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EMPIRICAL DEPENDENCE OF SORPTION HUMIDITY OF KERAMZYBETON CONCRETE ON RELATIVE HUMIDITY OF AIR

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Abstract:

In the calculations of the humidity regime of building envelopes to predict their performance, sorption isotherms of materials of structural layers are used. The article presents analytical expressions of sorption isotherms of expanded clay concrete of various densities for a range of relative humidity from 30 to 100%.

Keywords: Expanded clay concrete, humidity conditions, sorption isotherm, specific steam capacity, relative steam capacity, regression coefficient, Fisher criterion, variance of sorption moisture values, residual dispersion.

INTRODUCTION:

To assess the performance of the external building envelope in unsteady conditions of exposure to external and internal environment, it is necessary to have information about changes in humidity in the materials of individual layers of the structure. A lot of research has been devoted to the forecasting of the humidity regime of building envelopes under operational conditions.Mathematical methods have been developed for calculating the humidity of structures operating under non-stationary conditions [1] and, therefore, at present it is possible to take into account changes in humidity depending on the state of the environment, the influence of initial humidity on the humidity regime of the structure.

The differential equation for the diffusion of water vapor under non-stationary conditions through a flat wall, both single-layer and multi-layer, is proposed to be solved using the finite difference method [1].

In calculating the humidity regime of building envelopes for each material that makes up the building envelope, it is necessary to know such an indicator, called specific steam capacity ξ (mg / (kg · Pa), which is highly dependent on temperature.To take into account a significant change in the specific steam capacity ξ (mg / (kg · Pa) depending on the temperature, when solving the differential equation of moisture conductivity, the concept of "Relative steam capacity (ξ_0, g / kg)" was introduced, which means the amount of moisture required to increase the relative humidity of 1 kg of material from 0 to 100%. In the calculations of the humidity regime of external walling made of various materials, the relative steam capacity ξ_0 is determined from the graph of the sorption isotherm of each material.

$$\xi = \xi_0 / E , \qquad (1)$$

Between the values of specific steam ξ and relative steam ξ_0 of the material, there is the following dependencewhere E is the maximum value of the partial pressure of water vapor (Pa),corresponding to the temperature t under consideration.

Due to the fact that the sorption isotherms of almost the majority of building materials are curved lines, the value of ξ0 for individual sections of the isotherm is a variable value. For a small portion of the sorption isotherm, the following formula was proposed in [1] to determine the average value of the relative steam capacity $\xi_{0\cdot med}$ [1]

$$\xi_{0.cp} = \frac{\omega_2 - \omega_1}{\varphi_2 - \varphi_1} \cdot 10^6 , \qquad (2)$$

where ω_1 and ω_2 are the corresponding minimum and maximum moisture content of the material (in%) in a given section of the isotherm; φ1 and φ2 are the corresponding values of relative humidity; 106 is a constant introduced to convert% of the values of material moisture and relative air humidity to mg / kg. Based on the formula (2), it is possible to calculate the relative steam capacity ξo corresponding to a specific value of the relative air humidity φ

$$\xi_0 = \frac{d\omega}{d\varphi} \cdot 10^6 . \qquad (3)$$

This means that when the mathematical expression of the sorption isotherm is known, then when calculating the moisture regime of the structure (especially using computer programs), the regularity of the dependence of the relative steam capacity ξo on the relative humidity φ can be determined analytically.

Empirical equation of the sorption isotherm of keramzybeton concrete: Experimental studies of many scientists found that under the conditions of operation of building structures, the relative humidity φ in their thickness usually does not fall below 40%. Therefore, we can consider it sufficient to use the equation for the dependence of the sorption humidity of materials ω in the range of relative humidity φ in the range from 30% to 100% in the calculations of the humidity regime of building envelopes.

In this paper, for the analytical expression of the dependence of the sorption humidity ω of expanded clay concrete of various densities on the relative air humidity φ, the author proposes an empirical formula of the following form

$$\omega = \frac{a + b \cdot \varphi}{1 - c \cdot \varphi} \quad . \qquad (4)$$

Here, the values of the parameter C in the transforming function (1 – c · φ) vary between 0 and 1, and for different densities of γo expanded clay concrete is determined by the iterative method using multistep regression analysis. The coefficients a and b of equation (4) are determined by the least squares method.When choosing a value with the main criterion, the minimum residual dispersion s_o^2 between the experimental values of sorption humidity and the calculated values determined using the empirical formula (4) was adopted. When analyzing such non-linear regression equations, the forces of the correlation between the output parameter ω and the factor φ are usually estimated by the value of the correlation ratio η, determined by the formula

$$\eta = \sqrt{1 - \frac{s_o^2}{s_\omega^2}} \quad , \qquad (5)$$

where s_ω^2 -is the variance of the experimental values of sorption moisture relative to its average; it was determined by the formula

$$s_\omega^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n}\omega_i^2 - \left(\sum_{i=1}^{n}\omega_i\right)^2 / n\right]; \qquad (6)$$

s_o^2 -residual dispersion between the experimental values of sorption humidity and calculated values; it is determined by the formula

$$s_o^2 = \frac{1}{n-k}\sum_{i=1}^{n}(\omega_i - \tilde{\omega}_i)^2 \ . \qquad (7)$$

In this case, n = 8 is the total number of determined values of sorption moisture; ω_i - sorption humidity at experimental points (for individual values of φ),%;

$\tilde{\omega}_i$ - determined by the formula (4) the sorption moisture value of expanded clay concrete (in% by weight); k = 2 is the number of unknown coefficients in equation (4).

Moreover, the relative approximation error at each experimental point ε_i is often also determined by the formula [2]

$$\varepsilon_i = \frac{\omega_p - \omega_э}{\omega_p} \cdot 100\% \, . \qquad (8)$$

The average value of the relative approximation error was determined by the formula

$$\varepsilon_{cp} = \frac{\sum|\varepsilon_i|}{n}, \ \% \, . \qquad (9)$$

To test the adequacy of the empirical equation for the sorption isotherm, the Fisher F-test was used. The calculated value of the Fisher F-test was determined by the formula

$$F_p = \frac{S_\omega^2}{S_o^2}, \qquad (10)$$

The table value of the Fisher F-test was determined in accordance with the degrees of freedom of the variances S_ω^2 (n-1 = 7) and s_o^2 (n-k = 6). If the condition Fr> Ft is fulfilled, the recommended equation for describing the sorption isotherm is considered adequate.

The unknown coefficients of sorption equation (4) for expanded clay concrete with a density of 1400, 1200, 1000 and 800 kg / m^3 were determined on the basis of empirical data given in [3].

Table 1 shows the results of calculations of the residual dispersions s_o^2 and the corresponding values of the specified parameter C and the unknown coefficients of equations a and b, obtained as a result of regression analysis performed for the above expanded clay concrete.

Table 1

Material	Show-bodies	Values			Regression coefficients corresponding to the minimum value S_o^2	
					a	**b**
Expanded clay, γ_0=1400 кг/м³	C	0,86	**0,87**	0,88	1,578198	-0,01163
	S_o^2	0,047921	**0,03872**	0,056708		
Expanded clay, γ_0=1200 кг/м³	C	0,84	**0,85**	0,86	1,012107	0,638393
	S_o^2	0,019970	**0,012055**	0,019795		
Expanded clay, γ_0=1000 кг/м³	C	0,83	**0,835**	0,84	0,577244	1,079923
	S_o^2	0,029327	**0,029271**	0,031902		
Expanded clay, γ_0=800 кг/м³	C	0,85	**0,855**	0,86	0,219062	1,091288
	S_o^2	0,033001	**0,032246**	0,034807		

As can be seen from table 1, for expanded clay concrete with a density of γ0 = 1400 kg / m3 with a minimum value of residual dispersion $s_o^2 = 0{,}03872$ the specified parameter is c = 0.87, and the corresponding regression coefficients are a = 1.578198 and b = -0.01163. Thus, for expanded clay with a density of γ0 = 1400 kg / m³, the sorption isotherm can be expressed by the following empirical equation

$$\omega_p = \frac{1{,}578198 - 0{,}01163 \cdot \varphi}{1 - 0{,}87 \cdot \varphi}. \qquad (11)$$

The results of checking the adequacy of this equation are shown in table 2.

Table 2.

Results of statistical processing of data on sorption moisture for expanded clay concrete with a density of γ0 = 1400 kg / m³ at c = 0.87

№	φ	$\omega_э$,%, by [3]	ω_p, %, according to the formula (11)	ω_p- $\omega_э$	ε_i, %	ε_{cp}, ,	$\frac{S_\omega^2}{S_o^2}$	Condition F_p> $F_т$
1	0,3	1,9	2,130864	0,230864	10,8343	4,46	10,85125 / 0,03872	280,25 >4,21
2	0,4	2,5	2,413413	-0,08659	-3,588			
3	0,5	3	2,782977	-0,21702	-7,798			
4	0,6	3,5	3,287069	-0,21293	-6,478			
5	0,7	4	4,015488	0,015488	0,3857			
6	0,8	5	5,160832	0,160832	3,1164			
7	0,9	7	7,224561	0,224561	3,1083			
8	1	12	12,05051	0,050513	0,4192			

As can be seen from table 2, for expanded clay concrete with a density of γ_0 = 1400 kg / m3, the variance of the experimental values of sorption humidity relative to its average, determined by formula (6), is $S_\omega^2 = 10{,}85125$. And the value of the residual dispersion, determined by the formula (7), is equal to $S_o^2 = 0{,}03872$. The calculated value of the Fisher F-criterion according to the formula (10) is Fp = 280.25. With the degree of freedom f1 = 8-1 = 7 and f2 = 8-2 = 6, the tabular value of the Fisher F-test is Ft = 4.21 [2]. Since the condition Фр>Фт is satisfied, the empirical equation (11) can be considered adequate for the analytical expression of the sorption isotherm of expanded clay concrete with a density of γ0 = 1400 kg / m³.In this case, the value of the correlation ratio, which estimates the tightness of the correlation between the output parameter ω and the factor φ determined by formula (5), is

$$\eta = \sqrt{1 - \frac{0{,}03872}{10{,}85125}} = 0{,}998,$$

which indicates the presence of a very strong correlation between sorption humidity and relative air humidity. This means that in calculations of the humidity regime of building envelopes made using expanded clay with a density of γ0 = 1400 kg / m^3, within the range of relative air humidity φ from 30 to 100%, a confidence probability of 95%, one can use the empirical equation (11). In this case, the average relative error determined by the formula [9] ε_{med} = 4.46%.

Expanded clay with a density of γ0 = 1200 kg / m3 has a higher porosity than expanded clay with a density of γ0 = 1400 kg / m3. In this regard, the values of equilibrium sorption humidity for these expanded clay concrete at certain values of relative humidity differ from each other, while maintaining the nature of the isothermal curves. $s_o^2 = 0{,}012055$

As the results of the regression analysis show (Table 1), for expanded clay concrete with a density of γ0 = 1200 kg / m3 with a minimum value of residual dispersion, the specified parameter is c = 0.85, and the corresponding regression coefficients are a = 1.012107 and b = 0.683933 . Thus, for expanded clay concrete with a density of γ0 = 1200 kg / m3, the sorption isotherm can be expressed by the following empirical equation

$$\omega_p = \frac{1{,}012107 + 0{,}638393 \cdot \varphi}{1 - 0{,}85 \cdot \varphi} . \quad (12)$$

The results of checking the adequacy of this equation are shown in table 3.

Table 3.

Results of statistical processing of data on sorption moisture for expanded clay concrete with a density of γ_0 = 1200 kg / m3 at c = 0.85

№	φ	$\omega_э$,%, by [3]	ω_p, %, according to the formula (12)	$\omega_p - \omega_э$	ε_i, %	ε_{cp}, %	$\frac{S_\omega^2}{S_o^2}$	Condition$F_p > F_т$
1	0,3	1,5	1,615604	0,115604	7,1555	3,22	10,077 / 0,012055	835,93 >4,21
2	0,4	2	1,920400	-0,07960	-4,145			
3	0,5	2,5	2,315311	-0,18469	-7,977			
4	0,6	2,8	2,84723	0,04723	1,6588			
5	0,7	3,5	3,602425	0,102425	2,8432			
6	0,8	4,7	4,758817	0,058817	1,236			
7	0,9	6,8	6,751748	-0,04825	-0,715			
8	1	11	11,00333	0,003333	0,0303			

From the data of table 3 it can be seen that for expanded clay concrete with a density of γ_0 = 1200 kg / m^3, the variance of the experimental values of sorption humidity relative to its average, determined by formula (6), is $S_\omega^2 = 10{,}077$. And the value of the residual dispersion, determined by the formula (7), is equal to $S_o^2 = 0{,}012055$. The calculated value of the Fisher F-criterion according to the formula (10) is Fr = 835.93. Since the degrees of freedom remain unchanged, the tabular value of the Fisher F-test also remains unchanged, and is equal to Ft = 4.21 [2]. And in this case, the condition Fr>Ft is fulfilled; therefore, the empirical equation (12) can be considered adequate for the analytical expression of the sorption isotherm of expanded clay concrete with a density of γ_0 = 1200 kg / m^3. In this case, the value of the correlation ratio, which estimates the tightness of the correlation between the output parameter ω and the factor φ, determined by formula (5), is

$$\eta = \sqrt{1 - \frac{0{,}012055}{10{,}077}} = 0{,}999,$$

which also indicates the presence of a very strong correlation between sorption humidity and relative air humidity. Therefore, in the calculations of the humidity regime of building envelopes made using expanded clay with a density of γ_0 = 1200 kg / m^3, in the range of relative air humidity φ from 30 to 100%, a confidence probability of 95%, one can use the empirical equation (12). In this case, the average relative error determined by the formula [9] is ε_{med} = 3.22%.

Table 1 shows the data on the value of the set parameter C, corresponding to the minimum value of the residual dispersion for even more porous expanded clay concrete with a density of γ_0 = 1000 kg / m^3. For this expanded clay concrete with a minimum value of residual dispersion $s_o^2 = 0{,}029271$ the specified parameter is c = 0.835, and the corresponding regression coefficients are a = 0.577244 and b = 1.079923. Thus, for expanded clay concrete with a density of γ_0 = 1000 kg / m^3, the sorption isotherm can be expressed by the following empirical equation

$$\omega_p = \frac{0{,}577244 + 1{,}079923 \cdot \varphi}{1 - 0{,}835 \cdot \varphi} . \quad (13)$$

The results of checking the adequacy of this equation for the sorption isotherm are given in table 4.

Table 4.

Results of statistical processing of data on sorption moisture for expanded clay concrete with a density of γ_0 = 1000 kg / m^3 at c = 0.835

№	φ	$\omega_э$,%, by [3]	ω_p, %, according to the formula (13)	ω_p- $\omega_э$	ε_i, %	ε_{cp}, %	$\frac{S_\omega^2}{S_o^2}$	Condition F_p> $F_т$
1	0,3	1,3	1,202429	-0,09757	-8,114	3,9	$\frac{9,17357}{0,029271}$	313,4 >4,21
2	0,4	1,5	1,515335	0,015335	1,012			
3	0,5	1,9	1,917949	0,017949	0,9358			
4	0,6	2,3	2,455306	0,155306	6,3253			
5	0,7	3,0	3,20864	0,20864	6,5024			
6	0,8	4,5	4,34091	-0,15909	-3,665			
7	0,9	6,5	6,234102	-0,2659	-4,265			
8	1	10,0	10,04343	0,043434	0,4325			

The data in table 4 indicate that, for expanded clay concrete with a density of γ_0 = 1000 kg / m^3, the variance of the experimental values of sorption humidity relative to its average, determined by formula (6), is $S_\omega^2 = 9{,}17357$. And the value of the residual dispersion, determined by the formula (7), is equal to $S_o^2 = 0{,}029271$. The calculated value of the Fisher F-criterion according to the formula (10) is Fr = 313.4. The table value of the Fisher F-test is Ft = 4.21 [2]. The condition Fr>Ft is fulfilled, which means that the empirical equation (13) can be considered adequate for the analytical expression of the sorption isotherm of expanded clay concrete with a density of γ_0 = 1000 kg / m^3. In this case, the value of the correlation ratio, which estimates the tightness of the correlation between the output parameter ω and the factor φ determined by formula (5), is

$$\eta = \sqrt{1 - \frac{0{,}029271}{9{,}17357}} = 0{,}998,$$

which also indicates the presence of a very strong correlation between sorption humidity and relative air humidity. We can conclude that in the calculations of the humidity regime of building envelopes made using expanded clay with a density of γ_0 = 1000 kg / m^3, within the range of relative humidity φ from 30 to 100%, a confidence probability of 95%, we can use the empirical equation (13) . In this case, the average relative error determined by the formula [9] is ε_{med}=3,9 %.

Expanded clay with a density of γ_0 = 800 kg / m^3 has even greater porosity than expanded clay with a density of γ_0 = 1000 kg / m^3. Therefore, the values of equilibrium sorption humidity for these expanded clay concrete at certain values of relative air humidity also differ from each other. As the results of the regression analysis show (Table 1), for expanded clay concrete with a density of γ_0 = 800 kg / m^3 with a minimum value of the residual dispersion $s_o^2 = 0{,}032246$ the specified parameter is c = 0.855, and the corresponding regression coefficients are a = 0.219062 and b = 1.091288. Thus, for expanded clay with a density of γ_0 = 800 kg / m^3, the sorption isotherm can be expressed by the following empirical equation

$$\omega_p = \frac{0{,}219062 + 1{,}091288 \cdot \varphi}{1 - 0{,}855 \cdot \varphi} \quad . \qquad (14)$$

The results of checking the adequacy of this equation are shown in table 5.

Table 5.

Results of statistical processing of data on sorption moisture for expanded clay concrete with a density of γ_0 = 800 kg / m^3 at c = 0.855

№	φ	$\omega_э$,%, by [3]	ω_p, %, according to the formula (14)	ω_p- $\omega_э$	ε_i, %	ε_{cp}, %	$\frac{S_\omega^2}{S_o^2}$	Condition F_p> $F_т$
1	0,3	0,8	0,734964	-0,06504	-8,849	3,93	$\frac{8,0684}{0,032246}$	250,21 >4,21
2	0,4	1	0,996313	-0,00369	-0,37			
3	0,5	1,3	1,335724	0,035724	2,6745			
4	0,6	1,7	1,794312	0,094312	5,2561			
5	0,7	2,4	2,448214	0,048214	1,9693			
6	0,8	3,3	3,455967	0,155967	4,513			
7	0,9	5,6	5,211339	-0,38866	-7,458			
8	1	9	9,036839	0,036839	0,4077			

From the data of table 5 it can be seen that for expanded clay concrete with a density of γ_0 = 800 kg / m^3, the variance of the experimental values of sorption humidity relative to its average, determined by formula (6), is $S_\omega^2 = 8{,}0684$. And the value of the residual dispersion, determined by the formula (7), is equal to $S_o^2 = 0{,}032246$. The calculated value of the Fisher F-criterion according to the formula (10) is equal to Fr = 250.21. Since the degrees of freedom remain unchanged, the tabular value of the Fisher F-test also remains unchanged, and is equal to Ft = 4.21 [2]. And in this case, the condition Fr>Ft is satisfied, therefore, the empirical equation (14) can be considered adequate for the analytical expression of the sorption isotherm of expanded clay concrete with a density of γ_0 = 800 kg / m^3. In this case, the value of the correlation ratio, which estimates the tightness of the correlation between the output parameter ω and the factor φ, determined by formula (5), is

$$\eta = \sqrt{1 - \frac{0{,}032246}{8{,}0684}} = 0{,}9979,$$

which indicates the presence of a very strong correlation between sorption humidity and relative air humidity. Therefore, in the calculations of the humidity regime of building envelopes made using expanded clay concrete with a density of γ_0 = 800 kg / m^3, in the range of relative air humidity φ from 30 to 100%, a confidence probability of 95%, one can use the empirical equation (14). In this case, the average relative error determined by the formula [9] is ε_{med} = 3.22%.

Figure 1 shows the calculated graphs of sorption isotherms and experimental data on the sorption moisture of expanded clay concrete with a density of γ_0 = 1400, 1200, 1000, and 800 kg / m^3.

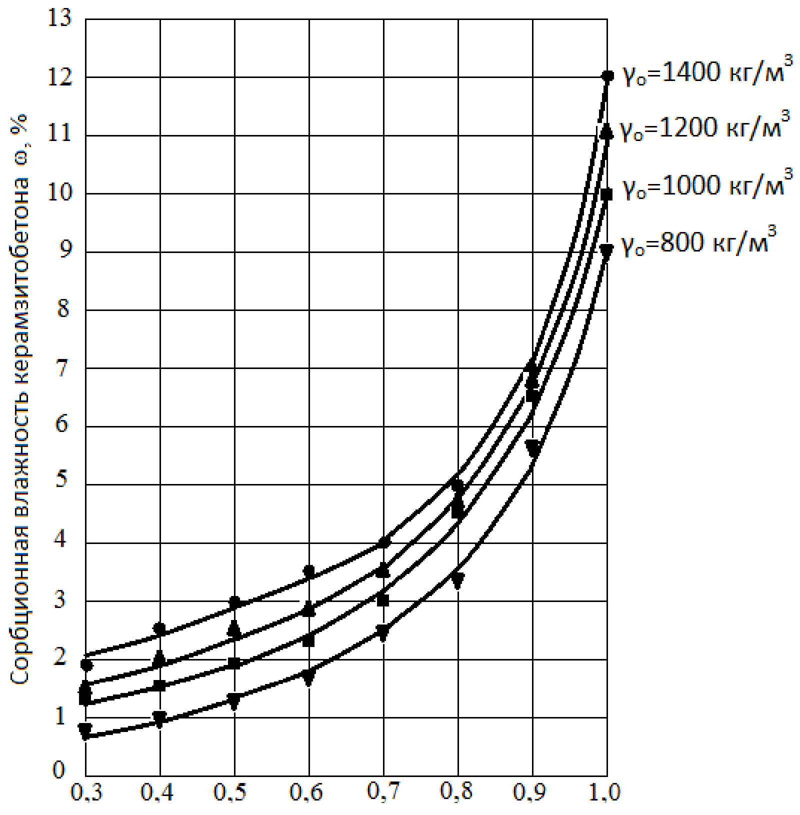

Fig. 1. Estimated graphs of sorption isotherms and experimental data on the sorption moisture of expanded clay concrete:
● - for γ0 = 1400 kg / m3;
▲ - for γ0 = 1200 kg / m3;
■ - for γ0 = 1000 kg / m3;
▼ - for γ0 = 800 kg / m3.

3. CONCLUSIONS

The results of the regression analysis show that for expanded clay concrete with a density of 1400, 1200, 1000 and 800 kg / m^3, the dependences of sorption humidity ω on relative air humidity φ ranging from 30 to 100% can be expressed using equations (11), (12), (13) and (14). At the same time, the values of the correlation ratio, which estimates the tightness of the correlation between the output parameter ω and the factor φ, for the above expanded clay aggregates range from 0.997 ... 0.999.This means that when expressing the sorption isotherms in the proposed form of the equation, the dependence of the sorption humidity ω of expanded clay concrete on the relative air humidity φ approaches almost functional. Therefore, it is possible to use them in the calculations of the humidity regime of building envelopes made using expanded clay concrete, operated in non-stationary temperature-humidity conditions.

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