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Modeling of Multi - Layer Foam Gypsum Drying Process

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Foam gypsum is a perspective material in construction. According to the requirements for the manufacturing process of foam gypsum, the initial moisture content should be very high. Drying of these products is obligatory requirement to obtain material with sufficient properties. It is possible to change the density of foam gypsum with hemp fibrous reinforcement technologically varying mechanical strength, thermal conductivity and sound absorption coefficients.

In the constructions of buildings foam gypsum can be used as filler bounded by gypsum paperboard. In this work we aim to study the moisture transfer in multi-layered wall as usual in construction design. It is important to clarify the structural drying time and the factors that allow it to shorten. For this sample arrangement it is not possible to correct analytical description of drying process. A numerical method is used for calculation of moisture content.

Drying process of foam gypsum coated with gypsum paperboard was researched with gravimetric and electrical methods. The validity of the numerical model was verified by comparison with experimental results.

1. Introduction

Nowadays multilayer walls, consisting of a framework, which on both sides is attached to the gypsum board, the mid- filled with a light, porous or fibrous material, became popular in the field of building construction. These walls, consisting of several layers are significantly better than the same material single layer, since they have many environmental benefits like low thermal conductivity, good sound absorption qualities and humidity buffering capacity. Light party wall structure may be formed by gypsum plates between which is placed absorbent material such as mineral wool, or by filling the void with solid lightweight filler as foam gypsum or hemp concrete. In this case some compaction of the material over a period of time or any problems arising during material drying must be taken in account. For different constructive systems the authors developed a new foam gypsum with hemp fibrous reinforcement composite, characterized by good heat (Skujans et al., 2007) and sound insulating properties (Brencis et al., 2011). Material with density 250 to 300 kg/m^3 is characterized by 0.07 to 0.08 W/(m K) thermal conductivity coefficient (Skujans et al., 2007) and the design, consisting of plasterboard with 10 cm foam gypsum hemp fibers composite filling, show sound insulation index R values greater than 45 dB (Brencis et al., 2012). According to the requirements for the manufacturing process of foam gypsum, the initial moisture content should be very high. Therefore it is important to clarify the structural drying time and the factors that allow it to shorten. Covering porous media with plasters significantly changes the hydrothermal properties of walls. When plasters are applied on hemp concrete, heat transfers are almost not modified, but moisture transfers are noticeably dampened (Colinart et al., 2013). The same results are obtained for gypsum walls coated with paint layer (Goosens, 2003). Therefore indoor humidity variations are more dampened compared with the external environment.

Drying process in foam gypsum is described by means of two mathematically connected models (Iljins et al., 2009). Theoretical model makes it possible to calculate local humidity conditions in different layers of sample during drying time. It is particularly important in the case of foam gypsum with hemp fibrous reinforcement to detect the moment, when moisture content during drying is about 10 kg/m^3, because under these conditions the material changes its physical - mechanical characteristics very quickly (reach

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design values): mechanical strength and thermal conductivity (Skujans et al., 2007). It is then possible to design a technological processing of foam gypsum constructions.

To validate the theoretical model conduct – metrical measurements were used for experimental research of foam gypsum drying process (Gross et al., 2013). Resistance measurements of moisture content in the sample can be used for high moisture content $W > 30$ kg/m^3. Capacitance measurements can be used for low moisture content $W < 30$ kg/m^3.

In this work we aim to study the moisture transfer in multi-layered wall as usual in construction design.

Moisture content in the sample was controlled by conduct – metrical measurements. We confirmed that electrical measurements are a useful nondestructive method for drying process control in porous materials (Iljins et al., 2008) and elaborated more recently (Gross et al., 2013). Comparing theoretical results with experimental ones should allow us to understand drying process in multi-layered walls.

2. Materials and methods

In order to investigate drying process in multi-layer constructions foam gypsum sample with hemp fibrous reinforcement was used. Sample final density in the dry condition was 410 kg/m^3. Thickness of the sample was chosen d_1 = 10 cm. All the surfaces of the sample, except the top surface, were covered with a vapor barrier. Top surface was covered with gypsum plasterboard with thickness d_2 = 1.3 cm (Figure 1). During the process of drying the average moisture content in the sample was determined by weighing the sample with scales manufactured by the company KERN, the maximum allowable weight of which is 16,100.0 g, but sensitivity ± 0.2 g. In order not to exceed the maximum allowable weight value, the surface area of the sample was 0.16 m^2. To electrically check the moisture changes in the sample, four pairs of electrodes with different immersion depths were inserted in the sample during the drying process with the distance between the electrodes being 15 mm, the height 15 mm and the length 120 mm (Figure 1). Electrical resistance and capacitance were measured with an HIOKI alternate current bridge HIOKI 3532-50 at the frequencies 0.5, 5, 50, 500 and 5,000 kHz in the parallel equivalent scheme. RF signal level was 1 V. During the drying process of the samples the resistance and the capacitance between the electrodes were measured. Above this frequency range the system capacitance was determined to be 18 – 22 pF. The data presented are corrected for this capacitance. We have used an automatic set-up with PC-based control and data register every 6 hours during sample drying.

3. Theoretical results

One-dimensional diffusion is a good approximation for most real situations (Iljins et al., 2009). Construction systems – foam gypsum with hemp fibrous reinforcement (FGH) and non-removable gypsum plasterboard (Figure 1) we will consider as composed of the two areas (1) and (2). The drying process in porous materials could be represented as diffusion phenomenon according Fick's law

$$\frac{\partial w_i}{\partial t} = D_i \frac{\partial^2 w_i}{\partial z^2}, \tag{1}$$

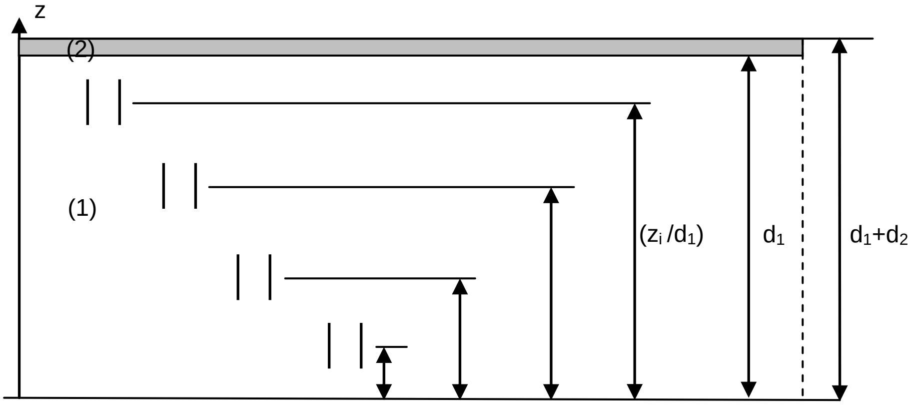

Figure 1: Cross section in region (1) of sample with inserted electrodes. Average immersion depth (z_i/d_1) were i: i=1 – 0.2230 (bottom); i=2 – 0.4015; i=3 – 0.5750; i=4 – 0.7675 (upper pair). Region (2) - gypsum plasterboard.

where D_i - diffusion coefficients, m^2/s;

w_i - moisture content, kg/m^3 for (FGH) and gypsum plasterboard, respectively;

z - coordinate, m;
t – time, s.

At z = 0 we assume that there is moisture transfer barrier. Then the corresponding boundary conditions are

$$\frac{\partial w_1(0)}{\partial z} = 0\,. \tag{2}$$

On the border z = d_1 let us use the cross-linking conditions

$$w_1(d_1) = w_2(d_1);$$
$$-D_1 \frac{\partial w_1(d_1)}{\partial z} = -D_2 \frac{\partial w_2(d_1)}{\partial z}. \tag{3}$$

The boundary conditions on external surface z=d_1 +d_2 changes during time. It is useful to distinguish three phases of drying

Phase 1; 0 ≤ t ≤ $t_{cr1.}$

In this phase, inside the area (1) initial moisture content of (FGH) w_s

$$w_1\big|_{t=0} = w_{s,} \tag{4}$$

but moisture content in gypsum plaster

$$w_2\big|_{t=0} = w_0\,, \tag{5}$$

where w_0 - equilibrium moisture.

The conditions Eq(4) and (5) can be considered the initial conditions of the first phase of the drying conditions. This drying phase boundary conditions on the surface z = d_1 + d_2 will be recorded shall form

$$w_2\big|_{z=d_1+d_2} = w_0\,. \tag{6}$$

This means that moisture has not yet passed through the gypsum plasterboard. In this first stage of drying diffusion of liquid water through gypsum plaster is a main mass transfer mechanism. Let us consider, that at the time t = t_{cr1}, the free water appears on external surface of gypsum plasters and opens the second drying phase.

Phase 2; t_{cr1} ≤ t ≤ t_{cr2}.

During this phase the drying rate is determined by the ambient air temperature, relative humidity, air velocity, the degree of surface smoothness. Suppose that the drying rate is φ, than we can write the second drying phase boundary conditions on the outer surface of the gypsum plaster

$$-D_2 \frac{\partial w_2}{\partial z}\bigg|_{z=d_1+d_2} = \varphi, \tag{7}$$

where φ - drying rate, kg/(m^2 s).

As a starting condition second phase will consider the distribution of moisture w_1 (t_{cr1}) and w_2 (t_{cr1}) in the area (1) and (2) at the end of the first phase at time t = t_{cr1}. As time passes moisture content on the outer surface of (FGH) increases and then decreases, reaching at time t = t_{cr2} equilibrium value w_0. This moment of time can be seen as the beginning of the third phase of drying.

Phase 3; t_{cr2} ≤ t.

In the third phase the boundary condition on the outer surface of (FGM) is an Eq(6). The start condition will be moisture distribution w_1 (t_{cr2}) and w_2 (t_{cr2}) in regions (1) and (2) at the end of the second stage at time t = t_{cr2}. Described in mathematical physics problems can be solved by the final method of difference. The time step Δt must be chosen small enough to ensure that the process of convergence

$$\Delta t < \frac{\Delta z_2^{\,2}}{6D_2}, \tag{8}$$

where Δz - difference along the z axis [in region (1) – 0.005 mm, in region (2) – 0.001 mm] (Figure 1).

In according with Eq(8) we choose time step $\Delta t = 60$ s. Since the experimentally measured sample weight change, the model described by the least squares method it is possible to determine the unknown parameters of the model: D_2, φ, t_{cr1}, t_{cr2}. D_1 in this model should be regarded as certain to ensure the convergence of the process and it can be determined from the literature (Brencis et al., 2012) at $\rho = 410$ kg/m^3: $D_1 = 4.8 \cdot 10^{-9}$ m^2/s.

The least squares method gives: $D_2 = 2.57 \cdot 10^{-9}$ m^2/s; $\varphi = 4.48 \cdot 10^{-6}$ kg/m^{2}s; $t_{cr1} = 0.34$ d; $t_{cr2} = 32.3$ d.

Numerical calculation results of moisture distribution in dependence on the drying time at different layers of the sample are shown in Figure 2. The results show, that gypsum plasterboard acts as diffusion barrier to moisture transfer. Thus, the distribution of moisture gradient along the z axis is quite small. This means that no significant differences of experimental moisture content measurements with electrodes inserted at different sample depth are expected (Figure 1). The same picture appears on the theoretical calculation results of the moisture content on drying time at the z coordinate values of 1: z = 0 [bottom - there is water flow barrier formula (2)], 2: z = 0.1 m – gypsum plasterboard and (FGH) contact plane and 3: z = 0,113 m – gypsum plasterboard upper free surface through which occurs moisture drying process; 4: experimental average moisture content obtained from a sample weighing (Figure 3). The figure shows that the highest moisture gradient is directly in gypsum plasterboard, which hinders the drying process. These results are confirmed by the theoretical calculation of moisture content distribution in the sample on the coordinate z at different drying times (Figure 4). It can be seen that the changes of moisture content along z axis in region (1) (FGH) are small at all moments during drying time. If the drying time $t < t_{cr1} = 0.34$ d, in accordance with the boundary conditions (6) on the surface $z = d_1 + d_2 = 0.113$ m moisture content will be equal to the equilibrium moisture w_0 and plaster have high moisture gradient. The same is true also if $t > t_{cr2} = 32.3$ d. It is clear visible to the drying times 40.13 d and 70.13 d (Figure 4).

4. Experimental results and discussion

The drying process of sample was carried out in a chamber at 20 °C temperature. Measurements were taken every 6 h. Experimental average moisture content obtained by sample weighing is shown in Figure 3. Coating (PGH) with gypsum plasterboard increases the drying time of 2 to 3 times compared to corresponding sample without coating (Gross et al., 2013). The resistance between the pairs of electrodes placed in the sample (Figure 5) gives adequate information about the moisture content changes in the sample at various depths during the drying process, the first 30 d, when the average moisture content is reduced to about 80 kg/m^3. A further decrease in moisture content leads to shrinkage of the sample resulting in resistance measurements not giving adequate information about the moisture content in the appropriate depth. Further decrease in moisture content shows capacity measurements of the pairs of electrodes in corresponding depths better (Figure 6). Drying rate reduction associated with gypsum plasterboard, resulting in a decrease in the resistance and capacitance measuring variations in the

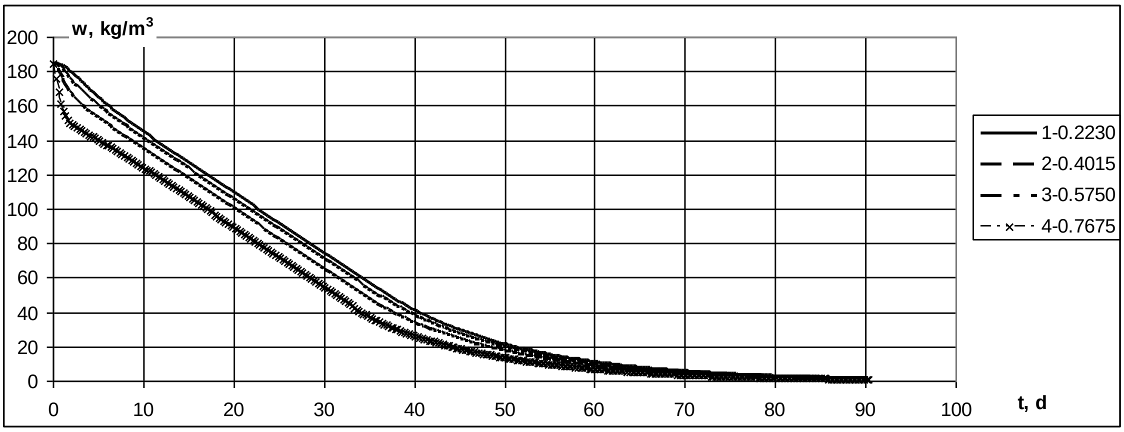

Figure 2: Plots showing theoretical moisture content in different sample depths zi/d1 versus drying time, where zi/d1: 1 – 0.2230 (bottom pair of electrodes); 2 – 0.4015; 3 – 0.5750; 4 – 0.7675 (upper pair).

different sample depths and at selected experimental geometry (sizes of electrodes and distances), therefore these measurements are not always accurately showing the distribution of moisture content in the sample corresponding depths. Overall, however, the resistance and capacitance measurements allow you to control this type of material drying - curing process.

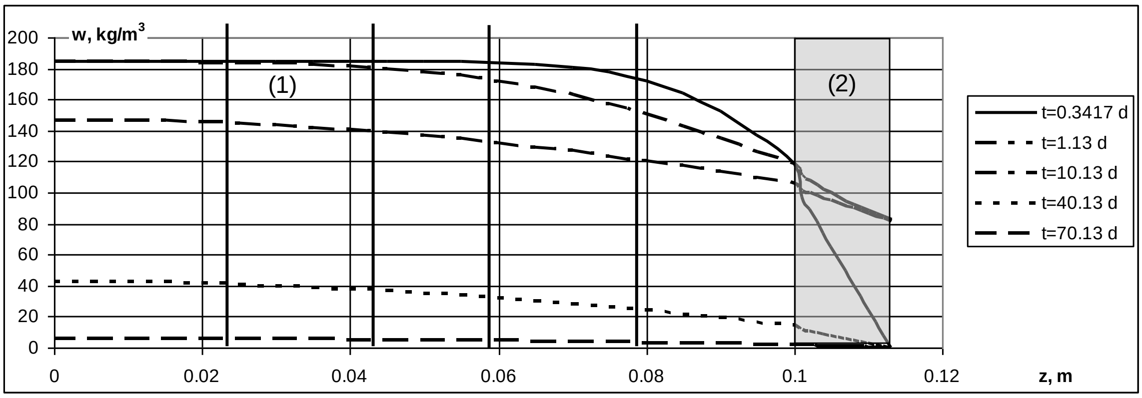

Figure 3: Theoretical calculations of moisture content of the sample at different depths (zi) on the drying time, where zi: 1 – 0 (bottom); 2 – 0.100 gypsum plasterboard and (FGH) contact plane; 3 – 0.113 free surface of gypsum plasterboard, 4 – experimental average moisture content obtained by sample weighing

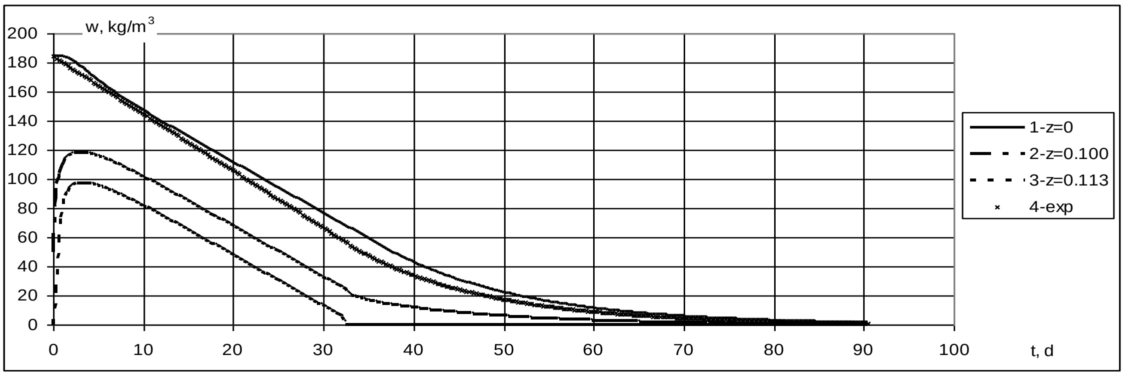

Figure 4: Theoretical calculations of moisture content distribution for different drying time depending on the coordinate z; z=0 – 0.1 m region (1) (FGH); z=0.1 – 0.113 m region (2) gypsum plasterboard (grey area). The vertical lines shows the depths of the sample, where the *pairs of electrodes placed.*

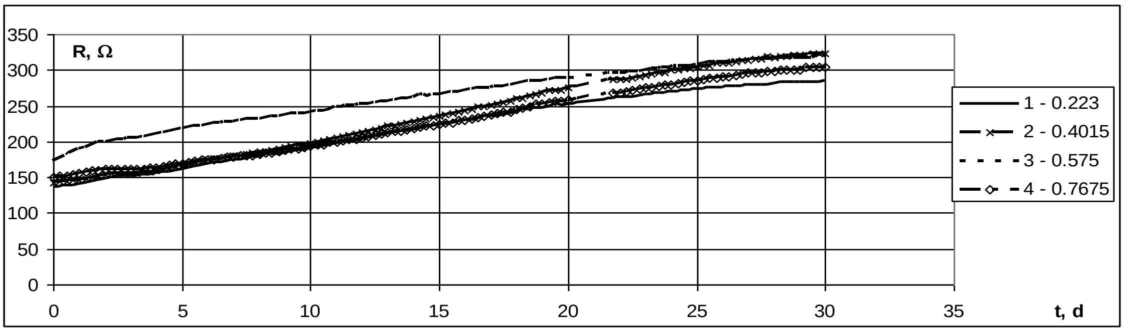

Figure 5: Resistance between inserted pairs of electrodes in dependence of drying time at different immersion depth (z_i/d_1), were i: 1 – 0.2230 (bottom); 2 – 0.4015; 3 – 0.5750; 4 – 0.7675 (upper pair), frequency - 5MHz.

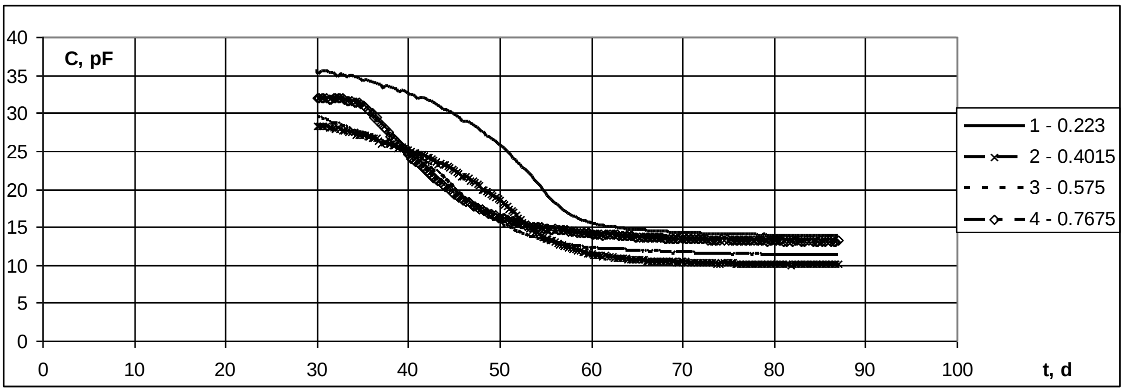

Figure 6: Capacitance of inserted pairs of electrodes in dependence of drying time at different immersion depth (z_i /d_1), were i: 1 – 0.2230 (bottom); 2 – 0.4015; 3 – 0.5750; 4 – 0.7675 (upper pair) frequency - 5MHz.

5. Conclusions

One-dimensional diffusion model is a good approximation for drying process. Numerical method makes it possible to calculate the dynamic of drying process, in multi-layered systems. Theoretical results are confirmed by experimental measurements at different sample depths by the conduct-metrical method. Coating foam gypsum with hemps reinforcement with gypsum plasterboard increases the drying time of 2 to 3 times compared to correspond sample without coating. In order to shorten the drying time is recommended to use removable moulds.

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