UDC 666.972.125
DOI: 10.15587/1729-4061.2022.251004

DETERMINATION OF RATIONAL PARAMETERS FOR HEAT TREATMENT OF CONCRETE MIXTURE BASED ON A HOLLOW ALUMINOSILICATE MICROSPHERE

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The research on determining rational parameters of heat treatment of a concrete mixture based on hollow aluminosilicate microspheres has defined the features of the intensifying action on the structural concrete mixture by low-pressure steam with optimum heat and mass transfer. Optimum values of temperature, humidity and speed of the medium have been identified. The obtained heat treatment parameters are subject to general regularities of structures for the formation of hydraulic bindings and are in accordance with production conditions, thus providing possibilities for their adaptation into production. The mechanisms for determining the strength of concrete stone according to the structural and thermal effectiveness of the active medium have been defined. Thanks to the strength-building mechanisms obtained, it is possible to reduce the thermal destruction capacity of the system while reducing the process heat consumption. It is confirmed that the main direction in reducing the destructive capacity is determined by the mass flow of moisture, which has the greatest heat capacity and the least thermal conductivity at the initial stages. The invention relates to periods of temperature rise and isothermal heating without impairing the mechanical properties of concrete. It is shown that the real duration excludes high-temperature destruction processes, thereby increasing the mechanical strength of concrete and reducing the overall energy consumption. Thus, there is a reason to argue that it is possible to produce strong and light concrete products under accelerated structure formation and new technologies for heat treatment of concrete based on lightweight fillers with reduced heat consumption

Keywords: hollow aluminosilicate microsphere, structural effectiveness, thermal effectiveness, concrete mixture, strength, energy and heat consumption

Received date 21.12.2021
Accepted date 25.01.2022
Published date 28.02.2022

***How to Cite**: Atyaksheva, A., Rozhkova, O., Sarsikeyev, Y., Atyaksheva, A., Yermekov, M., Smagulov, A., Ryvkina, N. (2022). Determination of rational parameters for heat treatment of concrete mixture based on a hollow aluminosilicate microsphere. Eastern-European Journal of Enterprise Technologies, 1 (6 (115)), 64–72. doi: https://doi.org/10.15587/1729-4061.2022.251004*

1. Introduction

The tendency to reduce the density and weight of structures in the context of rapid construction requires the creation of conditions for the production of lighter and simultaneously strong structures and materials in a short period of time.

There is no doubt that lightweight concretes formed from mineral binders and ultra-light microfillers, including aluminosilicate microspheres, can solve these problems by creating low-density concrete and heat conductivity while maintaining their mechanical characteristics.

However, many modern micro- and nano-fillers exhibit hydraulic activity under special conditions. The proof of this can be found in the works [1–3], which show that the increased strength of cement concrete based on aluminosilicate microspheres is determined by the hydraulic activity of microspheres in conditions of increased thermodynamic parameters, organized by high temperatures or in the presence of expensive agents at vibrocompression.

Thus, the current modes for the heat treatment of similar concrete and concrete based on a hollow aluminosilicate microsphere can only provide the required strength under conditions of increased heat and energy consumption, which is contrary to the main trends of construction production, which is oriented on high technology of products with low heat and material consumption.

This shows that the studies carried out within the framework of optimization of heat treatment modes of concrete based on hollow aluminosilicate microspheres to reduce heat and energy consumption, and therefore energy intensity, are relevant.

2. Literature review and problem statement

The paper [4] presents the results of research on the application of a hollow aluminosilicate microsphere from ash and slag waste from 5 to 10 % by weight of cement. They show that a foam concrete mixture with an aluminosilicate microsphere has better flowability of the mixture from 10 to 15.5 cm and reduced plastic shrinkage of natural hardening foam concrete by 28.8–52.3 %, which has a positive effect on the conditions of structure formation and strength gain processes. However, the research presents the results of determining the strength characteristics under normal hardening, which does not determine the possibility of applying these results to technological production processes occurring under different temperature and humidity conditions. The paper [5] presents the results of research on the correlation between viscosity and humidity modulus of products based on a hollow aluminosilicate microsphere, which reflect the possibility of determining optimal conditions for creating materials based on a hollow aluminosilicate microsphere with the highest strength and rigidity.

Nevertheless, the research does not reflect the issues of the influence of environmental humidity on the formation of strength of the structured product in conditions of elevated temperatures. The authors [6] confirm that the use of hollow aluminosilicate microspheres from burning Kazakhstan coals of increased ash content determines the possibility of obtaining concrete mixtures with improved properties without changing the basic structural characteristics. But at the same time, the authors do not take into account the heat engineering conditions for concrete production. The paper [7] shows the results of the chemical composition of a hollow aluminosilicate microsphere, which has a sufficient effect on the strength of thermal insulation materials and products based on a cement binder, which also proves the need for their use in structural products. Moreover, the paper [8] presents the results on the effect of introducing aluminosilicate microspheres on the rheometric, physical-mechanical and fire-resistance properties of elastomeric compositions, which makes it possible to increase the efficiency of bending concrete compositions when using hollow aluminosilicate microspheres by reducing the thermal conductivity and density of products while maintaining the optimal level of physical-mechanical properties. But there were unresolved issues related to the determination of the strength set of concrete products including the factors of humidity and porosity in production conditions, and especially in conditions of accelerated structure formation processes that occur in heat engineering devices and aggregates. At that, the authors [9] show that the thermal conductivity and porosity of a product, characteristic of concrete mixtures based on hollow aluminosilicate microspheres, sufficiently affect the temperature distribution in the temperature field of a porous body under the influence of pressure and humidity gradients, which proves the need for research to take these parameters into account when building the strength of concrete based on microspheres under various conditions of exposure to the temperature field of a body of a concrete mixture.

The research presented above shows certain difficulties arising in identifying the parameters of activation processes of strength gain processes from the degree of exposure to the active medium for structured products based on hollow aluminosilicate microspheres. A method to overcome these difficulties can be an approach based on exergic analysis and empirical analysis, which considered the dependence of the structure formation process on the temperature, humidity and velocity regime of the active medium, including in conditions of accelerated structure formation. This approach was used in [10], where, based on the exergic analysis of concrete mixtures in heat engineering units, the effectiveness of exergic balance of the concrete mixture preparation process was shown, taking into account the parameters of active medium exposure, and the need to take into account the degree of hydration of concrete products depending on heat release of a binder, the amount of moisture supplied and time intervals of strength gain was identified. However, the active medium pathways that take into account the processes of building up the strength of the structured product are not presented. At the same time, in accordance with [8], it is also necessary to evaluate the operating modes of heat engineering units in accordance with conditions of thermal conductivity processes, including non-stationary.

The paper [11] indicates the necessity of calculating the thermal treatment of concrete products with an account of active medium factors. However, these problems are suggested to solve using simulation methods of the temperature field in a solidified body of concrete. This is not acceptable because any model in such technology requires work under manufacturing conditions. Furthermore, there are experiments in the paper [12], which proved that the development of strength in the cement mortar directly depends on the temperature and humidity of the environment. Nevertheless, there is no result detecting the strength development at critical temperatures beyond normal in the heat-engineering equipment, which makes relevant research impractical.

All this assumes the expediency of research on the adjustment of standard and proposed regimes to identify optimal modes of thermal effects on the processes of structure formation of a concrete mixture based on a hollow aluminosilicate microsphere with an account of temperature and humidity conditions, taking into account the structural and thermal efficiency of active medium applied.

3. The aim and objectives of the study

The aim of the study is to develop the theory and practice of obtaining the optimal mode of thermal action on a concrete mixture based on mineral binders and a component released from the waste of the heat and power industry – a hollow aluminosilicate microsphere obtained through coal combustion of increased ash content. This will allow optimization of the heat treatment process of concrete based on the mineral binder and hollow aluminosilicate microsphere, taking into account the reduction of overall heat consumption and provide the possibility of adjusting the heat treatment processes of lightened concrete in the direction of energy efficiency reduction.

To achieve this aim, the following objectives are solved:

– to analyze the structural effectiveness of the active medium formed by low-pressure steam for detecting the kinetics of changes in compressive strength;

– to analyze the thermal effectiveness of the active medium formed by low-pressure steam during heat treatment of effects regimes;

– to propose heat treatment parameters for a concrete mixture based on a hollow aluminosilicate microsphere, taking into account the mechanisms of strength development obtained depending on structural and thermal efficiency.

In this research, complex physical-chemical methods were used to determine physical-mechanical parameters by standard methods according to EN 196-3:2016 (MAIN) Methods of testing cement to determine consistency, setting time and strength. To carry out test measurements, a laboratory chamber with thermal equipment was developed, shown in Fig. 1, 2.

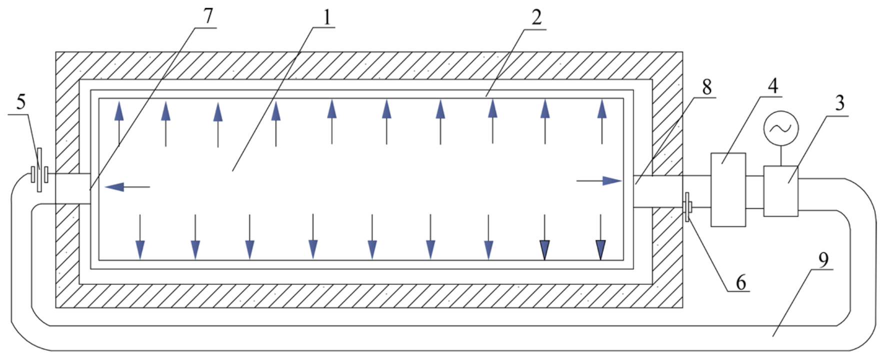

Fig. 1. Scheme of the laboratory chamber for heat and moisture treatment of concrete products: 1 – heat treatment chamber; 2 – perforated pipes for steam distribution; 3 – centrifugal fan; 4 – heater; 5, 6 – throttling valves; 7 – suction pipe; 8 – pressure pipe; 9 – air ducts

4. Materials and methods

The research material was a lightweight concrete mixture based on hollow aluminosilicate microspheres obtained by burning Kazakh coal of increased ash content. The bulk density of a microsphere with a density of up to 100 microns does not exceed 370 *kg*/m^3. The compressive strength of the microsphere is from 17–30 MPa. To identify comparative characteristics of the kinetics of strength growth, experiments were performed on 12 concrete compositions on various aggregates, including dense aggregates, expanded clay concrete mixtures (expanded clay crushed stone fractions 0–5) and mixtures on a light aggregate – hollow aluminosilicate microspheres with different water-cement ratios, presented in Table 1.

The thermal equipment of the chamber includes lower and upper perforated pipes for steam distribution. To create an air-steam circulating medium and medium provided with low-pressure steam and hot air in the units, including a fan, a heater and an air duct system are mounted on the chambers [13]. The chamber is equipped with temperature sensors of thermal resistance sensor (TRS) for measuring temperature in various zones and humidity sensors for measuring the relative humidity of the steam-air medium at a controlled temperature from 40 °C to 70 °C and from 70 °C to 100 °C. Additionally, the chamber is equipped with tubular electric heaters to provide the steam-air medium, two heaters and fans to ensure the circulation of the active medium and supply of dry hot air to the chamber with a temperature of up to 200 °C, according to Fig. 2.

Table 1

Compositions of concrete mixtures

No.	Binder	Material consumption, kg/m^3				Cone sediment	Water-cement ratio
		Cement	Sand	Aggregate	Water		
Crushed stone (ρ=750–900 kg/m^3)							
1	Ust-Kamenogorsk (Portland cement) PC 500	2.7	8.8	10.8	1.5	1	0.56
2		3.4	7.2	12	1.6	1	0.47
3		4.8	5.6	12	1.8	1	0.35
4		5.8	4.4	12	1.7	1	0.35
5	Karaganda PC 400	3	8.8	10.8	1.5	1	0.5
6		3.8	6.8	12	1.6	1	0.42
7		5.2	5.6	12	1.7	1	0.33
Keramzite crushed stone (ρ=210–340 kg/m^3)							
8	Karaganda PC 400	3.9	5.5	12.5	1.9	1	0.48
9	Karaganda (Slag Portland cement) SPC 400	3.9	5.5	10.5	1.9	1	0.48
Hollow aluminosilicate microsphere (ρ=250–370 kg/m^3)							
10	Ust-Kamenogorsk PC 500	3.9	5.5	12.5	1.9	3	0.48
11	Karaganda PC 400	3.9	5.5	12.5	1.64	3	0.42
12	Karaganda SPC 400	3.9	5.5	12.5	1.95	3	0.5

The chamber provided for the creation of zones with different temperatures, relative humidity and speed of the medium. For this purpose, separate areas of the chamber were equipped with inlet and outlet slots connected through gates to air ducts. When the gate was opened and the outdoor fans were working, air curtains were created to ensure the zoning of chamber medium parameters.

In the heat treatment chambers, experiments were carried out on concrete mixtures. The experiments included the determination of the compressive strength of samples to identify the thermal and structural efficiency of a product:

1) after heat treatment. The test was carried out after 4 hours of the cycle;

2) after full heat treatment and additional hardening for 27 days under normal conditions;

3) after normal hardening for 28 days.

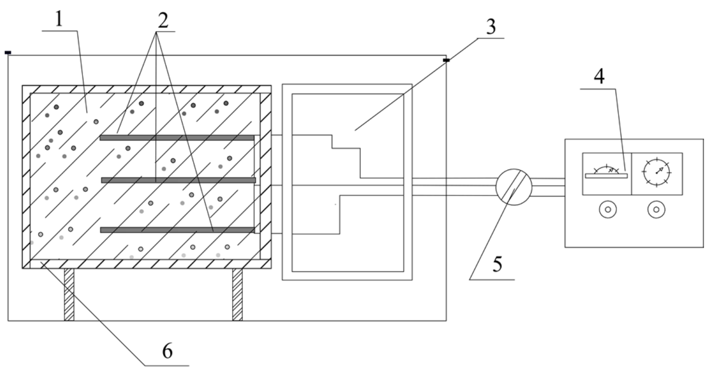

Fig. 2. Heat engineering equipment of the heat treatment chamber: 1 — concrete mixture under research; 2 — temperature sensors; 3 — insulation; 4 — temperature controller; 5 — switch; 6 — heat-insulated sides of form

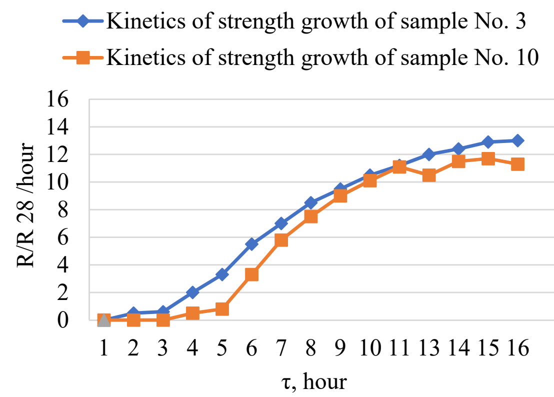

Fig. 3. Kinetics of strength growth of samples made of a concrete mixture of compositions No. 3 and 10 in a medium formed by low-pressure steam in time

When determining the kinetics of strength growth and changes in moisture content, test samples, measuring 10×10 cm, were extracted every hour, weighed and tested in a hot condition. They were weighed in plastic bags to exclude evaporation of moisture from the test material. The intervals between tests of the first and third samples were no more than 10 minutes. At the same time, experiments on the kinetics of changes in moisture content and deformation were performed in the laboratory chamber according to the standard method. Taking into account the influence of a factor of heterogeneity of temperature and humidity fields arising in concrete products during heat treatment on the formation of physical and mechanical characteristics of concrete, the structural efficiency of the corresponding active medium was determined. At that, as structural efficiency, the level of temperature differences between the center of processed products and their surface layer is assumed, and as thermal efficiency, complete heating of a product is assumed.

5. Research results of the thermal and structural effectiveness of the active medium formed by low-pressure steam at different regimes of exposure

5. 1. Analysis of the structural effectiveness for detecting the kinetics of changes in compressive strength

As an initial mode of heat treatment when determining the kinetics of strength growth, the following mode was selected: (2)+3+6+2→at (t_{is})=85 °C. The current mode is determined by the rate of binder consumption – a total cycle of 13 hours (standard regime).

In the course of research, it was identified that intra-batch variability for the compositions of dense concrete: C_{vb}=11–12 %, for porous aggregates (keramzite gravel and a hollow aluminosilicate microsphere): C_{vb}=12–13 %. During the experiments, it was identified that intra-batch variability C_{vb} is not the same at different stages of influence of the active medium during the processing of various concretes.

Fig. 3 shows the kinetics of strength growth of compositions when using Ust-Kamenogorsk PC 500 on a dense aggregate and on hollow aluminosilicate microsphere obtained from ash-slag hydraulic removal mixtures during combustion of Ekibastuz coal.

The highest value of C_{vb} is reached at the end of the temperature rise stage. Fig. 4 shows the kinetics of changes in the compressive strength of samples made of a concrete mix of Karaganda PC and SPC using dense and light aggregates, depending on strength gain.

The kinetics of strength gain intensity can be characterized by three periods. However, even for concretes made on cements with the same activity during steaming, determination of the duration of the intensity of the main periods of the kinetics of concrete hardening on various aggregates and boundaries of these periods is somewhat difficult.

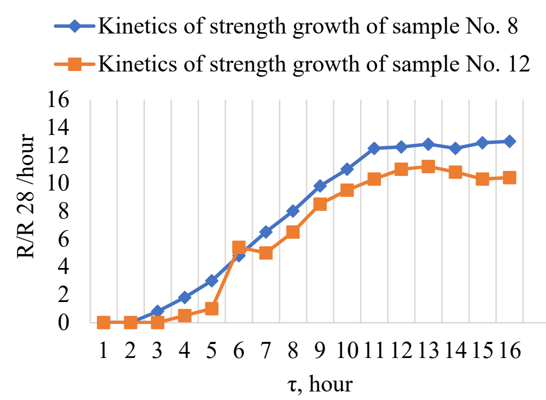

Fig. 4. Kinetics of strength growth of samples made of a concrete mixture of compositions No. 8 and 12 in a medium formed by low-pressure steam in time

Fig. 5 shows the kinetics of changes in the compressive strength of concrete samples when using Ust-Kamenogorsk PC 500 on a dense aggregate and a porous aggregate microsphere, depending on strength gain intensity.

The kinetics of strength gain intensity of concrete under heat treatment conditions both on a dense aggregate and on a porous one is characterized by an induction period in which there is no increase in strength, a period of intensive increase in strength and a period of slowing gain in strength, with possible strength drops. Fig. 6 shows the kinetics of changes in the compressive strength of concrete samples when using Karaganda PC 400 and Karaganda SPC 400 and a microsphere, depending on strength gain intensity.

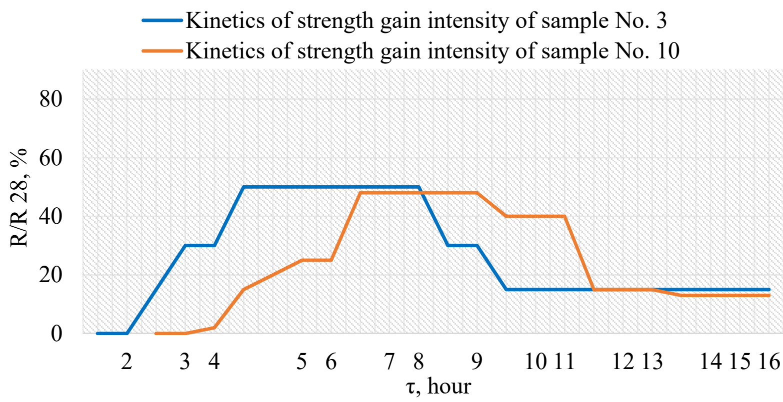

Fig. 5. Kinetics of strength gain intensity of samples made of a concrete mixture of compositions No. 3 and 10 in a medium formed by low-pressure steam

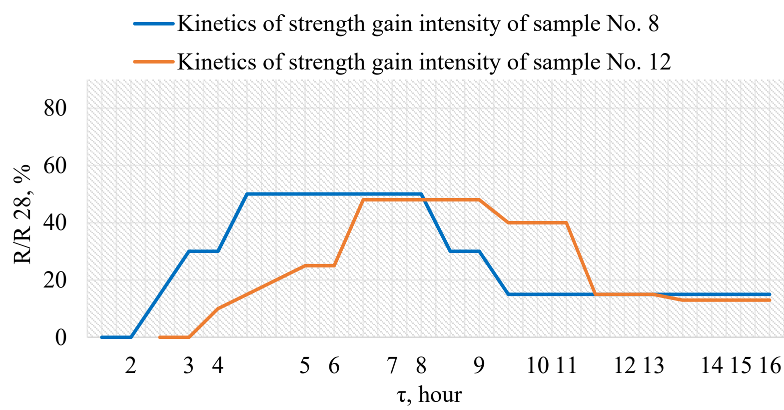

Fig. 6. Kinetics of strength gain intensity of samples made of a concrete mixture of compositions No. 8 and 12 in a medium formed by low-pressure steam

and amounted to 60 % R_{28}. Then, the growth of concrete strength continued at an almost constant rate equal to 4 % $R_{28}/_{hour}$.

The graph of the kinetics of strength gain of compounds on Karaganda PC and SPC is characterized by two strength drops in the period from 4 to 5 hours and from 7 to 8 hours of isothermal heating. The first and second strength drops are 3–4 % R_{28}. The main reasons for strength loss are physical and chemical transformations in the process of cement hydration. This is, first of all, the development of its own stresses caused by osmotic pressure, which arises due to peculiarities of hydration hardening of cements. The drop in concrete strength is caused by the fact that hardening of the structure, determined by the accumulation and compaction of hydration products of silicate components, at a certain moment of heat treatment lags behind the decrease in strength caused by recrystallization of hydration products of the aluminate components of a binder. Besides, during crystallization of hydrate neoplasms, a volumetric crystallization pressure arises, which leaves an imprint on the overall picture of the stress-strain state of a cement stone, regardless of an aggregate.

Experiments confirm the position that the cause of strength loss is the uneven flow of hydration processes of cement components. Thus, concretes on Ust-Kamenogorsk PC, having 7 % C_3A in their composition, did not show strength loss. Concretes on Karaganda SPC and PC, having 9–15 % C_3A in their composition, showed strength drops at the end of isothermal heating.

For concrete compositions on a dense aggregate, the duration of the induction period is 2 hours. The duration of the induction period on porous aggregates (both on keramzite gravel and hollow aluminosilicate microsphere) is 3 hours. This is determined by the high moisture content of the proposed concrete composition. The period of strength gain on both dense and porous aggregate is 5–7 hours, that is, the entire temperature period and from 1 to 3 hours of isothermal heating. The minimum strength gain intensity during the first hour of temperature rise is 3 % $R_{28/hour}$ for concretes on both dense and porous aggregates. The maximum strength gain intensity for all the studied samples is 8–10 % $R_{28/hour}$. The duration of the maximum period of intensive growth of strength is 3–6 hours. At the end of the present period, concretes on dense aggregates gained strength in the range of 40–50 % R_{28}, on keramzite gravel 40 % R_{28} and on aluminosilicate microsphere 38 % R_{28}. The period of retarding strength gain for mixtures on both dense and porous aggregates on Ust-Kamenogorsk PC has two main sections. The first one can be conditionally represented as transitional. In this area, the intensity is still quite high. The second section is characterized by a conditional constant intensity and in experiments it is 3 % $R_{28}/_{hour}$. For concretes on Karaganda PC and Karaganda SPC 400, the current period of strength gain has its own characteristics. Experiments identified a drop in the strength of a concrete composition on Karaganda PC 400 during heat treatment at the sixth hour of isothermal heating of 5 % R_{28}. The compressive strength of concrete after 9 and 11 hours of heat treatment was the same

5. 2. Analysis of the thermal effectiveness of the active medium formed by low-pressure steam during heat treatment of effects regimes

To identify optimal conditions for the isothermal heating of a concrete mixture and determine the thermal effectiveness of the active medium formed by low-pressure steam during heat treatment, two heat treatment regimes are proposed:

$$(2)+3+6+2 \rightarrow \text{at } (t_{is})=85\ ^{\circ}\text{C},$$

$$(2)+4+8+2 \rightarrow \text{at } (t_{is})=85\ ^{\circ}\text{C}.$$

The selected heat treatment modes are determined by the binder consumption rate (standard mode 13 hours) and conditions close to production (16 hours).

To conduct experiments to determine the thermal efficiency of the active medium, samples were made, measuring 30×30×20 cm. Temperature sensors were installed in the test sample in the center and at a distance of 5 cm from the upper and lower surfaces of the sample. Therefore, the intensity of warming of the surface layer, 5 cm deep, was determined by experiments. The corresponding temperatures – medium temperature, temperature of the upper surface layer, middle sample temperature and temperature of the lower surface layer were measured during the entire heat treatment period. The intensity of warming in cross-sections of samples processed under regime No. 1 with a common cycle of 13 hours is shown in Fig. 7.

Fig. 8 shows the intensity of warming in cross-sections of samples processed under regime No. 2 with a common cycle of 16 hours.

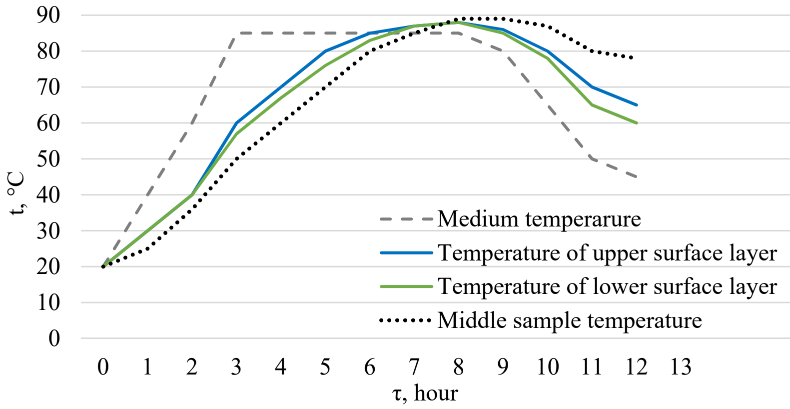

Fig. 7. Thermal effectiveness of the active medium formed by low-pressure steam during heat treatment according to the regime: (2)+3+6+2→at (t_{is})=85 °C

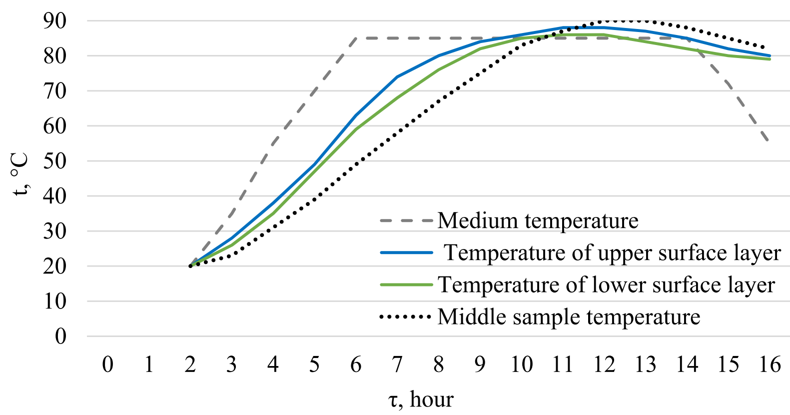

Fig. 8. Thermal effectiveness of the active medium formed by low-pressure steam during heat treatment according to the regime: (2)+4+8+2→at (t_{is})=85 °C

According to the experiments, the thermal efficiency of the 16-hour heat treatment regime for lightweight concrete is 3 hours, for the 13-hour one – 4.5 hours. Heating of the surface layer of the product in the 16-hour mode lags behind the ambient temperature by no more than 20 °C, at the same time in the 13-hour mode, this value reaches 25 °C. The experiments show that the temperature of the surface layer, 5 cm deep, reaches the temperature of the active medium after three hours of isothermal heating. In the 13-hour mode, the temperature of the surface layer of the center reaches the ambient temperature at the fourth hour of isothermal heating.

Therefore, a temperature gradient occurs in the surface layer of products, reaching 6 °C/cm in the 13-hour mode, 4 °C/cm in the 16-hour mode. At the same time, the temperature difference between the upper surface layer and the middle of the sample in the 13-hour mode is approximately 25 °C for every 15 cm. In the 16-hour mode, ≈20 °C for every 15 cm.

Different temperatures along the cross-section of a product leads to an inhomogeneous flow of hydration processes, this is especially noticeable at the initial stages of warming up. In order to attempt to evaluate structural and thermal efficiency from the chemical standpoint of structure formation, an experiment was conducted using a well-known method for determining the setting time of the studied Portland cement at temperatures: 20 °C, 40 °C, 60 °C and 80 °C [14].

The test results are presented in Table 2.

The increased temperature dramatically accelerates the setting time of cement. So, for Ust-Kamenogorsk PC 500, a medium with a temperature of 40 °C accelerates the setting start by 6 times and setting end by 4 times, compared with a medium at a temperature of 20 °C.

The setting time can be estimated taking into account the temperature-time factor "η".

$$\tau_{s.s.t} = \tau^{n1}_{s.s.t.20}, \quad (1)$$

$$\tau_{s.e.t} = \tau^{n2}_{s.e.t20}, \quad (2)$$

where $\tau_{s.s.t}$ – setting start time; $\tau_{s.e.t}$ – setting end time of cement.

For cements of the same activity group, the values of temperature-time factors are approximately the same. According to the experiments, at the site of the temperature rise of the 13-hour regime, Portland cements are in various hydration bonds. In the outer surfaces of products, the cement dough will turn into stone more quickly than in central layers, which will directly affect the overall picture of structure formation.

In the technological chain of obtaining high-quality concrete mixtures based on hollow aluminosilicate microspheres, the longest and most energy-intensive conversion is the heat treatment process. The research identified that the formation of strength characteristics of a lightweight concrete mixture is determined by the parameters of the active medium and moisture content. The rate of hardening acceleration in a medium formed by low-pressure steam is 0.58–0.72, and the rate of hardening acceleration after heat treatment is 0.8–0.98. Also, the research identified that no coolant will provide conditions for the formation of strength characteristics with normal hardening conditions for a given mixture.

Table 2

Setting time of cements depending on medium temperature

No.	Cement	Medium temperature, °C							
		20		40		60		80	
		$\tau_{s.s}$	$\tau_{s.e}$	$\tau_{s.s}$	$\tau_{s.e}$	$\tau_{s.s}$	$\tau_{s.e}$	$\tau_{s.s}$	$\tau_{s.e}$
1	Ust-Kamenogorsk PC 500	3 h. 20 min	5 h. 35 min	30 min	1 h. 31 min	28 min	1 h. 30 min	10 min	55 min
2	Karaganda PC 400	3 h. 00 min	5 h. 40 min	29 min	1 h. 25 min	27 min	1 h. 27 min	9 min	53 min
3	Karaganda SPC 400	3 h. 10 min	5 h. 50 min	27 min	1 h. 28 min	26 min	1 h. 26 min	11 min	50 min
$\tau_{s.s}$ – setting start time; $\tau_{s.e}$ – setting end time									

In this regard, an attempt was made to develop a method of influencing the active medium on the concrete mixture from two main positions:

1) high-quality hydration of a binder;

2) rational drying.

With a certain degree of accuracy sufficient for experiments on the relative analysis of hydration degree of a binder, the hydration degree α is determined as the ratio of volume increment at actual hydration to the volume increment at 100 % hydration of a binder according to the dependence:

$$\alpha = \frac{V_{cs} - V_c}{V_{cs\,\max} - V_c}, \tag{3}$$

where V_{cs} – volume of cement stone at the desired hydration of a binder;

$V_{cs\,\max}$ – maximum volume of the hydrated binder at 100 % hydration;

V_c – volume of initial binder in the concrete body.

It is presented that: $V_{cs\,\max}=2.2V_{cs}$.

In this case:

$$\alpha = \frac{V_{cs} - V_c}{1.2V_{cs}}. \tag{4}$$

This dependence is proposed to determine the quality of heat treatment in terms of the hydration degree of a binder, which is determined in relation to the maximum possible volume of the hydrated binder at 100 % hydration.

5. 3. Proposal of heat treatment parameters for a concrete mixture based on a hollow aluminosilicate microsphere

The qualitative hydration of a binder is determined by accelerated structure formation mode in accordance with increased thermodynamic parameters of the active medium. In this regard, it is necessary to technologically and economically justify the duration of heat treatment stages and determine the level of medium parameters.

It is proposed to ensure partial removal of excess moisture from the structured system at the pre-aging stage without destruction. A number of works proved that moisture removal from the structured system within 8–10 % of the mixing water will have a positive effect on hydration processes [15, 16]. Under normal conditions of holding for two hours, 4–5 % of water is removed from a concrete mixture based on a hollow aluminosilicate microsphere, with a volumetric shrinkage of 11–14 % of the value at 28 days of age. At the same time, at the holding stage before setting, the cement dough is reversible and the passage of water through it will not affect violations of the stone structure. Taking into account the need for sealing water for complete hydration and the possibility of functioning of a weak structure [17, 18], the duration of pre-exposure is taken within 2 hours.

Temperature rise is the most important stage in the formation of physical and mechanical characteristics of structured systems. A steam medium is used as the basis for heat treatment of a concrete mixture using hollow aluminosilicate microspheres. The thermal efficiency of the steam medium is 3 hours, respectively, the duration of isothermal heating is 4 hours. The final stage of heat treatment is temperature reduction, in which the most effective measures are aimed at eliminating or minimizing the external mass flow. The duration of the temperature reduction stage is proposed at the level of 2 hours. As a result, the following regime is proposed according to the temperature, humidity and speed of the medium:

– temperature regime:

(2)+4+4+2→at (t_{is})=85 °C;

– humidity regime:

40 %+60 %+100 %+100 %;

– medium speed regime:

4 m/s+4 m/s+0.5 m/s+0.5 m/s.

To test the effectiveness of the proposed method of influence of the active medium, a series of experiments were conducted by the method of determining the compressive strength of concrete mix samples having a water-cement ratio of 0.48, 0.42 and 0.45. [19]. The experimental results are presented in Table 3 and show a qualitative course of the processes of structure formation of a concrete mixture based on hollow aluminosilicate microspheres. Thus, the rate of hardening acceleration is from 0.63 to 0.73, while the rate of hardening acceleration after heat treatment is within 1.

Table 3 presents the results of experiments to determine the compressive strength of concrete samples based on a hollow aluminosilicate microsphere that were heat-treated in the medium according to the proposed mode of exposure to an active medium with a water-cement ratio of 0.48, 0.42, 0.5.

Table 3

Quality indicators of the proposed heat treatment of concrete samples

No.	Defined characteristics		Concrete mix samples with water-cement ratio		
			0.48	0.42	0.5
1	Compressive strength, MPa	After heat treatment	2.62	2.45	2.27
		After 20 days of normal storage of heat-treated samples	3.99	3.74	3.52
Factors characterizing the quality of samples immediately after the proposed heat treatment mode					
1	Intra-batch variability of samples		5.1	5.2	5.1
2	Optimality coefficient of structure		0.19	0.17	0.16
3	Hardening acceleration indicator		0.69	0.72	0.63
Factors characterizing the quality of heat-treated samples after 20 days of normal storage					
1	Intra-batch variability of samples		4.1	4.1	4.2
2	Optimality coefficient of structure		0.22	0.21	0.22
3	Hardening acceleration indicator		1.05	1.10	0.98

Fig. 9 shows the kinetics of changes in the moisture content of a concrete mixture based on hollow aluminosilicate microspheres during heat treatment according to the proposed method. According to this figure, the pattern of changes in moisture content provides a solution to two technological problems of structure formation of a lightweight concrete mixture.

According to the results of the research, it was identified that the proposed conditions of heat treatment provide further favorable conditions for the hydration of a binder as part of a concrete mixture based on hollow aluminosilicate microspheres. At the same time, the hydration degree of a binder α reaches 39 %.

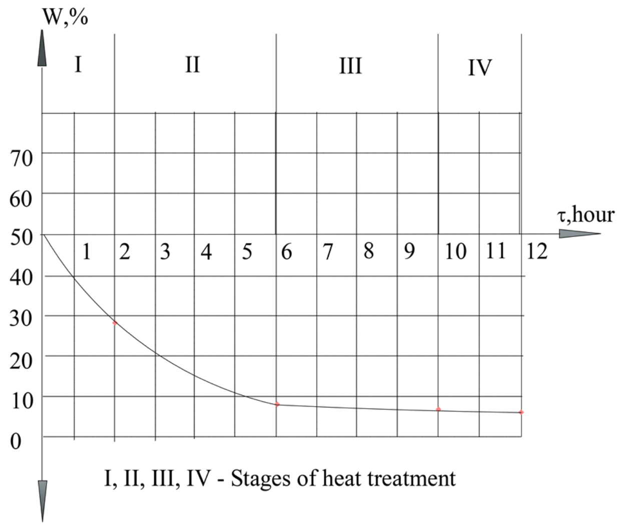

Fig. 9. Kinetics of changes in the moisture content of a concrete mixture based on a complete aluminosilicate microsphere

6. Discussion of optimum thermal exposure experimental results

Rational parameters of the heat treatment have been determined on the basis of an analysis of the structural and thermal effectiveness of the active medium formed by low-pressure steam.

The graphs of the structural effectiveness experiments (Fig. 3, 4) show that the strength growth of concrete samples with a hollow aluminosilicate microsphere occurs within 8 hours with the heat treatment duration of 16 hours. This is explained by the occurrence of external excess moisture flow at stages of heat treatment. At the same time, active strength growth (Fig. 3, 4) and strength gain intensity (Fig. 5, 6) begin only at the fourth hour of heat treatment. Such operating conditions of the strength development process indicate the choice to reduce the period of the most energy-intensive heat treatment stages compared to the standard (9 and 12 hours) for lighter concrete at the same binder consumption. The reduction of the stages is possible due to the correction of the moisture flow with the medium speed and humidity parameters at the pre-exposure stage and temperature rise stage. It undoubtedly will lead to a reduction in the heat and power consumption of the process. Analysis of Fig. 5, 6 shows a drop in the strength of concrete samples based on hollow aluminosilicate microspheres at 9 hours of heat treatment and the development of destructive processes caused by the emergence of a temperature gradient. Therefore, it is possible to reduce the full heat treatment cycle to 12 hours, which will also have a positive impact on the economy of production. According to the experimental relationships of thermal efficiency analysis shown in Fig. 7, 8, the thermal efficiency of the low-pressure steam medium for the 12-hour mode is 3.5–4 hours. Therefore, it is recommended that isothermal heating be taken within 4 hours at the isothermal temperature of 85 °C, which corresponds to the critical strength set for the cement of the second activity group in heat treatment processes. The proposed conditions demonstrate that quality structures can be established as shown in Table 3. Thus, the intra-batch variability of normal hardening samples is 3.9 %, samples heat-treated in the steam medium in the standard mode is 5.2 % and in the proposed mode is 4.2 %, which indicates that the concrete is very homogeneous in terms of strength in heat treatment according to the proposed mode. Thus, the compressive strength of heat-treated samples can achieve 3.99 MPa. In addition, studies have shown that the proposed conditions of heat treatment continue to provide favorable conditions for the hydration of the binder in a concrete mixture based on a hollow aluminosilicate microsphere. Thus, the main advantage of this study in comparison with those known on this subject [1–3] is the possibility of obtaining high-quality light concrete while reducing the heat consumption and energy intensity of the process, free of vibrocompression and expensive nano-additives and agents. Similar parameters in terms of strength and uniformity of concrete can be achieved under conditions of heat processing of products with less energy and heat engineering characteristics compared to known (temperature of isothermal heating is 95 °C, duration of isothermal heating is at least 6–7 hours). Furthermore, the resulting mode can be used for correcting the heat treatment parameters of composites based on lightweight and ultralightweight fillers.

The main limitation inherent in this study is the instability of the chemical and mineralogical composition of the aluminosilicate microsphere, which directly affects the hydration activity required for quality formation.

The main further direction in the development of this research is the optimization of regimes of active medium influence on different composite products, especially based on hollow aluminosilicate microspheres, including exposure of circulating and hot air in terms of energy efficiency.

7. Conclusions

1. Analysis of the structural effectiveness, based on detecting the kinetics of changes in compressive strength provides solutions for determining the kinetics of strength growth and the kinetics of strength gain intensity during given active medium periods. It is shown that during the analysis, it is possible to detect strength build-up intensity according to given temperatures and moisture flow. The main factor in this analysis is the temperature fall in the process of heat treatment and the choice of extra moisture flow correction with the medium speed and humidity parameters at the pre-exposure stage and temperature rise stage. The results show that the duration in the 13 hour-regime will be effective for the induction period because of considerable humidity. The period of strength growth for a concrete mixture based on hollow aluminosilicate microspheres ranges from 5 to 7 hours as in the concrete mixtures with crushed stone and keramzite crushed stone.

2. For detecting the optimum factors of active medium pressure in the process of structural formation, it is effective to use the **a**nalysis of the thermal effectiveness of the active medium formed by low-pressure steam. In that case, it will be possible to obtain the optimum factors of the temperature and humidity regimes and medium speed mode of the stage of performance heating and cooling processes for a given concrete mixture. The main feature of this approach is the possibility to take the information about the time of the thermal gradient in different cross-sections of concrete because of the destruction factor. There is a 6 °C/cm thermal gradient in the 13-hour regime and 4 °C/cm thermal gradient in the 16-hour regime. Thus, the drop in the strength of concrete samples shows the insecurity of the heat treatment time limitation.

3. The proposed heat treatment parameters for a concrete mixture based on hollow aluminosilicate microspheres are unified for heat treatment of concrete based on light and superlight fillers. It will be effective to use the 12-hour regime of heat treatment by the low-pressure steam active medium at the isothermal temperature of 85 °C. The minimum humidity can be 40 % at the beginning of the process and the maximum – 100 %. The recommended medium speed ranges from 4 m/s to 0.5 m/s during the process. Such rational parameters define the possibility of reducing the energy and heat consumption.

Acknowledgments

This work was carried out within the framework of the IRN research project Grant No AP09058149 "Study on electric discharge destruction of reinforced concrete products and solid waste for development of mobile complex for its recycling and disposal". The authors would like to acknowledge the Science and Production Association Testing Laboratory "Quality" for the provision of research equipment and tools and Joint-Stock Company "Parasat" Scientific and Technological Center for research support.

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