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The Improvement of the Quality of Construction Foam and Non-Autoclave Foam Concrete on Its Basis through the Introduction of Nanosize Additives

Anastasia Sychova, Larisa Svatovskaya and Maxim Sychov

Abstract

In order to improve the quality of a construction foam on a protein basis for non-autoclaved foam concrete, a proposal has been made to increase its stability by introducing nanosize additives—SiO_2 and $Fe(OH)_3$ sols. It is shown that the effect obtained is connected with various stabilization mechanisms. It is stated that these mechanisms are connected with different energies of chemical bonds formed between the molecules of the foaming agent and the injected sols. By means of electron microscopy, it is stated that the growth of foam stability is connected with an increase in the foam film thickness by one order. An increase in the coefficient of the foam resistance in the cement paste is shown. The stabilization of the construction foam leads to the possibility of using foam concrete hardening accelerators without destroying its structure. The resulting foam concrete is proved to get the increased compressive and bending tensile strength and reduced thermal conductivity and shrinkage in drying. The porosity of the foam concrete obtained is tested by means of mercury porometry. Its phase composition is investigated by X-ray phase and derivatographic analysis.

Keywords: construction foam, foam stability, protein foaming agent, nanosize additives, sol SiO_2 and $Fe(OH)_3$, non-autoclaved foam concrete

1. Introduction

Under the stability of the foam, one understands its ability to maintain the dispersed composition, volume, and ability to prevent delamination. Foam stability is directly connected with the properties of liquid thin layers (foam films) which determine the structure of the foam. To evaluate quantitatively the stability of the foam, the rate of its destruction is determined [1].

Foaming agents used for the production of foam concrete of different hardening are considered in [2, 3]. The paper presents the classification of foaming agents according to their chemical characteristics [4, 5]. Properties of various foams, the bases of their obtaining, and destruction are investigated in the works [6, 7]. For foam concrete on the cement binder, the influence of the foaming agent used on the

degree of cement hydration is considered. It is shown that the protein-based foaming agent is the best one [8].

Instability and destruction of the construction foam is one of the causes of volume instability in foam concrete. Especially sharply this question is on the lightweight foam concretes, because the volume of the foam in their composition is up to 90% [9].

In this regard, one of the ways to improve the stability of the foam concrete mixture can be the stabilization of the construction foam introduced into the cement-sand paste.

At present there are various ways to improve the stability of foams based on various stabilization mechanisms. The use of additives (glycerin, methylcellulose, ethylene glycol) increases the viscosity of foaming agent solutions and slows down the liquid slug from foam films [10]. Also, for the stabilization of foams, it is possible to use substances that contribute to the formation of colloidal particles in films, preventing their dehydration. This group includes gelatin, joiner's glue, starch, and polysaccharides [10, 11].

For the production of thermal insulation materials, it is also recommended to use substances polymerized in the foam as stabilizers. Such additions strengthen the foam film significantly. They include polymer compositions based on synthetic resins and latex [12].

In addition, there are some ways of improving the stability of the foam based on other mechanisms of stabilization.

In [13] the influence of spherical monodisperse SiO_2 particles with a diameter of 20 to 700 nm on the stabilization of foam based on sodium sulfonate was investigated. The positive effect obtained in this case is shown.

The question of obtaining stable foams formed from water dispersions of laponite modified by hexylamine is considered in [14]. It is shown that such a composition "surrounds" foam bubbles with a thin layer, providing a stabilizing effect.

It is also known that the foam can be stabilized by hydrophobic polymer particles with a diameter of less than 1 μm and a length of several tens of μm [15]. The stabilization effect is connected with the formation of dense thick layers of these particles around the foam films.

The paper [16] provides information that submicrometer-sized polystyrene particles in combination with poly[2–(diethylamino)ethyl methacrylate] of various degrees of polymerization—30, 60, and 90—can be used as stabilizers for foam. A higher degree of polymerization results in the highly stable foams.

It is also known that the use of hydrophilic silica particles and liquid paraffin in the foam increases its stability considerably [17]. It is shown that the stabilizing effect is connected with the adsorption of silica particles and oil droplets on the air-water layer of the foam film.

The publication [18] provides information that a significant increase in the stability of the foam can be achieved by the introduction of silica particles of the micrometer size. It is also proposed to use spherical silica particles with a diameter from 150 to 190 nm with their subsequent modification by silane substances [19]. It is established that the hydrophobicity of the surface achieved is a key factor affecting the stability of the foam.

In [20] the data confirming the fact that the stabilization of foams by solid particles is possible and results in a good effect are given. The result depends on the packaging of the particles on the surface of the foam films. The denser the packaging, the better the effect. Also, on the basis of calculations, it is shown that for stabilization of foams on the water basis and on the basis of the liquid, aluminum particles with a diameter less than 3 and 30 μm, respectively, are required.

In [21] the method of determining the coefficient of effectiveness and critical coverage as well as the coefficient of adsorption of particles on the interface of foam bubbles is considered. The possibility of obtaining the most stable foam is stated to depend on them.

The possibility of obtaining porous ceramics from a foamed suspension based on Al_2O_3–TiO_2/ZrO_2–SiO_2 is discussed in [22]. Suspension particles have a stabilizing effect and allow to obtain foam with air content up to 87%.

The carried out analysis suggests that the increase in the stability of the foam is mainly due to the mechanism of "armoring" the surface of the foam bubble by the injected solid particles. This process prevents the liquid from leaking out of the foam film under the influence of gravity and so prevents its subsequent destruction. The mechanisms of foam chemical stabilization with the purpose of getting the foam concrete are not considered yet.

The use of additives based on SiO_2 nanoparticles in modern construction is well known [23–25].

One of the highly effective nano-additives used today is known to be silica (SiO_2) sol [26–28]. Sols are colloidal aqueous solutions containing nanosize particles (1–100 nm) [29]. Chemistry of colloidal silica and its applications are discussed in detail in literature and primarily in [30, 31].

As the literature review shows, there is no knowledge concerning the methods of stabilization of construction foam on a protein basis for foam concrete at the expense of the introduction of sols of different nature into its composition. Also, the problems of improving the physical, mechanical, and thermal properties of the foam concrete of non-autoclaved hardening obtained on the basis of such a foam are not considered.

2. Method

The main idea of the work is: it is possible to use SiO_2 and $Fe(OH)_3$ sols as stabilizers for protein foaming agent (PFA), as it is possible to form various chemical bonds between them, for example, hydrogenous, in the case of using SiO_2 sol [30], or covalent, in the case of using $Fe(OH)_3$ sol [12]. These bonds should contribute to the formation of strong spatial silicon- and iron-protein complexes which will increase the thickness of the foam film and prevent its destruction. This effect should preserve the volume of foam when it is introduced into the cement-sand mixture, as well as improve the physical, mechanical, and thermal characteristics of foam concrete and its products.

The expected chemical bonds formed in the system "aqueous solution of protein foaming agent, sol of different nature," are shown in **Table 1**. The spatial stabilizing complexes based on them are also shown. The formation of these complexes is assumed to provide the foam stability increase. The expected influence of these effects on the physical and technical properties and quality of non-autoclaved foam concrete and its products is described.

The foam stabilization effect can be important for the production of heat-insulating foam concrete of low density (class of average density $\leq D_{200}$), as it will prevent volume instability of raw foam concrete mixture. Also, this effect will make it possible to use hardening accelerators—electrolytes—in the composition of foam concrete which usually destroy it. In high-rise construction when the foam concrete mixture is fed vertically to a great height, foam stabilization will prevent its destruction under the influence of its own pressure in the falling pipeline [12].

It is known that when getting foam concrete products by cutting technology, there appear problems with cutting the mass of foam concrete—there arise chips
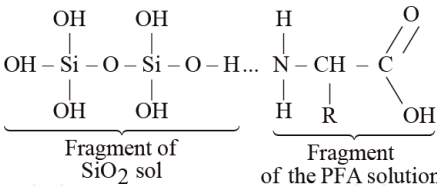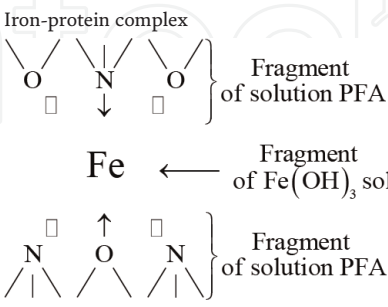
System "aqueous solution of protein foaming agent—sol of different nature"			
Stabilizer	Stabilizing complex	Type of chemical bond	Expected effect
SiO_2 sol	Silicon-protein complex	Hydrogenous H—N	- The foam stability increase - The increase of the foam stability rate in the cement paste and preservation of the concrete mix volume - The possibility of additives-electrolyte application - The increase of compressive and tensile strength of foam concrete - The reduction of thermal conductivity coefficient and shrinkage of foam concrete in drying - The quality category increase of the foam concrete products
$Fe(OH)_3$ sol	Iron-protein complex	Covalent Fe — O, Fe — N	

Table 1.
The expected influence of sols of different nature on the quality of foam, foam concrete, and its products.

and other geometric defects. They reduce the quality category of foam concrete products to category II (according to GOST 31360-2007).

To obtain the first quality category is important because in carrying out a brickwork, it allows to place the foam concrete blocks on the construction glue (coefficient of thermal conductivity, $\lambda \approx 0.3$ W/(m•°C)), and not on the cement mortar $\lambda \approx 0.3$ W/(m•°C)). The use of construction glue is proved to increase the thermal insulating properties of masonry walls significantly. It is assumed that the stabilized foam and the use of the hardening accelerator will considerably increase the number of products of the first quality category.

3. Study of the stabilized foam properties

To confirm the stabilizing effect of SiO_2 and $Fe(OH)_3$ sols, the stability of the construction foam was investigated depending on the concentration of the dispersed phase of the sols in the solution of the protein foaming agent.

In the study, a protein foaming agent "Foamcem" was used as a foaming agent, on the basis of which a 3% aqueous solution was prepared. In addition, SiO_2 sol of the industrial production "SITEC" was used, its characteristics being shown in **Table 2**. Also, $Fe(OH)_3$ sol obtained in the laboratory was used.

$Fe(OH)_3$ sol was obtained by the following method: 5 ml of a 10% solution of iron chloride $FeCl_3$ was slowly poured into boiling water with a volume of 100 ml.

Title	Density (kg/m^3)	Concentration, $\omega = SiO_2$ (%)	pH	Specific surface area, S (m^2/g)
KZ-1 "SITEC"	1165	25.6	3.2	120–140

Table 2.
Main characteristics of the industrial SiO_2 sol.

The stability of the foam was evaluated as the time of extraction (in minutes) of a half of the liquid phase from which the foam was prepared.

Foam stability in the cement paste was evaluated by the coefficient of the foam resistance. Determination of the resistance coefficient was made by mixing equal volumes of cement paste and foam for 1 min followed by measuring the volume of the porous paste. The resistance coefficient of foam in the cement paste is calculated as the ratio of the volume of the porous paste to the sum of the volumes of the cement paste and foam (with water/cement ratio = 0.4).

The results of the studies are shown in **Figures 1–4**. From the figures it can be seen that the stability of the foam stabilized with the SiO_2 and $Fe(OH)_3$ sols increases up to four times and the foam resistance coefficient in the cement

Figure 1.
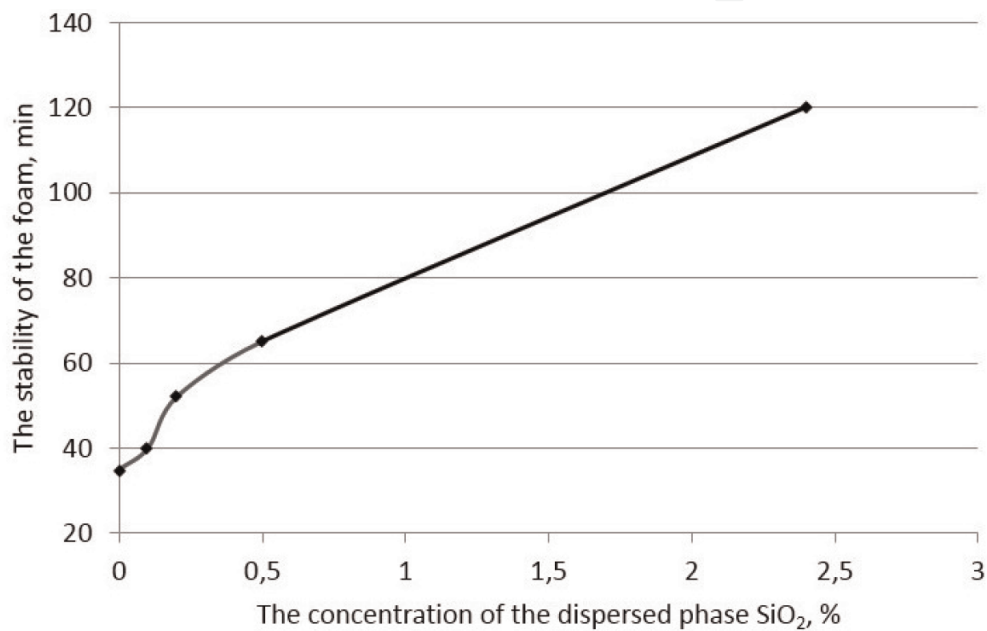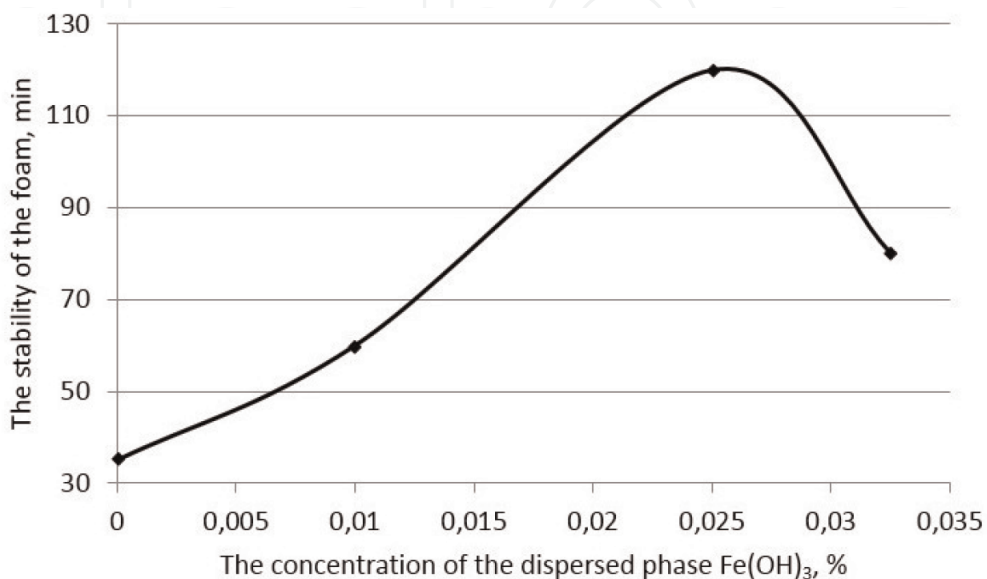*Stability of the foam stabilized with SiO_2 sol.*

Figure 2.
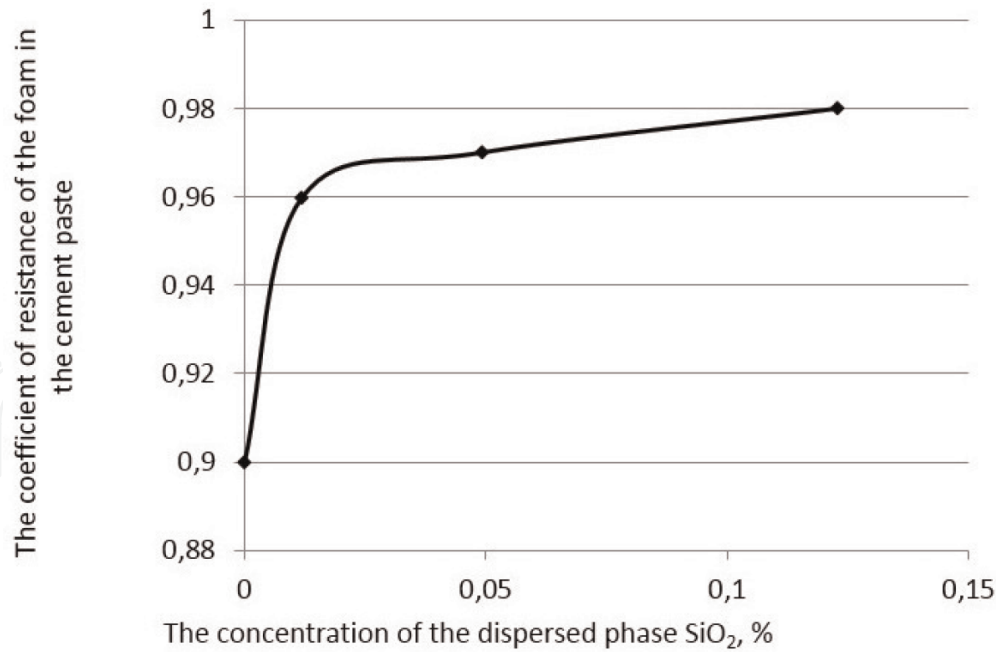*Stability of the foam stabilized with $Fe(OH)_3$ sol.*

Figure 3.
The coefficient of resistance of the foam stabilized with SiO_2 sol in the cement paste.

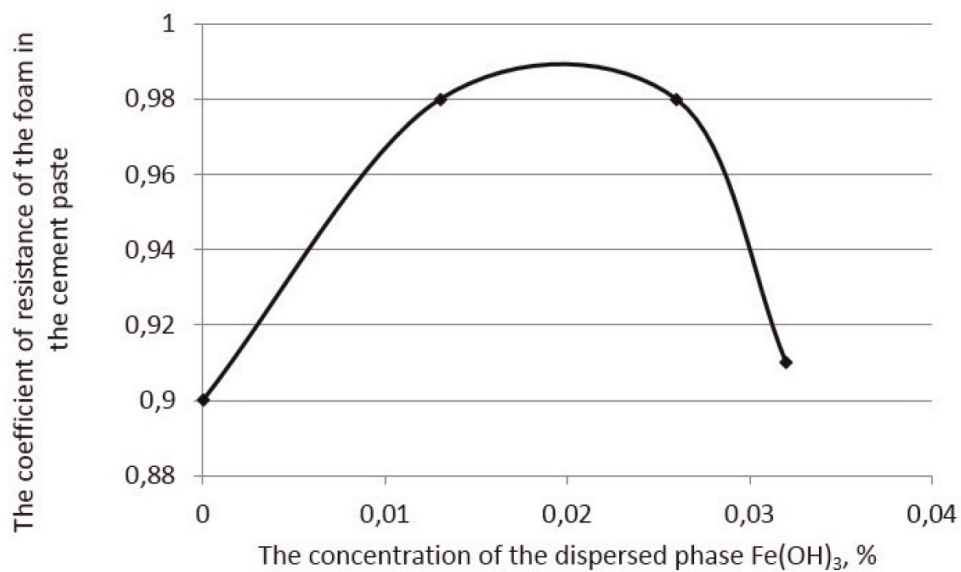**Figure 4.**
The coefficient of resistance of the foam stabilized with $Fe(OH)_3$ sol in the cement paste.

paste increases from 0.9 up to 0.98. These results agree with the forecast as shown in **Table 1**.

Further, in order to clarify the stabilizing mechanism, the surface tension of the foaming agent solution was measured at different concentrations of the dispersed phase of SiO_2 sol, as shown in **Table 3** [10]. The table shows that with increasing the sol concentration, the surface tension practically does not change.

Further, the foam multiplicity (frequency rate) when introducing of SiO_2 and $Fe(OH)_3$ sols into the solution of the foaming agent was investigated. The foam multiplicity was determined by the ratio of the foam volume (l) to the foam solution volume (l). It was found that the multiplicity of the foam on the sol basis does not change, which correlates with the results of measuring the surface tension of the modified foam solutions. The value of the foam multiplicity was 13.

Further, in order to determine the possible chemical bonds formed between the molecules of the protein foaming agent and the injected sols, infrared Fourier spectroscopy of the following model systems was carried out: "aqueous solution of the protein foaming agent" and "aqueous solution of the protein foaming agent—the injected sol" (**Figures 5** and **6**).

From spectrum No. 2, **Figure 5**, the shift and broadening of the band in the region of 3311 cm^{-1} corresponding to the valence vibrations of the hydroxide (OH$^-$) groups in comparison with spectrum No. 1 are seen. This effect can characterize the occurring hydrogen bonds between the nitrogen atom in the protein and hydrogen of the OH$^-$ group of SiO$_2$ sol with the formation of a silicon-protein complex, as shown in **Figure 7a**.

In both spectra (**Figure 6**) the bands in the region of adsorption 1630–1510 cm^{-1} correspond to the deformation vibrations of the carbonyl group C=O of protein. The shift and broadening of this line can be observed on spectrum No. 1, which may correspond to the formation of a covalent bond of iron ion (III) with oxygen of the amide group in the composition of the iron-protein complex formed, as shown in **Figure 7b**. The region of 1150 cm^{-1} corresponds to the deformation vibrations of the NH—C=O group, the shift and broadening of this band on spectrum No. 1 indicate a possible covalent bond of the iron ion (III) with nitrogen in the composition of the iron-protein complex formed, as shown in **Figure 7b**.

Thus, it can be concluded that the decoding of IR spectra of foaming agent solutions stabilized with various sols confirms the assumption expressed in **Table 1**

Concentration of the dispersed phase of the sol in the foaming agent solution (%)	0	0.306	0.610	3013
The surface tension coefficient of the foaming agent solution, σ^*, 10^{-3} (J/m^2)	52.9 ± 0.8	52.9 ± 0.8	53.2 ± 1.2	52.1 ± 1.1

*The value of the surface tension coefficient at the ambient temperature of 21°C.

Table 3.
Values of the surface tension coefficient of foaming agent solution stabilized with SiO$_2$ sol.
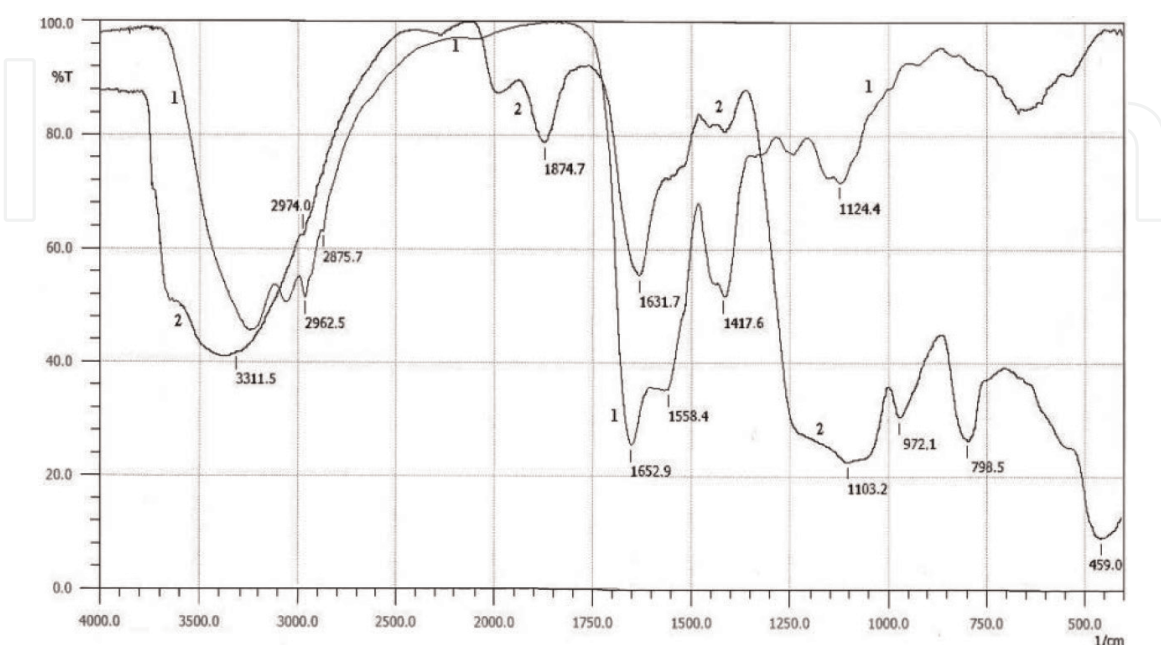

Figure 5.
IR spectra: No. 1, the system "aqueous solution of the protein foaming agent." No. 2, the system "aqueous solution of the protein foaming agent—SiO$_2$ sol."
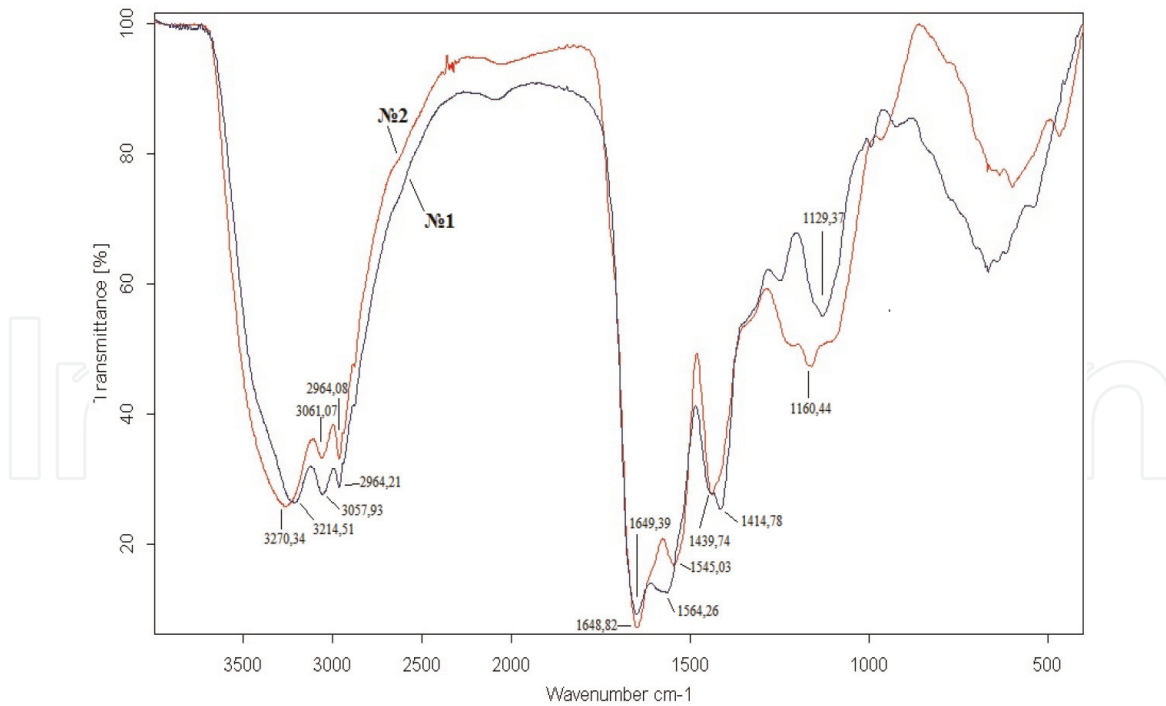
Figure 6.
IR spectra: No. 1, the system "aqueous solution of the protein foaming agent—$Fe(OH)_3$ sol." No. 2, the system "aqueous solution of the protein foaming agent."
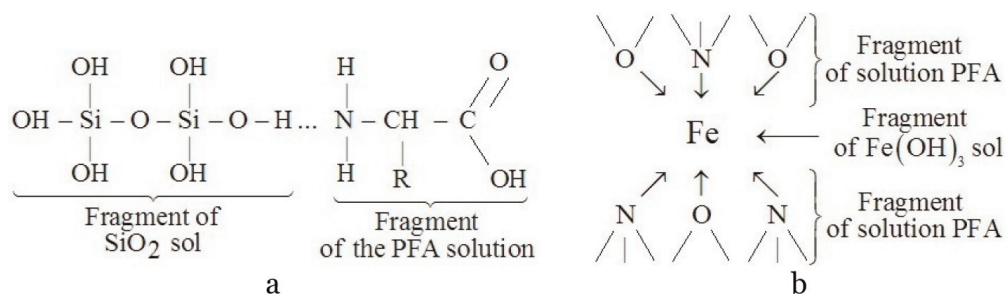

Figure 7.
Spatial stabilizing complexes formed by the introduction of various sols into the solution of protein foaming agent: (a) silicon-protein complex and (b) iron-protein complex.
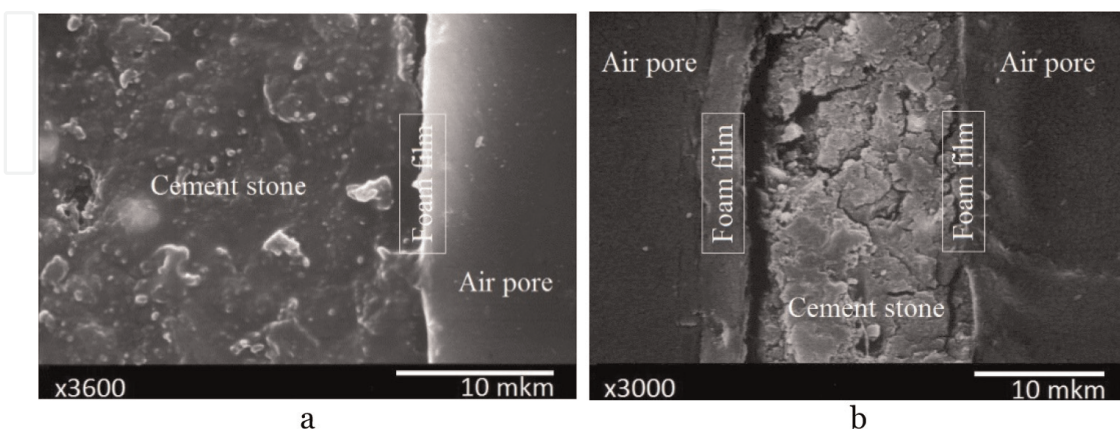

Figure 8.
Electron microscopy of the foam concrete samples of the medium density D600: (a) control sample and (b) sample based on foam stabilized with SiO_2 sol.

concerning the formation of hydrogenous and covalent chemical bonds in the composition of the stabilizing silicon- and iron-protein complexes.

Further, it was assumed that the appearance of chemical bonds and spatial stabilizing complexes should increase the thickness and strength of the foam film,

which results in the increase of the foam stability. For this purpose, electron microscopy of samples of the foam concrete with medium density D600 was carried out: a control sample and a sample prepared on the basis of the foam stabilized with the SiO₂ sol (**Figure 8**).

From the pictures it can be seen that the thickness of the foam film in the control sample is ~450 nm and in the sample based on the stabilized foam is ~3.5 μm, i.e., increase by one order. This result can explain the stabilizing effect and the increase in foam stability as well as confirm the assumptions made.

4. Research of the foam concrete properties of various average densities on the basis of the stabilized foam

Further the possibility of receiving heat-insulating non-autoclaved foam concrete of average density D_{200} on the basis of the foam stabilized with SiO_2 sol was investigated.

For light thermal insulating non-autoclaved foam concrete, one of the significant problems is the reduction of the volume of the foam concrete mixture because of the mixture destruction, which results in the deviation from the projected average density and uneven structure of the material and exerts a negative influence on the properties of thermal insulating foam concrete.

It was assumed that a more stable foam will allow to avoid the destruction of the mixture, to provide the necessary density of the foam concrete, and to obtain a reduced thermal conductivity coefficient.

The composition of the foam concrete with medium density D_{200} is shown in **Table 4**. Portland cement CEM 42.5 was used as a binder, dolomitized limestone was used as a filler [32], protein foaming agent "Foamcem" was used as a foaming agent, and SiO_2 sol of industrial production was used as a stabilizer (SITEC company).

To assess the stability of the foam concrete mixture, the volume instability of the foam concrete (mm) was measured at different contents of the dispersed phase of the sol in the foam. Volume instability was measured after 24 hours of the foam concrete hardening (**Figure 9**). From the figure it is seen that the use of the stabilized foam reduces the volume instability up to 0 when the concentration of the dispersed phase of sol in the foam is at least 0.2%. The coefficient of thermal conductivity of foam concrete of average density D_{200} at the design age was $\lambda = 0.04$ W/(m•°C); for comparison, $\lambda_{air} = 0.029$ W/(m•°C).

Further the physical-technical and thermal insulating properties of foam concrete and its products after the introduction of the stabilized foam into its composition were evaluated.

The compositions of the foam concrete mixtures of different average densities are shown in **Table 5**. During the preparation of foam concrete mixtures, 3% aqueous solution of foam on a protein basis stabilized with different sols was used. The samples were being solidified under normal conditions for 28 days.

During the experiment it was expected that a more stable foam will allow to use the electrolyte additives to activate the hardening of cement and to obtain the improved physical and mechanical characteristics of foam concrete and its

Cement (kg)	Filler (kg)	Water (l)	Foaming agent (l)	Stabilizer (SiO₂ sol) (kg)
125	45	102	2.52	0.3

Table 4.
Consumption of the materials for 1 m³ of foam concrete of average density D₂₀₀.

products. In the case of using a conventional foam solution, such additives destroy the foam. Sodium chloride (NaCl) in an amount of 5% by weight of cement was used as a hardening activator. The obtained characteristics of foam concrete are shown in **Table 6**.
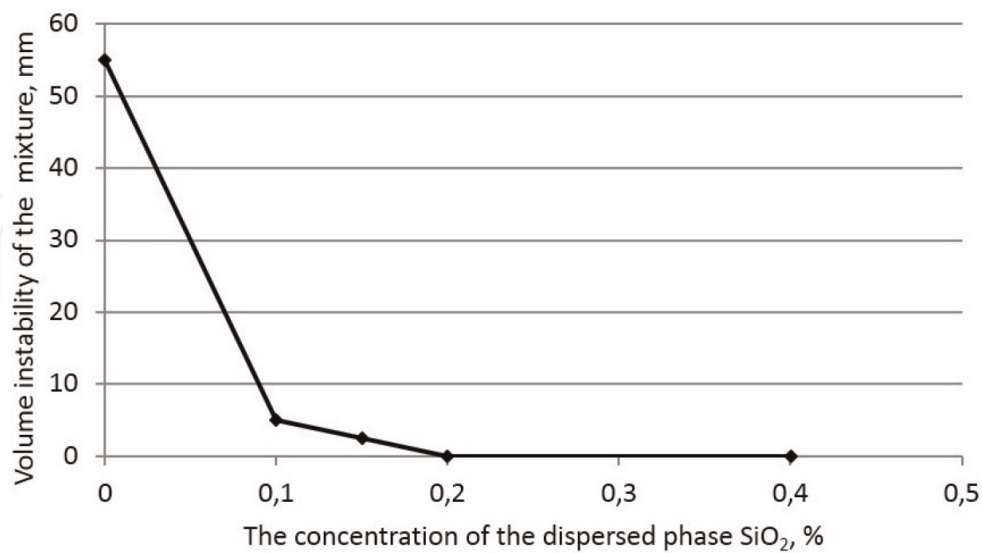

Figure 9.
Dependence of the volume instability of the foam concrete mixture on the content of the dispersed phase of SiO_2 sol in the foaming agent solution.

Class by average density	Cement (kg)	Filler (kg)	Water (l)	Foaming agent (l)	Stabilizer (l)	
					SiO_2 sol	$Fe(OH)_3$ sol
D_{400}	330	50	152	2.1	1.5	6.1
D_{500}	370	100	183	1.98	1.44	5.7
D_{600}	400	170	211	1.75	1.3	5.0

Table 5.
Consumption of materials per 1 m³ of foam concrete of different average densities.

Class by average density	Foam type	Stabilizer	Compressive strength, MPa/%	Bending tensile strength, MPa/%	Thermal conductivity, λ, W/(m•°C)/%
D_{400}	Control	—	0.8/100	0.45/100	0.100/100
	Stabilized	SiO_2 sol	1.2/150	0.76/169	0.086/86
		$Fe(OH)_3$ sol	1.2/150	0.66/147	0.09/90
D_{500}	Control	—	1.3/100	0.69/100	0.120/100
	Stabilized	SiO_2 sol	1.9/146	1.14/165	0.101/84
		$Fe(OH)_3$ sol	1.7/131	0.88/128	0.107/89
D_{600}	Control	—	1.7/100	0.88/100	0.140/100
	Stabilized	SiO_2 sol	2.3/135	1.38/158	0.117/84
		$Fe(OH)_3$ sol	2.2/129	1.15/131	0.132/94

Table 6.
Physical and mechanical characteristics of foam concrete samples of average density D_{400}–D_{600} prepared on the basis of the stabilized foam.

Stabilizer	Class of frost resistance
—	F15
Sol SiO_2	F35
Sol $Fe(OH)_3$	F35

All studies were conducted in accordance with GOST 25485-89.

Table 7.
Frost resistance samples of the foam concrete of average density D600 prepared on the basis of the stabilized foam.

When assessing the physical and mechanical characteristics of the foam concrete samples obtained on the basis of a stabilized foam, the following results were got:

- The use of electrolytes does not destroy the stable foam.

- The compressive strength of the samples with medium density D_{400}–D_{600} at the age of 28 days of normal hardening increases up to 50% compared to the control sample, and the tensile strength at bending increases up to 69%.

- The thermal conductivity coefficient of the samples with additives decreases up to 16% in comparison with the control sample.

Also, for samples of foam concrete of average density D_{600}, a study of their frost resistance was carried out. It showed an increase in the class of frost resistance from F15 to F35, as shown in **Table 7**.

5. Physicochemical studies of the composition of the obtained foam concrete and its porous structure

At the next stage of the work, physical and chemical studies of samples of foam concrete with medium density D_{500}, prepared on the basis of stabilized foam and NaCl additives, were carried out: X-ray phase and differential thermal analysis. Three samples of foam concrete were studied: No. 1, control; No. 2, based on the foam stabilized with SiO_2 sol and with the addition of NaCl; and No. 3, based on the foam stabilized with $Fe(OH)_3$ sol and with the addition of NaCl.

In all samples X-ray phase analysis showed the presence of reflexes corresponding to β-SiO_2 with d/n (interplanar spacing) = (3.337, 2.447, 2.280, 2.119, 1.657; 1.539) Å, as well as reflexes corresponding to $Ca(OH)_2$, d/n = (3.114, 2.625, 1.926, 1.675) Å, low-basic hydrosilicate C_6S_6H d/n = (3.030, 2.033, 1.95) Å, and hydrosilicate C_2SH_2 (d/n = (3.030, 2.765, 1.830, 1.565) Å). In the X-ray spectra of samples No. 2 and No. 3, new lines belonging to the low-basic hydrosilicate $C_3S_2H_3$ (d/n = 2.88; 2.766; 2.152; 1.973; 1.793; 1.627 Å) appear. The radiographs of samples No. 2 and No. 3 show the lines characterizing the dolomitized limestone. Alite analytical line (C_3S, d/n = 1.76 Å) is present only in the control sample; in other samples, it does not manifest itself, which indicates a deeper degree of cement hydration in them. The formation of additional low-basic hydrosilicates with increased strength, as well as the absence of an analytical line of alite on the radiographs, can explain the increase in the strength of foam concrete samples No. 2 and No. 3.

The derivatographic analysis, **Table 8**, confirmed the data of X-ray phase analysis and showed that the total mass loss of samples based on the stabilized foam and

NaCl additives increases by 20%; besides that, a new phase of low-basic hydrosilicate $C_3S_2H_3$ (endothermic effect in the region of 350–400°C) appears in the samples, which also confirms the increase in the strength of the foam concrete samples.

Then, in order to assess the porous structure of foam concrete based on the foam stabilized with SiO_2 sol, porosity of the samples was investigated by means of mercury porometry (**Figure 10**).

The figure shows that the specific surface area of the pores in the sample based on the stabilized foam is twice that of the control sample. This may be due to the fact that such a foam is more stable in preparing a foam concrete mixture and in subsequent hardening the fine porous structure of the material is retained. The studies of the macroporous structure of foam concrete confirm this conclusion, as shown in **Figure 11**.

No.	Stabilizer	Endothermic effects, °C					Total mass loss on the effects, mg	The total mass loss by the sample, mg
		Mass loss, mg						
	Additive	(130– 170)	(350– 400)	(520– 580)	(750– 880)	(930– 960)		
1.	—	88	—	24	14	—	126	179
2.	Fe(OH)$_3$ sol NaCl	86	16	20	33	28	183	213
3.	SiO$_2$ sol NaCl	90	18	19	40	30	197	227

Table 8.
Derivatographic analysis of foam concrete samples of average density D_{500}.
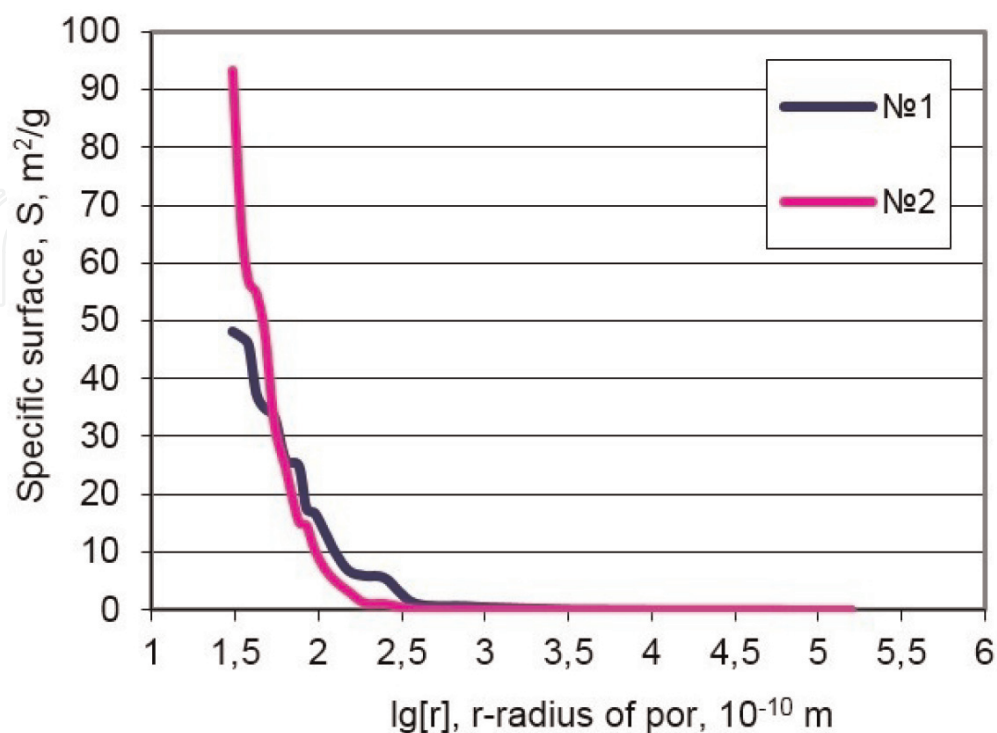

Figure 10.
The total specific surface of pores of foam concrete with average density of D_{500}: (1) a control sample, (2) a sample based on the foam stabilized with SiO_2 sol.
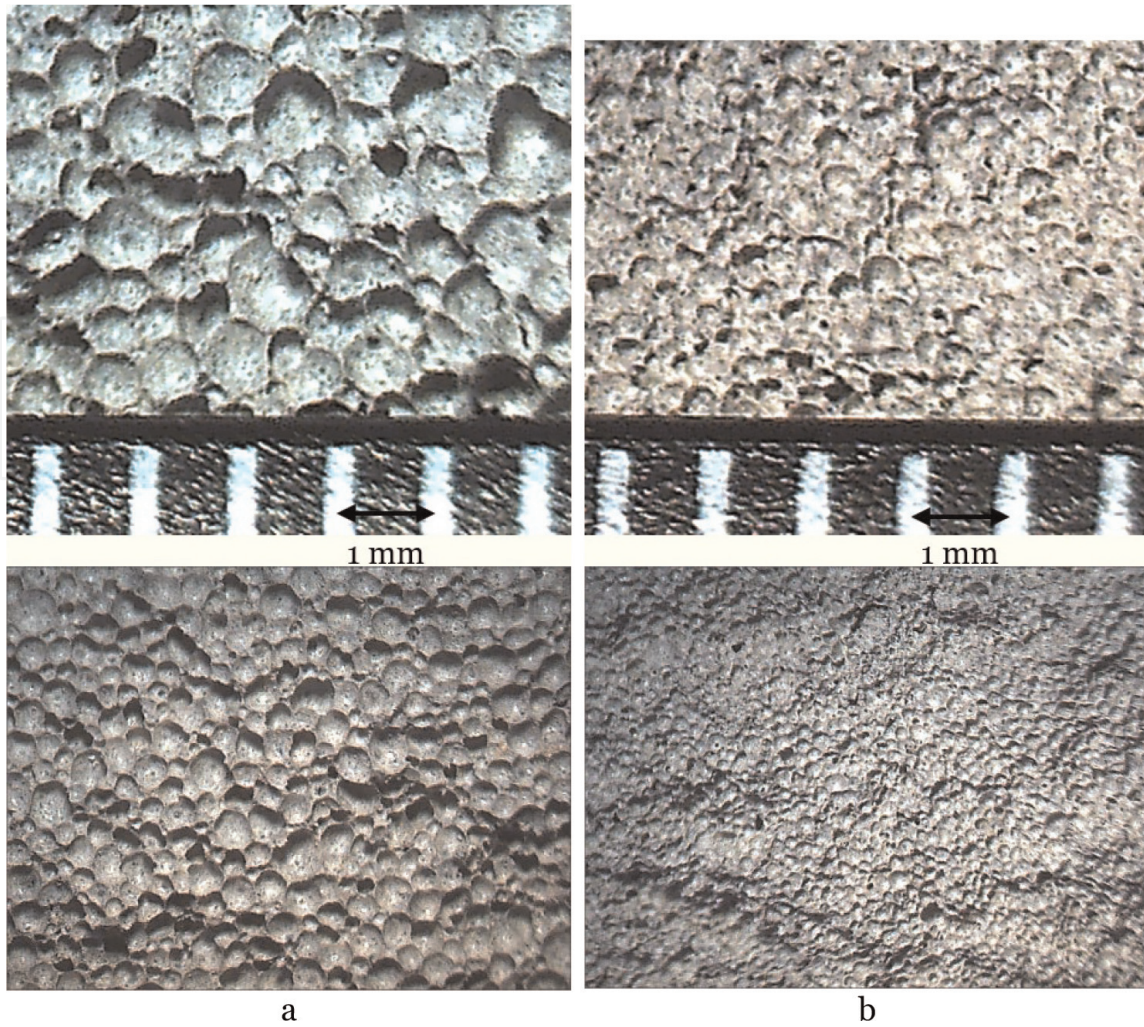
Figure 11.
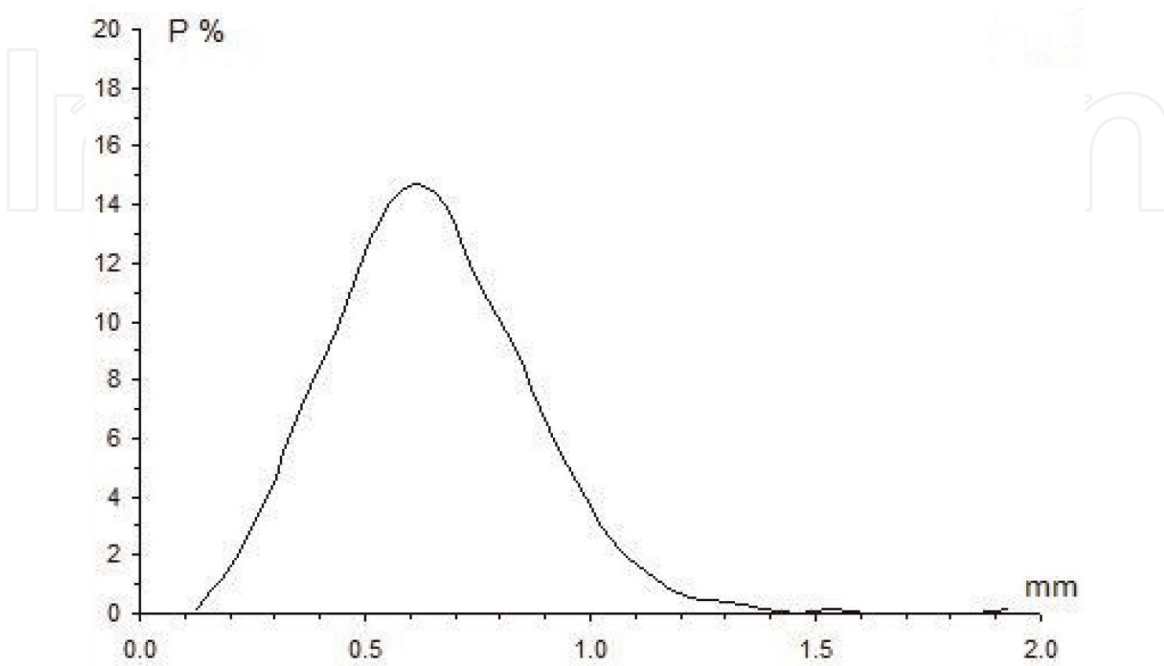*Macroporous structure of samples: (a) a control sample and (b) a sample based on the stabilized foam.*

Figure 12.
Distribution of macropores according to their size for the control sample of foam concrete.
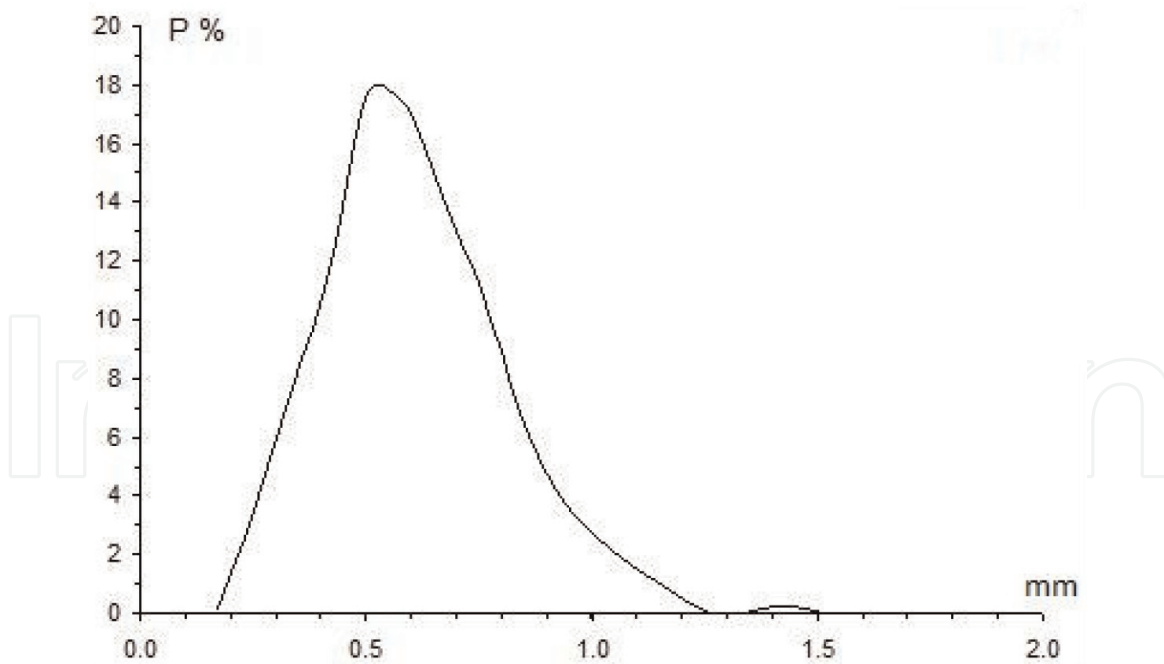
Figure 13.
The distribution of macropores according to their size for the foam concrete sample on the basis of foam stabilized with SiO₂ sol.

Figures 12 and **13** show the distribution of large pores according to their size for the foam concrete samples of average density D_{600}; the study was conducted by means of the electron microscopy.

As it can be seen from the figures, the peak of the pore distribution according to their size in the case of a foam concrete sample based on a stabilized foam is shifted toward a smaller pore diameter (D_{av} = 520 μm). The number of such pores is 18%, the half-width of the peak is 0.44 mm. For the control sample, the peak corresponds to D_{av} = 600 μm, the number of pores of the average diameter is 15%, and the half-width of the peak is 0.52 mm.

Thus, it can be concluded that the stabilization of foam with SiO₂ sol influences both the micro- and macropores of foam concrete. This increase in the foam concrete pore dispersion during the stabilization of foam explains the decrease in its thermal conductivity (**Table 5**).

6. Production of foam concrete on the basis of the stabilized foam in industrial conditions

The results obtained by our group were tested in the industrial conditions in accordance with the technological specifications for the production of foam concrete by cutting technology. In this technology the cutting process begins when a foam concrete mass develops a certain cutting strength. The time of cutting strength attainment can be 17–20 h depending on the composition of the foam concrete. To reduce the time of this technological stage is important from an economic point of view besides that it can improve the productivity of the enterprise.

The studies of samples obtained on the basis of the foam stabilized with SiO₂ sol in production conditions also showed that the foam was not destroyed by the introduction of NaCl additives. The compressive strength of foam concrete products increases up to 38%, and the coefficient of thermal conductivity decreases and

corresponds to the foam concrete the class of which is one class lower by the average density. At the same time, the duration of the cutting strength attainment reduces by 7 hours, which significantly speeds up the technological process.

In addition, the shrinkage value of the foam concrete samples was estimated in drying. It was stated to decrease by 18% compared to the control sample, as shown in **Table 9**.

Class by average density	Additive	The time of cutting strength attainment, hour	Thermal conductivity, λ, W/(m•°C)/%	Shrinkage in drying, mm/m
D_{500}	—	17	0.117/100	3.4
	NaCl	10	0.094/80	2.8

Table 9.
Physical and technical characteristics of industrial samples of non-autoclaved foam concrete of average density D_{500}.
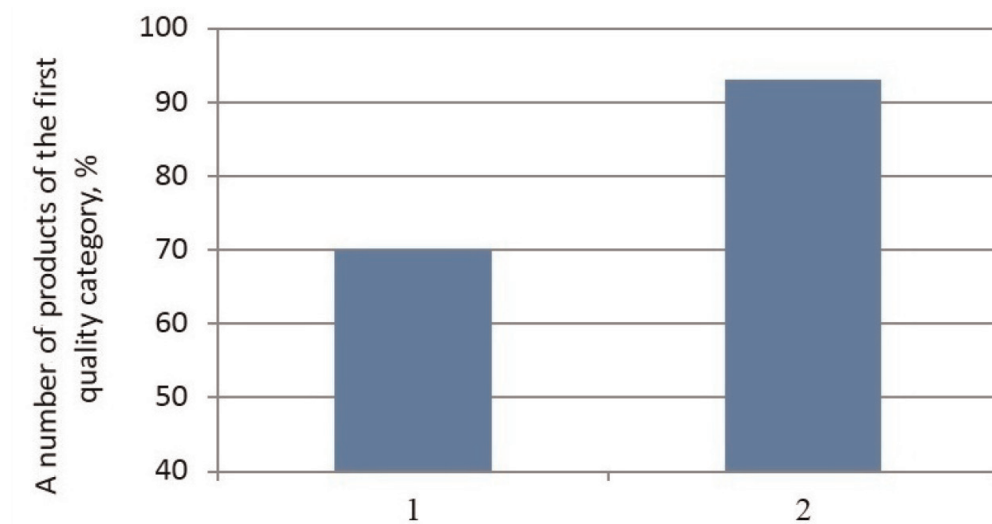

Figure 14.
The number of concrete products of the first quality category: (1) control products, (2) products based on the stabilized foam and NaCl additives.

Figure 15.
Foam concrete products based on the stabilized foam and NaCl additives.

Figure 14 shows the number of foam concrete products of the first quality category which increases by 23% compared to the control products made of foam concrete. These figures confirmed the earlier assumptions.

The quality category of products was evaluated in accordance with the specifications (GOST 21520-89). According to its requirements for the blocks of the first quality category the limit deviations in height can be ±1 mm, in length, thickness and deviation from the rectangular shape it can be ±2 mm. Damage to the corners on one block with a depth of no more than 5 mm, damage to the ribs on one block with a total length of no more than twice the length of the longitudinal edge and a depth of no more than 5 mm are limited by the specifications.

Figure 15 shows the industrial samples of foam concrete products of average density D_{500}.

7. Conclusions

1. For the first time it is proposed to use SiO_2 and $Fe(OH)_3$ sols to stabilize the construction foam on a protein basis in order to obtain high-quality non-autoclaved foam concrete.

2. It is shown that the stability of the foam stabilized with SiO_2 and $Fe(OH)_3$ sols increases up to four times and the coefficient of resistance of the foam in the cement paste increases from 0.9 to 0.98.

3. The method of IR Fourier spectroscopy shows that the mechanism of the foam stabilization is connected with the formation of various chemical bonds between the molecules of the protein foaming agent and sols: hydrogenous in the case of using SiO_2 sol and covalent in the case of $Fe(OH)_3$ sol.

4. It is established that the new chemical bonds result in the formation of spatial stabilizing complexes in the foam film. This leads to an increase in its thickness by one order, which is confirmed by electron microscopy.

5. Heat-insulating foam concrete of average density D_{200} with thermal conductivity coefficient 0.04 W/(m•°C) was obtained on the basis of the foam stabilized with SiO_2 sol.

6. On the basis of the foam stabilized with SiO_2 and $Fe(OH)_3$ sols and NaCl additive, high-quality foam concrete of medium density D_{400}–D_{600} was obtained. Compressive strength increases up to 50%, tensile strength in bending increases up to 69%, shrinkage in drying decreases by 18%, the coefficient of thermal conductivity decreases by 16%, and frost resistance increases by 20 cycles.

7. Studies of the porous structure of foam concrete based on the stabilized foam have shown that the specific surface area of the pores increases twice and the average pore diameter decreases from 600 to 520 μm.

8. Industrial testing of the developed foam concrete of the average density D_{500} has been made. The use of the foam stabilized with SiO_2 sol and the additive of NaCl in its composition allows to reduce the time of cutting strength attainment by 7 hours and to increase the number of products of the first quality category by 23%.

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