

Cellular concrete is this study's object with emphasis on the formation and evolution of its internal structure.

Currently, there is an issue related to the insufficient quantity and quality of tools for assessing the nature of building materials' structure. This does not allow the concept of controlled structure formation to be fully applied. The results reported here confirm that artificial composite materials in the design process follow stages that have the characteristics of open systems. They are capable of self-organization and are sensitive to external energy influences, which is reflected in the change in the nature of the structure.

The use of fractal and information dimensionalities as quantitative indicators of the nature of the material structure has been proposed. The influence of water content and acoustic activation parameters on the change in structural characteristics was investigated on physical models in the form of water-clay suspensions, justified as analogs of cement slurry.

The effect of acoustic activation on the properties of foam concrete was established: at a frequency of 12 kHz, the compressive strength was 1.8 MPa, while at a frequency of (22 kHz) the strength decreased to 0.5–0.7 MPa, and the humidity increased to 34–35%, which indicates destabilization of the structure. Changes in the degree of order and complexity of the structure were quantitatively recorded using fractal and information dimensionalities.

The results are attributed to the technology of manufacturing cellular concretes, in particular foam concrete, in which the use of acoustic activation at the early stages of structure formation makes it possible to control the structure of the material and its physical and mechanical properties. The proposed approach could be integrated into industrial technological schemes provided that stable parameters of acoustic influence are ensured; it does not require significant changes to standard equipment

Keywords: open system, cement slurry, building material, cellular concrete, acoustic activation

FRACTAL ASSESSMENT OF STRUCTURAL CHANGES IN CELLULAR CONCRETE UNDER ACOUSTIC EXCITATION

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1. Introduction

In modern building materials science, an approach is increasingly being formed according to which the operational properties of materials are determined primarily by their internal structure. Even with the same composition and technology, materials can differ in physical, mechanical, and functional characteristics.

The geometry and topology of the solid phase (especially in porous materials), pores, internal interface surfaces (IIS) of phases, cracks, etc. have a direct impact on the physical, mechanical, and functional properties of building materials. The formation of this structure occurs as a result of the interaction of a sequence of cause-and-effect processes.

At the early stages of the structure formation of materials based on mineral binders, processes with signs of chaos are observed. Modern research shows that initial chaos is an inherent property of open nonlinear systems and a necessary condition for the transition to an ordered

state. Such a transition is realized through self-organization mechanisms.

A typical example is the hardening process of cement stone. After mixing cement with water, a highly concentrated suspension in a disordered state is formed. During the hydration process, new reaction products are formed, the volume of which increases with time, and the system gradually acquires signs of an ordered structure. Presumably, this transition corresponds to the interval between the beginning and completion of cement hardening.

This view of structure formation is consistent with the philosophical triad “chaos-theos-cosmos”. In the technological interpretation, chaos corresponds to the initial disordered state of the system, theos – to the controlling influence of the technologist, and cosmos – to the formed structure of the material with predicted properties.

Controlling the transition from a chaotic to an ordered state is possible if there are quantitative tools for describing the structure. Conventional indicators, such as porosity,

density, or strength, give an integral assessment, but do not reflect the organization of structural elements. In this context, the use of fractal geometry and information approaches is promising.

Fractal and information dimensionalities allow us to quantitatively assess the degree of complexity and orderliness of the structure and sensitively respond to changes in the conditions of material formation. Their use creates the possibility of analyzing the effectiveness of external energy influences from the standpoint of the concept of controlled chaos.

Acoustic activation garners special attention as a type of external excitation that is relatively simple to implement and can influence the rheology of mixtures, the rate of hydration, as well as the nature of the material structure. This is especially true for cellular concretes in which the structure is formed in the early stages of hardening.

2. Literature review and problem statement

The physical and mechanical properties of building materials are determined not only by their composition but primarily by the features of the internal structure. The structure that is formed during hydration and subsequent hardening of cement stone determines the porosity, strength, crack resistance, and other operational characteristics of materials. Papers [1, 2] report the results of studies on the role of the structure of cement stone in the formation of the physical and mechanical properties of materials. It is shown that it is the nature of the structure that determines the operational indicators. However, the issues related to the quantitative description of the geometry and order of the structure remain unresolved, which limits the possibilities of purposeful control of its formation.

In fundamental works [3, 4], the concept of self-organization in non-equilibrium systems was formulated and elaborated. These studies show that the structure of composite materials arises as a result of the interaction of many processes that occur under conditions far from equilibrium. This opens up the possibility of purposeful control of structure formation – by changing the parameters of the environment or applied energy influences, which, in turn, makes it possible to regulate the properties of the material. At the same time, these papers are of a general theoretical nature and do not take into account the specificity of cement compositions. The reason for this is mainly the general theoretical nature of the studies, as well as the objective difficulties associated with transferring the provisions of the theory of self-organization to complex multiphase cement systems. This complicates the direct use of the results in the technology of building materials.

In the context of building materials, this is manifested, for example, in the processes of cement hydration. The formation of hydrated phases, and primarily C-S-H, occurs as a sequence of interconnected microprocesses under non-equilibrium conditions, which leads to the emergence of a spatially inhomogeneous, but structurally stable microsystem [5, 6]. However, the influence of external energy actions on the change in this morphology is not analyzed. In study [7], it is shown that changing the composition and hardening conditions allows for partial control over hydration processes. Thus, the above works show the possibility of partial influence on structure formation by changing the composition and hardening conditions. However, the issue of controlling the structure by external energy influences remains practically unexplored, which may be due

to the complexity of the experimental implementation of such influences and the lack of adequate quantitative criteria for assessing structural changes.

In papers [8, 9] it is shown that the formation of the structure during the hardening of cement stone has the features of an open nonlinear dynamic system, in which external energy influences are able to modulate the course of structure formation. Such behavior is consistent with modern ideas about self-organization and multilevel evolution of C-S-H-gel, which is confirmed in [10]. This creates grounds for the application of the concept of controlled chaos [11], according to which the partial non-equilibrium of the system plays a constructive role in the processes of structure formation. Recent studies show that changes in the local ordering of the gel significantly affect the macroscopic properties of composite materials, which makes it advisable to combine conceptual models with quantitative approaches to structural analysis.

Among the external excitations capable of modifying the course of self-organization, acoustic activation has garnered special attention. Modern studies demonstrate that sound and ultrasonic vibrations affect not only the hydration and dispersion of particles but also the kinetics of structure formation, cavitation processes, agglomeration, and micropore structure [12, 13]. As a result, the frequency modes of acoustic influence are considered as a tool for controlling the processes of structure formation, which opens the way to the implementation of the concept of controlled chaos in building materials technologies. For example, in paper [14] it is shown that resonant modes or those close to them cause qualitative changes in the structure of the system due to the intensification of cavitation processes. However, in most of the studies cited, the emphasis is on changing the integral properties of the material, while the quantitative analysis of structural parameters is practically absent. This does not make it possible to establish a cause-and-effect relationship between the parameters of acoustic influence and the nature of structure formation.

For quantitative analysis of the nature of the structure of composite materials, the apparatus of fractal geometry is increasingly used in modern research. Fractal dimensionality (D) is a statistical indicator that assesses the degree of filling of space with structural formations and in some cases correlates with mechanical properties, density, capillary porosity, and other characteristics [15, 16]. An additional indicator is the information dimensionality (D_i), which is used to assess the degree of orderliness of the structure from the standpoint of information theory. In work [17], information dimensionality is used to analyze the spatial distribution of structural elements, but without considering its sensitivity to external influences. In [18, 19], the possibility of using information indicators to describe self-organization processes is shown; however, these approaches are mainly descriptive in nature and are not focused on the analysis of controlled structural changes.

Despite the informativeness of fractal and information dimensionalities, in most of the cited works they are used mainly for describing the structure and are almost not used as a tool for analyzing the purposeful formation of material properties.

At the same time, these indicators have not yet been widely used for analyzing the nature of the structure of cellular concretes. Although they are especially valuable in analyzing the structure of materials with a high degree of heterogeneity, such as cellular concrete, where the chaotic distribution of pores, aggregates and compaction zones requires a complex

description [20]. In [21], data on the relationship between the fractal dimensionality of the microstructure of cement composite materials and their mechanical properties are summarized. However, the analysis is mainly of an overview nature and does not take into account the influence of technological parameters of structure formation, which is important for the development of controlled approaches. In studies [22, 23], a relationship between fractal characteristics and humidity and other physical and mechanical properties of building materials was established but the results are mainly of a descriptive nature and do not consider the possibility of controlling the structure formation process.

Thus, available studies confirm the informativeness of fractal dimensionality but do not solve the problem of purposeful formation of the structure of the material.

In paper [24], the hypothesis was put forward that the properties of cellular concretes are determined by the nature of the solid phase distribution. Further development of this idea in studies [25, 26] is associated with the introduction of internal interface surfaces as structural parameters. However, the question of the influence of external activation on these parameters remains open.

All this gives grounds to argue that it is advisable to conduct a study to quantitatively analyze the influence of acoustic excitations on the nature of the structure formation of cellular concretes using fractal and information criteria.

3. The aim and objectives of the study

The aim of our study is to establish regularities in the influence of acoustic excitation on the nature of structure formation in cellular concrete based on the analysis of fractal and information parameters of the structure. This will provide an opportunity to scientifically substantiate approaches to controlling the structure and physical and mechanical properties of cellular concretes at the early stages of their formation.

To achieve this aim, the following objectives were accomplished:

- to investigate the influence of water content and acoustic excitation parameters on the fractal characteristics of the structure of physical models – analogs of cement stone;
- to determine the change in the fractal and information dimensionalities of the structure depending on the porosity of model materials;
- to establish the influence of acoustic activation on the strength and moisture content of foam concrete.

4. The study materials and methods

The object of our study is cellular concrete and its structure. The principal hypothesis assumes that external acoustic excitations are able to change the nature of the structure of the material, which can be quantitatively recorded using fractal and information dimensionalities. The study assumes the possibility of using water-clay suspensions as physical analogs of cement slurry, and uses simplifications related to the geometry of pores and conditions of external influence.

As raw materials in experimental work on the production of foam concrete, the following were used: Portland cement M500, quartz filler, foaming agent, and water. Clay was used to produce physical models of various analogs of composite building materials.

When solving scientific problems, the method of analogies is sometimes quite effective. The study of the influence of acoustic influences on the nature of the change in the nature of the structure of the solid component was carried out on physical models. As a material for the manufacture of models, a water-clay suspension with a water-clay ratio of 0.8; 1.0; 1.2 was used. In this case, the analogy is that both during cement hydration and during drying of materials, volumetric changes occur in the direction of their reduction, which leads to a change in the nature of the solid phase.

After preparing the water-clay suspension, it was placed in PVC molds with a diameter of 150 mm; the height of the mortar mixture was 10 mm. The manufactured models were left indoors at a temperature of 20–25°C. Free water was removed from the models naturally. After the first signs of cracks appeared on the surface, one part of the models was placed in an acoustic chamber where acoustic activation was carried out for 10 minutes with specified sound parameters (oscillation frequency $\nu = 100, 200, 300, \text{ and } 400 \text{ Hz}$). This procedure was repeated twice every 12 hours. The other part of the models was not activated (control samples). The samples were kept in air until the nature of the structure visually changed. After that, photofixation was carried out. Photofixation was carried out using a digital camera at a fixed distance from the model, and with a fixed image resolution. The photographs of the structures were uploaded to a specially developed program that calculated the quantitative indicators of fractal and information dimensionalities. To construct graphical dependences, the arithmetic mean of 3 measurements was calculated.

In another experiment, the influence of water demand and porosity on the nature of the model structure was also studied on models in which the analog of the mortar mixture was a water-clay suspension. For this purpose, pore simulators were formed in the water-clay suspension using plastic inserts in the shape of a circle. After the models reached a certain strength, the simulators were removed and voids were formed in their places. The models were kept under natural conditions in the laboratory at an ambient temperature of $23 \pm 2^\circ\text{C}$ until completely dry. The nature of the model structure was also recorded using a camera. The restrictions adopted were as follows: pores of the same size, spherical in shape, cubic packing.

It is known that in the initial period of the emergence of the “foam concrete” system, the system is in an unbalanced state. During this period, it is very sensitive to any external energy influences. Therefore, at the next stage, the influence of acoustic energy on the change in the strength and humidity of foam concrete was studied.

For this purpose, foam concrete was prepared in the following sequence. First, a mixture of dry components was prepared, consisting of 60% Portland cement M500 and 40% carbonate filler (ground limestone-shell rock). Then, technical foam was added to the solution mixture, with an average density of $50 \pm 5 \text{ kg/m}^3$, to obtain a foam concrete mixture with an average density of $780 \pm 10 \text{ kg/m}^3$. The molds with the foam concrete mixture were placed in an acoustic chamber. Speakers were installed in the acoustic chamber, and with their help, from a CD player, the foam concrete mixture was exposed to acoustic energy of different oscillation frequencies for 60 minutes. The hardened samples were kept in a normal hardening chamber before testing.

Elements of fractal geometry were used to quantitatively assess the nature of the structure. Unlike conventional charac-

teristics of the quality of materials, which are evaluated through physical and technical properties (porosity, density, strength, etc.), fractal parameters make it possible to describe the structure as a system consisting of elements ordered according to the principles of scale and self-similarity. That is why this device is especially useful for analyzing composite materials based on cement systems, in which the processes of structure formation occur under non-equilibrium conditions and are characterized by stochastic behavior.

A common quantitative criterion is the fractal dimensionality, which reflects the degree of filling of space with structural elements. In the case, for example, of cellular concrete, it characterizes the degree of filling with the solid phase. The value of D varies from 1 to 2 for surfaces and from 2 to 3 for volumetric formations. An increase in fractal dimensionality indicates the formation of a denser, more developed structure with a high area of phase interface surfaces. On the contrary, a decrease in D reflects a simplification of the structure, an increase in the size of elements or a decrease in the number of bonds in the system.

The second important parameter is the information dimensionality, which is related to the degree of order of the structure from the standpoint of information theory [27]. Whereas fractal dimensionality describes geometric complexity, the information dimensionality characterizes the features of the distribution of structural elements in space and their entropic properties. For building materials, the information dimensionality can be an indicator of the stability of self-organization processes.

Fractal characteristics are sensitive to external influences (acoustic, mechanical, temperature), which are able to change the spatial configuration of the solid and gas phases. Therefore, fractal analysis can be considered as a tool for quantitative control of self-organization processes in systems where non-equilibrium physicochemical transformations occur.

In this work, fractal and information dimensionalities are used as the main quantitative parameters for assessing the structure of physical models and cellular concrete. That has made it possible to track the influence of the water-clay ratio, porosity, and acoustic activation on the nature of the self-organization of the solid and gas phases, which is a necessary condition for implementing the concept of controlled chaos in the technology of building materials.

5. Results of investigating structural changes in cellular concrete under the influence of acoustic excitation

5.1. Influence of water content and acoustic excitation parameters on the characteristics of the structure of physical models

Fig. 1 shows a fragment (at a vibration frequency during acoustic activation of 100 Hz) of photofixation of the final structures of water-clay models of cement stone analogs. Similar structures were processed after activation at a frequency of 100, 200, 300, and 400 Hz. In addition, as Fig. 1 demonstrates, the water-clay ratio was changed.

Based on the results of the quantitative assessment of the fractal and information dimensionalities, graphical dependences were constructed. Fig. 2 shows a graphical interpretation of the experimentally derived dependences of fractal dimensionality on the frequency of acoustic vibrations for models with different water-clay ratios.

Each plot shows the dependences for samples to which activation was not applied (control), as well as activated ones. The regression equation and the level of approximation are also given. The dependences have a different nature for each value of W/C_l .

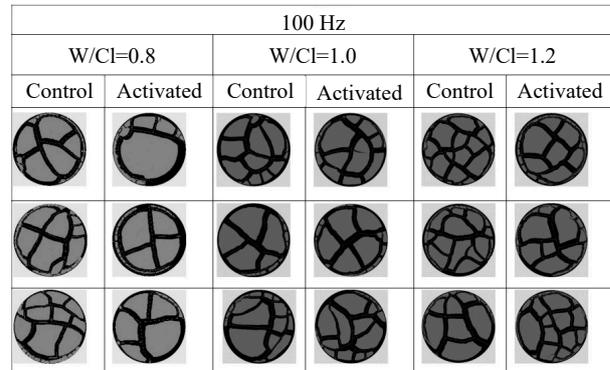


Fig. 1. Photofixation of model structures

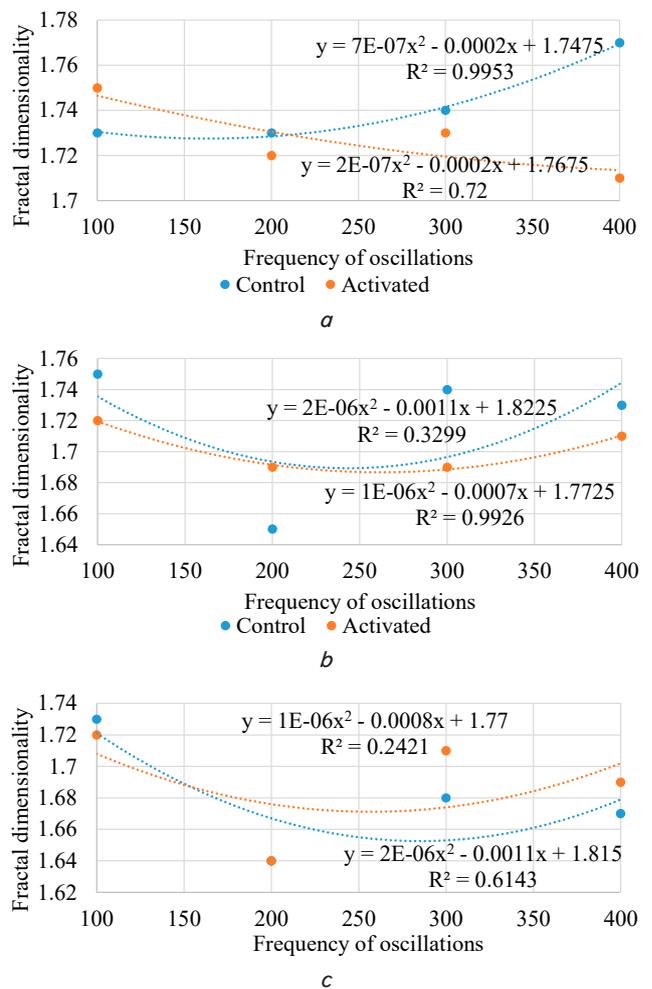


Fig. 2. Dependence of fractal dimensionality on the frequency of oscillations of models of materials with a dense structure at a water-clay ratio of: $a - 0.8$; $b - 1.0$; $c - 1.2$

5.2. Changes in the fractal and information dimensionalities of the structure depending on the porosity of model materials

At the next stage, the influence of the water-clay ratio on the change in the nature of the structure of the porous

material at different porosity values was determined. Photofixation of the models are shown in Fig. 3.

After processing the results, graphical dependences of fractal and information dimensionalities on porosity and water-clay ratio were constructed, which are shown in Fig. 4–6.

The graphical dependences in Fig. 4–6 reflect the change in fractal and information dimensionalities of the structure of model porous materials in a wide range of porosity and water-clay ratio. The results make it possible to trace the differences in the behavior of these parameters for the solid and gas phases at different values of W/Cl.

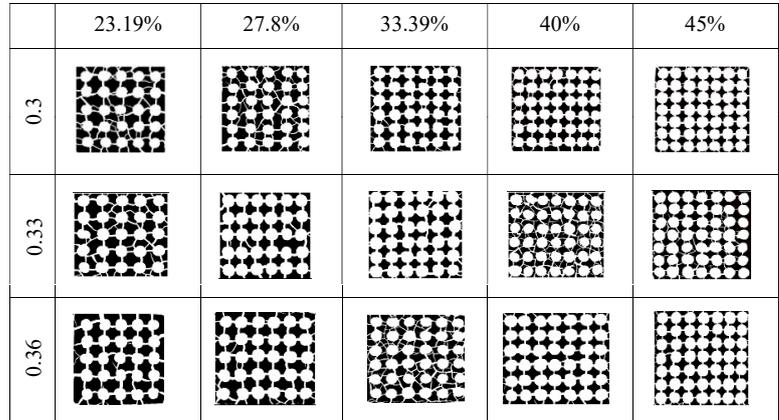


Fig. 3. Photo fixation of models of porous materials after dehydration

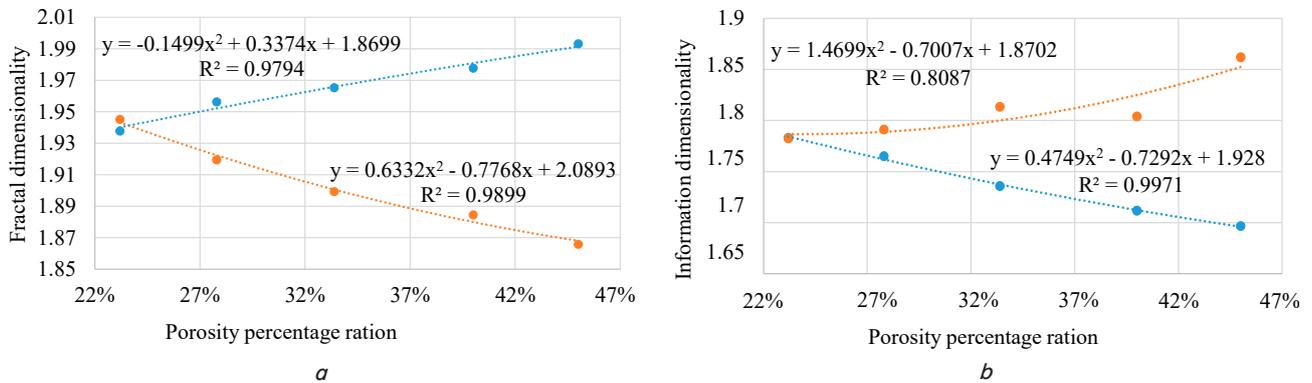


Fig. 4. Dependence of fractal and information dimensionalities of the structure of models of porous materials: *a* – dependence of fractal dimensionality on porosity at W/Cl 0.3; *b* – dependence of information dimensionality on porosity at W/Cl 0.3

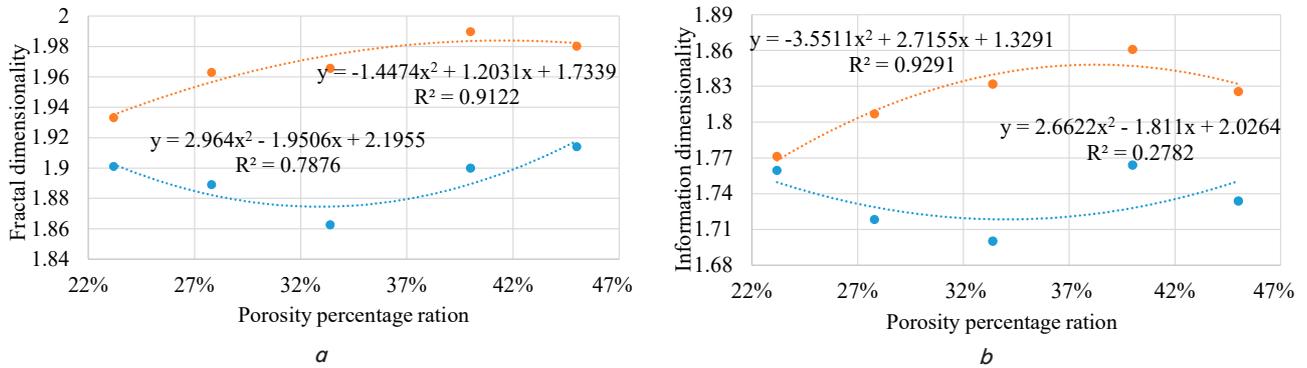


Fig. 5. Dependence of fractal and information dimensionalities of the structure of models of porous materials: *a* – dependence of fractal dimensionality on porosity at W/Cl 0.33; *b* – dependence of information dimensionality on porosity at W/Cl 0.33

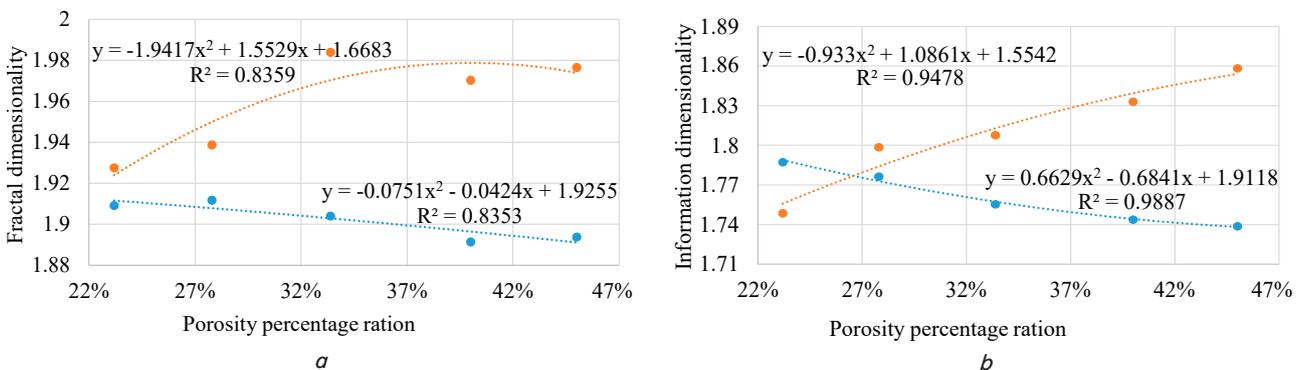


Fig. 6. Dependence of fractal and information dimensionalities of the structure of models of porous materials: *a* – dependence of fractal dimensionality on porosity at W/Cl 0.36; *b* – dependence of information dimensionality on porosity at W/Cl 0.36

5.3. Determining the influence of acoustic activation on the strength and humidity of foam concrete

At the final stage of the study, the influence of acoustic activation of the foam concrete mixture on the compressive strength and change in humidity of foam concrete was determined. The results are given in Table 1 and in Fig. 7, 8.

Table 1

Results of the experiment

Max. oscillation frequency, Hz	Mean density, kg/m ³	Moisture content, %	Strength, MPa:	
			On day 14	On day 28
0 (control)	620	28.1	1.0	1.4
12000	620	28.1	1.2	1.8
22000	600	33.8	0.6	0.7

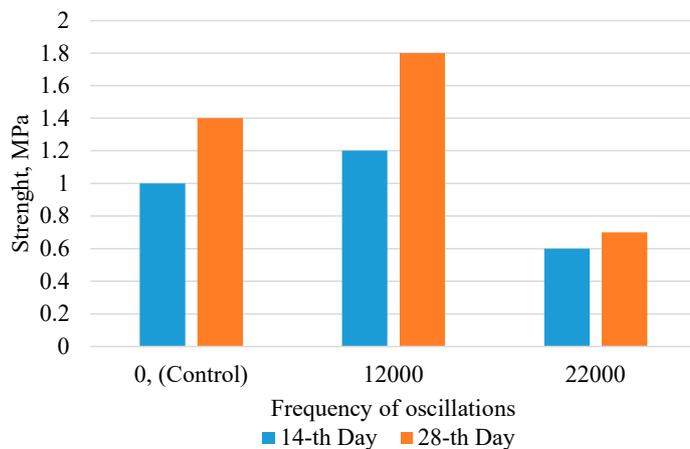


Fig. 7. Effect of acoustic activation on the strength of foam concrete

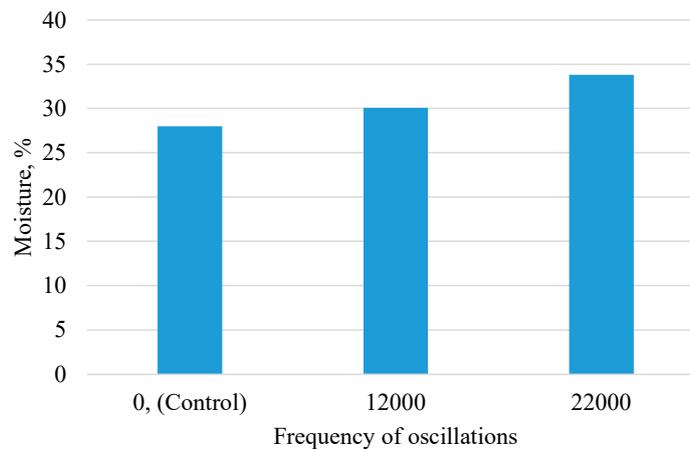


Fig. 8. Effect of acoustic activation on the moisture content of foam concrete

In order to assess whether the tasks set have been completed and the goal achieved, the reported results of the experimental studies require detailed analysis and interpretation.

6. Discussion of the results of study of structural changes in cellular concrete under the influence of acoustic excitation

The experimental results (Fig. 2–6) indicate that the nature of the structure formation of models and foam concrete significantly depends on the water-clay ratio and acoustic

activation parameters. Changes in fractal and information dimensionalities reflect the restructuring of the spatial organization of the solid and gas phases. This is due to a change in the conditions of the course of self-organization processes in an open non-equilibrium system, primarily the ratio of solid and liquid phases and the parameters of acoustic excitation.

Considering the graphical dependences shown in Fig. 2, it can be seen that at a low ratio ($W / Cl = 0.8$) the structure of the models has the clearest dependence of the fractal dimensionality on the oscillation frequency, which may indicate a fairly good order of the structure. In control samples, with an increase in the oscillation frequency, the fractal dimensionality also increases. At the same time, a slight decrease in fractal dimensionality occurs in activated samples.

At an average ratio ($W / Cl = 1.0$), the structure also responds to oscillations (Fig. 2, b). It is worth noting the rather high coefficient of determination for activated samples – 0.99. Again, we note that in control samples this indicator is rather low.

At the maximum water-clay ratio ($W / Cl = 1.2$), from the same coefficient of determination, we can conclude that the process of structure organization becomes difficult to predict for both types of samples.

The graphical dependences in Fig. 2 show that acoustic activation leads to a decrease in fractal dimensionality. In most cases, activated samples demonstrate higher stability and predictability of the dependence of fractal dimensionality on frequency (high R^2 values).

The experimental results confirm that activation and water-clay ratio are quite influential factors that determine the fractal properties of the structure of water-clay suspension. It is important that to obtain the most predictable structure; there are optimal values of water-clay ratio ($W / Cl = 1.0$). Excess water ($W / Cl = 1.2$) sharply reduces the stability of the structure even during activation.

The results represented in the form of graphical dependences in Fig. 4–6 make it possible to assess the change in the nature of the structure in terms of fractal and information dimensionalities. Further, the analysis is carried out according to the results of calculations on black and white areas (Fig. 3). Black areas characterize the solid phase, i.e., interpore partitions, white – gas phase, directly the nature of porosity.

Black areas. In all ranges of W / Cl the fractal dimensionality of black areas either decreases or changes very weakly with increasing porosity. The most stable decrease in fractal dimensionality was observed at the lowest $W / Cl = 0.30$ with a very high correlation ($R^2 \approx 0.99$). The information dimensionality of black areas constantly decreases in all ranges of W / Cl .

White areas. For white areas, a clear increase in fractal dimensionality is observed with increasing porosity. This increase is most pronounced at $W / Cl = 0.30$ and 0.36 ($R^2 = 0.83–0.97$). The information dimensionality of white areas also increases at all W / Cl , especially noticeably at $W / Cl = 0.33$ and 0.36 , which indicates a certain ordering of structures.

Influence of W / Cl on the behavior of the structure. At a water-clay ratio of 0.3, the dependences have a fairly high correlation. With an increase in the amount of water ($W / Cl = 0.33$), the behavior of black areas becomes less predictable (the correlation for information dimensionality decreases), while white areas retain a stable relationship with porosity. At high W / Cl (0.36), the nature of the structure of

white areas becomes more complicated in both parameters. Black areas gradually lose information complexity, while maintaining almost constant fractality.

Unlike most known studies [12–16], in which acoustic activation is evaluated mainly through changes in physical and mechanical properties, in this work the focus is on quantitative analysis of the nature of the structure. The use of fractal and information dimensionalities allowed us not only to record the effect of acoustic influence but also describe the direction of structure evolution depending on the activation parameters.

The effect of acoustic activation of foam concrete mixture. The results represented in the form of diagrams (Fig. 7, 8) indicate that the maximum strength is observed at a frequency of 12000 Hz. The strength of foam concrete on the 28th day is 1.8 MPa, which exceeds the indicators of the control sample (1.4 MPa). At the same time, the activated samples have a higher humidity (up to 30%). This indicates that acoustic activation affects not only the final strength but also the conditions for the formation of the pore and interpore structure of foam concrete. In contrast, activation at a frequency of 22,000 Hz leads to a decrease in strength to 0.5–0.7 MPa and an increase in humidity to 34–35%, which may indicate destabilization of the structure. The results of the experiments confirm the effectiveness of the external influence on the system, as indicated by an increase in strength by almost 30%. Thus, acoustic activation can be considered as a tool for controlled influence on the course of self-organization processes, which is manifested in an increase in the strength of foam concrete.

Our results of the study on structural changes in cellular concrete under the action of acoustic excitation make it possible to form a general idea of the influence of various factors on the nature of structure formation in composite materials. It was established that both in models of dense structure and in models of porous material there is a clear dependence of the behavior of fractal and information dimensionalities on formulation and technological factors. For models of analogs of dense materials, the determining factor is the water-clay ratio. A decrease in the amount of water leads to the formation of a more coherent system, which is reflected in a more stable behavior of fractal dimensionality. On the contrary, with an increase in water concentration, the structure passes into a state with a less predictable organization.

In models of porous material, the interaction between the solid and gas phases plays a key role. It is shown that an increase in porosity leads to an asymmetric effect on these phases: the solid phase loses the complexity and length of the interface surfaces, while the gas phase forms an increasingly developed structure. This is especially important for cellular concretes, in which the pore system determines the functional and operational properties.

Acoustic activation, as a type of external energy influence, was not chosen by chance. The fact is that the cellular concrete mixture at the stage of formation of the pore structure is a rather unstable system. Therefore, sensitive external influences can destroy this process, which will lead to delamination, or “settling” of the mixture. The choice of acoustic activation is explained by the following ideas about the spatial-temporal processes of structure formation of cellular concrete. After the formation of the primary stable porous structure, the geometry of the interpore partitions is formed, and their corresponding structural elements and the interfaces between them (connections). In this case, the evolution of the system will follow the

corresponding trajectory. If, during the period when the pore structure has not yet acquired a stable state, “soft” external influences are applied, the evolution of the system will follow a different trajectory. This will create a cellular concrete structure with different characteristics.

The data from our experiments indicate that acoustic excitations at early stages can change the nature of the spatial organization of the solid phase. Although the mechanism of this phenomenon requires additional clarification, the results are consistent with the ideas of self-organization. It is obvious that the acoustic field not only creates mechanical vibrations in the medium but also affects the distribution of solid particles, the interaction between aggregates and the behavior of interphase boundaries. At low frequencies, acoustic waves can act as catalysts of local density fluctuations, which is consistent with the mechanisms of self-organization in non-equilibrium colloidal systems.

Fractal and information dimensionalities make it possible to trace how the nature of the structure changes under the influence of acoustic excitation. The frequency regimes that were studied turned out to be not neutral. In the frequency ranges where the excitation energy contributes to the ordering of the structure, foam concrete has greater strength, which was observed in the corresponding series of experimental samples. In cases where the impact energy is excessive or the frequency does not match the conditions for structure formation, a decrease in strength is observed. Thus, the experiment shows not only the presence of optimal frequency regimes but also confirms that the acoustic effect is not universally positive and requires correct selection. In view of this, acoustic activation can be considered as a tool for controlling the system during its passage through “critical states” (between the terms of binder hardening). It is at these moments that minor external excitations can significantly affect the path of further evolution of the system. This is the essence of the controlled chaos approach: not suppressing randomness but directing it in the desired direction. Such results confirm that acoustic effects can become an effective means of forming specified properties even before the completion of hydration processes.

Our results are consistent with the ideas in modern models of cement stone structure formation, in particular colloidal models of C-S-H gel, which describe a sequential change in the stages of cluster growth from the diffusion to the aggregative regime [10, 15]. In known works, most attention is paid to the description of hydration mechanisms and the morphology of reaction products, while the quantitative assessment of changes in the nature of the structure at different stages of the process, as a rule, remains out of consideration.

In contrast to these approaches, our work focuses on quantitative analysis of the structure evolution using fractal and information dimensionalities. This allowed us not only to record the presence of different stages of structure formation but also trace their change under the influence of external acoustic excitation. In particular, under the regimes corresponding to aggregative growth, increased values of structural indicators were observed, while for inconsistent activation parameters these indicators decreased, which is not reflected in conventional descriptions of the hydration process.

Similarly, most studies on the influence of acoustic activation on cement systems [12–14, 16] are limited to the analysis of physical and mechanical properties or hydration kinetics. Our work shows that fractal characteristics are more sensitive to changes in the spatial organization of the

solid and gas phases and make it possible to assess the direction of structure evolution at the early stages of its formation.

The results of acoustic activation indicate that at the initial stages of structure formation, the system is characterized by the presence of a large number of short-lived bonds between the elements of the solid phase. Further development of physicochemical processes leads either to the stabilization of these bonds or to their destruction, which determines the further nature of the structure. Acoustic influence during this period is able to shift the course of processes towards order or destabilization, which is reflected in a change in fractal and information dimensionalities.

The influence of the water-clay ratio additionally confirms this pattern. With an excess amount of water, the system moves away from the conditions for the formation of a coherent structure, while with the optimal ratio of the solid phase, more organized structures are created. Thus, the proposed approach complements existing models of structure formation with quantitative criteria that make it possible to assess the sensitivity of the structure to external excitations and justify the use of acoustic activation as a tool for controlling the evolution of the material.

Our studies have a number of limitations, due to both the experimental base and the features of the methods used. First, physical models based on water-clay suspensions, although they reproduce the general regularities of the formation of the solid phase, do not make it possible to fully simulate all the processes occurring during cement hydration. In particular, the influence of chemical reactions, heat release, and rheology of cement slurry are more complex. Therefore, studies on the influence of acoustic activation are adequate for systems in which the formation of the structure occurs at the early stages of hardening and is accompanied by high sensitivity to external excitations. The application of the proposed approaches to materials with a rigidly fixed structure or to systems where the structure formation is complete requires additional justification.

Secondly, the work investigates the influence of only one type of external excitation – acoustic activation. Other energy influences (mechanical vibrations, electromagnetic fields, combined modes) can cause other mechanisms of self-organization and change the fractal characteristics of the structure.

Thirdly, fractal analysis was carried out using only two parameters – fractal and information dimensionalities. This approach can be extended by using multifractal spectrum, correlation dimension or entropy indices.

It should also be noted that the reproducibility of the obtained effects is ensured only within the studied ranges of water-clay ratio and acoustic activation frequencies. Going beyond these limits may lead to qualitatively different scenarios of structure evolution, which requires separate experimental studies.

Prospects for further research are related to studying combined energy activation modes, modeling structure formation during real cement hydration processes, and applying multifractal analysis. An important direction of further research is to identify the quantitative relationship between the parameters of external energy influence and the structural stability of the material. All this will make it possible to expand the scope of knowledge and enhance the technological possibilities of regulating the nature of the material structure and create conditions for the synthesis of new building materials.

Practical significance of the results. Our results have important applied value for the technology of building materials, in particular cellular concrete. It is shown that acoustic activation can be used as a tool for targeted influence on the

formation of the material structure at the early stages of hardening. It is established that optimization of acoustic influence parameters makes it possible to increase the strength and stability of the foam concrete structure.

The use of fractal and information dimensionalities as structural indicators makes it possible to implement systems for operational quality control of the material structure. This makes it possible to predict the properties of materials even before they reach full strength and to adjust technological parameters in real time.

The disadvantages of this study include the lack of direct experimental observation of the evolution of interphase boundaries in the process of acoustic activation. Changes in the nature of the structure were estimated indirectly – through fractal and information indicators. This disadvantage can be eliminated by combining fractal analysis with direct visualization methods. Another drawback is the limited number of experimental series for foam concrete, which does not make it possible to build a full-fledged statistical model of the influence of acoustic parameters. In further studies, this can be eliminated by expanding the experimental sample.

The results could be integrated into the practice of producing thermal insulation and structural thermal insulation concretes, where the stability of the pore structure plays a key role in ensuring the durability and energy efficiency of the material. The application of the concept of controlled chaos opens up prospects for devising new technological approaches in the production of these building materials.

7. Conclusions

1. We have established the influence of water content and acoustic excitation parameters on the fractal characteristics of the structure of physical models – analogs of cement stone. It has been shown that when the water-clay ratio and the frequency of acoustic exposure change, the fractal dimensionality of the structure changes within wide limits, and the nature of these changes is significantly different for activated and non-activated samples. In particular, at the optimal water-clay ratio ($W / Cl = 1.0$), the most stable and reproducible dependence of the fractal dimensionality on the frequency of acoustic oscillations (R^2 up to 0.99) is observed. This indicates that acoustic excitation changes the conditions of the course of self-organization processes, affecting the formation of the spatial structure of the solid phase at the early stages.

2. A change in the fractal and information dimensionalities of the structure depending on the porosity of the model materials has been revealed. It is shown that with increasing porosity, the fractal and information dimensionalities of the solid phase (interpore partitions) decrease, while for the gas phase they increase ($R^2 = 0.83–0.99$ depending on W / Cl). This means that in porous systems it is the pore structure that determines the general nature of the fractal organization of the material. Our results confirm the feasibility of using fractal and information dimensionalities as sensitive quantitative indicators of changes in the nature of the structure under conditions of high heterogeneity.

3. The effect of acoustic activation on the physical and mechanical properties of foam concrete has been established. It has been experimentally shown that acoustic activation of the foam concrete mixture at the early stages of structure formation leads to a significant change in the strength and moisture content of the material. The maximum strength

of foam concrete (1.8 MPa) was achieved at a frequency of 12 kHz, which is approximately 30% higher than the indicators of control samples (1.4 MPa). At the same time, at excessive frequencies (22 kHz), a sharp decrease in strength to 0.5–0.7 MPa and an increase in humidity to 34–35% were observed, which indicates destabilization of the structure. This confirms that acoustic excitation is not a universally positive factor and its effectiveness is determined by the compliance of the impact parameters with the conditions for structure formation.

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

In the process of preparing the manuscript, the artificial intelligence tool ChatGPT (OpenAI, version 5.2) was used exclusively for auxiliary technical and editorial tasks.

The AI tool was used to assist in the formation of editorial responses, to prepare a cover letter, for preliminary linguistic verification of individual fragments of text outside the scientific content, to check the logical consistency of the manuscript structure at the stage of internal editing.

Artificial intelligence tools were not used for writing an abstract and introduction, analyzing literary sources, forming or interpreting experimental results, constructing graphs, tables, or calculations, formulating scientific conclusions.

All specified sections were prepared and edited exclusively by the authors.

Verification of results. All texts formed with the participation of AI tools were carefully checked by the authors from the point of view of scientific correctness, compliance with experimental data, compliance with the requirements of the journal.

The use of artificial intelligence tools did not affect the scientific results, interpretation of data, or conclusions of the study. All scientific statements, numerical values, and experimental results were obtained and substantiated by the authors.

Authors' contributions

Volodymyr Martynov: Conceptualization, Methodology, Formal analysis, Software, Writing – original draft, Writing – review & editing; **Svetlana Sukhanova:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration; **Svetlana Makarova:** Methodology, Investigation, Formal analysis, Resources; **Dmytro Taichan:** Software, Investigation, Validation, Formal analysis, Writing – original draft, Writing – review & editing; **Ihor Sychov:** Software, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing.

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