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ISOTHERMS OF WATER VAPOR SORPTION BY LIGHT INORGANIC AND POLYMER HEAT-INSULATING MATERIALS

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This paper presents the results of an experimental study of the isotherms of water vapor sorption by glass-fiber and mineral-wool products, expanded polystyrene plates, and ecowool. It has been shown that the equilibrium specific moisture content of glass-fiber and mineral wool products depends on the binder content and density and that of expanded polystyrene plates is density-dependent.

As a warmth-keeping jacket of fencing constructions, glass-fiber and mineral-wool products, polystyrene foam plastic plates, and also ecowool — a loose heat-insulating material — are widely used. Rational design of fencing constructions requires knowledge of their thermophysical and mass-exchange characteristics [1–3]. In calculating the mass-transfer coefficients, as input quantities, the equilibrium moisture-content isotherms characterizing the sorption properties of materials are used [1, 2, 4]. While for load-carrying and finishing coats of fences they have received a fairly exhaustive study, a large portion of information on light effective heat-insulating materials [2, 4–7] has become outdated and, moreover, was obtained for types that are no longer used [2, 7], is fragmentary [5] or is devoted to narrow, exclusively practical purposes of optimization of the heat-insulating layer [6]. In [4], sparse experimental data on the equilibrium moisture content of such building materials as fiber boards (ρ = 301 kg/m^3), plywood (ρ = 578 kg/m^3), perlite boards (ρ = 173 kg/m^3), polyisocyanurite boards (ρ = 32.5 kg/m^3), and glass-fiber boards (ρ = 122 kg/m^3) are given.

The presence of several forms of moisture-material bonding at a different air humidity, as well as the indefiniteness of the geometry of the porous structure of heat-insulating materials make it impossible to give a rigorous analytical description of the dependence of their equilibrium specific moisture content on the air humidity [1, 3, 4].

In the present paper, an experimental study of the sorption isotherms has been performed and empirical dependences for light inorganic and polymeric heat-insulating materials have been obtained.

The experiments were performed by the tensimetric (exciccator) method [8, 9] The maximum size of specimens of any shape did not exceed 20 mm, and their mass depending on the material density was 1–4 g. The equilibrium specific moisture content at each given relative air humidity was determined by the results of testing three specimens. The preliminarily dried specimens were brought to the equilibrium state in artificially created vapor-air media having a relative air humidity of 40, 60, 80, 90, and 97% at a temperature of 20°C. The possible error in determining the sorption moisture content by the tensimetric method, with all methodological instructions being observed, does not exceed 5% [9]. The reason for the spread of repeated determinations of W_{eq} is mainly the non-identity (dissimilarity) of specimens. To reduce it, we used the average sampling technique [10].

The experimental data on the equilibrium specific moisture content W_{eq} (in volume or mass percent) of the investigated materials in the range of relative humidity φ from 0 to 0.97 are given by the two-constant empirical equation [11–13]

$$\overline{W}_{eq} = \frac{b_0\varphi}{1-\varphi}(1-b_1\varphi) . \quad (1)$$

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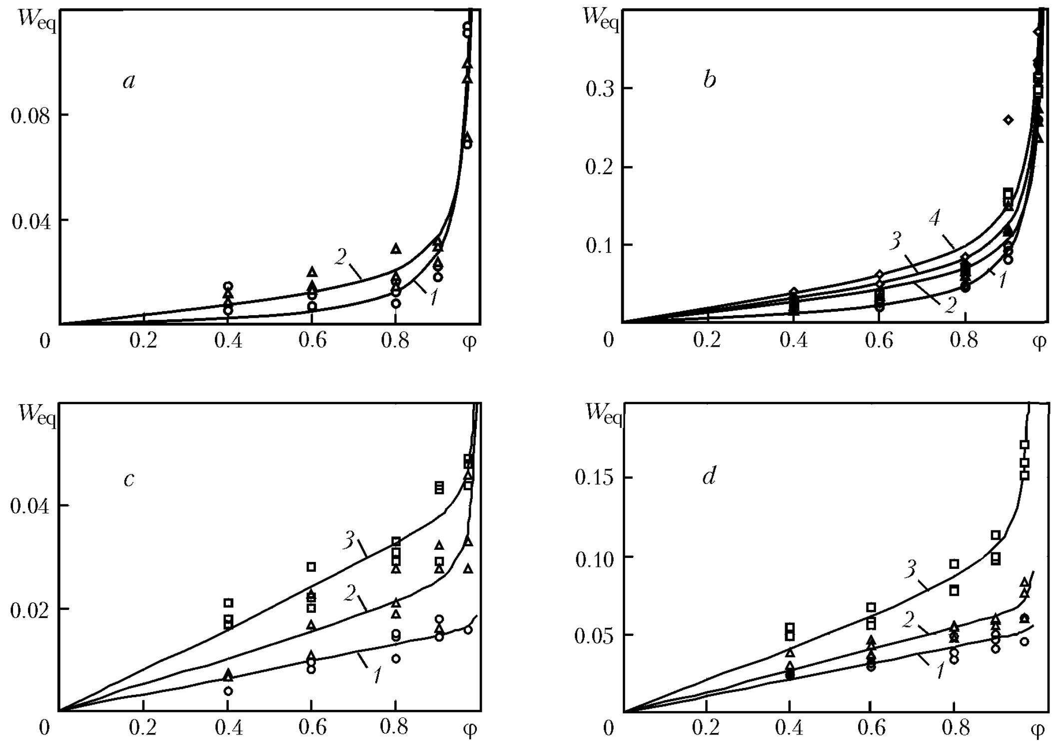


Fig. 1. Isotherms of water vapor sorption by the glass-fiber (a, b) and mineral-wool (c, d) products at their different densities: a) glass-fiber mats [1) ρ = 13.1; 2) 16.3 kg/m^3]; b) glass-fiber boards [1) ρ = 31.9; 2) 55.0; 3) 75.0; 4) 79.6 kg/m^3]; c) mineral-wool boards [1) ρ = 28.2; 2) 73.2; 3) 111 kg/m^3]; d) the same [1) 136; 2) 159; 3) 225 kg/m^3].

To estimate the values of min W_{eq} and max W_{eq} with the use of (1), we suggest using the standard deviation S_{cal} (absolute value of the mean measure of deviation of experimental data from the calculated curve that is constant for all its sections):

$$S_{cal} = \sqrt{\frac{\sum_{i=1}^{n} \left(W_{eqi} - \overline{W}_{eqi}\right)^2}{n - m}} \, . \tag{2}$$

Glass-Fiber and Mineral-Wool Products. We have investigated specimens of glass-fiber products made by the open stock company FLaiderer–Chudovo (Russia) and the company Isover (Netherlands, Finland), as well as mineral-wool plates manufactured by Paroc Oy Ab (Finland), Partek Paroc Polska Sp.z.o.o., Izolacija S.A., Gullfiber Polska Sp.z.o.o. (Poland), and the closed stock company Paroc (Lithuania). The mean diameter of the glass fiber was 4–5 μm and that of the mineral fiber — 5–6 μm.

The experimental results on the equilibrium specific moisture content W_{eq} are presented in Fig. 1, and the values of coefficients b_0 and b_1 of the empirical dependence (1) are given in Table 1. The moisture content of the investigated products was expressed in volume percent, since in this case, judging from the experiments of [14, 15], it is approximately the same at all their densities.

The investigated glass-fiber products exhibit a higher (sorbed) hygroscopicity than the mineral-wool ones. For example, the mean value of W_{eq} of the glass-fiber boards of density 79.6 kg/m^3 at φ = 0.9 is equal to 15 volume % and is 4.3–9.7 times higher than the mean values of the investigated mineral-wool products of density 49.5–117 kg/m^3. An increase in the hygroscopicity of the fiber-glass products at their higher density can be noted (see Fig. 1a, b, and Table 1).

TABLE 1. Results of Statistical Processing of the Experimental Data on the Equilibrium Specific Moisture Content of the Glass-Fiber and Mineral-Wool Products

Products	ρ	$M_{o.b}$	Values of coefficients of Eq. (1)		S_{cal}, mass %	φ				
						0.4	0.6	0.8	0.9	0.97
			b_0	b_1		$\overline{W}^*_{eq}$, mass %				
Glass-fiber mats	13.1	2.3	0.0037	0.1966	0.0110	0.0023	0.0049	0.0124	0.0272	0.0962
	16.3	6.5	0.0169	0.8666	0.0075	0.0074	0.0122	0.0207	0.0335	0.0871
Glass-fiber boards	31.9	6.4	0.0227	0.6075	0.0153	0.0114	0.0216	0.0466	0.0925	0.3013
	55.0	8.8	0.0608	0.8944	0.0161	0.0260	0.0423	0.0692	0.1067	0.2603
	79.6	7.2	0.0877	0.9019	0.0345	0.0374	0.0604	0.0977	0.1487	0.3551
	87.0	6.7	0.0720	0.8943	0.0205	0.0308	0.0500	0.0819	0.1264	0.3083
Mineral-wool mats	49.5	2.0	0.0185	0.9632	0.0034	0.0076	0.0117	0.0169	0.0221	0.0392
Mineral-wool boards	28.2	1.8	0.0162	0.9983	0.0022	0.0065	0.0097	0.0130	0.0148	0.0165
	59.0	2.0	0.0152	0.9872	0.0020	0.0061	0.0093	0.0128	0.0153	0.0209
	73.2	3.1	0.0254	0.9862	0.0058	0.0103	0.0156	0.0215	0.0257	0.0356
	87.8	4.4	0.0374	0.9964	0.0034	0.0150	0.0226	0.0304	0.0348	0.0406
	111	4.0	0.0397	0.9931	0.0041	0.0159	0.0241	0.0326	0.0379	0.0471
	117	2.4	0.0275	0.9859	0.0039	0.0111	0.0168	0.0232	0.0278	0.0388
	121	4.0	0.0469	0.8771	0.0393	0.0203	0.0331	0.0559	0.0888	0.2261
	136	4.6	0.0518	0.9990	0.0052	0.0207	0.0311	0.0416	0.0470	0.0518
	159	4.8	0.0662	0.9962	0.0063	0.0266	0.0400	0.0538	0.0617	0.0722
	161	2.7	0.0328	0.9885	0.0042	0.0132	0.0200	0.0274	0.0326	0.0436
	191	4.0	0.0640	0.9792	0.0084	0.0260	0.0396	0.0555	0.0684	0.1038
	225	4.8	0.0999	0.9800	0.0089	0.0405	0.0617	0.0863	0.1061	0.1597

*Calculated by the empirical relation (1) at T = 20°C.

The mean value of $\overline{W}_{eq}$ of the mineral-wool products of density from 49.5 to 117 kg/m^3 at φ = 0.9 does not exceed 0.038 volume %. For boards of density 136 and 159 kg/m^3 (Fig. 1d), an increase in the value of $\overline{W}_{eq}$ has been observed; at φ = 0.9 it reaches 0.062%. At a board density of 225 kg/m^3, the value of $\overline{W}_{eq}$ at φ = 0.9 is 0.106%.

On all curves of water vapor sorption by the investigated products (see Fig. 1), two clearly defined regions can be distinguished: $0 < \varphi < 0.8$ (adsorptionally bound moisture) and $0.8 < \varphi < 0.97$ (capillary-bound moisture). The observed spread of the experimental data on W_{eq} for both kinds of products can be explained by the structural dissimilarity of these materials.

The investigated products represent a material consisting of fine glassy fibers interconnected by a synthetic binder (solidified phenolformaldehyde resin). The acidity modulus of the fibers of the investigated products is larger than 1.4 [10]. Therefore, they are resistant to a higher humidity and the presence of aggressive media and exhibit a negligibly small hygroscopicity. The service life of these products is largely determined by the time stability of the synthetic binder.

Below, we consider the influence of the binder content in the glass-fiber and mineral-wool products on their equilibrium specific moisture content, which, according to the results of the investigations performed, is represented by the regression equation (1). According to this equation, the sorption properties of the products are characterized by a change in the values of the coefficients b_0 and b_1. The influence of the binder content in the glass-fiber and mineral-wool products on the value of the coefficient b_0, according to the results of the investigations performed, is shown in Fig. 2a.

The empirical equation of coefficient b_0 regression by the quantity of the binder (in kg/m^3) for the fiber-glass products, according to [16], is of the form

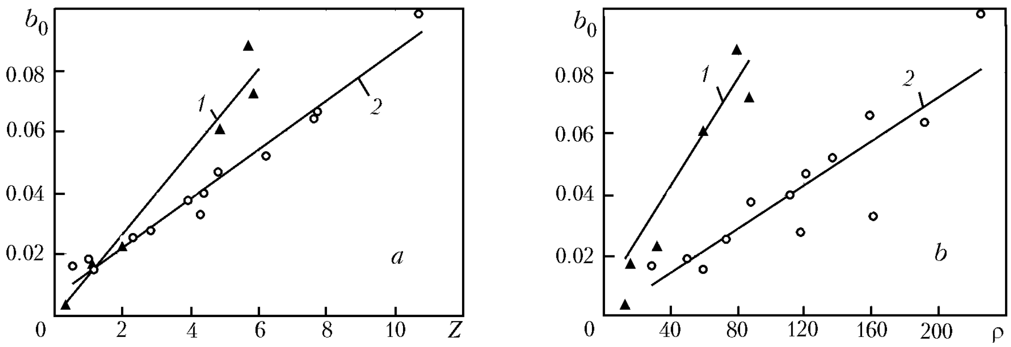


Fig. 2. Coefficient b_0 as a function of the binder content (a) and density (b) of the glass-fiber (1) and mineral-wool (2) products. Z, ρ, kg/m^3.

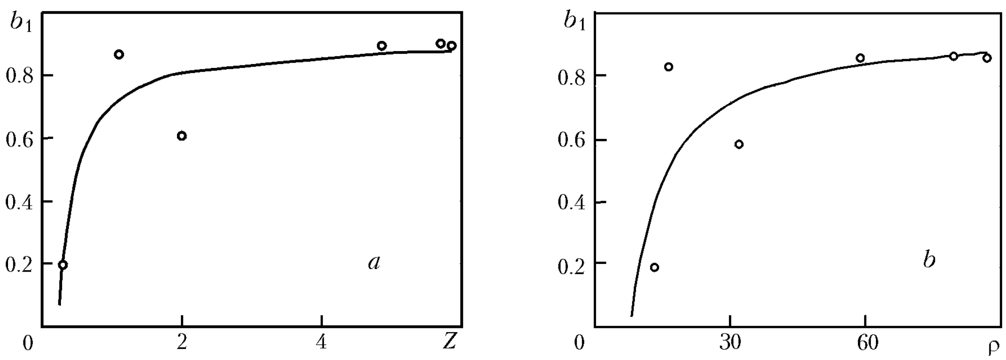


Fig. 3. Coefficient b_1 as a function of the binder content in the glass-fiber products (a) and their density (b). Z, ρ, kg/m^3.

$$b_0 = 0.0134Z \tag{3}$$

with a standard deviation S_{cal} = 0.0065 and a determination coefficient $r^2_{b_0 Z}$ = 0.963 (squared correlation coefficient), and for the mineral-wool products

$$b_0 = 0.00658 + 0.00794Z \tag{4}$$

with S_{cal} = 0.0043 and $r^2_{b_0 Z}$ = 0.969.

In both cases, the values of the determination coefficient show that the variation of the coefficient b_0 of the regression equation (1) is 96.5% on average due to the change in the binder content in the products, and only 3.5% is due to other factors.

The empirical equation of regression of the coefficient b_1 by the binder content in the glass-fiber products has the following form (Fig. 3a):

$$b_1 = \frac{0.913Z - 0.211}{Z}. \tag{5}$$

For dependence (5), S_{cal} = 0.112, and the determination coefficient $\eta^2_{b_1 Z}$ = 0.843 (squared empirical correlation ratio) shows that the change in the value of the coefficient b_1 in the regression equation (1) is 84.3% due to the variation of the binder content in the products and 15.7% — to the influence of other factors.

The value of the coefficient b_1 for the mineral-wool products is practically independent of the binder content in them. Its mean value (n = 12) is equal to 0.9878 with S_{cal} = 0.0103. Therefore, in calculating W_{eq} by the empirical dependence (1), the value of $b_1$0 can be considered to be a constant.

TABLE 2. Results of Statistical Processing of the Experimental Data on the Equilibrium Specific Moisture Content of the Foam Polystyrene Boards (T = 20°C)

ρ	$W_{\hat{a}}$	Values of coefficients of Eq. (1)		S_{cal}, mass %	φ						n in the range of φ = 0.4–0.97
					0.2	0.4	0.6	0.8	0.9	0.97	
		b_0	b_1		$\overline{W}_{eq}^{*}$						
13.3 ± 0.8	1—3.3	1.1974	0.9844	0.57	0.24	0.48	0.74	1.02	1.23	1.75	89
17.8 ± 1.3	1.1—3.3	0.7040	0.9727	0.43	0.14	0.29	0.44	0.62	0.79	1.29	53
21.1 ± 1.1	1.3—2.6	0.4650	0.9805	0.18	0.09	0.19	0.29	0.40	0.49	0.74	26
32.8 ± 0.2	2.0—4.4	0.4045	0.9805	0.07	0.08	0.16	0.25	0.34	0.40	0.53	24

*Calculated by the empirical relation (1).

Thus, the values of the equilibrium specific moisture content $\overline{W}_{eq}$ of the glass-fiber and mineral-wool boards can be calculated by the empirical dependence (1) if the density of the products and the binder content in them, as well as the coefficients b_0 and b_1 needed for the calculations and determined by the regression equations (3)–(5), are known. The computed values of W_{eq} differ from the values calculated by the coefficients b_0 and b_1 from Table 1 by no more than ±8% in the range of relative air humidity between 40 and 80% and by no more than ±12% in the 90–97% range.

On the basis of the experimental studies made, we have additionally considered the case where only the density ρ of the products is known and information on the content of the synthetic binder is absent. In so doing, the constant coefficients b_0 and b_1 of the empirical dependence (1) can be calculated by the regression dependences given below:

for the glass-fiber products

$$b_0 = 0.00103\rho - 0.00521 \quad (S_{cal} = 0.0087\,,\ \ r^2_{Zb_0} = 0.935)\,, \tag{6}$$

for the mineral-wool products (Fig. 2b)

$$b_0 = 0.00036\rho \quad (S_{cal} = 0.0109\,,\ \ r^2_{Zb_0} = 0.797)\,. \tag{7}$$

The empirical equation of regression of the coefficient b_1 by the density of the glass-fiber products ρ (Fig. 3b) is of the form

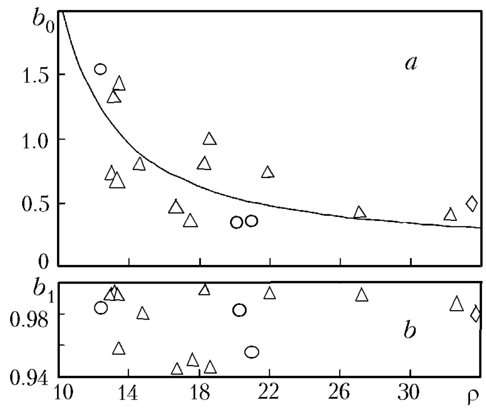
$$b_1 = \frac{\rho - 7.7}{\rho} \quad (S_{cal} = 0.192\,,\ \ \eta^2_{\rho b_1} = 0.539)\,, \tag{8}$$

and the value of the coefficient b_1 for the mineral-wool products can be taken to be equal to 0.9878.

The values of the determination coefficient for the regression dependences (6)–(8) show that the change in the coefficients b_0 and b_1 of the regression equation (1) is to a greater extent due to the variation in the content of the synthetic binder and to a lesser extent to the variation in the density of the products.

The values of the equilibrium specific moisture content of the glass-fiber and mineral-wool products calculated with the use of the coefficients b_0 and b_1 computed according to (6)–(8) differ from the values calculated by b_0 and b_1 from Table 1 by ±15% on average in the range of relative air humidity from 40 to 80% and by no more than ±20% in the range between 90 and 97%.

Foam Polystyrene Boards. We have investigated specimens of foam polystyrene boards manufactured by a nonpressing technique — foaming of foam plastic in a closed volume of the reactor [17] from a raw material in the form of beads (solid granules with ∅(0.9–2.5) mm) of the companies StyroChem (Finland), BASF (Germany), and Dwory SA (Poland).



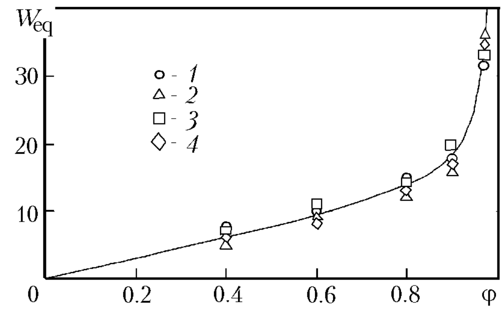


Fig. 4. Coefficients b_0 and b_1 of Eq. (1) as a function of the density of the foam polystyrene boards of different manufacturers. ρ, kg/m^3.

Fig. 5. Isotherms of water vapor sorption by ecowool [Manufacturers: 1) closed stock company Ekorema, Lithuania, 1998; 2) the same, 2002; 3) stock company Walsekto, Estonia; 4) Selluvilla-SV, Finland).

The coefficients b_0 and b_1 of the empirical dependence (1) and the mean values of $\overline{W}_{eq}$ of foam polystyrene calculated by it are given in Table 2. The values of W_{eq} are given in mass percent, since exactly this quantity has approximately the same value at any density of the material. But if the moisture content is given in volume percent, then its value would double, e.g., at a doubled density.

The investigated foam polystyrene exhibits an insignificant hygroscopicity. The value of $\overline{W}_{eq}$ at $\varphi = 0.97$ does not exceed 2.32%. As the density of foam polystyrene is increased, its hygroscopicity decreases (see Table 2). Based on the results of the experiment performed, we give in Fig. 4 the values of the coefficients b_0 and b_1 depending on the foam polystyrene density. There is an increase in the coefficient b_0 in the region of the smaller density of the material. The relation between the coefficient b_0 and the density of foam plastic is approximated by the dependence (Fig. 4a)

$$b_0 = 0.138 \exp(27.3/\rho) \tag{9}$$

with a standard deviation $S_{cal} = 0.278$.

Analyzing the experimental data obtained, it can be noted that the coefficient b_0 largely depends on the foam polystyrene density in the range between 12 and 20 kg/m^3, and at a density higher than 20 kg/m^3 it changes but slightly. From Fig. 4b it is seen that the coefficient b_1 is practically independent of the material density. According to the experimental data ($n = 15$), its mean value is 0.9769 with a standard deviation equal to 0.0198, and in calculating the values of the equilibrium specific moisture content of polystyrene foam plastic by Eq. (1), the value of the coefficient b_1 can be considered to be constant.

Ecowool*. We have investigated the ecowool produced by the closed stock company Ekorema (Lithuania) and the stock company Walsekto (Estonia) with the use of the Makron technology and equipment (Finland). We have also analyzed the indices of the equilibrium specific moisture content of the analogous material Selluvilla-SV (Finland) [18]. The experimental data on the dependence of the equilibrium specific moisture content W_{eq} of the ecowool specimens on the relative air humidity φ are given in Fig. 5, and the coefficients b_0 and b_1 of relation (1) and the mean values of $\overline{W}_{eq} = f(t)_T$ calculated by it are presented in Table 3.

The investigated ecowool exhibits an appreciable (sorbed) hygroscopicity which can reach 34 mass % at a relative air humidity $\varphi = 0.97$. A considerable portion of the sorption moisture is absorbed at $\varphi > 0.8$, which is characteristic of the capillary mechanism of sorption. There is a comparatively insignificant spread of experimental values of W_{eq} of the ecowool of different companies.

*Light downy cellulose wool is ground chipboard or paper waste (up to 82 mass %) with harmless chemical additives of crystalline boric acid (9–12 mass %) and borax (8–10 mass %).

TABLE 3. Results of Statistical Processing of the Experimental Data on the Equilibrium Specific Moisture Content of the Ecowool (T = 20°C)

ρ	Additives, mass %		Values of coefficients of Eq. (1)		S_{cal}, mass %	φ						
						0.1	0.2	0.4	0.6	0.8	0.9	0.97
	Boric acid	Borax	b_0	b_1		$\overline{W}_{eq}^*$						
35—44	7.5—12.0	8.0—9.5	14.84	0.96	1.1	1.5	3.0	6.1	9.4	13.8	18.2	33.0

*Calculated by the empirical relation (1)

Thus, the isotherms of water vapor sorption by the glass-fiber and mineral-wool products, foam polystyrene boards, and ecowool have been determined. The obtained experimental values of the equilibrium specific moisture content of the investigated materials in the range of the relative air humidity from 0 to 97% are given by the two-constant regression equation (1). The degree of influence of individual factors on its constant coefficients b_0 and b_1 has been determined.

NOTATION

b_0, b_1, constant coefficients depending on the material properties; n, number of experiments; m, number of evaluated constant coefficients in empirical equations; r^2, determination coefficient at linear dependence; S_{cal}, standard deviation; T, temperature, °C; W_{eq}, equilibrium specific moisture content, vol. % (mineral-wool and glass-fiber products), mass % (foam polystyrene boards, ecowool); $M_{o.b}$, content of organic binder, mass %; Z, mass content of binder, kg/m^3; η^2, determination coefficient at curvilinear dependence; ρ, density, kg/m^3; φ, relative air humidity. Subscripts: eq, equilibrium; o.b, organic binder; cal, calibration.

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