there was a significant increase in all types of strength from 7 to 180 days, while for autoclaved concrete, such an increase is practically not observed. In this study, the humidity of samples at the age of 3, 7, 14, 21, 28, and 180 days was also determined. At the same time, the humidity of autoclaved aerated concrete remained practically unchanged from 3 to 28 days and then decreased to 3...5% and became slightly lower than that of non-autoclaved concrete. However, at the age of 3 days, it was 1.5 times lower than that of non-autoclaved aerated concrete. This is due to the conditions of concrete hardening in an autoclave and the end of the Portland cement hydration process, when water is chemically bound into calcium hydrosilicates and other hydration products. The study also lacks data on monitoring the density of samples at different hardening periods, which is important for the selection of cellular concrete compositions when developing it with a given density. The solution to this problem will make a certain contribution to scientists and engineers involved in the development of cellular concrete recipes and would significantly save their time.

Our previous study [10] was devoted to experiments with aerated ash concrete. In continuation of this initiative and considering the gaps in the existing studies, this study aims to investigate the dynamics of changes in the strength and density of non-autoclaved aerated concrete.

To achieve the goal, the following tasks were solved:

1. To conduct a theoretical review of data on the variability of strength and density of cellular concrete in the selection of their compositions, including the use of industrial waste.

2. To conduct an experiment to study the dynamics of strength and density of non-autoclave curing aerated ash concrete to select the composition of a given quality.

## 2. Methods

The experiments were performed in cooperation with an enterprise of the East Kazakhstan region, which specializes in the production of gas blocks according to [4]. The composition of aerated ash concrete from which the samples were prepared in that enterprise was taken from [10] and incorporated the following components: the ash-slag waste from the coal-fired thermal power plant in

Ust-Kamenogorsk, East Kazakhstan region, was used as the main filler; Portland cement of grade SEM I 52.5N served as the binder; aluminum powder of grade PAP-1, activated with caustic soda, was employed as the pore-forming (gas-forming) agent. Figure 1 shows the experimental procedures.

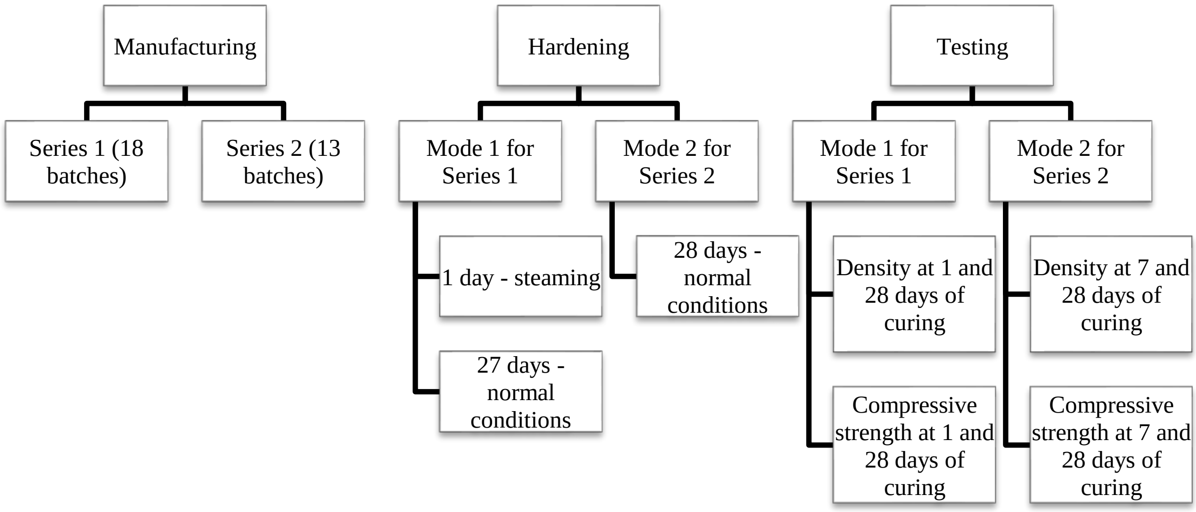
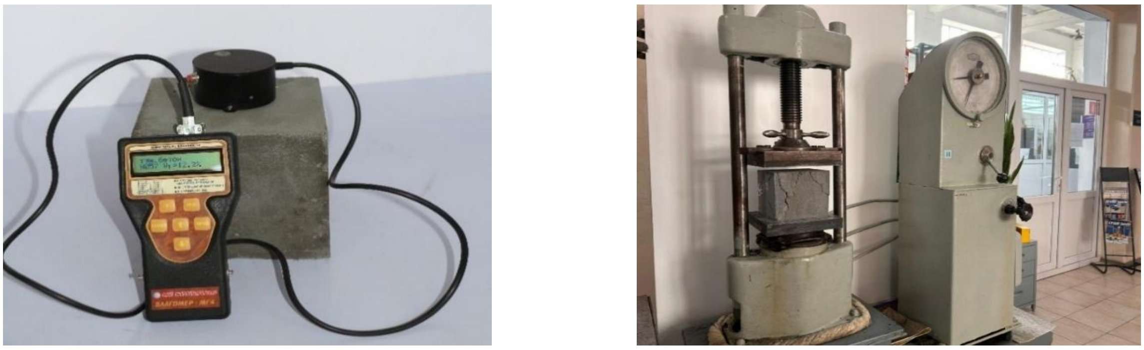



Figure 1 – Experimental procedures

As shown in Figure 1 above, for predicting the strength and density of aerated ash concrete, two series of batches were manufactured, cured in two modes, and tested for density and compressive strength. Density was estimated following [11] based on moisture content, which was determined using a moisture meter of MG4B brand (Figure 2a). Strength tests were carried out according to [12] on a hydraulic press 2PG-10 with two ranges of gauges 0-5 tons and 0-10 tons (Figure 2b).



a) Moisture content b) Compressive strength

Figure 2 – Determination of moisture content and compressive strength of aerated concrete

Each batch comprised 6 samples. Each sample was made in a cubic shape of 15×15×15 cm in size. After production, the samples were set in the air for 40-60 minutes at a temperature of 18-20°C. Series 1 and 2 comprised 18 and 13 batches, respectively, so altogether, 186 samples were manufactured, including 108 for series 1 and 78 for series 2. Each series was hardened at its mode of curing. In mode 1, the samples of series 1 were cured for 1 day in steaming and 27 days in normal conditions. The samples were steamed in a steaming chamber KUP-1 in the following mode: temperature increase to the required parameters – within 60 minutes from 20 to 90 °C and humidity of 90%; steaming – within 6 hours at a temperature of 90 °C and humidity of 90%; cooling to 20 °C. After that, half of the samples within each batch were tested (54 samples), and the rest were placed in normal conditions in a KNT-120 chamber for further strength gain. In mode 2, the samples of series 2 were cured for 28 days in normal conditions in the same chamber. Besides, half of them (39 samples) were tested after 7 days of curing. After 28 days of curing, the samples from each mode (54 samples from series 1 and 39 samples from series 2) were also tested.

To predict the strength and density of aerated ash concrete, this study uses the Statistica 10 software package as in [13]. The software enabled the development of mathematical dependencies between strength, density, and the values of increase in strength and decrease in the density of the samples throughout the curing period.

## 3. Results and Discussion

The results of testing the samples of the first series are presented in Table 1 below.

Table 1 – Test results of the first series of samples

| Batch No. | Additives [10] | Compressive strength, MPa | | Density, kg/m$^3$ | | Increase in strength, MPa | Decrease in density, kg/m$^3$ | Density reduction, % | Reduction in density, % |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 day | 28 days | 1 day | 28 days | | | | |
| 1 | Zeolite | 1.28 | 2.03 | 691 | 610 | 0.75 | 81 | 37.04 | 13.28 |
| 2 | Zeolite | 1.46 | 2.18 | 717 | 663 | 0.72 | 54 | 33.08 | 8.14 |
| 3 | - | 1.42 | 2.23 | 772 | 677 | 0.81 | 95 | 36.30 | 14.03 |
| 4 | - | 1.56 | 2.42 | 761 | 683 | 0.86 | 78 | 35.60 | 11.42 |
| 5 | - | 1.54 | 2.45 | 766 | 692 | 0.91 | 74 | 37.23 | 10.69 |
| 6 | - | 1.73 | 2.66 | 766 | 705 | 0.93 | 61 | 35.00 | 8.65 |
| 7 | Anhydrite | 1.92 | 2.83 | 785 | 712 | 0.91 | 73 | 32.23 | 10.25 |
| 8 | Anhydrite | 1.98 | 3.00 | 828 | 730 | 1.02 | 98 | 33.97 | 13.42 |
| 9 | Gypsum | 1.88 | 3.04 | 826 | 741 | 1.16 | 85 | 38.21 | 11.47 |
| 10 | Fullerenol | 2.03 | 3.12 | 817 | 748 | 1.09 | 69 | 34.94 | 9.22 |
| 11 | Fullerenol | 2.23 | 3.21 | 870 | 758 | 0.98 | 112 | 30.52 | 14.78 |
| 12 | Fullerenol | 2.19 | 3.46 | 856 | 778 | 1.27 | 78 | 36.72 | 10.07 |
| 13 | Fullerenol | 2.29 | 3.49 | 862 | 796 | 1.20 | 66 | 34.38 | 8.25 |
| 14 | Quicklime | 2.23 | 3.55 | 935 | 808 | 1.32 | 126 | 37.27 | 15.65 |
| 15 | Quicklime | 2.58 | 3.66 | 904 | 812 | 1.08 | 92 | 29.49 | 11.33 |
| 16 | Quicklime | 2.51 | 3.70 | 903 | 820 | 1.19 | 83 | 32.07 | 10.12 |
| 17 | Quicklime | 2.50 | 3.85 | 909 | 828 | 1.35 | 81 | 35.00 | 9.78 |
| 18 | Quicklime | 2.51 | 3.87 | 902 | 830 | 1.36 | 72 | 35.07 | 8.67 |

Table 1 above shows the values of compressive strength and density of the samples from 18 batches at the curing ages of 1 and 28 days. The table also shows the estimated values of the increase in strength and decrease in density of the samples, along with their ratios. These tables show that regardless of the composition of the ash concrete in batches, there is an increase in strength at the design age of 28 days compared to the strength at the reference period of 1 day, as well as a decrease in density. For visual analysis of changes in strength and density dynamics, a histogram of strength increase and a density graph are plotted in Figure 3, a histogram of density change and a strength graph in Figure 4, and a graph of the dependence of strength, density, and change in strength in Figure 5.

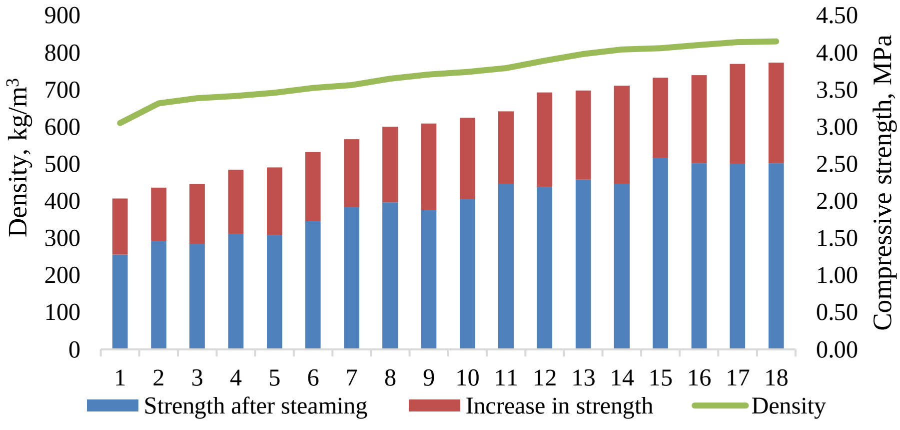



Figure 3 – Histogram of strength increase and density plot

Analysis of the obtained results showed that in samples that were subjected to heat treatment, the strength at the design age of 28 days compared to the strength immediately after steaming (at the age of 1 day) increased by an average of 34.67%. The minimum increase in strength was 29.49%, and the compressive strength changed from 2.58 to 3.66 MPa. The maximum increase in strength was 37.23%, i.e., from 1.54 to 2.45 MPa in batch No. 5.

The increase in the strength of cellular concretes due to the use of various additives is consistent with the previously conducted studies on the selection of compositions of non-autoclave concretes [5], [6]. The slightly smaller increase in strength is due to the use of other additives.

At the same time, there was a decrease in density (Figure 4).

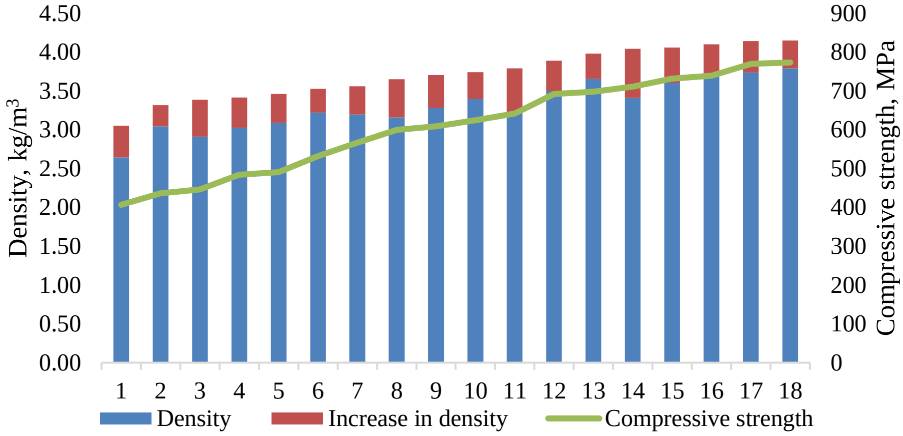
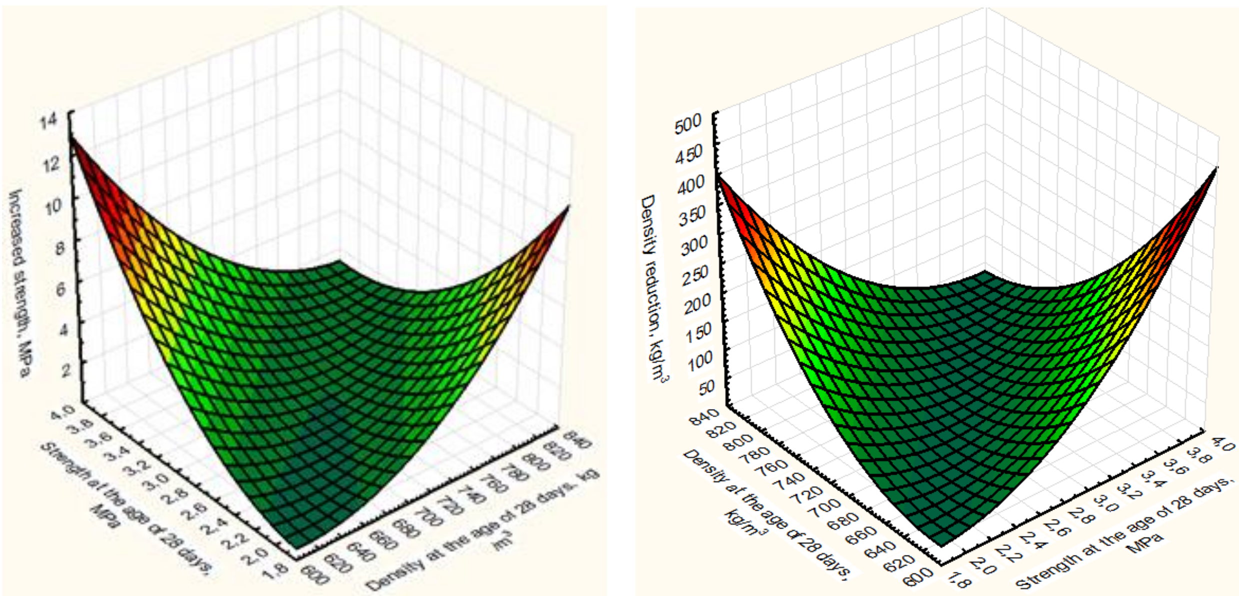



Figure 4 - Histogram of density variation and strength plot

The density reduction in the samples after 28 days compared to the samples after steaming averaged 11.07%. The minimum density reduction was 8.14% and amounted from 717 to 663 kg/cm$^3$, i.e., the density class of aerated ash concrete decreased from D750 to D700. The maximum density reduction of 15.65% from 935 to 808 kg/cm$^3$ gave a reduction in density class from D950 to D850.

The obtained results on density reduction extend the previous studies on the selection of cellular concrete compositions [5], [6], [8].

The results of predicting the strength and density of cellular ash concrete of the first series of samples using the Statistica 10 software package are shown in Figure 5.




a) Graph of dependence of strength, density, and strength increase

b) Graph of dependence of strength, density, and density reduction

Figure 5 – Dependency graphs for heat-treated aerated concrete

Analysis of the obtained results showed that the increase in strength and decrease in density at the design age of 28 days compared to the strength immediately after steaming (at the age of 1 day) occurs evenly proportionally.

The average strength gain of 34.67% is quite consistent with previous studies that showed the dynamics of increasing the strength of cellular concrete of non-autoclave hardening. The results on the dynamics of density of cellular concretes of non-autoclave hardening (density decrease by 11.07% on average) are new and expand the studies [5], [6], [7], [9].

The results of testing the samples of the second series are presented in Table 2 below.

Table 2 – Results of testing samples of the second series

| Batch No. | Additives [10] | Compressive strength, MPa | | Density, kg/m$^3$ | | Increase in strength, MPa | Decrease in density, kg/m$^3$ | Increase in strength, % | Reducing density, % |
|---|---|---|---|---|---|---|---|---|---|
| | | 7 days | 28 days | 7 days | 28 days | | | | |
| 1 | Zeolite | 0.88 | 1.80 | 762 | 142.03 | 620 | 0.92 | 51.01 | 22.91 |
| 2 | Zeolite | 1.29 | 2.23 | 802 | 121.83 | 680 | 0.94 | 42.27 | 17.92 |
| 3 | - | 1.68 | 2.36 | 1082 | 241.37 | 841 | 0.68 | 28.70 | 28.70 |
| 4 | - | 1.18 | 2.37 | 871 | 180.94 | 690 | 1.19 | 50.12 | 26.24 |
| 5 | Anhydrite | 1.55 | 2.47 | 898 | 187.36 | 711 | 0.92 | 37.25 | 26.35 |
| 6 | Anhydrite | 1.53 | 2.89 | 1049 | 225.10 | 824 | 1.36 | 47.14 | 27.32 |
| 7 | Fullerenol | 1.76 | 2.89 | 1063 | 212.50 | 850 | 1.13 | 39.00 | 25.00 |
| 8 | Fullerenol | 1.94 | 3.09 | 945 | 166.74 | 778 | 1.15 | 37.31 | 21.43 |
| 9 | Fullerenol | 1.78 | 3.48 | 995 | 155.91 | 839 | 1.70 | 48.90 | 18.58 |
| 10 | Quicklime | 2.06 | 3.51 | 1026 | 224.63 | 801 | 1.45 | 41.35 | 28.04 |
| 11 | Quicklime | 2.03 | 3.67 | 982 | 168.21 | 814 | 1.64 | 44.69 | 20.66 |
| 12 | Quicklime | 2.35 | 4.45 | 1028 | 167.92 | 861 | 2.10 | 47.23 | 19.51 |
| 13 | Quicklime | 2.55 | 4.61 | 1090 | 192.04 | 898 | 2.06 | 44.76 | 21.38 |

Table 2 above shows the compressive strength and density values of samples from 13 batches at the curing ages of 7 and 28 days. The table also shows the estimated values of the increase in strength and decrease in density of the samples, along with their ratios. Just as in the first series of samples, the test results of the second series presented in table 2 indicate that, regardless of the gas-ash concrete composition, there is an increase in strength at the design age of 28 days compared to the strength at the reference period of 7 day, as well as a decrease in density.

For visual analysis of changes in strength and density dynamics, a histogram of strength increase and a density graph are plotted in Figure 6, a histogram of density change and a strength graph in Figure 7, and a graph of the dependence of strength, density, and change in strength in Figure 8.

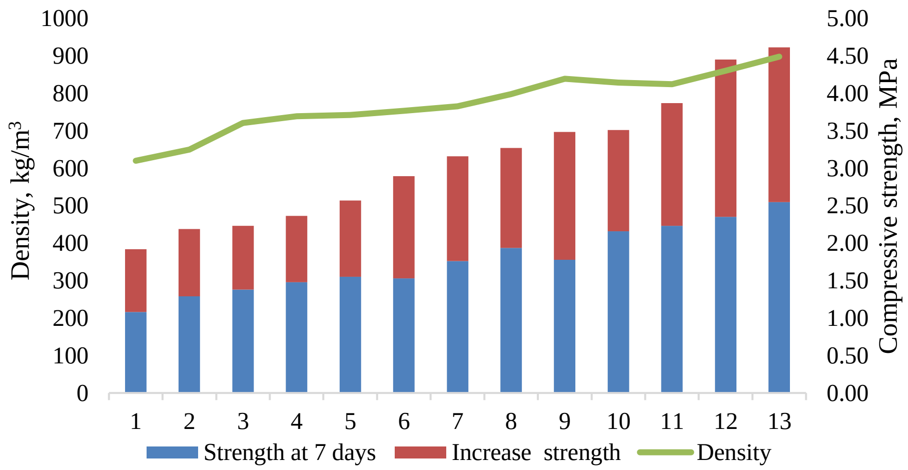



Figure 6 – Strength change histogram and density graph

Analysis of the obtained results showed that in the samples that gained strength under natural conditions, the strength at the design age of 28 days compared to the strength at the age of 7 days increased by an average of 42.62%. The minimum increase in strength was 37.44%, and the compressive strength changed from 1.48 to 2.37 MPa. The maximum increase in strength was 48.90%, i.e., from 1.78 to 3.48 MPa in batch No. 9.

Increasing the strength of cellular concretes through the use of various additives is consistent with previous studies [5] and [6]. The slightly smaller increase in strength compared to [5] is due to the use of other additives.

At the same time, there was a decrease in density (Figure 7).

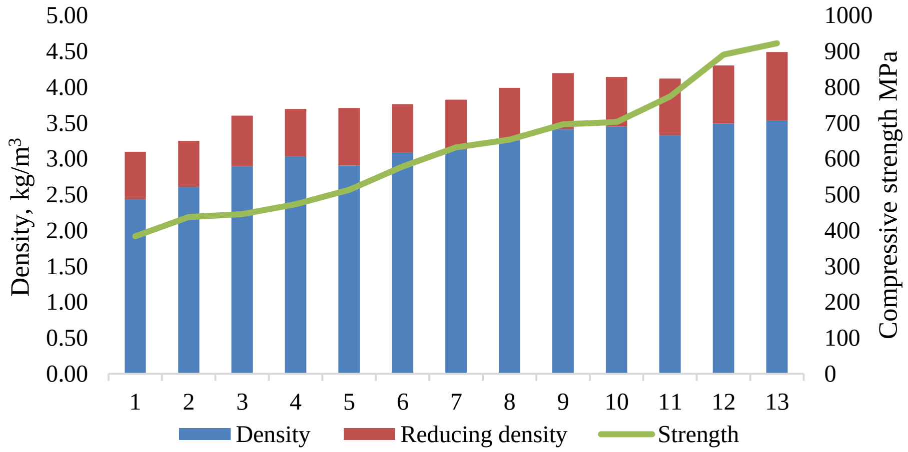
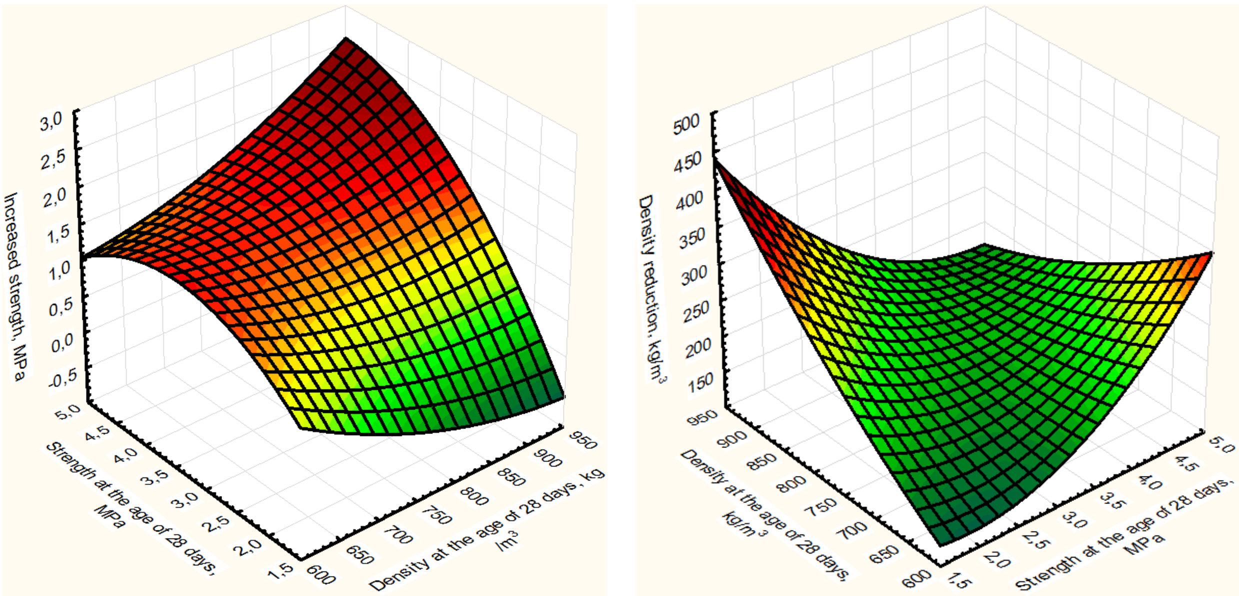



Figure 7 – Histogram of density change and strength graph

In the samples gaining strength under natural conditions, a decrease in density was also observed. The decrease in density in the samples after 28 days compared to the samples at the age of 7 days averaged 19.19%. The minimum density decrease was 16.77% – from 968 to 829 kg/cm$^3$, which corresponds to a change in the density class of gas-reinforced concrete from D1000 to D850. The maximum density reduction is 21.70% from 903 to 765 kg/cm$^3$, i.e., from D950 to D800.

The obtained results on density reduction also extend the previous studies on the selection of cellular concrete compositions [5], [6], [7].

The results of predicting the strength and density of the cellular ash concrete of the second series of samples using the Statistica 10 software package are shown in Figure 8.




a) Graph of the dependence of strength, density, and strength increase

b) Graph of the dependence of strength, density, and density reduction

Figure 8 – Dependency graphs for aerated concrete hardened under normal conditions

Analysis of the obtained results showed that as in series 1, the observed increase in strength and decrease in density at the design age of 28 days compared to the strength at the age of 7 days during the strength gain under natural conditions occurs evenly proportionally.

The average strength gain of 42.62% is quite consistent with previous studies that showed the dynamics of increasing the strength of cellular concrete of non-autoclave hardening at the ages of 7 and 28 days. The results on the dynamics of density of cellular concrete of non-autoclave hardening at the age of 7 and 28 days (density decrease by 19.19% on average) are new and expand the studies [5], [6], [7], [9].

## 4. Conclusions

This study proves that it is possible to predict both the compressive strength and the density of ash concrete.

It was found that the strength at the design age increased by 34.67% compared to the strength at the age of 1 day during heat treatment of samples and by 42.62% compared to the strength at the age of 7 days without heat treatment of samples.

Changes in the density of aerated ash concrete at different hardening periods have been established. It was revealed that the density at the design age decreased by 11.07% compared to the density at the age of 1 day during heat treatment of samples and by 19.19% compared to the density at the age of 7 days without heat treatment of samples.

The results obtained have practical significance for scientists and engineers involved in the development of cellular concrete formulations.

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*Nikolai Soshnikov* – data collection, testing.
*Meiram Begentayev* – funding acquisition, visualization.

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