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# DETERMINING TECHNOLOGICAL PARAMETERS FOR STABILIZING THE POROUS STRUCTURE OF SILICA CONCRETE

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***The object of this study is a gas-silicon concrete mix. The task under consideration is to synchronize the processes of pore formation and increase plastic strength, which ensures the stability of the porous structure. The optimal values of water-solid mixture (0.3–0.35), the amount of ground quicklime (up to 1.5 %) and aluminum powder (0.04–0.1 %) were experimentally determined to enable the formation of a stable porous structure with a minimum plasticity of 10 kPa, sufficient for autoclave processing. The formation of a porous structure is enabled by synthesizing tricalcium hydroaluminate, which is a product of reaction between quicklime and aluminum powder. Tricalcium hydroaluminate is highly reactive, which ensures accelerated increase in strength. This allows the sedimentation of the material to be eliminated and the porous structure to be stabilized before the autoclave process begins. The results show that the increase in the amount of aluminum powder has a positive impact on the structural value of the mixture, so that the excess of the permissible level of ground quicklime (1.5 %) leads to a decrease in the strength of the end product. Thus, an important compromise task has been solved: synchronization of the processes of pore formation of the silica-concrete mixture and the growth of plastic strength over time in component ratios that do not interfere with the hardening of the silicon concrete mixture during autoclave processing. The use of crushed quicklime and aluminum powder in specific dosages helps achieve high environmental standards by reducing the volume of conventional resources such as Portland cement in industrial processes. Thus, the results of the study form a scientific basis for the introduction of new types of environmentally friendly construction materials with improved characteristics***

***Keywords: aerated silica concrete, structure, plastic strength, rheology, quicklime, aluminum powder, binder, autoclave***

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## 1. Introduction

Modern construction is impossible without the use of basic building materials, such as cement, metal, and wood. However, their production faces increasing challenges because of the limited natural resources. The rapid growth of construction needs contributes to the depletion of the available raw material base, which poses a threat to the sustainable development of the industry.

At the same time, there are huge deposits of silica on the planet, the basis of which is quartz, as well as minerals where it acts as a forming component. Silica is one of the most common chemical compounds in the earth's crust, but its potential in creating building materials remains underutilized.

The solution to the problem of depletion of conventional raw materials can be found in the development and implementation of new technologies for the synthesis of silica-containing building materials. One of such materials is silica concrete. Silica concrete is an artificially synthesized material, the basis of which is silica in crystalline form, such as quartz sandstone. More effective use of silica concrete in construction can be facilitated by expanding its range, for example, by designing a lightweight version. In conventional building materials, this problem is solved by introducing air-forming additives. An example is the widespread cellular concretes – aerated concrete and foam concrete. The creation of cellular silica concrete is associated with a number of difficulties caused by the peculiarities of hardening of the silica binder. Therefore, research and development of technological conditions for creating a stable porous structure of aerated silica concrete are relevant as they open up the possibility of creating a light, durable, and chemically resistant material.

## 2. Literature review and problem statement

The growing need to produce more mineral binders leads to the depletion of the raw material base for their production [1]. In [2], the authors propose the use of alternative materials to reduce large-scale greenhouse gas emissions and the massive consumption of natural resources in the production of Portland cement. Such measures can only partially replace conventional clinker, and its raw material base is limited. In [3], the established practice of using industrial waste to replace conventional raw materials for the production of Portland cement is considered. Among the disadvantages of this approach, one can identify the heterogeneity of waste, the presence of harmful substances, as well as logistical problems. In the production of autoclaved aerated concrete, a significant amount of Portland cement is used and its replacement with an alternative binder can reduce the dependence of manufacturers on the decreasing raw material base.

In [4], the resistance to chemical attack of modified autoclaved aerated concrete based on Portland cement was analyzed. The authors noted a significant decrease in strength under the influence of acid solutions, which is explained by the high content of calcium-containing salts in the final product. This problem can be solved by using a two-component silica binder in the production of autoclaved aerated concrete. In [5], autoclaved silica concrete is considered as a chemically stable, high-strength material, and is used for the manufacture of protective structures in the chemical, petrochemical, pulp and paper industries and at thermal power plants. In the production of autoclaved aerated concrete based on a two-component silica binder, it is possible to combine heat-shielding properties and high chemical resistance, which allows it to be used as a structural and thermal insulation material for walls exposed to aggressive environments.

A common practice is to apply polymer protective coatings to protect building structures from the effects of aggressive environments [6, 7]. Quartz filler increases the chemical resistance of polymer protective coatings, but such composites have a high cost and low heat resistance. In addition, increasing the dosage of quartz negatively affects the adhesion of the polymer composite to the surface, reduces the impact strength, bending strength and deformation at break due to the agglomeration of quartz particles. All this gives grounds to argue that the use of quartz as a filler in composite chemically resistant coatings has certain limitations.

In works [8, 9], the influence of the chemical composition of silica additives on the strength and corrosion resistance of concrete was investigated. It was shown that silica finally increases the compressive strength, which precedes the ingress of acidic liquids into the internal areas due to the additional pozzolanic and filling effect, which leads to a more compact and denser microstructure of concrete. Thus, the use of micro silica significantly increases the density and strength of concrete. But the issues related to the economic feasibility of using micro silica in large volumes, which is due to its high cost, remain unresolved. The reason for this is the cost associated with the production of micro silica. An option to overcome this may be the use of more affordable man-made additives or combining different types of silica components.

Thus, the issues related to the expansion of the practical use of quartz in building materials remain unresolved. The likely reason is objective difficulties associated with the complexity of the synthesis of silica compounds with high strength and chemical resistance at moderate costs. An option to overcome these difficulties may be to improve synthesis technologies using modified binder components. In work [10], the properties of silica concrete under the influence of an aggressive environment are considered; however, the issues of optimizing formulations and ensuring a stable porous structure remain open.

In [11, 12] the results of research on the synthesis of silica materials under autoclave conditions are reported. It is shown that autoclave treatment makes it possible to obtain high-strength porous materials. However, issues related to the need for expensive equipment and significant energy consumption remain unresolved. The reason for this is the fundamental impossibility of ensuring the necessary conditions for autoclave treatment under standard production conditions. An option for overcoming these difficulties may be the development of technologies based on more economical synthesis conditions.

In study [13], the change in physical, mechanical, and functional properties of autoclaved aerated concrete is considered depending on the autoclaving mode and the amount of gas generator. It is shown that the use of aluminum powder makes it possible to obtain porous mixtures with a uniform distribution of pores, which subsequently leads to an improvement in the properties of aerated concrete. However, issues related to the insufficient stability of the obtained structures, which leads to their destruction during autoclave treatment, remain unresolved. The likely reason is insufficient research into the stabilization of the structure at the early stages of formation. A solution may be the use of stabilizing additives that increase the plastic strength of mixtures at the initial stages.

All this allows us to argue that it is advisable to conduct research on establishing the formulation and technological conditions for the synthesis of silica mixtures with a stable porous structure, which would enable the development of economically feasible and technologically efficient methods for obtaining aerated silica concrete.

## 3. The aim and objectives of the study

The aim of our work is to establish the formulation and technological conditions for obtaining a stable porous structure of the silica mixture. This will create conditions for the development of a technology for a strong, light, chemically stable, and environmentally friendly material – aerated silica concrete.

To achieve the goal, it is necessary to solve the following tasks:

– to construct kinetic dependences of the increase in plastic strength of the aerated concrete silica mixture;

– to determine the water demand of the silica mixture, which contributes to the stable formation of a porous structure.

## 4. The study materials and methods

The object of our research is aerated silica concrete mixture. The subject of research is rheological characteristics: plastic strength of the aerated silica concrete mixture and water consumption of the silica mixture.

To achieve the high porosity of composite building materials by introducing gas-forming additives, it is necessary to comply with certain conditions. Such conditions are the mandatory synchronization in time of the processes of gas formation and the increase in the plastic strength of the molding mass. The issue is the silica concrete mixture is able to harden only under autoclave conditions at a water vapor pressure of 1.2–1.6 MPa. To create porous silica concrete, it is necessary to create and fix a porous structure before autoclave treatment. Therefore, it is assumed that this is possible by introducing a stabilizing additive, or additives of complex action. In addition, an important condition is that these additives should not interfere with the hardening of the silica concrete mix.

The chemical composition of the active components of the binder and ground quartz sand, as well as the particle size composition of high-silica alkali glass (HSG) and tridymite-cristobalite binder (TC binder) are given in Tables 1, 2.

Table 1

Chemical composition of silica mixture components (% by weight)

| Chemical formula of the compound | Material name | | |
|---|---|---|---|
| | HSG | TC binder | ground sand |
| $Al_2O_3$ | 0.163 | 0.113 | 0.071 |
| MgO | 0.729 | 0.51 | 0.622 |
| CaO | 0.741 | 0.903 | 0.180 |
| FeO | 0.437 | 0.991 | 1.183 |
| $SiO_2$ | 89.644 | 90.067 | 96.105 |
| $TiO_2$ | 0.022 | 0.028 | 0.030 |
| $MnO_2$ | 0.027 | 0.046 | 0.058 |
| $K_2O$ | 0.029 | 0.057 | 0.165 |
| $Na_2O$ | 7.6 | 5.2 | 0.430 |
| $Fe_2O_3$ | 0.53 | 0.6 | 0.250 |
| Fe’’’ | 0.078 | 0.325 | 0.906 |
| n.n.n. | 0.814 | 1.16 | 0.00 |

Table 2

Granulometric composition of HSG and TC binder (% by weight)

| Material name | Sieve hole size, mm | | | | Sieve 0.14 mm passage | Size modulus |
|---|---|---|---|---|---|---|
| | 1.25 | 0.63 | 0.315 | 0.14 | | |
| HSG | – | 41 | 33 | 18 | 8 | 2.01 |
| TC binder | – | 0.9 | 48 | 37.5 | 13.6 | 1.36 |

At the first stage of the research work, the task of choosing the type of pore former and stabilizer of the cellular structure was solved. As pore formers, the following were used: gas former – aluminum powder and foam formers. The additive for stabilizing the cellular structure was selected from:

a) inorganic binders in the form of quicklime, gypsum binder, Portland cement, and liquid glass with sodium fluorosilicate;

b) organic – casein glue;

c) polymeric – PVA of various concentrations and ethyl silicate with ammonia hardener.

The desired result, namely obtaining a silica mixture of a stable cellular structure, was achieved when using a gas former in the form of aluminum powder and ground quicklime as a stabilizing additive. In other cases, precipitation of the formed masses occurs.

The plastic strength of the aerated concrete silica mixture was determined using a conical plastometer, the diagram of which is shown in Fig. 1.

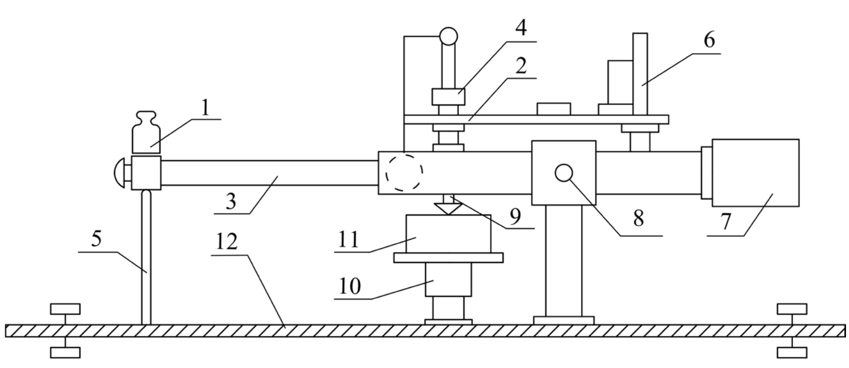


Fig. 1. Diagram of a conical plastometer: 1 — load; 2 — area for mounting the sleeve; 3 — lever; 4 — guide sleeve; 5 — lever movement limiter; 6 — indicator; 7 — counterweight; 8 — lever rotation axis; 9 — cone; 10 — lifting table; 11 — mold with mixture; 12 — base of the device

According to the calculated concrete compositions, aerated silica concrete mixture was prepared, which was placed in cylindrical molds with a diameter of 70 mm and a height of 43±3 mm. After the formation of the “edge” stopped, the mixture in the mold was leveled with a spatula and installed on the lifting table 10 of the device. Lever 3 was set in a horizontal position by moving counterweight 7 and the lever movement limiter 5. Then the table was raised to such a height that the tip of cone 9 touched the surface of the mass. After that, the lever movement limiter 5 was removed with a sharp movement and the readings of the depth of immersion of the cone in the mass were taken on the indicator scale 7. The result was determined as the arithmetic mean of the five indicator indicators. Measurements were carried out 30, 60, 90, and 120 minutes after the mixture was prepared. The plastic strength was determined from the formula:

$$\Theta = K\frac{H}{h^2}, \quad (1)$$

where Θ is the ultimate shear stress, kPa;

$H$ – mass of the load, g;

$h$ – depth of immersion of the cone, cm;

$K$ – constant of the device at the cone angle; at the apex of 30 °K=0.96.

In addition to the plastic strength, the rheological characteristics were used to determine the influence of formulation factors on the water consumption of the silica mixture. As a parameter reflecting the water consumption of the mixture, the value of the water-solid ratio was taken, which enables the spread of the mass, determined by the Suttard viscometer, 10...12 cm. As previous experiments have shown, such plasticity of the mixture has sufficient gas-holding capacity and, when using vibration during the gas generation reaction, makes it possible to obtain mixtures of a stable porous structure by the end of the reaction. At the same time, the structural strength after 2–4 hours of product aging makes it possible to cut off the “edge” and is sufficient to withstand the pressure created in the autoclave during the period of switching to the isothermal aging mode at a rate of 0.4 MPa/h.

To obtain a highly porous structure of aerated silica concrete and create conditions for good gas-retaining capacity of the mass, it is necessary to determine the recipe and technological parameters under which the process of releasing working gas would be accompanied by a corresponding increase in plastic strength. Its value should be sufficient to prevent the mass from settling during the swelling process, ensure the possibility of cutting the “edge”, and withstand the pressure in the autoclave during the period of strength formation.

To determine the formulation and technological conditions for obtaining aerated silica concrete on silica binder, three series of experiments were conducted to study the plastic strength depending on some variable factors. The water-solid ratio, the gas-forming agent content, and the ground quicklime content as a percentage of the mass of dry components were taken as variable factors. Probably, all three factors should affect the plastic strength of the mixture. The water-solid ratio as a regulator of rheological characteristics, the gas-forming agent content as a regulator of porosity, and lime as a regulator of strength gain. The ground quicklime content varied from 1.5 to 6 %. The gas-forming agent content was taken as 0.04; 0.07; and 0.1 % of the mass of dry components. The water-solid ratio was selected in such a way as to ensure approximately the same consistency of the mixture in all experiments. Therefore, with an increase in the lime consumption, the water consumption was increased accordingly. In the first series of experiments, the W/S ratio was taken to be 0.3...0.4; in the second, 0.35...0.45; and in the third, 0.4...0.5, with a change interval of 0.05.

As the active component of the binder, high-silica alkali glass with a specific surface area of 50.0 kPa was used, and as the silica component, ground quartz sand. The ratio between HSG and ground sand was 1:1. The value of the plastic strength was taken as the optimization parameter.

## 5. Results of investigating the influence of formulation and technological conditions on obtaining a stable porous structure of a silica mixture

### 5. 1. Studying the kinetics of growth of plastic strength of aerated concrete silica mixture

To determine the kinetics of growth of plastic strength of aerated concrete silica mixture, experimental studies on the influence of the studied factors on the plastic strength of the aerated silica concrete mixture over time ($t$) were conducted. The plastic strength was determined according to the methodology given above. Then, according to the results of the arithmetic mean values, dependence plots of the plastic strength of the aerated silica concrete mixture on aging time were constructed. Based on these results, plots of changes in plastic strength over time were constructed (Fig. 2).

For better interpretation of the results of experimental studies, they are grouped depending on the lime content, gas generator content, and water-solid ratio. Then, each of the lines was fitted to the logarithmic dependence of change in plastic strength ($R$, kPa) on time ($t$, min); the kinetic equations of plastic strength were built. The level of approximation probability is 0.99. Examples of such equations are given below.

Curves 1 and 3 at a lime content of 1.5 % and W/S=0.3:

$$R_1 = 13.962 \cdot \ln t - 29.093, \quad (2)$$

$$R_3 = 14.263 \cdot \ln t - 18.509. \quad (3)$$

Curves 1 and 3 at a lime content of 1.5 % and W/S=0.4:

$$R_1 = 3.49 \cdot \ln t - 8.82, \quad (4)$$

$$R_3 = 3.63 \cdot \ln t - 4.57. \quad (5)$$

It is known that the minimum plastic strength of the porous mass, which is necessary for cutting the "edge" and installing the product in the autoclave, is assigned to 0.0 kPa. As can be seen from the above graphical dependences, there are certain combinations of factors under consideration at which this requirement is met. All factors affect the value of the plastic strength of the mass. The water-solid ratio and lime consumption have the greatest impact on the structural strength of the porous mixture. The gas generator consumption has a less significant impact. The fact that with an increase in the lime content in the dry components, the plastic strength of the porous silica mixture decreases is thought-provoking.

This contradicts the assumption about the role of hydration hardening of lime in the formation of the porous structure of the silica mixture. Indeed, a more detailed analysis refutes this assumption. The water-solid ratio in the experiments varies from 6.7 and 27. Even if we take into account the water that is "bound" by the silica mixture (20 %), then in this case the water-lime ratio is large enough (4...13) to demonstrate the binding properties of lime. At a water-lime ratio of 1.9, lime no longer hardens, and at W/W=1, hardening is observed in 17 minutes. By this point, the gas formation reaction usually ends. Then it is not clear why the porous structure is fixed. Silica binder does not harden under natural conditions, there are no conditions for hydration hardening of quicklime, and there are no other minerals with binding properties in the composition of the initial components of the raw material mixture.

During the formation of the mixtures, it was visually noted that the loss of mass viscosity and the increase in structural strength occur during the most intense gas formation. From the plots shown in Fig. 2, it is also clear that the greatest increase in plastic strength is observed in the first 0.5 hours after the formation of the mixture. Subsequently, the increase in strength slows down and practically stops by two hours, or, if it increases, then only slightly, and therefore further measurements were not carried out.

Immediately after the introduction of water into the mortar mixture, ground quicklime (CaO) reacts, resulting in the formation of Ca hydroxide. Then this product reacts with aluminum powder and water:

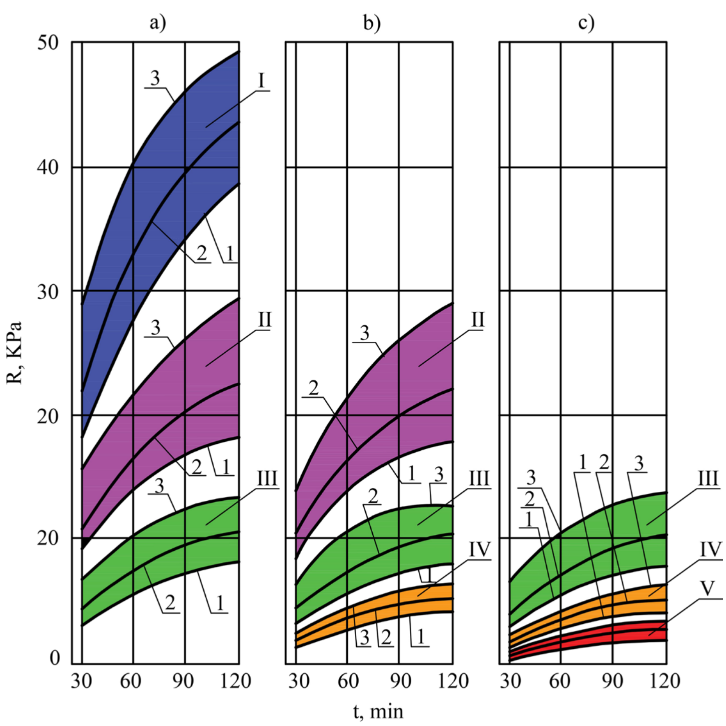


Fig. 2. Kinetics of plastic strength growth, at: lime content: $a$ – 1.5 %; $b$ – 3 %; $c$ – 6 %; gas-forming agent content: 1 – 0.04 %, 2 – 0.07 %, 3 – 0.1 %; water-solid ratio: I – 0.3, II – 0.35, III – 0.4, IV – 0.45, V – 0.5

$$3Ca(OH)_2 + 2Al + 6H_2O = \\ = 3CaO \cdot Al_2O_3 \cdot 6H_2O + 3H_2 \uparrow, \quad (5)$$

with the release of working gas – hydrogen and tricalcium hydroaluminate. Tricalcium hydroaluminate ($C_3AH_6$), known in mineralogy as cubic hexahydrate hydrogrossular, is the first mineral in a series of hydrogarnets, which are united by the general chemical formula:

$$3CaO \cdot Al_2O_3 (SiO_2) x \cdot H_2O(6-2x), \quad (6)$$

where $x$ is the molar fraction of $SiO_2$.

**5. 2. Determining the water demand of silica mixture**

To determine the water demand of silica mixture, a three-factor experiment was conducted according to plan B–3 [14]. TC binder with a maximum grain size of 0.63 mm was used as the active binder component. The experiment investigated the influence of the following factors:

$X_1$ – percentage content of gas generator by mass of dry components. Symbol of the variable – A. Range of change – from 0.04 to 0.1 % with an interval of 0.015 %;

$X_2$ – percentage content of lime in dry components. Symbol – U. The value of this factor varied from 0.6 to 1.2 % with a step of 0.15 %;

$X_3$ – proportion of TC binder in its mixture with ground sand. Symbol – $m$. The levels of change are from 0.4 to 0.6 with an interval of 0.1.

The optimization criterion [15] was taken to be the value of a water-solid ratio, which ensures the fluidity of the solution on a Suttard viscometer with a diameter of 100...120 mm. The experimental results are given in Table 2.

Table 2

Planning matrix and experiment results

| No. of entry | Factor | | | Water-solid ratio | |
|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | Actual | Theoretical |
| | $A$ | $U$ | $m$ | | |
| 1 | – | – | – | 0.18 | 0.184 |
| 2 | + | – | – | 0.33 | 0.328 |
| 3 | – | + | – | 0.24 | 0.24 |
| 4 | + | + | – | 0.4 | 0.396 |
| 5 | – | – | + | 0.24 | 0.24 |
| 6 | + | – | + | 0.18 | 0.184 |
| 7 | – | + | + | 0.3 | 0.296 |
| 8 | + | + | + | 0.25 | 0.252 |
| 9 | – | 0 | 0 | 0.27 | 0.265 |
| 10 | + | 0 | 0 | 0.32 | 0.315 |
| 11 | 0 | – | 0 | 0.23 | 0.229 |
| 12 | 0 | + | 0 | 0.3 | 0.291 |
| 13 | 0 | 0 | – | 0.23 | 0.233 |
| 14 | 0 | 0 | + | 0.28 | 0.277 |
| 15 | 0 | 0 | 0 | 0.27 | 0.27 |

As a result of conducting and statistically processing the results of the experiment, a mathematical model of the water demand of the silica mixture was built, which takes the form:

$$W/S = 0.27 + 0.025x_1 + 0.031x_2 - 0.022x_3 + \\ +0.003x_1x_2 - 0.005x_1x_3 + \\ +0.02x_1^2 - 0.01x_2^2 - 0.015x_3^2, \quad (7)$$

The adequacy of the mathematical model was assessed by the Fisher criterion. With a 5 percent error of the experiment, the Fisher criterion is equal to 3.33 with a critical value of 7.59. This confirms the adequacy of the model. The graphical dependences of the water demand of the silica mixture are given in the form of isolines of the water-solid ratio in Fig. 3.

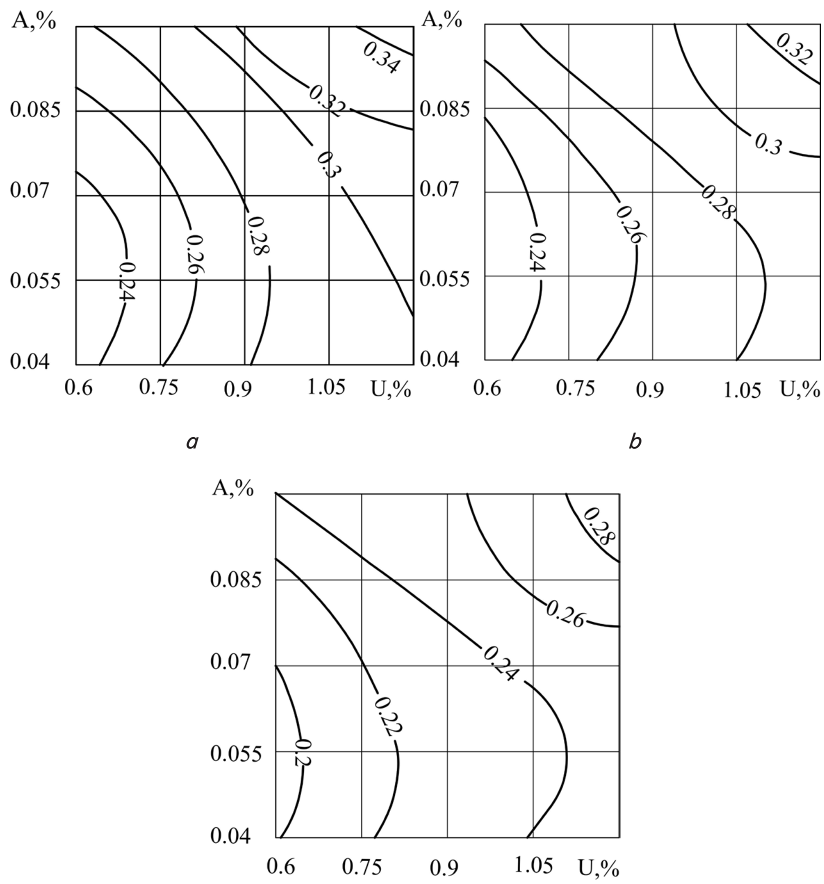


Fig. 3. Isolines of water-solid ratio: *a* – *m*=0.4; *b* – *m*=0.5; *c* – *m*=0.6

**6. Discussion of results based on investigating the influence of formulation and technological conditions on obtaining a stable porous structure of the silica mixture**

Our results on the stabilization of the porous structure of aerated silica concrete are explained by the synthesis of tricalcium hydroaluminate by reaction (5). $C_3AH_6$ has binding properties, is a product of the hydration of some hydraulic binders, in particular, alumina cement. It belongs to minerals that harden quickly and has high strength. This gives grounds to argue that it is $C_3AH_6$ that performs the role of a stabilizer of the porous structure of the silica mixture.

The synthesized tricalcium hydroaluminate has a strength after heat-moisture treatment of 12.1 MPa, at 28 days of hardening – 30.3 MPa, and at the sixth month – 62.5 MPa. As can be seen, $C_3AH_6$ has sufficient strength. Therefore, taking into account that it belongs to minerals that harden quickly, it can be assumed that tricalcium hydroaluminate, which is formed as a result of the gas generation reaction, can act as a stabilizer of the porous structure of the silica mixture. This assumption is also confirmed by the kinetic equations (2) to (5) and the graphical dependences shown in Fig. 2. Considering, for example, the plot of change in the plastic strength of the silica mixture with W/S=0.4, it can be noted that the value of the plastic strength practically does not depend on the lime consumption. At the same time, the plastic strength increases with increasing gas-forming agent consumption (for example, curves 1 and 3). Moreover, the greater the consumption of aluminum powder, the greater the value of the plastic strength, which is unexpected, since with increasing gas-forming agent content, the amount of gas phase increases. This leads to a decrease in the average mass density and, accordingly, should reduce the plastic strength.

Considering once again the chemical reaction of gas formation and knowing the molecular masses of the reacting substances, we can determine that to create normal conditions for the reaction to occur per 1 g of aluminum, 4.12 g of calcium oxide hydrate are required. The lime consumption adopted in the experiments meets these conditions. And therefore, the amount of product – tricalcium aluminate, formed as a result of the reaction, depends only on the aluminum consumption. The greater the consumption of aluminum powder, the more $C_3AH_6$ is obtained. And, if the assumption about the influence of $C_3AH_6$ as a stabilizer of the porous structure of the silica mixture is correct, then it becomes clear that the plastic strength of the mixture increases with increasing gas-forming agent consumption. That is, the higher the aluminum consumption, the more tricalcium hydroaluminate and, ultimately, the stronger the structure of the porous mixture.

Analyzing the results of our experiments, it should also be noted that the most intensive increase in plastic strength is observed in the first 30 minutes after the preparation of the cellular concrete mixture. Moreover, it was noticed that if after 30 minutes the plastic strength of the order of 50 g/cm$^2$ is not achieved, then the concrete mixture "settles".

To create high porosity of composite building materials by introducing gas-forming additives, it is necessary to observe certain conditions. Such conditions are the mandatory synchronization in time of the processes of gas formation and the increase in the plastic strength of the molding mass. In the technology of conventional cellular concrete, such conditions are provided by the hardening of mineral binders (cement, lime, gypsum) [16]. But the silica binder does not harden under natural conditions. The effect of stabilizing the porous structure of the silica mixture revealed as a result of the research is explained by the combined action of the gas-forming agent and lime and is not obvious. Of course, the reaction product – $C_3AH_6$ – is also formed in ordinary aerated silica concrete. But its effect there on the plastic strength of the mixture is not obvious since the hydration hardening of lime is more influential. Therefore, the effect of this mineral, which is capable of influencing the increase in the plastic strength of the mixture, was not paid attention to. The discovery of the effect of calcium hydroaluminate as a stabilizer of the structure of the silica mixture is a feature of our research and distinguishes it from analogs [14].

The water demand of the silica mixture is given in the form of a mathematical model (7) and isolines of the water-solid ratio in Fig. 3. The linear coefficients of the mathematical model indicate that all three factors affect the change in the water-solid ratio. The most significant effect is exerted by an increase in the amount of lime. With an increase in the amount of lime, W/S increases. The mathematical model of the water-solid ratio is described by a second-order polynomial, which characterizes the significance of quadratic coefficients. This is clearly confirmed by the nature of the isolines of the water-solid ratio (Fig. 3). The influence of the amount of gas generator and the content of the TC-binder is quantitatively approximately the same but have the opposite nature. With an increase in $m$, the water demand of the mixture decreases. This is explained by the fact that the larger $m$, the larger the amount of TC binder, which is used in the form of sand fractions. The water demand of the TC binder is less than the water demand of the finely ground component (ground sand).

Taking into account the results of our research, technological mixtures that meet the requirements for obtaining a stable porous structure should include mixtures with a water-solid ratio of 0.18 to 0.35, which provides a fluidity of the solution of 10...12 cm. The lime content is not more than 1.5 %. The upper limit of the CaO content is limited due to its negative impact on the strength properties of silica concrete.

The study does not take into account the possibility of scaling the process to large production volumes, which may require additional experiments. In addition, the stabilization of the porous structure of the aerated silica concrete mixture is carried out within a fairly narrow range of the water-solid ratio, which leads to the use of vibration technology, which increases material and energy costs. Further research aimed at finding more effective additives for stabilizing the porous structure could help eliminate these shortcomings. Such additives can be various polymer additives that have binding properties. In addition, their content may not be so limited since they do not interfere with the hardening of the silica cement binder.

## 7. Conclusions

1. As a result of our experimental studies, it was established that obtaining a stable porous structure of the silica mixture occurs at a water-solid ratio of 0.3 to 0.35, a lime content of not more than 1.5 %. Aluminum powder should be used as a pore former. The interaction of ground quicklime and aluminum powder leads to the formation of tricalcium hydroaluminate ($C_3AH_6$). It is a product of hydration of some fast-hardening hydraulic binders and, as a separate mineral, has a fairly high strength. Thus, this mineral acts as a stabilizer of the porous structure of the silica mixture. The upper limit of the CaO content is due to its negative effect on the strength properties of silica concrete.

2. Using mathematical and statistical research methods, the water requirements of the silica concrete mixture were determined, which ensures the fluidity of the solution of 10–12 cm according to the Suttard viscometer. The influence of the amount of gas generator, lime, and TC-binder on the change in the water-solid ratio was determined. The mathematical model of the water-solid ratio is adequately described by a second-order polynomial with a 5 percent experimen-

tal error. From the mathematical model it follows that the greatest influence on the water consumption of the silica mixture is exerted by the lime consumption. The influence of the amount of gas generator and the content of TC-binder is quantitatively approximately the same but has an opposite character. In general, in the entire factor space, the water-solid ratio varies from 0.18 to 0.35.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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## Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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