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The possibilities of optimization of cutting technology for the production of autoclaved aerated concrete and the use of low-clinker binders in it are investigated. Taking into account the price factor, energy-ecological trends in the development of the industry of building wall and heat-insulating materials, autoclaved aerated concrete has significant prospects for the development of production.

With the transition to the production of autoclaved aerated concrete of lower density, on the one hand, the total material consumption of production decreases, and on the other, the specific costs of the binder (cement) per unit mass of aerated concrete increase. The research was aimed at implementing a number of technological solutions. They imply a decrease in the energy intensity of production by minimizing the clinker component in the raw mix and an intensification of the production process in order to increase the coefficient of the structural quality of the material, as well as the possibility of mass production of low-density aerated concrete. Reducing the clinker component by replacing it with active mineral additives, blast-furnace granular slag, under the conditions of cutting technology, is possible provided that the problem of accelerating the plastic strength gain of aerated concrete raw material at the stage of formation of its macrostructure is solved.

It has been established that the implementation of forced synthesis of ettringite at the stage of formation of aerated concrete mixture with a high W/T ratio reduces the time of pre-autoclave holding of the raw massif. This allows the use of mineral additives and enhances the strength of the final product. Replacing 10–15 % of cement with the GBFS addition in the composition of the aerated concrete mixture in the presence of an additional content of gypsum stone of 5–10 % in the composition of sand slime provides an intensive increase in the plastic strength of the raw material before cutting it into products and high strength of the final product

Keywords: aerated concrete, mineral additives, granulated blast furnace slag, low-clinker binder, ettringite

THE USE OF LOW CLINKER BINDERS IN THE PRODUCTION OF AUTOCLAVED AERATED CONCRETE BY CUTTING TECHNOLOGY

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1. Introduction

Autoclaved aerated concrete combines excellent structural and thermal insulation properties. In terms of environmental properties, it is close to wood, and available raw materials are used for its production – cement, lime, sand and the addition of aluminum powder.

Comparison of regulatory requirements for representative Finland, which is similar in climatic conditions, indicates a significant lag in Ukrainian standards. If the thermal resistance for walls and the climatic zone in Ukraine is $3.3 \text{ m}^2/\text{K}\cdot\text{W}$ and the combined overlap, respectively, $6.0 \text{ m}^2/\text{K}\cdot\text{W}$, then in Finland the similar indicators are almost 2 times higher and, respectively, are 5.88 and $11.1 \text{ m}^2/\text{K}\cdot\text{W}$. Thermal resistance for windows in Ukraine is $0.75 \text{ m}^2/\text{K}\cdot\text{W}$ in Finland – $1.0 \text{ m}^2/\text{K}\cdot\text{W}$. The thickness of single-layer enclosing walls of buildings made of traditional wall materials such as solid clay bricks, silicate bricks, expanded clay concrete, due to their low thermophysical properties, increased significantly and became unacceptable for single-layer wall structures.

Aerated concrete today is quite common in European and CIS countries. Its market share in the walling materials of the countries of the former Soviet Union is approximately 40–60 % in Ukraine – 53 %. From 2000 to 2019, the production of this material in Ukraine increased 36 times – up to $3,600,000 \text{ m}^3$. According to the All-Ukrainian Association of Autoclaved Aerated Concrete Manufacturers, approximately 80 % of this material is used by private developers in the construction of low-rise housing, the rest – in monolithic frame high-rise construction.

It should be noted that today only 0.3–0.4 % of housing is being built in Ukraine at the expense of the state. The growth trends in the share of low-rise housing correspond to international experience and global trends. In the USA, Canada, developed EU countries, approximately 75–80 % of the population lives in low-rise buildings, and the construction of multi-storey residential buildings is actually limited.

Taking into account the price factor, energy and environmental trends in the development of the building materials industry in general, and in particular the production of wall

materials, autoclaved aerated concrete, as a wall structural, heat-insulating and heat-insulating material, has significant prospects for the development of production and use.

In connection with the need to increase the energy saving requirements and the predicted potential improvement of the aerated concrete production technology in DSTU B V.2.7-45:2010 «Building materials. Cellular concretes. General technical conditions» changes were made – in subdivision 4.1 under the D200 brand were added the D100 and D150 brands as effective mineral thermal insulation (Table 1). Such changes motivate scientists and autoclaved aerated concrete manufacturers to improve the technology of its production. The only European manufacturer of cellular mineral insulation for aerated concrete of the D100 brand is the German company Xella, which produces it under the Multipor brand, the composition of which is patented.

By increasing the coefficient of structural quality of autoclaved aerated concrete in DSTU B V.2.7-45: 2010, changes were made and the brand of aerated concrete D300, depending on the strength class, while remaining heat-insulating, simultaneously received the category of structural and heat-insulating material, making it possible to foresee this in construction projects. Aerated concrete grades D300 and D400 with strength class C1.5 to C2.5 provides load-bearing capacity for 2-storey buildings, the walls of which do not need insulation and complies with the standards in force in Ukraine.

Table 1

Expansion of grades of heat-insulating autoclaved aerated concrete in accordance with the amendments made to DSTU B.2.7-45: 2010 «Cellular concretes. General technical conditions»

Medium density grade	Average density, kg/m ³	Strength class, C	Strength, MPa, not less	Dry heat conductivity, W/m·°C, no more
D100	70–120	C0.25	>0.4	0.052
D150	120–170	C0.25	>0.4	0.058
D 200	180–220	C0.35	0.50	0.055
D 250	220–270	C0.5	0.72	0.065
D 300	270–320	C0.75	1.06	0.08

When switching to the production of autoclaved aerated concrete of lower density, on the one hand, the total material consumption of production decreases, on the other, the specific consumption of cement per unit mass of aerated concrete increases. It is quite obvious that with a decrease in the density of aerated concrete, the thickness of the interpore partitions will decrease. To ensure their strength, the consumption of the mineral binder (in particular, cement) must be increased.

Manufacturers of autoclaved aerated concrete are interested in the implementation of a number of technological solutions aimed at intensifying production, increasing the coefficient of structural quality of the material, switching to the production of wall blocks of lower density, and reducing the energy consumption of production by minimizing the clinker component of the mineral binder.

Expanding the resource base in the production of autoclaved aerated concrete using cutting technology by using a low-clinker binder is now an urgent scientific and technical task that simultaneously solves a number of energy and environmental problems.

2. Literature review and problem statement

As is known from work [2], the production of autoclaved aerated concrete is based on the artificial synthesis of calcium hydrosilicates (mainly of the tobermorite group) at a temperature of 192...200 °C in a saturated steam medium with a pressure of 1.2–1.4 MPa. The basic component of the aerated concrete binder is cement with the addition of lime, and this practice is generally accepted in the EU and CIS countries [3]. Although [2] provides for the use of additives of granulated blast furnace slag (GBFS), fly ash, fuel slag and other specially manufactured types of mineral binders.

Studies that were intensively carried out at the stage of formation of the industry for the production of autoclaved aerated concrete, both in European countries and in the countries of the former USSR in the 70–80s of the last century, were first reflected in CH 277-70 later in CH 277-80 (Instructions on manufacture of products from aerated concrete) [2], which is valid to this day.

Considering the relevance of reducing energy for the production of autoclaved aerated concrete, other binders, there is a constant search for alternative raw materials and additives to cement to reduce the environmental consequences of its production, in particular CO₂ emissions and energy consumption [4–6].

In the conditions of cutting technology, it is necessary to solve the problem of accelerated growth of the plastic strength of aerated concrete mass at the stage of formation of its macrostructure to cutting the raw material into blocks.

At the same time, an important role is played by mineral additives of multifunctional action, which will not only contribute to an increase in the strength of the final product and a reduction in cement consumption, but will ensure an increase in the plastic strength of the raw material at the stage of formation, which is necessary for tilting and cutting the aerated concrete mass.

The use of gypsum stone additives, active mineral additives of natural and artificial origin, GBFS under conditions of elevated temperatures and excess steam pressure has been the subject of many studies presented in numerous publications. Research carried out earlier should be conventionally considered somewhat «laboratory». They do not take into account the presence of reverse sludge in the mixture (15...20 %), which, with the cutting technology of production, is an obligatory component of the aerated concrete mixture – modern plants and the air removal factor are drawn into the mixture when the mold is quickly filled.

According to studies [7], the crystalline phase of granular slag is represented by microlites of okermanite and merwinite, interspersed into slag glass, exhibits hydration activity, especially in the presence of an activator additive. When a part of Portland cement is replaced by blast-furnace slag from 20 to 80 %, the strength of slag-cement stone increases by 17–41 %, but the period of growth of the plastic strength of the raw material is lengthened.

Analysis of research results [4–11] show that in complex systems (cement, lime, GBFS, natural mineral additives, reverse sludge) the role of gypsum has not been fully investigated.

On the one hand, according to CH 277-80, gypsum stone is intended to regulate the rate of lime hydration. On the other hand, according to various studies [6, 7], gypsum stone is a multifunctional component of binder autoclaved aerated concrete. At the stage of massif formation, it not only inhibits the hydration of lime and balances the kinetics of gas release with an

increase in the plastic strength of the raw material, but in the process of autoclaving it provides an increase in the strength of the final product. According to [8], with preliminary slaking of 20–30 % lime with dihydrate gypsum and replacing up to 50 % of cement in steelmaking slag, an increase in the strength of aerated concrete samples to 9.0 MPa is provided.

Analyzing the results [9] heat treatment of molded aerated concrete products with GBFS, it is possible to conclude that the rate of strength gain increases by 1.5–2 times, and the final strength of cinder-gas concrete is 45–60 % higher than without steaming at an average density of 550–700 kg/m³ compressive strength is 1.8–3.0 MPa.

According to [10, 11], the optimal addition of gypsum in cement systems during steaming is close to the value required to bind the entire amount of C3A into monosulfate calcium hydroaluminates by 1 % C3A in clinker, up to 1.6 % of hemihydrated gypsum can be added. Hydration of C3A in the presence of gypsum under any temperature conditions results in the formation of a high-sulfate form of hydrosulfoaluminate (ettringite), which is a denser and stronger phase than hexagonal hydroaluminates.

When using the cutting technology for the production of autoclaved aerated concrete, a rather significant technological stage was the need to hold the massif and the need to accelerate the growth of the plastic strength of aerated concrete raw material, which is necessary for its cutting. If this process is delayed in time, the entire technological process of autoclaved aerated concrete production is inhibited.

It is the problem of the need for a rapid increase in the plastic strength of aerated concrete mixture with a high water-solid ratio ($W/T=0.6-0.7$) with the lithium technology that requires a comparison in time of the rate of lime slaking, gas evolution, the kinetics of hydration of the clinker component of the mineral binder to the rapid recruitment of aerated concrete raw plastic strength.

Extended holding of molded aerated concrete masses until the moment of loading into the autoclave affects the schedule of the autoclave department, lengthens the technological cycle of aerated concrete production and leads to a decrease in the final strength of aerated concrete by 5.5–84 % [12].

Thus, with the cutting technology, the conflict of goals of individual technological processes for the production of autoclaved aerated concrete remains:

- excessive exposure of the molded massifs in time before autoclaving significantly affects the final strength of aerated concrete and the work schedule of the autoclave department of the enterprise;

- implementation of cutting technology presupposes the need to hold the molded raw material until such a plastic strength is achieved, which makes it possible to transport and carry out its longitudinal and transverse cuts into individual wall products;

- implementation of measures to reduce the clinker component of the mineral binder and the consumption of lime in the composition of the raw mixture, by introducing GBFS and other additives into its composition, almost always leads to an extension of the period for the plastic strength of the raw material required for cutting the massif. As a result, the period of its pre-autoclave exposure and, in fact, the entire technological process of autoclaved aerated concrete production increases.

Analysis of literature data and actual requests of modern autoclaved aerated concrete production allows to assert that it is expedient to conduct research on the solution of these conflicts.

3. The aim and objectives of research

The aim of research is to develop optimal technological parameters for the production of autoclaved aerated concrete by cutting technology using low-clinker binders. The use of such raw materials will make it possible to reduce energy consumption and intensify the production process by minimizing the clinker component in the raw mixture and to establish mass production of low-density products with an increased coefficient of constructive quality.

To achieve the aim, the following objectives are set:

- to investigate the features of cutting production technology and determine the possibilities of implementing technological measures aimed at intensifying production;
- to evaluate the possible parameters for optimizing the composition of the binder in the raw mixture;
- to conduct a study of the effect of the addition of GBFS and gypsum on the rheological properties of the raw mixture and the properties of the finished product.

4. Features of cutting technology for the production of aerated concrete

In the 70–80s, the world's leading firms (Ytong, Hebel, Verhan (Germany) Calsilox (Denmark), Durex (Netherlands), Chori (Japan), Unipol (Poland) abandoned the brewing of aerated concrete in individual forms and switched to cutting production technology. In the Soviet Union, within the framework of «catch-up», some of the delayed production of the equipment «Universal-60» and «Silbetblock», «Bobruisk-1,2», «Conrex 90/240».

European manufacturers of equipment for the production of autoclaved aerated concrete «Wehrhahn» (Germany); Aircrete (Netherlands); Hess (Netherlands); Masa Henke (Germany) and others for a long time will provide for the use of cutting technology for the production of aerated concrete with certain technological features to ensure product quality. With the revival of the autoclaved aerated concrete industry, after its destruction during the transformation of the economy to the market, modern European plants were built in the former Soviet republics, which replace the outdated Universal 60 and Silbetblock lines. The new factories have implemented cutting technology, which provides for high-precision cutting of the mass into separate wall blocks before autoclaving. It guarantees high accuracy of linear dimensions of wall blocks (± 1 mm), provides a «groove-comb» joint to reduce freezing of walls and a «gripper» device for hands for easy masonry.

In contrast to the formation and brewing of products in individual forms, when using the cutting technology, the turnover of the forms increases, their metal consumption decreases more than 2 times, the filling factor of the autoclave increases to 0.4–0.45. It is believed that this reduces the specific energy consumption by 20–30 % for autoclaving 1 m³ of aerated concrete. Since the autoclaving of aerated concrete products is carried out without boarding – on a special steaming grid, the aerated concrete blocks are warmed up better. This contributes to the better synthesis of low-basic calcium hydrosilicates, which are the main carriers of the strength of autoclave silicate materials. The side boards of the rig are used to move and tilt the raw massif. The plastic strength of the raw material for cutting it must be sufficient for performing cutting technological operations and tilting

the massif and completely exclude the possibility of its deformation and the appearance of cracks.

Calibration of the massif provides for leveling the surface and occurs by cutting on the sides by about 3–5 cm. An extra layer of raw material using special knives and strings, thus the lateral surfaces of the green massif are formed. Then the mass is cut in two directions with the device in the aerated concrete blocks of the «groove/ridge» system. The cutting complex is mounted above a pit, in which a container for preparing and collecting cut raw material is located, or, more often, a system of conveyors is provided for feeding it into the receiving container of the return sludge. The cutting technology is generally accepted in the practice of European manufacturers of equipment for aerated concrete plants, although each manufacturer of equipment has certain technological differences.

5. Determination of possible parameters for optimizing the composition of the binder in the raw mixture

As noted above, the main goal of scientists and manufacturers of autoclaved aerated concrete to this day remains to increase the CCQ, reduce the energy consumption of production, ensure high strength and accuracy of the geometric dimensions of wall blocks.

To reduce the density of concrete for every 50 kg/m³, it is necessary to increase its porosity by about 3.5...4%. At the same time, for each percentage increase in porosity, the strength of concrete decreases by about 3...4% [13]. Autoclaved aerated concrete is a relatively new building material that has been used on a large scale in construction since 1950–1960, this separates the issue of its durability into a separate plane and is especially important [14, 15]. Currently, aerated concrete with a density of 400 and 500 is in demand on the Ukrainian construction market, the D300 brand is quickly gaining popularity and aerated concrete with a density of 600–700 kg/m³ and higher is not produced at all.

The production and use of autoclaved aerated concrete is constantly aimed at reducing its density. Reducing the density of aerated concrete wall blocks in today's indicators (400–300 kg/m³), while maintaining high physical and mechanical characteristics of the material, provides a number of advantages at the production stage and especially at the operation stage. A special niche in the structure of wall materials is occupied by structural and heat-insulating autoclaved aerated concrete with a density of 300 kg/m³. This brand of heat-insulating and structural material appeared on the construction market relatively recently. Its dry heat conductivity coefficient is 0.08 W/(m·°C), and its compressive strength is 2.5 MPa. Aerated concrete with such characteristics is produced in large quantities at factories in Germany. In the CIS countries, only a few factories have mastered its production. In Ukraine, the production of D300 aerated concrete was started by Aeroc, which today is the only manufacturer of these products.

Since 2013, the plants of Aeroc LLC have started serial production of heat-insulating aerated concrete with a density of 150 kg/m³.

Reducing the density of aerated concrete wall blocks in today's indicators (400–300 kg/m³), while maintaining high physical and mechanical characteristics of the material, provides a number of advantages at the production stage and especially at the operation stage.

However, with the transition to the production of products with a lower density, the specific consumption of cement

increases to ensure the strength of the interpore partitions of the material.

Fig. 1 shows the calculated indicators of the specific consumption of cement in kg, determined per unit volume (1 m³) of silicate material of autoclaved aerated concrete D150; D300; D400 and D500. It is clear that an additional increase in the strength of autoclaved aerated concrete, in addition to cement, is provided by the addition of lime and natural gypsum, which simultaneously acts as a regulator of lime hydration. The return sludge, in addition, acts as a crystal seed, increases the sedimentation stability of the mixture, ensures uniformity of density and strength over the entire molding height.

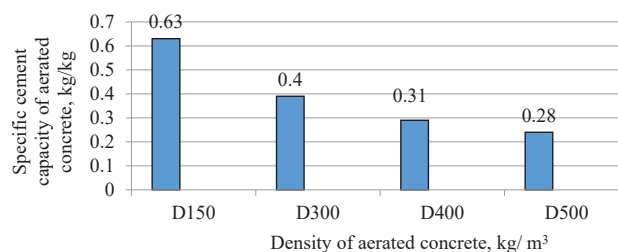


Fig. 1. Dependence of energy consumption (cement consumption) in kg to with the given aerated concrete of various density, kg of cement/kg of dry components of the raw mix

As seen from Fig. 1, as the density of aerated concrete decreases, the consumption of cement per 1 m³ of aerated concrete increases. This is an additional argument regarding the feasibility of research on reducing the energy intensity of the production of autoclaved aerated concrete by using GBFS, fuel slag in production. This is also substantiated by numerous scientific studies since 60–80 years [15, 16], that replacing a part of Portland cement with GBFS in autoclaved concrete is not only equivalent to Portland cement, but also leads to an additional increase in the strength and frost resistance of aerated concrete.

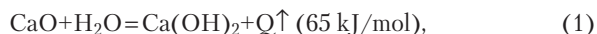
In the production conditions of Aeroc LLC, after the massifs are formed, they are kept in plastic strength chambers for about 2.5–3 hours at a temperature of about 50–55 °C to accelerate the growth of the plastic strength time sufficient for transportation and the massif calibration.

In the process of forming a batch of loaded autoclave trolleys until they are moved to the autoclave, the cut massifs are stored in temporary holding chambers. The importance of such a technological method as the presence of chambers for gaining plastic strength and temporary holding of aerated concrete is quite reasonable. The optimal plastic strength of the massif depends on the composition of the aerated concrete mixture and will be different for different compositions of the mixtures. The aerated concrete mass is sent for a sharp one when the plastic strength is set up to 340 Pa.

In SN 277-80, in the production of autoclaved aerated concrete, the use of cement is envisaged with the start of setting no later than 2 hours, and the end of setting no later than 4 hours. As it is known, the mineralogical composition of traditional Portland cement is represented by four minerals: C₃S, C₂S, C₃A, C₄AF and the addition of gypsum stone. In decreasing hydration rate, minerals are arranged in the following row: C₃A>C₄AF>C₃S>C₂S. The greatest strength for all periods of cement hardening is provided by C₃S, and in terms of hydration rate – by C₃A. That is why CH 277-80

provides for a C_3S content of at least 50 %, and a C_3A content of no more than 6 %.

In a composite binder, the rate of CaO hydration affects the rate of cement hydration. A saturated lime solution almost doubles the setting time of cement. The exothermic reaction of lime hydration occurs with the release of thermal energy (1), while the aerated concrete mass is heated and dehydrated and is accompanied by a gas release reaction due to the presence of an additive of aluminum powder in the mixture (2):



From the reaction equation (2) it can be seen that 2 grams of aluminum molecules (54 g), when interacting with lime, release 3 hydrogen molecules. Under normal conditions, one gram molecule has a volume of 22.4 liters. Therefore, when 1 gram of aluminum enters the reaction, approximately 1.244 liters of hydrogen are released $(3 \cdot 22.4) / 54$.

Ukrainian producers of aerated concrete use aluminum powder with an active aluminum content of 85–93 %, and Russian, Polish, Chinese and German pastes with an active aluminum content of 75–92 % in the solid residue. Since the aerated concrete mixture is poured into the mold in industrial conditions at a temperature of about 40 °C, then, taking into account the temperature factor of the Gay-Lussac law of hydrogen (V is the volume of hydrogen), it will be released in accordance with (3):

$$V_{hydrogen} = 1.244 \cdot \left(1 + \frac{40}{273} \right). \quad (3)$$

The temperature for slaking lime into aerated concrete mixtures depends on many factors – its activity, water-solid ratio, grinding dispersion, temperature conditions of the process, the composition of the binder and the mixture, etc. Lime for the production of autoclaved aerated concrete has a slaking period of 5–25 minutes and activity ($CaO \cdot MgO$) not less than 80 % [17].

As a result of the hydration reaction of lime, a significant amount of heat (Q) = 1160 kJ per 1 kg calcium oxide is released. [18]. According to [19], during autoclave treatment, calcium hydroxide provides additional heating of the silicate mass when interacting with silicate components and the formed calcium hydrosilicates (80 kJ/kg for tobermorite and 45 kJ/kg for xonotlite). This leads to an additional increase in the temperature inside the aerated concrete mixture, and accordingly can be taken into account in the future when introducing energy-saving modes of autoclaving aerated concrete. Preliminary utilization of this heat energy for production needs can also be envisaged (steam passage to other autoclaves, heating of raw material pre-ripening chambers, additional heating of water, heating, and other purposes).

6. Influence of the addition of DSHS and gypsum on the rheological properties of the raw mixture and the properties of the finished product

The conducted studies of the effect of the addition of GBFS and gypsum in the composition of autoclaved aerated concrete on the rheological properties of the mixture after

molding were carried out in several stages. At the first stage, laboratory studies were carried out with a fairly wide range of raw materials and a dosage of GBFS, after which the composition of the mixture was adjusted and at the subsequent stages experimental molding of aerated concrete mixture was produced in the industrial conditions of an operating enterprise.

Aerated concrete composition D300 was used as the base raw mix with the following raw material costs:

- cement – 128 kg/m³;
- lime – 16.7 kg/m³;
- sand sludge (dry residue) – 157 kg/m³ of which sand 141 kg/m³;
- gypsum stone – 16 kg/m³;
- return sludge (dry residue) – 53 kg/m³ or 15 % of all dry components;

- gas generator aluminum powder – 0.53 kg/m³.

During the research, let's use the Volyn-cement Portland cement of PJSC «Dyckerhoff Cement Ukraine» in accordance with DSTU V.2.7-46: 2010 PC II/A-Sh-500. According to the Quality Certificate, the cement already contains the additive GBFS 6.0...20 % and has the following mineralogical composition: C_3S 62...70 %; C_2S 8.3...18 %; C_3A 6.3...7.7 %; C_4AF 10.0...12.6. The beginning of setting 110...205 min, end 165...270 min. SO_3 content is up to 3.5 %.

An additional addition of natural gypsum stone in the aerated concrete mixture was introduced during wet grinding of sand and GBFS in a ball mill.

Aerated concrete mixture with a temperature of 43.7 °C was poured into a mold, the W/T ratio was 0.69. The spread of the mixture over the standard Suttard cylinder was 31 cm.

After pouring the mixture for 0.2...0.5 minutes with the poured aerated concrete mixture, air was removed, which was entrained in the mixture during the casting of the mold. For this, a vibration unit was used and immersed in the mixture. From the moment of pouring the massif to its processing in an autoclave, the temperature of the massif and the plastic strength of the raw material were measured in its cutting into wall blocks.

Fig. 2 shows the dynamics of temperature growth after the formation of the massif. It was measured with an electronic thermometer with an accuracy of ± 0.01 °C at a distance of approximately 50–60 cm from the edge of the mold board every 10 minutes.

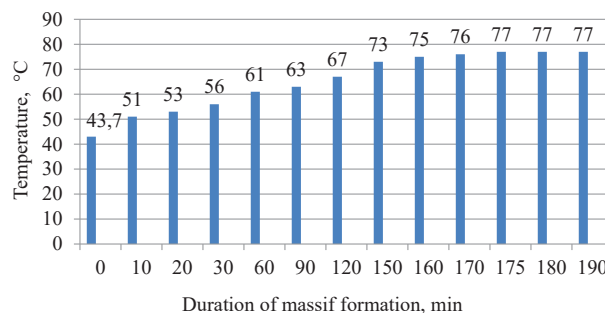


Fig. 2. Kinetics of the temperature rise of the D300 aerated concrete massif after molding

As seen from Fig. 2, after pouring the aerated concrete mixture for 175 minutes, there is an increase in temperature due to the exothermic reaction of hydration of lime and cement. After about 3 hours the temperature of the massif rises to 77 °C. Simultaneously with the temperature measurement, the plastic strength of the aerated concrete raw material was measured. Lime was used in the production of pilot batches of autoclaved

aerated concrete, little activity more than 80 %, quenching time 6 minutes, temperature 60 °C, total quenching time no more than 25 minutes, lime grinding fineness was characterized by a residue on a sieve of 80 microns no more than 4 %.

To assess the effect of adding gypsum stone on lime hydration, standard studies were carried out. Lime of the Ukrainian manufacturer – Liubomyrsk silicate plant – with activity (CaO+MgO) 80 % was used. The presence of an additional addition of gypsum stone in the aerated concrete mixture leads to inhibition of the lime hydration process (Fig. 3).

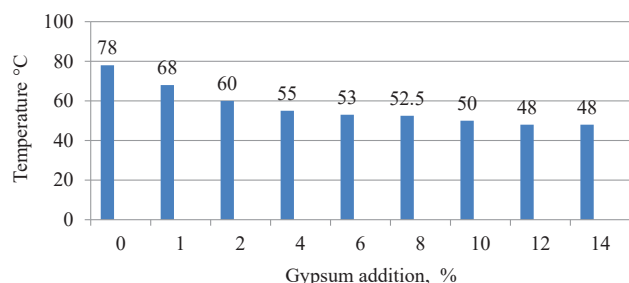


Fig. 3. Influence of gypsum addition on lime slaking temperature

As seen from Fig. 3, with a dosage of gypsum up to 6 %, there is a sharp decrease in the temperature of lime hydration.

The addition of gypsum stone in the casting technology of massif formation first slows down the initial reaction of lime slaking and the hydration of the clinker component of the mineral binder. This has a positive effect on the rheology of the mixture, the viscosity of which ensures uniform growth of the rock mass due to the release of hydrogen and the formation of macroporosity in the raw material. As gas evolution ends, cement hydration is accelerated. An additional factor in stabilizing the macroporosity of aerated concrete is the formation of a highly basic form of calcium hydrosulfoaluminate, which densifies and reinforces the small pores and partitions of aerated concrete and ensures the fixation of the macrostructure of the molded mixture.

Fig. 4 shows the dynamics of the growth of the plastic strength of aerated concrete raw. As can be seen from the graph, when the plastic strength reaches 200–250 kPa and more, the massif is moved for calibration and subsequent cutting into products. The plastic strength of aerated concrete raw materials was measured using a standard cone penetrometer, measurements were carried out at a distance of 50–60 cm from the edge of the mold board.

According to [18], gypsum, regardless of whether it is included in the hydrosulfoaluminate or not, is converted into anhydrite CaSO₄ in an autoclave. At a temperature of 180 °C, it hydrates and transforms into hemihydrate calcium sulfate, and at 120–130 °C – into gypsum CaSO₄·2H₂O.

These processes are accompanied by a local increase in the volume of the solid phase, compacting the microstructure of the inter-pore partitions of aerated concrete, since the W/T ratio of the mixture adopted by us is quite high and is 0.65 for aerated concrete of the D300 brand. Gypsum in the presence of Ca(OH)₂ and SiO₂ in the mixture promotes the accelerated synthesis of calcium hydrosilicates, as it increases the degree of saturation of the liquid phase with calcium ions. In addition, having a higher solubility for Ca²⁺ ions in comparison with lime, it increases the capacity of the liquid phase for these ions, additionally stimulates the synthesis of calcium hydrosilicates. The massifs were autoclaved at

a temperature of 200 °C in a saturated steam environment at an overpressure of 14 bar according to the standard mode adopted at the Aeroc enterprise.

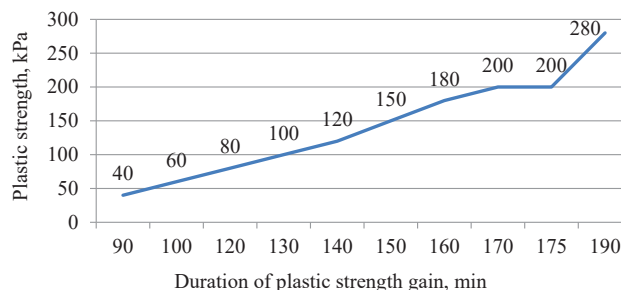


Fig. 4. Dynamics of growth of plastic strength of aerated concrete raw

The results are consistent with the results of the authors' studies [3]. The formation of the phase composition of new formations of autoclaved aerated concrete falls under the well-known and studied processes of hydration hardening of the components of the mineral binder of autoclaved aerated concrete.

From theoretical studies, it is known that when natural gypsum is dehydrated, semi-aqueous gypsum is first formed, when dehydrated, soluble γ -CaSO₄ anhydrite is obtained, which at temperatures above 170 °C transforms into insoluble β -CaSO₄ [20, 21]. Under the existing conditions of lime hydration in a saturated steam environment, semi-aqueous gypsum CaSO₄·0.5H₂O may not be dehydrated, and does not crystallize, retaining its properties. It does not become insoluble and retains its chemical properties.

The ettringite influence on the properties of cement materials has always been perceived ambiguously and depends both on the composition of the mineral binder and on external factors of the operation of cement materials. It is known that if ettringite crystallizes in a medium saturated with calcium hydroxide, it causes expansion and compaction of the material and can lead to destruction. When the concentration of calcium hydroxide in the pore fluid of the material is below 0.5 g/l, ettringite crystallizes without significant expansion, reinforcing and strengthening its structure. At elevated temperatures above 80–90 °C, it turns into the monosulfate form 3CaO·Al₂O₃·CaSO₄·12H₂O.

The expediency of introducing an additional gypsum additive into the aerated concrete mixture when grinding quartz sand at Aeroc LLC is consistent with the experience of European aerated concrete manufacturers and the author's recommendations [3], which note the positive and negative effects of this additive and propose to limit its costs for injection molding technology – 7 %, for shock – up to 2.5 %.

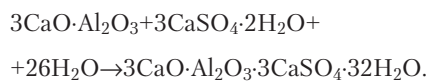
Highly dispersed products of lime slaking and the formed semi-aqueous gypsum increase the strength of autoclaved aerated concrete based on cement, sand and lime with the addition of natural gypsum by 1.5 times as compared with no additive mixtures of a composite binder. The ratio of the components: lime-sand-cement-aluminum paste was 1-3.2-0.8-0.0048 [18].

The peculiarity of the formation of neoplasms at the stage of growth of the plastic strength of the raw material to the autoclave stage of the formation of aerated concrete mixture is associated with its multicomponent. In this case, several chemical processes take place simultaneously: lime hydration with the release of heat; hydration of cement, which is associated with the mineralogical composition of the clinker, primarily with the aluminat phase (C₃A). This mineral is cha-

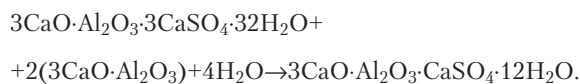
acterized by the highest rate of hydration with the formation of calcium hydroaluminates, which instantly fill the pore space.

At the same time, due to the presence of hydration activators of DSHH, hydration hardening of the slag components begins. The cement itself, calcium hydroxide, serves as activators for the GBFS hardening. In addition, it is appropriate to refer to the scientific developments [15, 16] of sulfate-slag cement, in which GBFS is activated by gypsum in the presence of an insignificant content of $\text{Ca}(\text{OH})_2$. GBFS activity depends on the content and structure of slag glass, which reacts more intensively with water than the crystalline phase of the same composition. The maximum hydraulic activity of GBFS is achieved with a crystalline phase content of up to 5 %.

Under normal conditions, in cement concretes during hydration of C_3A , hydroaluminates of variable composition C_4AH_x are formed, which, depending on the temperature and humidity of the environment, can have from 19 to 7 water molecules. When the pH of the liquid phase of the cement stone or temperature changes, it gradually transforms into a more stable cubic C_3AH_6 , which creates stress in the structure of the cement stone under normal conditions and reduces its strength [22]. In the presence of gypsum stone, the hydration process slows down and a shell of ettringite is formed on the surface of the C_3A grains.



Ettringite as a primary product stably exists only as long as there is a sufficient amount of sulfates. It has been proven by many studies that as soon as the concentration of SO_3 in solution decreases, ettringite becomes unstable and turns into monosulfate:



At a certain concentration of ettringite, calcium hydrogen monosulfoaluminate and calcium hydroxide, equilibrium is established between the hydration products, which positively affects the properties of the cement stone formed. In comparison with Portland cement stone, the potential for self-healing of microcracks in aerated concrete increases with an increase in the proportion of slag [6, 11].

Fig. 5 shows the interpore partition of autoclaved aerated concrete in which the products of hydration hardening of a multicomponent binder are presented. The X-ray phase analysis of autoclaved aerated concrete samples showed that new formations are traditional for autoclaved concretes, they are represented by: quartz $\text{Ca}(\text{OH})_2$, $\text{CaSO}_4\cdot 0.5\text{H}_2\text{O}$ peaks and hydrosilicates of the tobermorite group. On samples with the addition of gypsum stone, the intensity of the peaks characteristic of SiO_2 decreases and the intensity of the lines characteristic of low-basic calcium hydrosilicates such as tobermorite and calcium hydrosulfoaluminate increases. This is logical and fully consistent with the general provisions of the hydrothermal synthesis of new formations of silicate materials with an identical composition of components.

In the presence of gypsum in the composition of Portland cement, back sludge and a separate additional additive, which is introduced into the mill when grinding the silica component, an additional addition of Al_2O_3 is required to form ettringite (Fig. 6).

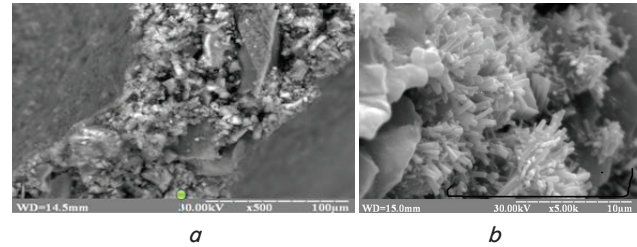


Fig. 5. Interpore partition of autoclaved aerated concrete: a – 100 nm; b – 10 nm

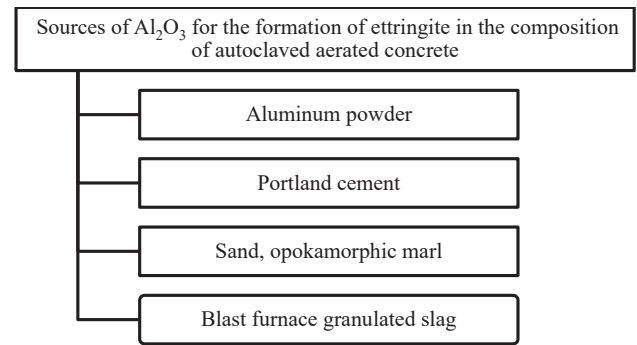


Fig. 6. The main sources of Al_2O_3 entering the composition of autoclaved aerated concrete for the synthesis of ettringite

The sources of Al_2O_3 entering the aerated concrete mixture are the aluminum powder itself (one gr. Which leads to the formation of 46.5 grams of ettringite), Portland cement (DSTU B.2.7-46:2010 PC II/A-SH-500 in accordance with the Quality Certificate cement contains additive GBFS 9.0...16 % and S_3A 6.3...7.7 %), GBFS (which contains from 7.5 to 12 % Al_2O_3 in accordance with the Certificate of ArcelorMittal PJSC).

In [3], it is recommended to limit the total limiting content of Al_2O_3 to 7 %, but this must be linked to the optimal dosage of GBF and the additional content of gypsum in the composition of the aerated concrete mixture. Ground GBFS replaces Portland cement (5, 10, 15, 20 and 25 %), performs the function of a binder and partially a siliceous component, and also simultaneously serves as a source of Al_2O_3 for the formation of ettringite when an increased addition of gypsum stone is added to the aerated concrete mixture (Fig. 7). As seen from Fig. 7, the replacement of 10–15 % cement with GBFS simultaneously solves several important practical problems.

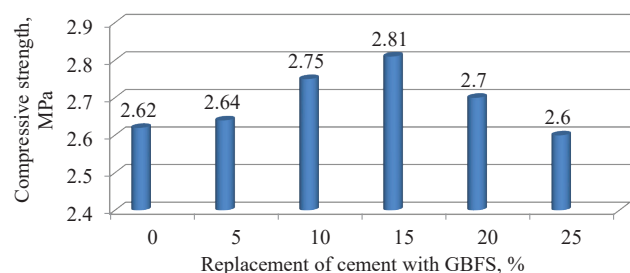


Fig. 7. Influence of replacing Portland cement with the GBFS additive and gypsum on the strength of autoclaved aerated concrete D300

The effectiveness of adding GBFS in a mixed binder consists of a proportion corresponding to the effect of replacing a part of the cement, and a proportion of the change in the

strength of the binder itself. To assess the efficiency of the slag, taking into account the assessment of these two effects, the formula proposed in [11] can be used:

$$E_m = \frac{100 \cdot \left(\frac{C_1}{R_1} - n \cdot \frac{C_2}{R_2} \right)}{\frac{C_1}{R_1}}, \quad (4)$$

where C_1 – consumption of cement without slag in concrete of a certain composition, kg; R_1 – strength of concrete on the outlet cement, MPa; C_2 – consumption of mixed binder, kg; R_2 – strength of concrete on a mixed binder, MPa; n – proportion of the original cement in the mixed binder.

Moreover, such an assessment of the effectiveness of GBFS supplementation is not complete. Taking into account the specifics of the production of autoclaved aerated concrete, the effectiveness of the addition of GBFS and the additional addition of gypsum stone at the stage of formation of the macroporosity of the raw aerated concrete and the factor of increasing the frost resistance of the material, which is generally known and characteristic of concretes containing GBFS, is not taken into account.

Purposeful rapid formation of hydrosulfoaluminate at the stage of aerated concrete mixture formation at a high W/T ratio ensures the formation of a high-quality aerated concrete macrostructure has a positive effect on the strength of the material. In the process of autoclaving, high-water ettringite is transformed into stable monosulfohydroaluminates, which have a higher strength and additionally reinforce and compact low-basic hydrosilicates of calcium.

7. Discussion of the results of the study of the use of low-clinker binders in the production of autoclaved aerated concrete using cutting technology

At the initial stage of the formation of aerated concrete mixture, an additional gypsum additive of 2–6 % [3] reduces the temperature of lime slaking (Fig. 3) and lengthens this period of its quenching. After about 150–170 minutes, it is due to the heat generation of predominantly lime that the temperature of the massif rises to 77 °C, although the standard slaking time for lime is 6 minutes.

Due to the high temperature of the massif, part of the water evaporates from it, and the aluminate component contained in the cement (C_3A), in the blowing agent (aluminum powder), in the GBFS in the presence of gypsum additive promotes the formation of ettringite [18]. Its crystals in the form of long thin needles, resembling some bacilli under a microscope (this is why it is known in the technical literature as «cement bacillus»), binds free moisture, provides the setting and strengthening of the structure and conditionally «reinforcing» aerated concrete mixture [18]. As seen from Fig. 4, after about 170 minutes, the mixture acquires a plastic strength of 280 kPa or more, allows it to be transported, open the sides, tilt the massif by 90 degrees, cut the «top crust» and side shavings and cut the massif into wall blocks. Thus, the intensification of the technological process of increasing the plastic strength of the raw aerated concrete mixture to a level that provides the possibility of removing the formwork, tilting the massif and cutting it into wall blocks is provided. After all, overexposure of the molded aerated concrete mixture in autoclave treatment [12] can lead to a decrease in the strength of the final product of aerated concrete treatment up to 80 %.

An additional positive effect of the increased content of gypsum additive in aerated concrete mixtures is the balancing in time of the kinetics of its solidification processes with the end of the gas evolution process. This is especially important and a sensitive factor in the formation of high-quality macroporosity of low-density aerated concrete D150 and D300 at a high (0.65) W/T ratio, provided that part of the cement is replaced by GBFS. It is the correct form of macropores and the strength of the silicate mass that provide the strength of aerated concrete.

Due to the polyfunctionality of the action of the gypsum additive [6, 7] under conditions of autoclave treatment of aerated concrete mixture due to sulfate-alkaline activation of GBFS in a composition containing hydration products of Portland cement, lime, reverse sludge, the thermodynamically unstable equilibrium of slag glass is disturbed, its hydraulic activity awakens and low-basic calcium hydrosilicates [16, 18], which will reduce the consumption of the mineral binder and increase the strength of autoclaved aerated concrete.

Fig. 5, *a* shows the interpore partition of autoclaved aerated concrete, in which new formations are presented, which are traditional for autoclaved concretes – hydrosilicates of the tobermorite group, quartz (SiO_2), $Ca(OH)_2$, $CaSO_4 \cdot 0.5H_2O$ and large particles of GBFS. The hydraulic potential of GBFS, due to its relatively low dispersion can't be completely exhausted, GBFS is ground in an industrial wet mill together with sand and its dispersion should be much higher and amount to 4000–5000 cm^2/g [3]. The European experience of using GBFS indicates that it is mainly realized in already ground form and ready for use in various cement materials.

The studies carried out did not give a specific answer regarding the contribution of reverse sludge (up to 20 % in the composition of the aerated concrete mixture) to the increase in the strength of aerated concrete. In modern plants, through a closed cycle of waste-free technology for the production of aerated concrete, return sludge is ubiquitous for reuse. As it is known, it performs the function of a crystalline «seed» and ensures uniformity of the properties of aerated concrete along the height of the mixture molding and, to a certain extent, contributes to an increase in strength and saving of the clinker component. Directed synthesis of low-basic calcium hydrosilicates CSH (I), tobermorite 11.3 Å, which are capable of bonding, contributes to the formation of a more perfect microstructure of high-strength cement stone.

The proposed technological solution for the use of a low-clinker binder ensures large-scale production at Aeroc LLC (Ukraine) of D300 aerated concrete with a strength class within C1.5-C2.5 and autoclaved heat-insulating aerated concrete D150, which is not produced in the CIS and EU countries and is an alternative to traditional heat-insulating materials.

Further development of this study provides for the study of the possibility of further reducing the clinker component through the use of mineral additives of hydraulic and pozzolanic action in the composition of binder autoclaved aerated concrete.

9. Conclusions

1. In connection with the need to increase the requirements for energy saving and the predicted potential improvement of the range of products made of autoclaved aerated concrete, the advantages and features of the use of cutting technology in production have been determined. Technological solutions have been identified that will allow obtaining

a material of lower density and expanding the possibilities of using the raw material base. In particular, the need after forming the massifs of holding in the chambers of plastic strength for 2.5–3 hours at a temperature of 50–55 °C to accelerate the growth of the time of plastic strength. The necessity of using chambers for preliminary temporary holding of cut raw masses at the stage of forming a batch of loaded autoclave trolleys until they are transferred to the autoclave has been proved. This contributes to the better synthesis of low-basic calcium hydrosilicates, which are the main carriers of the strength of autoclave silicate materials.

2. The necessary parameters for the optimization of the raw material mixture of autoclaved aerated concrete in the industrial conditions of cutting technology have been determined, which will make it possible to use a low-clinker binder and store the technological regulations at the same time. In particular, the dependence of the energy consumption of cement consumption with the reduced aerated concrete of various densities and the dynamics of the growth of the

plastic strength of the massif and the necessary temperature factors during the formation of the material structure. In industrial conditions of using cutting technology, a large-scale technology for the production of autoclaved aerated concrete using a low-clinker binder has been implemented.

3. Replacing 10–15 % of cement by adding GBFS in the composition of aerated concrete mixture in the presence of an additional content of gypsum stone of 5–10 % in the composition of sand slime provides an intensive increase in the plastic strength of the raw material before it is cut and high strength of the final product after autoclaving while maintaining all technological processes to ensure the temperature regime of the mixture formation.

It has been proven that the implementation of forced synthesis of ettringite at the stage of formation of aerated concrete mixture with a high W/T ratio accelerates the duration of pre-autoclave exposure of the raw massif, provides the possibility of using mineral additives and contributes to the growth of the strength of the final product.

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