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Aerated dry mix concrete for remote northern territories

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Abstract. The study results on aerated concrete based on imported long-term storage clinker and mineral additives for northern remote construction sites are presented here. The relevance of the research is due to the need for cement composites of stable quality to install enclosing structures at remote northern construction sites. It is impossible to ensure stable quality and safety of construction objects using imported cement due to a significant decrease in its activity during transportation and long-term storage. This problem is shown to be solved by organizing the production of aerated concrete from imported Portland cement clinker using a mechano-chemical technological platform, including: scientific substantiation of the components' choice, mechanical or mechano-chemical activation of clinker by joint grinding with additives and obtaining a dry mixture, preparing aerated concrete mixture and hardening aerated concrete in molded products. Modern physicochemical methods for studying cement compositions are used in this scientific work. Ensuring the required characteristics of aerated concrete on imported Portland cement clinker is provided by introducing activated mineral additives of wollastonite and diopside, which have a chemical affinity with cement minerals and hydrosilicates. It was found that the activity of the binder increased by 30 % and 59 %, respectively when 7 % wollastonite and diopside with a specific surface area of 309 and 323 m^2/kg were added to cement from imported clinker for long-term storage. At the same time, the initial activity of cement (43 MPa) is restored even with the 2 % content of diopside of a specific surface area of 323 m^2/kg. An increase in the activity of cement from imported clinker was explained by the formation of an additional amount of low-basic hydrosilicates and a decrease in stone porosity. Aerated concrete from cement, based on imported clinker, has a homogeneous structure of evenly distributed pores with an average diameter of 6.81 microns, which provides a 10–15 % increase in strength with a compression variability coefficient of 5.4. The obtained aerated concrete had the strength of B2 class, F75 grade frost resistance and thermal conductivity coefficient of 0.14–0.15 W/(m·°C). The developed aerated concrete and the technology of its preparation from imported Portland cement clinker are intended for the construction of buildings in the remote northern territories.

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1. Introduction

When forecasting the development of the economy, much attention is paid to the northern construction and climatic zone. It is necessary to develop technologies and methods of resource provision of construction facilities with materials, taking into account the peculiarities of these remote areas. Modern economic conditions suggest new approaches to the selection and justification of production and use of efficient construction materials [1–5]. Energy efficiency and predicted payback period of construction projects in the northern regions significantly depend on the thermophysical characteristics of the enclosing structures and the rational use of material resources [2, 6–8].

Regional industry of building materials is developing with the use of local and imported raw materials for effective resource support and safety of buildings construction in remote northern territories of Russia. The main material is cement aerated concrete for the purpose and scope of use for the enclosing structures of energy-saving buildings. The technical characteristics of aerated concrete, as well as the operational reliability of the structures made from it, significantly depend on the level and stability of the quality parameters of the used Portland cement [9–13]. Cement is delivered to the regions only in the summer period. It is practically impossible to organize the production of cellular concrete products with the required quality parameters for remote construction sites, due to the significant loss of Portland cement activity during long-term transportation and storage [14–17].

Previously, the scientific substantiation of technological processes for the cement hardening mixtures manufacture in the northern territories by joint wet grinding of imported clinker from the Achinsk cement plant with natural mineral additives and waste from the metallurgical industry was carried out by the scientists of the Leningrad Civil Engineering Institute under the leadership of P.I. Bozhenov, the Academician of the Russian Academy of Architecture and Construction Sciences and introduced at the Norilsk Mining and Metallurgical Plant for laying mine workings. The available scientific results and practical recommendations for the joint wet grinding of clinker with mineral additives do not allow effectively controlling the structure formation processes of non-autoclaved aerated concrete in the wall structures manufacture with the required characteristics under extreme conditions. In order to solve this problem, the most effective is the dry method of joint grinding of imported Portland cement clinker with modifying additives, a dry mixture production, followed by a cellular concrete mixture preparation and molding products, using prefabricated products of wall structures (wall blocks) or directly at construction sites. (monolithic structures) [13, 15, 16, 18].

The technological processes of dry grinding of Portland cement clinker for long-term storage together with modifying mineral additives and the aerated concrete mixture production, as well as the structure formation control and aerated concrete properties, based on the prepared dry mixtures in relation to the production of wall products have not been previously studied. This is relevant for the construction industry development and resource provision of facilities construction in remote northern clusters, including the Arctic zone of Russia, as well Canada, Finland, Norway, Sweden and Iceland.

The purpose of the scientific work is to scientifically substantiate the technological processes for the manufacture of cement from imported Portland cement clinker with mineral modifying additives, dry building mixtures and effective and stable in quality aerated concrete wall materials on their basis.

2. Methods and Materials

During laboratory research, we used Portland cement clinker of Joint Stock Company “Iskitimcement” (Novosibirsk region). The chemical composition of clinker is given in Table 1. Mineralogical composition,% by weight: C_3S–63, C_2S–16, C_3A–8 and C_4AF–13. In order to regulate the timing of the initial structure formation of cement from imported clinker, we used "A" gypsum class with $CaSO_4 \cdot 2H_2O$ –content of 80.6 %. Wollastonite and diopside were used as mineral additives (Table 2), and the silica component was fine quartz sand (Size module SM – 1.8) with a content of dusty, silty and clay particles of 0.5 % of "Kamnerechensky Stone Quarry" production, Novosibirsk. Aluminum suspension was used, including PAP-1 aluminum powder and sulfanol, as well as grade II lime of Joint Stock Company Iskitimizvest, Iskitim, to form the porous structure of the aerated concrete mixture.

Table 1. Chemical composition of Portland cement clinker, wt. %

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on Ignition
21.95	5.73	4.27	65.95	1.62	0.26	0.22

Table 2. Chemical composition of mineral additives

Additive	Mine	Chemical composition,% wt.					
		SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	Loss on Ignition
Diopside	Aldansk, Republic of Sakha, Yakutia	50.99	24.78	15.78	4.63	3.58	0.24
Wollastonite	Mine "Vesely", Altai Republic	53.43	34.63	0.30	3.06	2.34	6.24

During the research, real conditions were simulated in transporting and storage the clinker at construction sites in the Russian northern territories, the used clinker was stored for 12 months at 80 % of humidity. The clinker was used after 7 days of storage in normal conditions and fineness modulus for long-term storage in northern conditions and Portland cement for the manufacture of reference samples (control).

In order to establish the structure formation regularities of binders, as well as to determine the quality parameters of aerated concrete, standard methods of mechanical testing, modern physicochemical research methods, verified instruments and certified equipment were used.

Mineral additives were ground in an AGO-3 mill to a given specific surface area.

The analysis of the granulometric composition of the additives was carried out using PRO-7000 laser dispersion analyzer from SeishinEnterpriceCo., LTD, Tokyo.

The activity of cement (ultimate compressive strength) was determined by testing standard specimens-beams 40×40×160 mm in size, made from a cement-sand mortar of normal consistency with a composition of 1: 3 by weight with a water-cement ratio of 0.42. The samples were solidified under normal conditions (above water for the first day and in water at a temperature of (20 ± 2) °C, for 27 days), and they were also subjected to steam curing at atmospheric pressure according to the following mode: temperature-rise period to 85 °C – 3 hours, isothermal curing – 8 hours, temperature reduction to 20 °C – 3 hours.

The ultimate compressive strength of aerated concrete was determined by testing concrete samples on a hydraulic press at a constant loading rate until failure. The aerated concrete samples were hardened under normal conditions in a chamber with a temperature of (20 ± 2) °C and relative air humidity (95 ± 5) %, and they were also subjected to steam curing at atmospheric pressure according to the mode: 4 hours – preliminary curing, temperature-rise period to 85 °C – 3 hours, isothermal curing – 8 hours at this temperature and 3 hours – temperature reduction to 20 °C.

The density of aerated concrete was determined in the dry state and frost resistance, due to the values of strength loss in compression and weight reduction of samples subjected to alternate freezing in water saturation state at a temperature of minus (18 ± 2) °C and their thawing at a temperature of plus (18 ± 2) °C and relative humidity (95 ± 2) %.

Differential thermal studies of hardened cement paste were carried out using a DTG 60H analyzer from Shimadzu, Japan. The rate of temperature rise was 10 °C/min. The measurements were carried out with NETZSCH software from Proteus.

The structural characteristics of aerated concrete samples (macro-Vma, Sma and mesopores – Vme, Sme) were investigated using AutoPoreIV 9520 automated mercury porosimeter (Microme-ritics, USA). The experimental research process was controlled by a computer using a special program Milestone-100-software from Fisons.

3. Results and Discussion

In order to improve the quality of cement from long-term storage clinker, the authors proposed to use mineral additives wollastonite and diopside, which had similar chemical composition and thermodynamic characteristics with clinker minerals (alite and belite), as well as the main products of their hydration (calcium silicate hydrates).

The establishment of patterns in the influence of type and amount of mineral additives on the cement composites' properties was carried out in the following sequence:

1. determination of the effect of the specific surface area and the content of mineral additives on the clinker binder activity and the structure of the hardened cement paste;

2. influence of all mineral additives and joint grinding of raw mixture components on aerated concrete properties.

At the initial stage 2.1, their optimal specific surface was established to ensure the efficiency of adding mineral additives into cement [16–19]. The maximum strength of the hardened cement paste was achieved with a minimum intergranular void between the grains of the mineral additive and the binder. The specific surface of particles and their content are taken as parameters for controlling the quality of cement from clinker with mineral additives.

The studies were carried out at the specific surface area of the used wollastonite powder after grinding – 309, 764, 888 and 982 m^2/kg, diopside powder – 323; 635; 979 and 1157 m^2/kg. The granulometric composition of the diopside and wollastonite powders is given in Table. 3.

Table 3. The studies' results of the granulometric composition of mineral additives

Specific surface, m^2/kg	Volumetric average particle size, μm	Volume fraction of particles with sizes ≤ 4 μm	Volume fraction of particles with sizes ≤ 12 μm
diopside			
323	27.0	19.5	31.9
635	12.8	32.2	48.4
979	4.3	49.2	66.6
1157	2.9	58.2	74.7
wollastonite			
309	28.6	13.3	27.9
746	9.0	36.4	57.6
888	5.9	43.6	65.1
982	4.3	49.0	68.6

3.1. Influence of the specific surface and dosage of mineral additives on the activity of Portland cement clinker and the structure of the hardened cement paste

We used cement, obtained by grinding Portland cement clinker with 5 % gypsum, studying the effect of specific surface and content of mineral additives on the activity and structure of hardened cement paste. The specific surface of the cement was 280 m^2/kg.

The studies' results on changes in the cement activity with the adding of wollastonite and different specific surface are shown in Fig. 1. It was found that the adding of wollastonite into cement from clinker increased the strength characteristics of the hardened cement paste:

- in order to use clinker, stored for 7 days under normal conditions, and the adding of wollastonite with a specific surface area of 309 m^2/kg into the cement during hardening under normal conditions, the hardened cement paste in compression increased by 30 %, and with steam curing at atmospheric pressure – by 31 %;
- in order to use clinker, stored for 12 months in humid conditions and introducing wollastonite with a specific surface area of 309 m^2/kg during hardening under normal conditions, the compressive strength increased by 20 %, and during steam curing at atmospheric pressure – by 35 %.

The changes' results in the activity of the binder with the diopside and different specific surface areas adding are shown in Fig. 2.

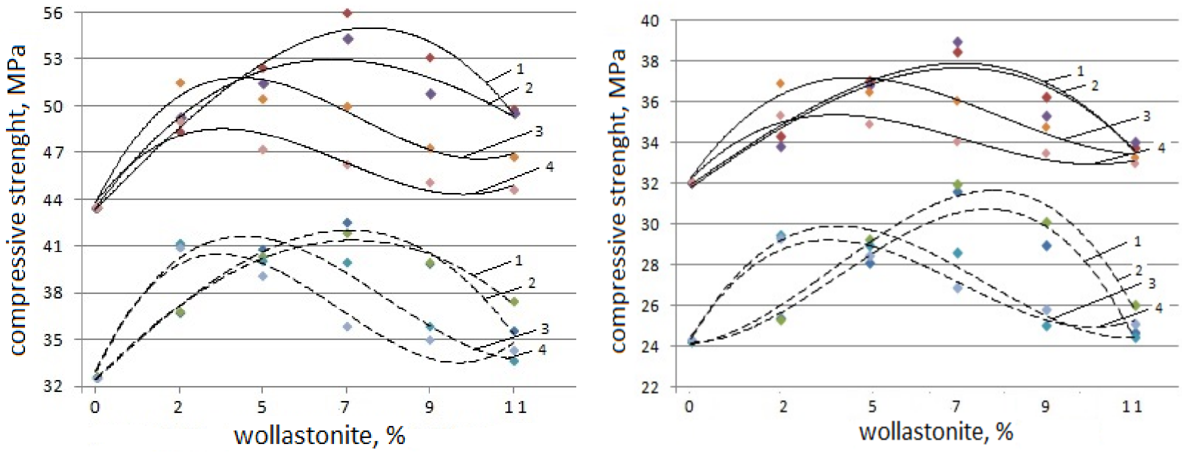
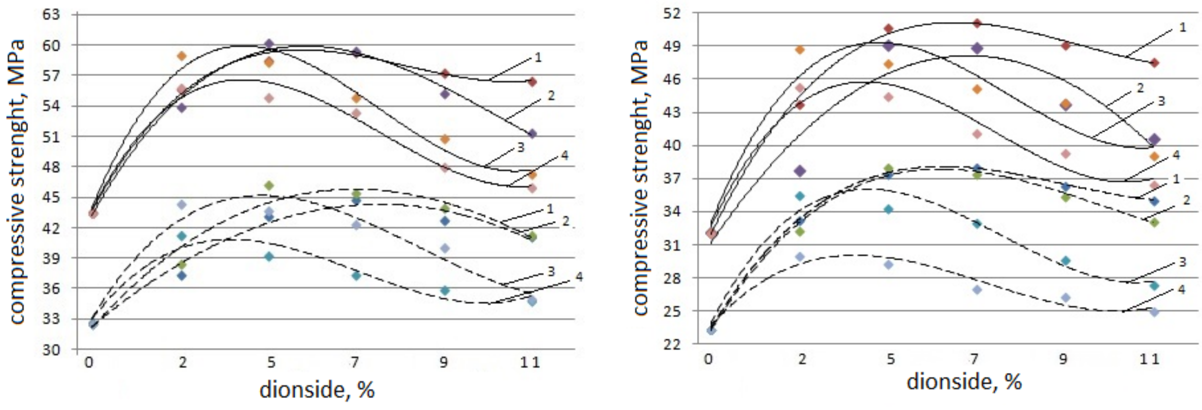


Figure: 1. Influence of the wollastonite amount and specific surface and quantity on cement activity made from ground clinker stored: a) 7 days under normal conditions; b) 12 months in humid conditions
1 – wollastonite with a specific surface of 309 m^2/kg; 2 – 746 m^2/kg; 3 – 888 m^2/kg; 4 – 982 m^2/kg

The dotted line indicates the curves for specimen hardening under the conditions of steam curing at atmospheric pressure, the solid line indicates 28 days under normal conditions.



a) **b)**

Figure: 2. Influence of specific surface and diopside amount on the binder activity made from ground clinker stored: a) 7 days under normal conditions; b) 12 months in humid conditions 1 – diopside with a specific surface of 323 m^2/kg; 2 – 635 m^2/kg; 3 – 979 m^2/kg; 4 – 1157 m^2/kg

The dashed line indicates curves during the hardening of the samples under the conditions of steam curing at atmospheric pressure, the solid line – 28 days under normal conditions.

The compressive strength increased by 30 %, and during steam curing at atmospheric pressure – by 37 %, using clinker stored for 7 days under normal conditions and adding of diopside with a specific surface area of 323 m^2/kg during cement paste hardening under normal conditions.

The cement paste compressive strength made of cement, based on clinker, stored for 12 months in humid conditions with the diopside addition of a specific surface area of 323 m^2 / kg, increased by 59 % during cement paste hardening under normal conditions, and increased by 62 % during steam curing at atmospheric pressure. At the same time, the initial activity of cement (43 MPa) is restored even at the diopside content with a specific surface area of 323 m^2/kg – only 2 %.

It can be noted that the activation of Portland cement clinker, stored for 7 days under normal conditions and for a long time under humid conditions, by adding finely dispersed diopside leads to an increase in the binder activity, analyzing the research data in Fig. 1 and 2. The greatest increase in the strength of the binder is achieved with the addition of milled diopside, which has a high hardness value (7 on the Mohs scale), i.e. the highest value of the modulus of elasticity containing calcium and silicon oxides, as well as the specific surface area equal to that of ground clinker. Wollastonite has a lower hardness (4.5–5.0 on the Mohs scale). An increase in the strength of the hardened cement paste with additives is explained by micro-reinforcement and redistribution of stresses between the components of the cement stone, while the greatest efficiency is provided by the use of diopside.

With an increase in the content of the mineral additive over 7 % and an increase in the specific surface areas of wollastonite to 982 m^2/kg and diopside to 1157 m^2/kg, the effect of hardened cement paste decreases as a result of additives' aggregation, in addition, the energy consumption for their grinding increases significantly.

Thereby, in the process of conducting further studies of aerated concrete on cement from imported clinker (point 2.2), we used additions of wollastonite with a specific surface area of 309 m^2/kg and diopside with a specific surface area of 323 m^2/kg, i.e. close to the dispersion of ground clinker. The content of additives was 7 %.

We conducted a complex thermal analysis (Fig. 3 and 4) and porosimetry to explain the structure formation processes of hardened cement paste with the addition of dispersed wollastonite and diopside.

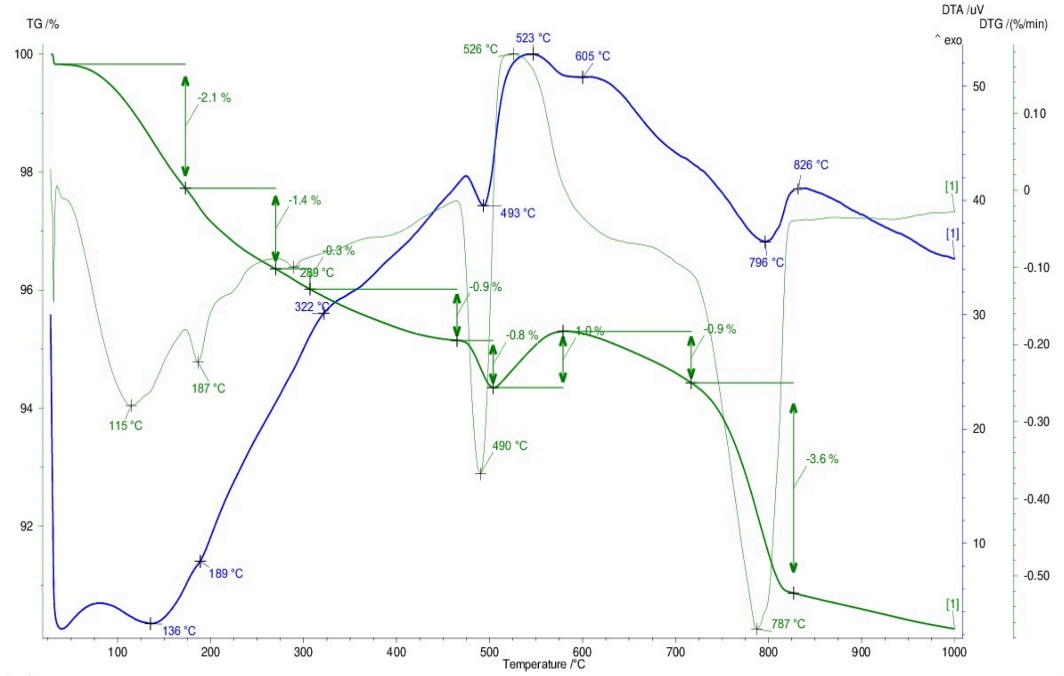


Figure. 3. Thermal analysis' results of hardened cement paste made on ground clinker with gypsum without mineral additives introduction.

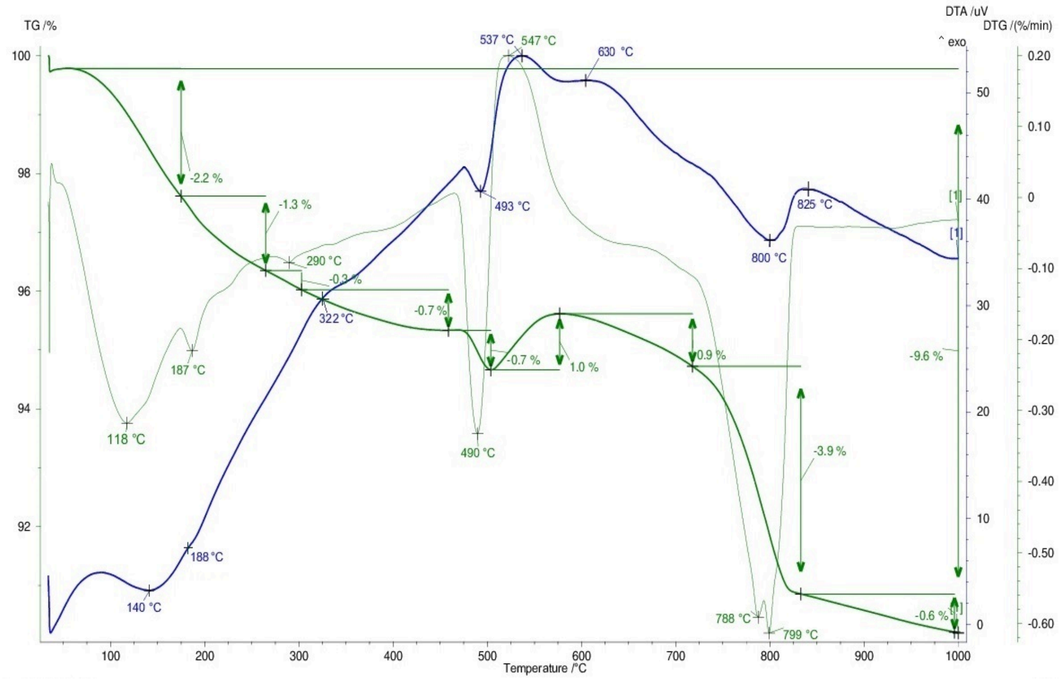


Figure. 4. Thermal analysis' results of hardened cement paste made on ground clinker with gypsum and 7 % diopside.

According to the results of a comprehensive thermal analysis, there is no significant change in the phase composition during the cement paste hardening with diopside. A change in the temperature of the thermal effect and a transition to a higher temperatures zone (from 605 to 630 °C) are observed, which can be caused by the structure strengthening due to the interaction of diopside with portlandite, which is released during the hydration of alite, and the additional amount of low-basic calcium silicate hydrates.

The study's results of the hardened cement paste porosity from clinker with 7 % dispersed diopside are given in Table 4.

Table 4. Porosity of hardened cement paste with the dispersed diopside addition

Average pore diameter, μm	Type of cement			
	from clinker without additives		from clinker with 7% diopside	
	pore volume, ml/g	pore volume,%	pore volume, ml/g	pore volume,%
73.1 – 361.0	0.0919	33.53	0.0275	12.72
15.4 – 73.1	0.0115	4.19	0.0106	4.9
1.2 – 15.4	0.0164	5.96	0.0165	7.63
0.15 – 1.2	0.0513	56.32	0.0560	74.75
0.003-0.15	0.1030		0.1056	
Total	0.2741	100	0.2162	100

Analyzing mercury porosimetry results, the following can be noted:

- the total pore volume decreases from 0.274 to 0.216 ml/g in hardened cement paste from 7 % diopside in comparison with hardened cement paste from clinker without additives;
- the pores volume with a diameter of more than 73.1 microns is reduced by 2.6 times;
- the pores content with a diameter of less than 1.2 microns increases significantly.

A decrease in the total porosity of hardened cement paste with a dispersed addition of diopside, as well as a decrease in large-diameter pores, is one of the factors explaining an increase in the hardened cement paste strength. Increase in the pores number (capillaries) of small diameter (less than 1.2 μm), forming partitions structure (matrix) in aerated concrete, which can contribute to an increase in frost resistance of the developed aerated concrete.

3.2. Influence of mineral additives and joint grinding of raw mix components on the aerated concrete properties

A number of scientists' researches have shown the effectiveness of cellular concrete preparation for wall products and structures from a dry mixture [20, 21]. Manufacturability of construction processes significantly increases, mixing the dry mixture with water and pouring the aerated concrete mixture into molds or formwork directly on the construction site. In the study of aerated concrete based on dry mixtures, the data specified in paragraph 2.1 on the optimal specific surface area and the content of mineral additives in the cement from clinker, providing the maximum increase in strength, were used. Since the greatest increase in the strength of the hardened cement paste was obtained with the addition of diopside and wollastonite with a specific surface area close to that of Portland cement, then at stage 2.2 the joint grinding of all raw materials was studied. The dry mixture was prepared by joint grinding of clinker with gypsum, natural gypsum, mineral additive, silica and lime components.

3.2.1. Influence of mineral additives on the density and strength of aerated concrete

The tests' results of the density and strength of aerated concrete obtained on the basis of a dry raw mixture are presented in Table 5.

Table 5. Dependence of the density and aerated concrete strength on a type and number of additives

Type of cement	Density of aerated concrete, kg/m^3	Compressive strength of aerated concrete, MPa
Clinker stored for 7 days under normal conditions		
Cement without mineral additives	610	2.8
Cement with wollastonite, 7 %	600	3.1
Cement with diopside, 7 %	580	3.3
Clinker stored for 12 months in humid conditions		
Cement without mineral additives	610	2.1
Cement with wollastonite, 7 %	605	2.3
Cement with diopside, 7 %	590	2.4

The density does not significantly decrease in aerated concrete with mineral additions of wollastonite and diopside. Thus, we have obtained structural and heat-insulating aerated concrete of D600 brand.

The strength characteristics of aerated concrete on normal storage clinker cement increase with the adding of wollastonite by 11 %, and diopside – by 18 %.

The strength of aerated concrete from imported long-term storage clinker without mineral additives is reduced by 25 %. The strength characteristics of aerated concrete increase by 10 and 14 %, respectively, using clinker cement with additions of wollastonite and diopside. The strength indicators of aerated concrete decreased to 0.6 MPa (2.5 times) and the density of aerated concrete increased by 30 %, using Portland cement from the same composition, prepared in the factory and stored for 12 months.

The coefficient of variation in determining the compressive strength of aerated concrete from a dry mix, based on imported clinker is 5.4 %, the density of samples is 4.2 %, which characterizes the high stability of the aerated concrete's quality indicators. Compressive strength class of aerated concrete is B2. Thus, the preliminary preparation of the dry mixture by joint grinding of long-term storage clinker with gypsum, mineral additives, silica and lime components, followed by the aerated concrete mixture production, makes it possible to form products for building structures that meet regulatory documents.

3.2.2. Influence of mineral additives on the pore structure of aerated concrete

The properties of aerated concrete are greatly influenced by the microstructure and porosity, as well [22–25]. The type and content of pores in aerated concrete, based on long-term storage clinker cement, were studied using mercury-vacuum porosimetry. The total pore volume of the developed aerated concrete on cement from long-term storage clinker with diopside addition was 7.26 sm^3/g. Differential curve of pores distribution in aerated concrete are shown in Fig. 5.

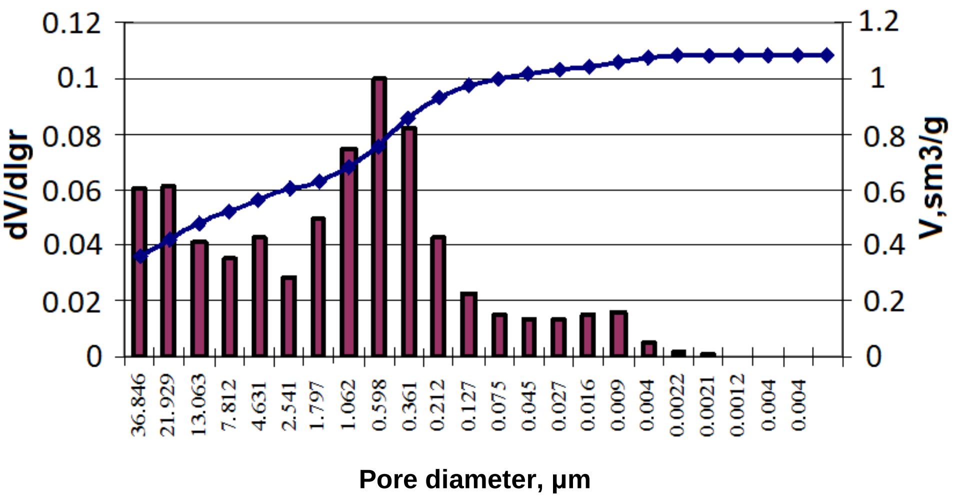


Figure: 5. Differential pore distribution curve in aerated concrete, made from a dry mix, based on clinker stored for 12 months in humid conditions and diopside

The average pore diameter in aerated concrete is 6.81 microns. Aerated concrete has uniformly distributed porosity in the range of pores with a size of 0.0012 – 0.075 and 1.062 – 13.063 microns.

Mineral additives influence on frost resistance of aerated concrete

Change in strength and weight of aerated concrete, tested for frost resistance, is given in Table 6.

Table 6. Changes in the properties of aerated concrete, tested for frost resistance (as a percentage of the original value)

Binder composition in dry mix	Reduction of strength after testing, depending on the number of cycles,%				Reduction of mass after testing, depending on the number of cycles,%				Frost resistance grade
	50	75	100	125	50	75	100	125	
Prefabricated Portland Cement	–14.1	–21.2	–	–	–3.5	–6.3	–	–	F50
Ground clinker	–14.3	–21.4	–	–	–3.8	–6.1	–	–	F50
Ground clinker with 50 % siliceous component	–7.6	–11.2	–22.7	–	–3.1	–4.5	–7.0	–	F75
Ground clinker with 50 % siliceous component and 7 % wollastonite	–7.0	–9.6	–16.4	–	–2.8	–4.2	–6.7	–	F75
Ground clinker with 50 % siliceous component and 7 % diopside	–6.0	–10.0	–17.1	–	–2.7	–4.0	–6.7	–	F75

For aerated concrete sample, made on the basis of ground clinker without additives, a noticeable decrease in strength (14.3 %) was noted after 50 test cycles. Compressive strength of such aerated concrete decreased by 21.4 % after 75 cycles. The mass of the samples decreased after 50 cycles by 3.8 %, after 75 cycles by 6.1 %. Frost resistance grade was F50. The decrease in strength after 75 test cycles was 9.6–10.0 % with adding of 7 % wollastonite or diopside and the weight of the samples decreased by 4.0–4.2 %. The frost resistance grade of aerated concrete rose to F75. The increase in frost resistance of aerated concrete with additions of wollastonite or diopside was explained by the increased content of small pores in the structure, which degree of filling with water and transformation into ice slowed down.

The thermal conductivity coefficient of the developed aerated concrete from a dry mixture, based on imported clinker with mineral additions of wollastonite and diopside in a dry state at a temperature of 25 °C was 0.14–0.15 W/(m °C).

4. Conclusion

1. A scientifically based technology has been developed for the manufacture of aerated concrete from a pre-prepared dry mixture, obtained by joint grinding of imported clinker with mineral additives wollastonite or diopside, gypsum, silica and lime components, which make it possible to mechanically activate the components surfaces and significantly intensify the physicochemical processes of structure formation of the porous cement composition that makes it possible to ensure a homogeneous structure, to increase the strength of interpore partitions and aerated concrete.

2. It was found that 7 % wollastonite and diopside with a specific surface area of 309 and 323 m^2/kg, which have chemical affinity, added to cement, prepared from imported clinker for long-term storage, as well as the similarity of thermodynamic characteristics with clinker minerals and products of their hydration, the activity of the binder increased by 30 % and 59 %, respectively. At the same time, the initial activity of cement (43 MPa) was restored even at the content of diopside with a specific surface area of 323 m^2/kg – 2 %.

3. An increase in the cement activity from imported clinker with dispersed additions of wollastonite and diopside, occurred mainly due to the interaction of mineral additives with portlandite, released during hydration of alite and the formation of an additional amount of low-basic calcium silicate hydrates, as well as a decrease in the pore content from 0.274 to 0.216 ml/g.

4. In the aerated concrete of non-autoclave hardening, made by a two-stage technology on cement from imported clinker with additions of wollastonite and diopside at 28 days of age, the strength increased by 10 and 15 %, which made it possible to produce goods with the required B2 strength class.

5. The average pore diameter was 6.81 microns in aerated concrete on cement from long-term storage clinker with mineral additives. Pores with a size of 0.0012 – 0.075 and 1.062 – 13.063 microns were evenly distributed over the volume, which ensured high stability of quality parameters. The index of variability in average density was 4.2, in compressive strength – 5.4, grade for frost resistance – F75, thermal conductivity coefficient – 0.14 – 0.15 W/(m °C).

6. The developed technology of aerated concrete is recommended for industrial use in wall structures molding from imported clinker at construction sites in the remote northern territories.

Thus, the authors have formed a set of technological principles for managing the processes of improving the non-autoclaved aerated concrete quality for organizing the facilities construction in remote hard-to-reach areas, taking into account the complexities of resource provision and maintaining the technical characteristics of the concrete – cement’s main component, namely:

- aerated concrete production of the required stable quality from a dry construction mixture, by joint grinding (mechanical activation) of the base components that form the matrix of porous concrete (interpore partitions) with the physicochemical processes intensification of structure formation and ensuring the specified porosity;
- scientific substantiation of the components choice and the sequence of introduction into the construction composition, based on their functional purpose in the manufacture of dry mix and aerated concrete mix with subsequent participation in the structure formation of porous cement concrete;
- taking into account the degree of hydration and the activity loss of Portland cement clinker in long-term storage, as well as the synergistic effect from the activation effect during joint or separate grinding of components in the scientific substantiation of the type and processes sequence.

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