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Theoretical and experimental research on foam gypsum drying process

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Nowadays in the world the technical progress in the construction of buildings is aimed at the use of materials with desirable properties where in multilayer constructions each layer carries out the functions it is assigned to. Gypsum binders are widely used in manufacturing gypsum paperboard, sound insulation material, in building monolithic one-to-two storey houses, etc. In all these fields foam gypsum is an appropriate material. The drying of gypsum products is an obligatory requirement for the technological process, that essentially influences both its physical (density, heat conductivity coefficient) and mechanical (strength indicators in dried gypsum are several times higher than in a wet sample) properties. However, according to the requirements of the manufacturing technology of foam gypsum, the initial moisture content in the material should be very high. Therefore the research on foam gypsum drying is of particular importance. It is possible to theoretically describe the drying process in foam gypsum by means of two mathematically connected models. It has been demonstrated that experimentally the drying of foam can be researched wih electrical methods, which do not destroy the material during the process of research.
Key words: moisture, thermal insulation, foam gypsum.

1. Materials and methods

In order to test the obtained theoretical results, a range of foam gypsum samples were made with the final density in the dry condition of approximately 670 kg/m^3 and the research on their drying at room temperature 20 - 22 $^\circ$C and relative air humidity 30-40%. The following description presents the physical data of one of the most typical sample. The moisture content of foam gypsum was calculated according to the following formula

$$W = \frac{m}{V}, \quad (1)$$

where m – water mass in the sample, kg; V –volume of foam gypsum sample, m^3.

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Usually the initial moisture content is high W = 300 – 350 kg/m^3 or (45 – 50%) in relation to a dry sample.
Experimentally the drying speed of the sample is determined by the following formula

$$\varphi = \frac{1}{S} \cdot \frac{\Delta m}{\Delta t}, \tag{2}$$

where φ – drying speed of the sample, kg/(m^2 s); Δm – change of mass, kg; Δt – interval of time, s; S – surface area of the sample, m^2.
According to our theoretical calculations, the drying time of the sample is inversely proportional to the thickness squared (formulae 7, 10). Therefore, the thickness of the sample was chosen d = 10 cm, so that the drying time would be within 2 months. All the surfaces of the sample, except the top surface through which the moisture evaporates (Fig. 1), are covered with a vapour barrier.
During the process of drying the average moisture content in the sample was determined by weighing the sample with the scales manufactured by the company KERN, the maximum allowable weight of which is 16100.0 g, but sensitivity ± 0.2 g. The surface area of the sample was chosen 0.1 m^2 in order not to exceed the maximum allowable weight value. To electrically check the moisture changes in the sample, two pairs of electrodes were inserted in the sample during the pouring process with the distance between the electrodes being 14 mm, the height 15.5 mm and the length 112 mm. Electrical resistance and capacity were measured with an HIOKI alternate current bridge HIOKI 3532-50 at the frequency 1 MHz in the parallel equivalent scheme.

2. Theoretical research

In most cases moisture drying theoretical models is based on the solution of a simple diffusion equation (Togrul I. T., Pehlivan D., 2003, Sharaf-Eldeen Y.I. et al. 1980). However, they cannot describe the changes of moisture in the material in time accurately enough (El-Beltagy et al., 2007). Therefore we offer to describe the drying process on the basis of the solution of diffusion equation in two interconnected stages with different borderline conditions in each stage.

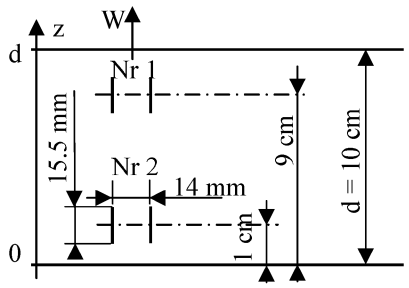

Fig. 1. Cross section of the foam gypsum sample. Thickness of the sample d-10 cm, distance between electrodes 14 mm, height of electrodes 15.5 mm, length of electrodes perpendicularly to the depicted plane 112 mm.

Right after the pouring of samples the initial moisture content in foam gypsum is high - approximately 350 kg/m^3 of free unbound water. Under these conditions it is expected that initially evaporation from surface of the sample will take place at a constant speed, which is determined not by the properties of the sample material, but by the temperature and relative moisture of the ambient air. Thus, the mathematical model of the drying for the sample which has been

freshly poured, initially (in the Ist stage) would be the following. In the sample with the thickness d the moisture W_I diffunds in the direction of the axis z (Fig. 1). The sample whose initial moisture

$$W_I\big|_{t=0} = W_S\,, \tag{3}$$

where W_s- initial moisture of the sample kg/m^3; t – drying time, s;
on one side (z=0) is covered with a vapour barrier or there is a sample symmetry plane (middle), if both sides of the sample do no contain moisture drying limitations. It means that on the surface z=0 the will be in force a borderline condition (4), but through the outer surface z=d drying with constant speed φ will take place, which is described by the borderline condition (5). The process is subjected to Fick's equation (6).

$$\left.\frac{\partial W_I}{\partial z}\right|_{z=0} = 0\,. \tag{4}$$

$$-D\left.\frac{\partial W_I}{\partial z}\right|_{z=d} = \varphi\,, \tag{5}$$

$$\frac{\partial W}{\partial t} = D\frac{\partial^2 W}{\partial z^2}\,, \tag{6}$$

where D- diffusion coefficient, m^2/s.
Solving the mathematical physics problem (3 - 6), with the variable separation method, the following is obtained

$$W_I(t;z) = W_S - \frac{\varphi\cdot t}{d} - \frac{W^*}{2}\left(\frac{z^2}{d^2} - \frac{1}{3} - \frac{4}{\pi^2}\sum_{k=1}^{\infty}\frac{(-1)^k}{k^2}\cdot\cos\frac{\pi k z}{d}\cdot\exp\left(-\frac{\pi k^2}{d^2}Dt\right)\right), \tag{7}$$

where – $W^* = \dfrac{\varphi\cdot d}{D}$, kg/m^3.

In the course of time, the sample dries and after a certain time t_{cr}, when the first stage of drying period is completed, on the surface of the sample z=d, the moisture has reached the equilibrium moisture W_0. From this time (t_{cr}) on the sample, has entered the second stage of drying, in which the drying speed φ(t) is determined by the physical parameters of the sample material. Now it decreases depending on the time (Fig. 2) and is lower than the initial constant drying speed φ of the first stage. It means that in the second stage of drying the initial condition (3) and borderline condition (5) change. The initial condition at time t_{cr} is given by the solution of the first stage (7), but instead of the borderline condition (5) we obtain (9)

$$W_{II}\big|_{t-t_{cr}=0} = W_I(t_{cr};z)\,. \tag{8}$$

$$W_{II}\big|_{z=d} = W_0\,, \tag{9}$$

where W_0 – equilibrium moisture kg/m^3.

Also in the second stage of drying, the equation (6) is preserved. Then, solving the problem (4, 6, 8, 9) by means of a variable separation method, we obtain the following:

$$W_{II}(t-t_{cr};z)=W_0+\sum_{n=0}^{\infty}A_n\cos\frac{\pi}{2d}(2n+1)z\cdot\exp\left(-\frac{\pi^2(2n+1)^2}{4d^2}D(t-t_{cr})\right), \tag{10}$$

$$A_n=\frac{(-1)^n}{\pi}\left(\left(W_s-W_0-\frac{\varphi}{d}t_{cr}+\frac{W^*}{6}\right)\cdot\frac{4}{2n+1}-\frac{2W^*}{2n+1}\cdot\left(1-\frac{8}{\pi^2}\cdot\frac{1}{(2n+1)^2}\right)-\right.$$
$$\left.-\frac{8W^*}{\pi^2}\sum_{k=1}^{\infty}\frac{2n+1}{k^2}\cdot\frac{1}{(2k)^2-(2n+1)^2}\cdot\exp\left(-\frac{\pi k^2}{d^2}Dt_{cr}\right)\right). \tag{11}$$

Experimentally when weighing the samples, the average moisture <W> was determined depending on time. Thus, the moisture experimental measurements depending on time should be theoretically compared with the integral.

$$<W(t)>=\begin{cases}\frac{1}{d}\int_0^d W_I(t;z)dz=W_s-\frac{\varphi\cdot t}{d}, & \text{if } t<t_{cr};\\ \frac{1}{d}\int_0^d W_{II}(t;z)dz=W_0+\frac{2}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^nA_n}{2n+1}\cdot\exp\left(-\frac{\pi^2(2n+1)^2}{4d^2}D(t-t_{cr})\right), & \text{if } t>t_{cr}.\end{cases} \tag{12}$$

Using this comparison, it is possible to calculate the unknown values t_{cr}, φ, D, W_0 by means of the least square method. For the given foam gypsum sample the following was obtained:

$$t_{cr}=20.89\,d=1.8\cdot10^6\ s;\quad \varphi=1.38\cdot10^{-5}\ kg/(m^2 s);\quad D=4.89\cdot10^{-9}\ m^2 s;\quad W_0=0. \tag{13}$$

The obtained drying speed φ under the given external conditions are from 30 to 40 % more than from a free water surface. We attribute it to the fact that the effective drying surface of a porous material - foam gypsum is correspondingly larger, but additional research is necessary here.

Equilibrium moisture W_0 cannot be determined from this model, therefore it should be accepted as equal to zero, but its influence can show up, if the external conditions of the sample drying (temperature and relative moisture of the surrounding air) during the time of the experiment are substantially changing.

The drying speed depending on time can be determined by means of the following formula:

$$\varphi(t)=\begin{cases}-D\left.\frac{\partial W_I}{\partial z}\right|_{z=d}=\varphi, & \text{if } t<t_{cr};\\ -D\left.\frac{\partial W_{II}}{\partial z}\right|_{z=d}=D\cdot\frac{\pi}{2d}\sum_{n=0}^{\infty}(-1)^nA_n\cdot(2n+1)\cdot\exp\left(-\frac{\pi^2(2n+1)^2}{4d^2}D(t-t_{cr})\right), & \text{if } t>t_{cr}.\end{cases} \tag{14}$$

Fig. 2a shows the comparison of the experimental moisture measurements obtained by the weighing (points in Fig. 2a) with the integral (12) depending on time, but in Fig. 2b with points are shown experimental drying speed measurements, which were obtained using the formula (2) and theoretically calculated drying speed depending on time, which is generated by the expression equation (14)), at higher obtained (13) values.
Fig. 3 taking into consideration (7, 10) shows the theoretical distribution of moisture inside the sample along the coordinate z at different drying times, which are numbered from 1 to 9. The curve 5 shows the distribution of moisture at $t = t_{cr}$=20.89 d. With the times $t < t_{cr}$ the distribution is calculated with the expression (7), but at $t > t_{cr}$ with the expression (10). As can be seen from the curve 5, the borderline (critical) time is reached when the moisture on the exterior surface of the sample (z/d=1) approaches zero.

3. Experimental part

In order to determine the moisture of the sample experimentally without using destructive methods, during the pouring of the sample, two pairs of electrodes were inserted in the sample (Fig. 1) with the immersion depths of 1 and 9 cm. As at the coordinate z=0 the vapour barrier was put on, the moisture way is possible only in the direction of axis z (W). During the drying process of the samples the resistance and the capacity between the electrodes were measured. At smaller levels of moisture reactive resistance is determinative, therefore, the capacity change can be used for measuring moisture.
Fig. 4 shows the capacity change for the pairs of electrodes 1 and 2 (Fig. 1) depending on the average moisture, which is obtained by weighing the sample.
As there exists a distribution of moisture in the sample (Fig. 3), by using the mathematical model it is possible to recalculate the capacity change shown in Fig. 4, depending on the real moisture W in the respective depth of the sample, taking into account the fact that the pair of electrodes Nr 2 is in an increased, but the pair Nr 1

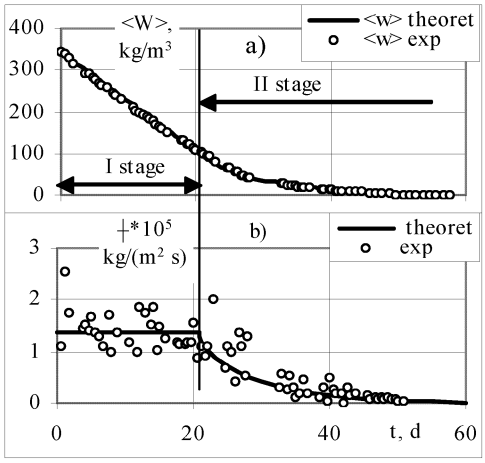

Fig. 2. Comparison of theoretical and experimental average moisture (a) and drying speed (b) the sample depending on drying time.

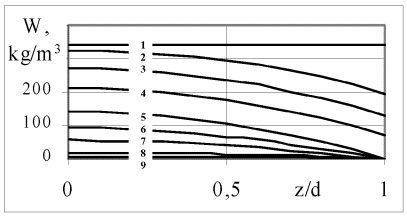

Fig. 3. Theoretical distribution of 1- initial moisture (t=0, W_1=343.6 kg/m^3); for further numbers in Fig. 2 – 9 (presented as indices) times of drying in days are given 5_2; 10_3; 15_4; t_{cr}=20.89$_5$; 25_6; 30_7; 40_8; 50_9.

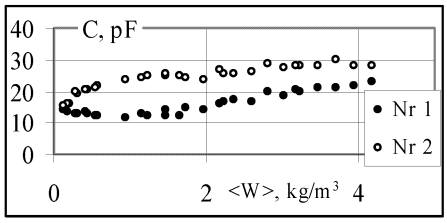

Fig. 4. Capacity changes for electrode pairs Nr.1 and Nr.2, which are shown in Fig.1 depending on the average moisture of the sample.

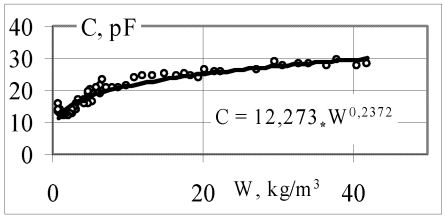

Fig. 5. Capacity between the electrodes depending on the actual moisture in the corresponding depth.

is in decreased moisture conditions, comparing to the average <W>, which is obtained by weighing the sample. After the respective recalculation instead of Fig. 4 we obtain Fig. 5. As can be seen in Fig. 5 experimentally found points are positioned on the curve, which can be described with power function.

At high moisture values the moisture in foam gypsum can be determined with the conductometric method. In foam gypsum the dependence of electric resistance on moisture has a hyperbolic character (Iljins U., et. al., 2008). Since practically foam gypsum in building is used only at low moisture, this dependence has only an indicative character.

Conclusions

1. Mathematical drying model has been created, which adequately describes the experimental research.
2. The moisture content in foam gypsum samples can be determined with the electrical methods which do not destruct the material (at small moisture with capacitive measurements, but at increased moisture by means of the conductometric method).

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