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Study of thermal-physical properties of porous ceramic insulation products

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Abstract. The detailed description of the main parameters, influencing the thermal insulation characteristics of building walls is presented in this article. In addition the analysis of this parameters study in modern construction practice is made. The main characteristics of concrete based on porous expanded clay granules are presented, including the results of studies of capillary absorption, moisture transfer rate and moisture absorption properties of porous expanded clay concrete samples affecting the thermal conductivity coefficient. The research results are presented in the context of thermal insulation and fire-resistant ceramic granules application as fillers in porous concrete walls. On the basis of results of study of the organomineral additives influence on the thermal conductivity coefficient of porous expanded clay concrete the study of porous expanded clay concrete samples were carried out. The porous and dense wall concrete sorption moisture and vapour permeability are determined in laboratory conditions. Also the main changes of these parameters at different values of relative humidity of surrounding air are determined.
Keywords: industrial waste, expanded clay, granulate, porous structure, concrete samples, environmental engineering, capillary suction, humidity, moisture transfer rate, vapor permeability, characteristics

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1. INTRODUCTION

The development of modern artificial porous fillers involving industrial waste from various industries [1, 2] and their use in the production of lightweight concretes with significantly reduced thermal conductivity is crucial for improving the energy efficiency of modern buildings [3, 4]. This represents a significant area of research and development [5], both domestically and internationally, focusing on optimizing the material properties and construction techniques [6, 7].

The development of advanced artificial porous fillers and their application in production of lightweight concretes with significantly reduced thermal conductivity is crucial for enhancing the energy efficiency of modern buildings. This represents a significant area of research and development, both domestically and internationally, focusing on optimizing the material properties and construction techniques.

The research of the clay raw materials of the Southern region of Kazakhstan, in particular their chemical and granulometric compositions, as well as the physical and technical properties of clays have been conducted, for determination of possible ways of using of low-melting and bentonite clays of montmorillonite and colloidal composition for further production of thermal insulation expanded clays. During the research, the selected clay samples were subjected to modern physical and chemical studies, in particular, chemical, granulometric, raster-electron-microscopic, differential-thermal and X-ray phase analysis [1].

1.0 - 10.0% of internal fossil rocks from coal production were added to the initial raw materials taken for the study and the nature of their influence on the physicochemical properties of expanded clay was determined. The recommended amount of the wastes in expanded clay is 4.0 - 6.0%, the effective burning temperature is determined to be 1150°C. Under these conditions, expanded clay samples with a sowing density of 0.337-0.348 t/m^3 and a compressive strength of 1.37-1.51 MPa were obtained. The results of the study of the possibility of the obtained expanded clay samples using as lightweight filler are presented in our works [8].

The use of such concretes in building enclosures offers a compelling advantage: the material simultaneously acts as a load-bearing structure and a highly effective thermal insulator, eliminating the need for separate insulation layers and simplifying construction [9,10].

The main benefit of lightweight concrete, particularly expanded clay concrete is that, according to the author [11], porous fillers provide greater stability compared to ordinary gravel and sand. It is economically reasonable to use the concrete based on porous fillers in production of entire range of reinforced concrete structures.

Lightweight concretes with porous fillers differ greatly from other thermal insulation and structural materials: they have lower thermal conductivity at negative temperatures than at positive outdoor temperatures. The free water absorbed in the pores of lightweight concrete freezes at low temperatures, turning into frost instead of ice. Research of the author [12] indicates that the thermal conductivity of these concretes decreases at lower temperatures, as a result (λ_{ice}= 2,32 W/m·°C), (λ_{fr} = 0,104 W/m·°C).

All these positive points could support the widespread use of lightweight concrete structures with porous fillers. This approach allows reducing the thickness of the walls with rational structural design of buildings. The material savings at producion of external wall panels from lightweight concrete with porous fillers based on expanded clay can reach 45-50%.

The expediency for the large-scale use of expanded clay concrete panels is that porous clay serves as the main raw material for production of expanded clay granules. Many regions across the country have clay deposits.

Theoretical analyses and experimental results of the use of expanded clay concrete grade 50 show that, according to thermal and statistical requirements, a thickness of 26-30 cm is sufficient for load-bearing external walls. Nevertheless, in large-scale housing construction, self-supporting expanded clay concrete panels with a thickness of 35-40 cm are currently used for external walls. This is due to the lack of lightweight expanded clay granules and, to a certain extent, to the violation of the basic rules of the technology for preparing of expanded clay concrete mixtures. It has been established quite accurately that the technical, economic and thermal efficiency of single-layer expanded clay concrete panels directly depends on their density [13]. One of the main measures to ensure the efficiency of expanded clay concrete walls is to reduce the density of expanded clay concrete by using a rational grain composition.

The comprehensive studies conducted to optimize the composition of expanded clay concrete mixture [14, 15] revealed the possibility of increasing the thermal and strength properties of panels [16, 17], respectively reducing the thickness of panels to 30 cm in urban conditions and to 22-26 cm in experimental conditions [18, 19], reducing cement consumption and reducing the cost price by 20% [20].

To modify and choose the mix for lightweight expanded clay concrete, it is essential to establish the design characteristics of the porous filler based on fractional seeding density [21].

At the beginning of the 20th century, due to the widespread use of large-sized structural and heat-insulating expanded clay concrete products of high density in industrial construction, the lack of production of porous fillers convincingly demonstrated the feasibility of porization of lightweight concrete mixtures.

The results of the analysis of the efficiency of pore formation in expanded clay concrete mixtures showed that the density of concrete can be reduced by approximately 10%, the thickness of panels - by 13%, and the cost – by 10% [22].

Improving the quality of thermal insulation of building envelopes and the relevance of energy saving issues require a revision of technologies and technical solutions in industrial construction. At the same time, the main advantages should be given to the heat, air and water-impermeable properties of walls, increasing their technical and economic indicators, as well as reducing energy and heat losses during operation.

One of the main ways to increase the thermal efficiency of expanded clay concrete mixtures and reduce energy costs is to use low-energy and low-thermal-conductivity additives that minimize density and thermal conductivity. The essence of this article is optimization of the thermal and strength structure of the expanded clay concrete mixture and giving it a porous structure by using the optimal grain size.

2. METHODS AND MATERIALS

Laboratory studies allow to determine the characteristic properties of materials that determine their thermal insulation qualities, as well as to evaluate the results of visual inspection.

The objective of the laboratory study is to determine the following thermophysical indicators of porous expanded clay concrete:

- sorption;
- vapor absorption;
- moisture permeability;
- moisture absorption;
- thermal conductivity in dry and wet conditions.

The important stage in the process of production of enclosing structures is the selection of a concrete composition with optimal thermophysical properties and mechanical strength. The selection of technology and composition for the preparation of expanded clay concrete samples with using of a mixture of coal production wastes was carried out in laboratory conditions.

To determine the thermal conductivity coefficient for each composition, 3 square samples with the size 100 mm and 2 samples in the form of plates with the size of 250x250x50 mm were made. During the molding process, a thermocouple was installed in the center of each sample.

To determine the sorption properties, pieces of expanded clay concrete were used. To determine the strength of porous expanded clay concrete cubes, the thermal conductivity coefficient of the prepared composition was determined.

As a binder the cement of the grade M-400 was used which meets the requirements of the GOST 310.1-76 "Cement. Test methods. General Rules".

The main physical and mechanical characteristics of cement grade M-400: specific gravity - 2.76 t/m^3, bulk density - 1100 kg/m^3, specific surface - 2500 cm^2/g, residue on sieve № 0.08 - 5.8%, normal density - 29.1%, setting time: initial - 3 hours 20 min., execution time - 4 hours 40 min.

To prepare the samples, the expanded clay granules obtained from Badambentonite clay and internal fossil rocks of coal production were used, corresponding to the requirements of GOST 9758-2012 “Inorganic additives for concrete. Test methods”. According to this requirement, the fractional seeding density of expanded clay filler is $K_{0\text{-}10}$ = 500-550 kg/m^3; $K_{2,5\text{-}10}$= 550-600 kg/m^3; humidity – 0.2%; grain porosity – 54.2%; compressive strength in a cylinder – 3.8 MPa.

3. RESULTS AND DISCUSSIONS

Sorption moisture of porous expanded clay products. The nature of moisture binding to the material, quantitative and qualitative assessment of bound water are of great importance in the heat and mass transfer processes occurring in insulating structures during manufacture and operation. One of the methods for studying the nature of moisture binding to the material and assessing bound moisture is to study sorption and desorption isotherms. It can also serve as a basis for calculation of some thermodynamic parameters of mass transfer [23].

Sorption characteristics of porous expanded clay concrete were determined by the strain gauge method at the ambient temperature of to = 20°C (±2). The strain gauge method is based on the following principle: a test sample weighing up to 10 g is pre-dried to a constant weight, is weighed with an accuracy of 0.001 g and is placed in a glass jar. Weighed samples are kept in a drying cabinet at a temperature of 105°C until a constant weight is achieved. Next, the samples are placed in a desiccator containing a solution of sulfuric acid of various concentrations, in which a given relative air humidity is maintained.

In our case, the sorption humidity of the materials is selected at a relative air humidity of 40, 60, 80, 90 and 97%. Due to the possibility of obtaining of erroneous results due to moisture condensation with possible temperature fluctuations, the sorption humidity of the material at full saturation (φa = 100%) is not determined.

The desiccator with the samples is placed in a laboratory room at a temperature of 20°C (±2).

The results of determination of the sorption humidity of the studied samples are presented in Table 1 and Fig. 1.

Table 1. Results of determination of sorption moisture of porous expanded clay concrete samples.

Material name	Dry density, kg/m^3	Equilibrium sorption moisture by mass depending on relative air humidity (φa), %				
		40	60	80	90	97
Porous expanded clay concrete sample	1000	2.6	3.7	5.4	7.7	10.1
- / -	950	2.1	3.0	4.9	7.3	9.3
- / -	900	1.8	2.9	4.8	7.1	9.1
- / -	800	1.4	2.4	4.2	6.8	8.8
Sample made of expanded clay concrete with a dense structure	1150	2.7	3.6	6.0	8.0	11.0
- / -	1080	3.0	3.9	5.8	8.1	10.8
- / -	900	1.5	2.3	4.2	7.3	9.0
Expanded clay perlite concrete sample	900	2.1	2.6	5.2	7.3	10.7
- / -	800	1.6	2.1	4.3	7.7	10.2
Expanded clay sand concrete sample	1000	-	2.2	-	-	8.3
Expanded quartz sand concrete sample	1080	1.4	2.1	3.7	5.3	7.2

As it can be seen from Table 1, at φ_a = 97%, the sorption moisture content increases slightly with the growth of the density of concrete samples, regardless of their type. For example, with the increase in the density of a porous expanded clay concrete sample by 200 m^3, the sorption moisture content increases by 1.3% (from 8.8 to 10.1%).

Comparison of the sorption moisture content values of different expanded clay concrete samples of the same density at a relative air humidity of φ_a = 97% shows that the expanded clay concrete sample based on quartz sand has the lowest sorption moisture content (W_m = 7.2%), followed by the expanded clay sand concrete sample W_m = 8.3% and the expanded clay concrete sample of a dense structure W_m = 9%.

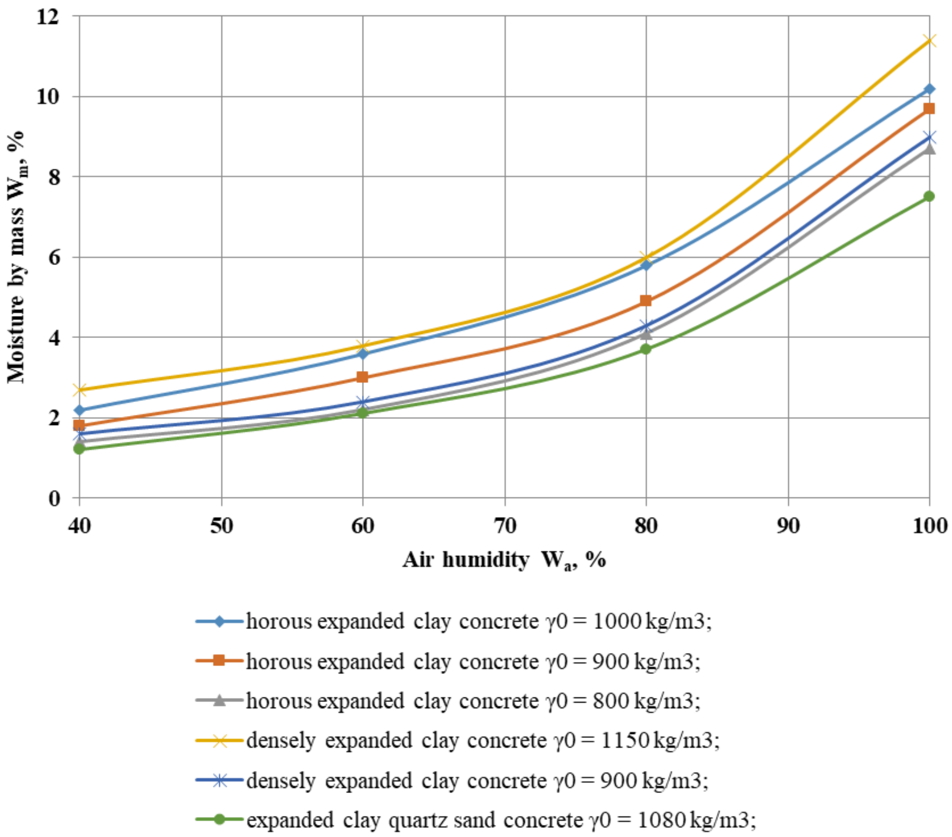

Fig. 1. Sorption isotherms of various expanded clay concrete samples.

The equilibrium moisture content of the expanded clay concrete sample with a porous structure is significantly higher W_m = 10.1% than that of the expanded clay sand concrete sample W_m = 8.3% and is relatively lower than that of the dense expanded clay concrete sample W_m = 10.8%. This can be explained by the higher consumption of coal production wastes (approximately 400 l per 1 m^3) compared to the porous expanded clay concrete structure (150 l). The equilibrium moisture content of the porous and dense expanded clay concrete samples (φ_a = 900 kg/m^3) is practically the same.

The addition of perlite to the expanded clay ash concrete sample, as a rule, increases the sorption moisture content at the same density.

Vapor absorption of porous expanded clay products.

The vapor permeability of building materials for water vapor is characterized by the value of the vapor absorption coefficient. This is the proportionality coefficient between the wall thickness of a given material and the partial pressure of water vapor.

In this work, the vapor absorption coefficient of the studied expanded clay concrete samples was determined by using a standard technique, the essence of which, in brief, is as follows [23]: a sample of the material with a diameter of 100 mm and a thickness of 30-35 mm is placed on a metal coating. The side surface of the sample was pre-coated by a vapor-permeable composition. This composition was used to seal the gaps between the coating and the sample. The samples with a coating prepared by this way were installed on a rubber seal. A plastic container filled with distilled water is placed under the sample. As a result of saturation with water vapor, a partial pressure difference of 799.8-933.1 Pa is formed in the space under the sample. This creates vapor diffusion from the bottom of the sample to the top.

To reduce the impact of changes in temperature and humidity in the room, the sample testing procedure was carried out in a special cabinet. Temperature, humidity and barometric pressure inside the cabinet were measured during the day by using a thermograph, hygrograph and barograph. In addition, the state of the air environment inside the cabinet was monitored by using the Assmannpsychrometer. The amount of water vapor that passed through the sample over time was determined by periodic weighing, while the surface of the plastic container was tightly closed during the measurement by a light lid.

The vapor absorption coefficient is determined by the following relationship:

$$\mu = \frac{P \cdot \delta}{F - P \cdot R_{\text{п.в.}}}, \text{ mg/(m·h·Pa)} \qquad (1)$$

where: P is the amount of water vapor passing through the sample per unit time, mg/(m·h·Pa);

δ is the thickness of the sample, m;

F is the geometric area of the sample perpendicular to the steam flow, m^2.

The diffusion resistance of the air layer between the lower surface of the sample and the water surface on the evaporator plate, (m^2·h·Pa), determined by the formula.

In the given research, samples of dense and porous expanded clay concrete were cut into plates with a thickness of the panel. For each material sample, their dry density was determined. The density values of the samples are from 900-1080 kg/m^3 for porous samples, and from 1050-1130 kg/m^3 for dense samples.

The test results showed that, despite the differences in the densities of individual samples, the differences in their vapor absorption coefficients were not significant (Table 2).

Table 2. Results of determination of the vapor absorption coefficient of expanded clay concrete samples of different structures.

Material	Dry density, γ_0, kg/m^3	Vapor absorption coefficient, μ, mg/(m·h·Pa)
Porous expanded clay concrete sample	1080/1140	0.066/0.058
- / -	1060/1105	0.068/0.061
- / -	1050/1100	0.070/0.066
- / -	1025/1095	0.071/0.073
- / -	1000/1080	0.072/0.074
- / -	950/1000	0.070/0.077
- / -	900	0.071
Densely structured expanded clay concrete sample	1130	0.065
- / -	1110	0.067
- / -	1100	0.072
- / -	1080	0.073
- / -	1050	0.079
Note – the value before the fraction is a concrete sample based on expanded clay granules with the addition of internal fossil rocks from coal production, and in the fraction is a concrete sample based on standard expanded clay.		

The average vapor absorption coefficient of a porous expanded clay concrete sample with a density of 1010 kg/m^3 is 0.070 mg/(m·h·Pa), and for a densely structured expanded clay concrete sample (γ_0 = 1075 kg/m^3) - 0.074 mg/(m·h·Pa). The tendency to decrease the vapor absorption coefficient of a porous expanded clay concrete sample is explained by the high porosity of expanded clay granules and good filling of the space between the grains.

In general, the vapor absorption of a porous expanded clay concrete sample is comparable to it value of lightweight aggregate concrete samples and fully satisfies the requirements for enclosing structural materials.

Capillary absorption and moisture transfer rates of porous expanded clay products.

The capillary absorption rate is one of the moisture properties characterizing the displacement of moisture in the high sorption zone of wetting. Capillary hydration is the property of porous materials to be saturated by water under the influence of capillary forces and to retain moisture under the influence of capillary forces.

The rate of capillary moisture absorption of porous expanded clay concrete samples was determined according to the standard method [24]. The research work was carried out on samples dried to constant weight. The samples with geometric dimensions of 5x5x25 cm were weighed after being removed from the form, and their frames were covered by a water-vapor-proof layer (paraffin and rosin in a ratio of 1:3) and immersed in a tube with water for 3 cm.

The weight of the samples was measured at 15 min, 30 min, 60 min, in the first 6-7 hours from the start of the test and daily for 2 days. According to the test results, the average daily capillary moisture absorption rate $\nu_{k.v.}$ for porous expanded clay concrete samples with a density of 980 - 1080 kg/m^3 was = 1.22·10^{-3} cm/min. The change in the capillary wetting rate of the samples under study is presented in Figure 2.

As can be seen from Fig. 2, the capillary moisture absorption process occurs intensively in the first hour of the test. In the last hours of the first day, its value decreases to 0.2 cm/min. According to the test data, the change in the moisture content of the samples does not have a significant difference depending on the composition.

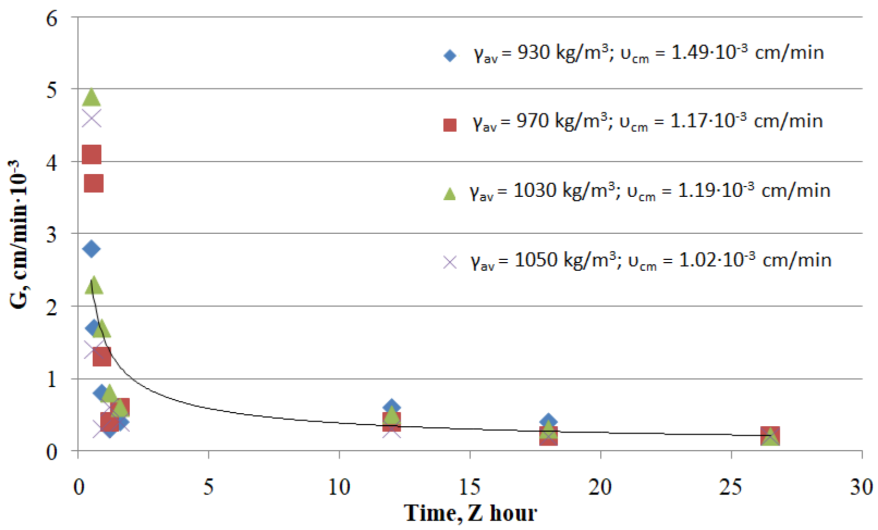

Fig. 2. Time-dependent capillary moisture absorption rate of porous expanded clay concrete samples.

One of the moisture characteristics of materials is the moisture permeability coefficient. These coefficients are determined for a porous expanded clay concrete sample in accordance with the GOST 12730.5-2018 methodology applied to certain building materials.

To determine the coefficient of moisture permeability, samples with geometric dimensions of 5x5x25 cm were used, in which the rate of capillary moisture absorption was determined. The samples were kept in a fixed container in the atmosphere of constant temperature and air humidity. By periodically measuring of the samples weight, a stationary moisture movement was established, or the constancy of the moisture flow removed from the open surface of the sample. At reaching of steady-state conditions, the samples are cut into several equal parts along the length. The weight of each part is measured and dried to a constant weight. Based on these data, a moisture distribution curve in the material is constructed (Fig. 3a) and the moisture permeability coefficient is determined.

The change in moisture content along the length of the porous expanded clay concrete samples can be monitored according to the curve in Fig. 3. It was established that the amount of moisture passing through a unit area, at a test condition of γa = 55% and t_a = 20°C was 0.13 - 0.21 kg/m^2·day.

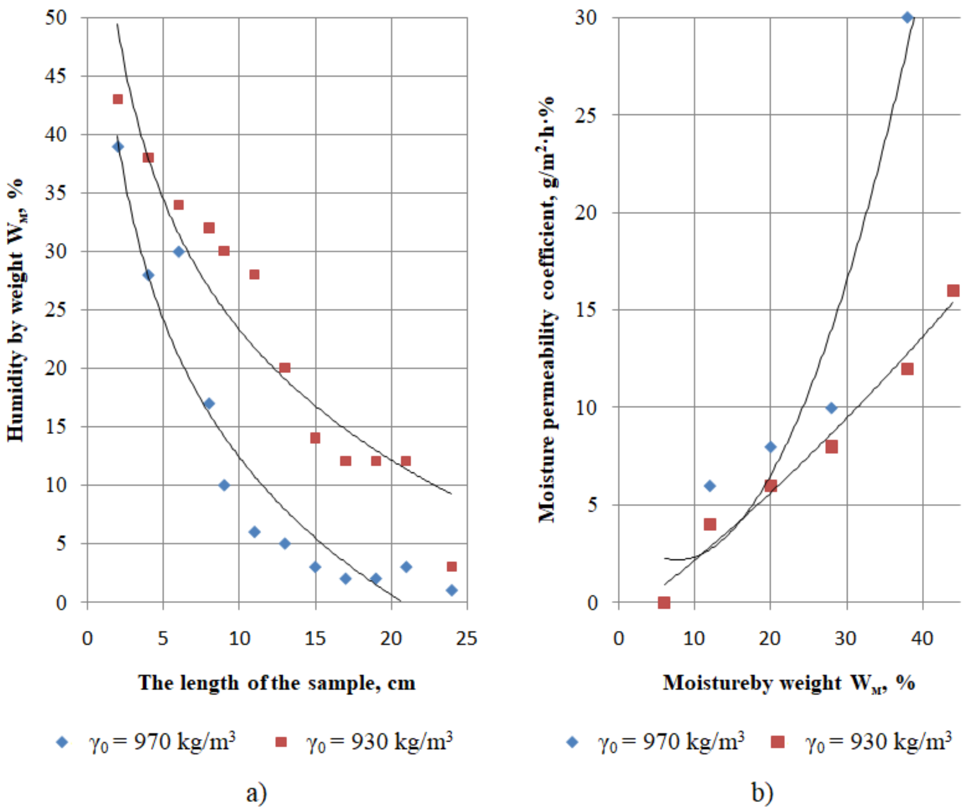

Fig. 3. Change in moisture content along the length of a porous expanded clay concrete sample (a), dependence of the moisture permeability coefficient on the moisture content of porous expanded clay concrete (b).

In stationary conditions the amount of moisture displaced in the material is directly proportional to the moisture gradient:

$$G = -\frac{dw}{dx} Z\beta, \text{ g/m}^2 \quad (2)$$

where: G – the amount of moisture passing through a unit of the material surface, g/m^2;

Z – time, h;

B – the coefficient of proportionality of the moisture displacement rate in a given material, g/m·h·%;

$\frac{dw}{dx}$ – material moisture gradient, %/m.

$$\beta = \frac{G'}{dw/dx}, \text{where} G' = \frac{G}{Z} \quad (3)$$

G' – the amount of moisture passing through a unit area of the sample section for 1 hour, g/m^2·h.

The change in humidity along the length of the samples and the dependence of the moisture transfer coefficient on humidity for the studied porous expanded clay concrete compositions are presented in Fig. 3 and Table 3.

Table 3. Moisture permeability coefficient of a porous expanded clay concrete sample.

Material name	Density, γ_0, kg/m^3	Material humidity / Moisture permeability coefficient, $\beta \cdot 10^{-2}$ g/m·h·%				
Porous expanded clay concrete sample	970	12 0.038	20 0.062	28 0.08	38 0.093	43 0.161
- / -	930	12 0.060	20 0.081	28 0.091	32 0.123	38 0.296
- / -	1050	12 0.025	20 0.051	23 0.066	31 0.072	33 0.101
- / -	1030	12 0.028	18 0.050	25 0.071	30 0.083	34 0.123

As it can be seen from Table 3 and Fig. 3 the moisture permeability coefficient increases with the increasing of moisture content in the material.

Moisture absorption of porous expanded clay products.

The research work investigated the moisture absorption indicators of porous expanded clay concrete depending on the material density, as well as the adopted technology.

For testing, samples of cubic shape with the size of 15 and 7 cm, dried to constant weight according to GOST 30629-2011, were used. The basis of the method is the measurement of the amount of water absorbed by the sample under study. The method is based on measuring of the weight of the samples after they have been in distilled water at room temperature and normal pressure for a specified period of time. The samples were placed on a grid so that the water level exceeded them by 2-10 cm, and were kept for a period from 1 to 40-42 days. The weight of the samples was measured periodically.

The arithmetic mean of the results of three samples was taken as the value of water absorption of products made of porous expanded clay concrete.

The volumetric water absorption of the sample was calculated by using the following formula:

$$W_0 = \frac{W_{\text{н}} \cdot \gamma_0}{1000}, \% \tag{4}$$

where: γ_0 – density, kg/m^3;

W_m – moisture absorption of the sample in percent by weight.

$$W_{\text{м}} = \frac{m_c - m_\beta}{m_c} \cdot 100\% \tag{5}$$

Table 4 shows the moisture absorption values of porous expanded clay concrete samples for 1-40 days. Daily hydration is the standard for moisture absorption, and the 40-day value can be considered close to the limit value.

Table 4. Moisture absorption of porous expanded clay concrete samples.

Material name	Dry density, kg/m^3	Moisture absorption, %					
		24 hours		48 hours		40 hours	
		$W_{м}$	W_0	$W_{м}$	W_0	$W_{м}$	W_0
Porous expanded clay concrete sample (size 150x150x150 mm)	1065	14.2	15.1	15.6	16.6	27.6	27.5
- / -	1035	15.1	15.6	16.0	16.6	27.6	28.6
- / -	985	17.1	16.8	18.0	16.5	28.0	27.5
- / -	970	18.6	18.0	19.1	18.5	29.3	28.5
Porous expanded clay concrete sample (size 70x70x70 mm)	960	21.4	20.5	22.6	21.6	30.6	29.4
- / -	950	21.3	20.4	26.0	24.7	33.6	31.9
- / -	930	23.1	21.3	24.2	22.2	33.7	31.3
- / -	915	23.1	21.9	24.4	22.4	34.4	31.5

The kinetics of moisture absorption of the porous expanded clay concrete sample during the specified period is presented in figure 4. As it can be seen from table 4, the value of moisture absorption of the heat-insulating sample of porous expanded clay concrete at the initial moment of the testing period, 24 and 48 hours, significantly depended on the size of the tested samples. Sample №4 (150x150x150 mm) and №5 (70x70x70 mm) with similar densities have different moisture absorption value during the 48-hour test. The moisture absorption value of sample №5 is 4.6% higher than that of sample №4. A comparison of the moisture absorption results after 40 days shows that the mentioned samples have approximately the same moisture absorption values. This rule is not contradictory, since the rate of moisture exchange in capillary-porous bodies depends on their size.

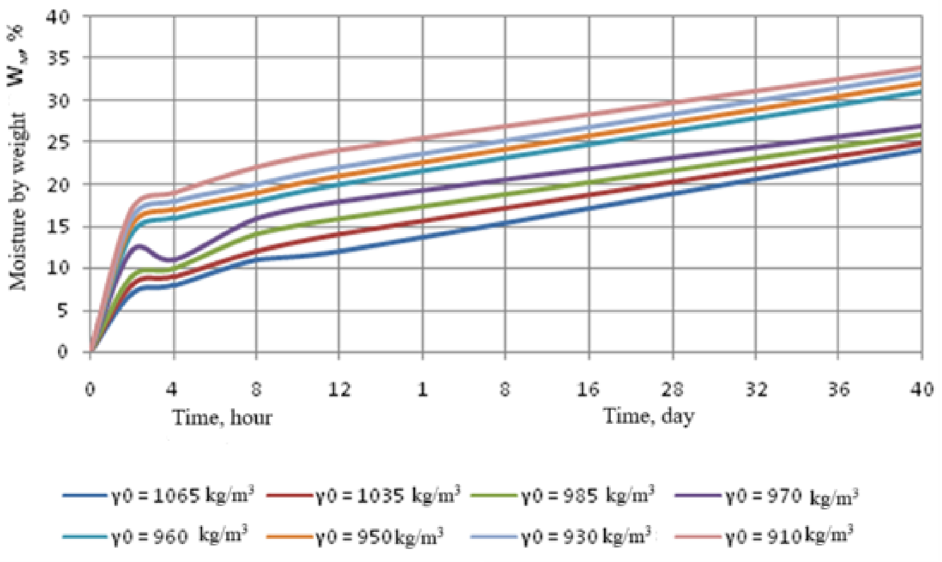

Fig. 4. Moisture absorption kinetics of thermally insulating porous expanded clay concrete samples.

4. CONCLUSIONS

Experimental studies of the thermophysical properties of heat-insulating porous expanded clay concrete samples have shown that this material has the following advantages over other types of expanded clay concrete used in the domestic construction industry:

1. The maximum sorption humidity varies in the range of 8.8 - 11.1%, with the increase in the density of porous expanded clay concrete, its sorption humidity increases.

2. The value of the vapor absorption coefficient of expanded clay concrete can be taken as μ = 0.075 mg/m·h·Pa according to SP 50.13330.2012 «Thermal protection of buildings».

3. The value of the capillary absorption rate is in the range of $1.49 \cdot 10^{-3} \div 1.02 \cdot 10^{-3}$ cm/min. The moisture permeability coefficient at 12% humidity varied from 0.036 ÷ 0.019 g/m·h·%.

4. The moisture absorption by weight for 24 hours is 14.2 ÷ 23.1%; for 48 hours is 15.6 ÷ 26.0%; for 40 days is 26.7 ÷ 34.4%.

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