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Research on Fire Safety Parameters on Foam Gypsum Products

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The study examines determination of fire influencing parameters in foam gypsum products, such as fire resistance, fire reaction class, performance of foam gypsum boards in high temperatures. Taking into consideration the high fire resistance of gypsum, it may have significant role in the construction of fireproof structures, not only as fireproof boards, but also as acoustic boards. Foam gypsum is a perspective construction material not only of high fire resistance, but also of good acoustic and heat insulating properties. Foam gypsum content includes gypsum, i.e. calcium sulphate dihydrate, $CaSO_4$ $2H_2O$, characterized with the chemical reaction of gypsum at high temperature and energy absorption. As a result of physical chemical processes the foam producer forms a porous structure of the material. Such material provides A1 fire reaction class. Based on these properties and varying the foam gypsum content and production technology, a material of wide application can be acquired, because it provides meeting of such basic requirements of construction materials as fire safety, hygiene, protection against noises, heat insulation and sustainable use of nature resources.

Introduction

One of the most important basic requirements of structures is fire safety, which provides retention of the carrying capacity of structures provides safe exit for users from structures and limits fire expansion. Most often fire safety requirements in construction of buildings are met with the help of passive fire safety solutions. The good fire protection qualities of gypsum products as a material have been known and observed already long before. These qualities are known to provide the necessary requirements of the bearing structures for the increase of fire protection (Marani, 1916), related to the thermo chemical reaction of gypsum (Dean, 1968). Nowadays for the implementation of fire safety requirements metal and wood frame structures with gypsum board panelling are used. Pure gypsum is calcium sulphate dihydrate $CaSO_4 \cdot 2H_2O$, which is a crystalline mineral containing approximately 21 % of crystalline bound water and approximately 79 % of calcium sulphate. When heating gypsum to 100 – 120 °C, it partially dehydrates, losing 75 % of the chemically bound water (Mehaffey et al., 1994), which results in the start of gypsum collapse (Benichou and Sultan, 2005) Continuing heating to 200 – 250 °C second reaction of dehydration takes place, as a result of which gypsum loses the remaining 25 % of chemically bound water resulting in decreased heat conductivity of gypsum boards (Wakili and Hugi, 2009). During these reactions layer of water steam forms on the surface of gypsum boards, slowing down the heating of the material.
Former studies have proved the good properties of gypsum products in high temperatures (Manzello et al., 2007). Up to now, studies of foam gypsum products have been implemented, related to the drying process of foam gypsum (Skujans et al., 2010), absorption of noise (Bencis et al., 2012), reinforcing possibilities (Gross et al., 2013), but there are no studies about the effects of high temperatures on foam gypsum products. The widely used gypsum boards have the volumetric weight of 600 - 900 kg/m^3, but foam gypsum can be acquired with the volumetric mass of 250 – 350 kg/m^3. This provides the possibility to incorporate fire resistance of gypsum and beneficial properties of porous materials in foam gypsum..

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The goal of this study is to experimentally examine the fire resistance of foam gypsum boards in high temperature and to create a comparatively simple theoretical board heating model based on experimental studies for the prediction of foam gypsum board fire resistance.

Materials and methods

Tests of fire resistance have been executed using samples of pure foam gypsum without organic reinforcement or filling additives. As the main ingredient for the production of foam gypsum β $CaSO_4 \cdot 0.5H_2O$ industrial gypsum of 2,550 kg/m^3 density has been used with grinding fineness of 3.86 g (7.72 %) and bounding time of 18 min 30 s. Foam concentrate STHAMEX®–AFFF 3 % F-15 has been used as surfactant substance. For determination of fire resistance of foam gypsum boards in high temperatures, samples of foam gypsum have been used with the volumetric mass of 250 - 300 kg/m^3, in sizes 300 x 300 mm and depth from 25 mm to 60 mm.

For the study tests of fire resistance a small-sized experimental device – furnace has been used (Figure 1). Furnace has been produced of Knauf FIREBOARD 20 mm boards and of removable internal panelling from Knauf GKB 2 x 12.5 mm boards. As the furnace heating element laboratory burner BOCHEM Meker-Ficher with maximum temperature of 1,300 °C has been used, which is connected to propan-butan gas cylinder. The lower part of the furnace has Ø40 mm opening for the insertion of Meker type burner, but the top of the furnace has opening 250 x 250 mm for the placement of sample.

The furnace temperature is measured at the side of fire on the sample surface with K type thermocouple Omega XC-20-K-12, accuracy ±0.5 % of measurement. At the opposite side of the fire four K type thermocouples Omega 5TC-GG-KI-20-1M have been installed, accuracy ±0.5 % of measurement, as well as one thermocouple – on the sample surface, one thermocouple – in ¼ of sample depth, one thermocouple – in ½ of sample depth and one thermocouple – in ¾ of sample depth, when measuring from the sample surface at the side not subject to fire (Figure 2b). The readings of thermocouples are registered every 10 s by data recorder OM-DAQPRO-5300. For the control of external surface temperature two-point infrared thermometer Testo 830-T2 has been used with operating temperature of -30 to +400 °C. For the processing of the obtained data computer software “DagLab” version 1.40.01 has been used.

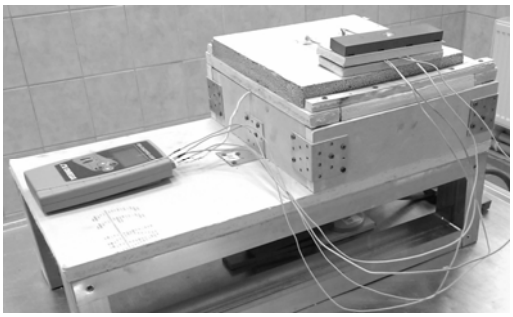

Figure 1: Experimental device for fire resistance study of foam gypsum boards

A mathematical model was created for the theoretical description of sample fire resistance experiment, which is based on thermal conductivity process description (Figure 2a).

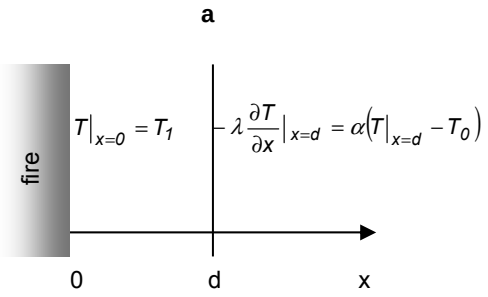

Figure 2a: Theoretical calculation scheme

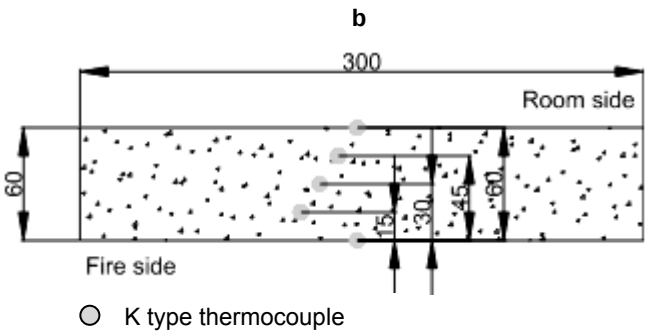

Figure 2b: Thermocouple layout scheme

Thermal conductivity is described by the non-stationary thermal conductivity equitation

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2}, \tag{1}$$

where a – temperature conductivity coefficient, m^2/s;
t – time, s;
x – coordinate, m;
T – temperature, ^0C,
With boundary conditions

$$\begin{aligned} &T\big|_{x=0} = T_1; \\ &-\lambda\frac{\partial T}{\partial x}\big|_{x=d} = \alpha\left(T\big|_{x=d} - T_0\right) \end{aligned} \tag{2}$$

where T_1, T_0 – respectively fire temperature and ambient temperature, ^0C;
d – sample depth, m;
λ – sample thermal conductivity coefficient, W/(m K);
α – heat transfer coefficient, $W/(m^2K)$;
with initial condition

$$T\big|_{t=0} = T_0 \ . \tag{3}$$

The experimentally determined sample surface temperature, when x=0 (fire) is displayed in Figure 3. It can be observed that along time increase to 1.2 min temperature reaches already 855 ^oC, which further on changes only slightly. In the theoretical model it is reflected by boundary condition (2), when x=d.

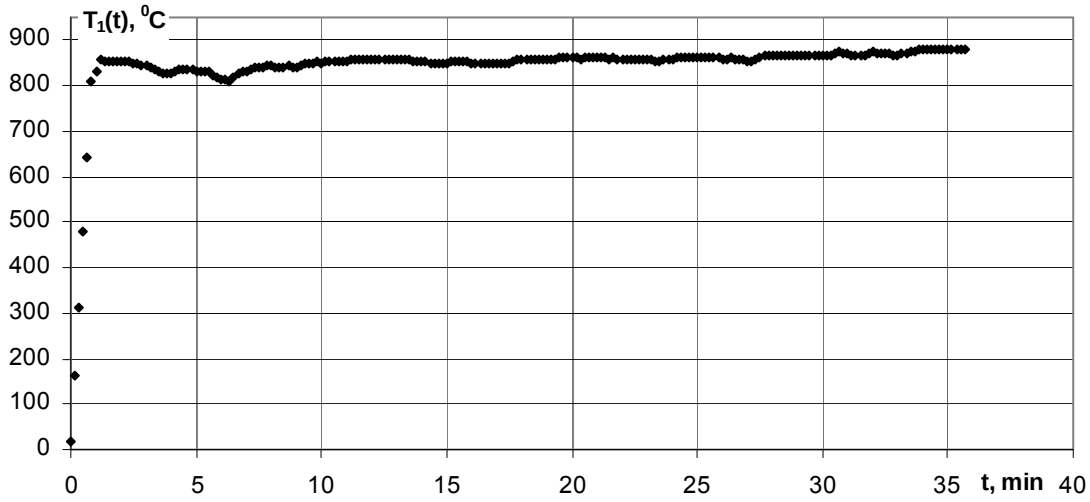

Figure 3: On the sample fire side (x=0) experimentally established change of temperature

Result of the mathematical problem Eq(1-3) can be formulated with expression

$$T(t;x) = T_1 - \frac{(T_1 - T_0)}{1+b}\cdot\frac{x}{d} - 2(T_1 - T_0)\sum_{k=1}^{\infty}\frac{exp\left(-a\mu_k^2 t\right)\cdot \sin\mu_k x}{\mu_k d\left(1 - \frac{\sin 2\mu_k d}{2\mu_k d}\right)} \ , \tag{4}$$

where; $b = \frac{\lambda}{\alpha d}$

μ_k – problem eigenvalues, that are found by resolving a transcendent equation

$$tg\mu_k d = -b\mu_k d \ . \tag{5}$$

If boundary condition (2), when (x=0) is substituted with the temperature dependency on time $T_1(t)$ demonstrated in Figure 3, the boundary condition can be obtained

$$T\big|_{x=0} = T_1(t) \ . \tag{6}$$

Solving the problem of mathematical physics Eq(1-3) with the changed boundary condition (6), we obtain result

$$T(t;x) = T_1(t) - \frac{T_1(t) - T_0}{1+b} \cdot \frac{x}{d} - 2\sum_{k=1}^{\infty} \frac{\sin \mu_k x}{\mu_k d\left(1 - \frac{\sin 2\mu_k d}{2\mu_k d}\right)} \int_0^t \frac{\partial T_1(\tau)}{\partial \tau} exp\left(-a\mu_k^2 (t-\tau)\right) d\tau \ . \tag{7}$$

Figure 4 demonstrates the experimental temperature changes and temperature changes calculated theoretically with Eq(4) and (7) depending on the time on sample surface x = d.

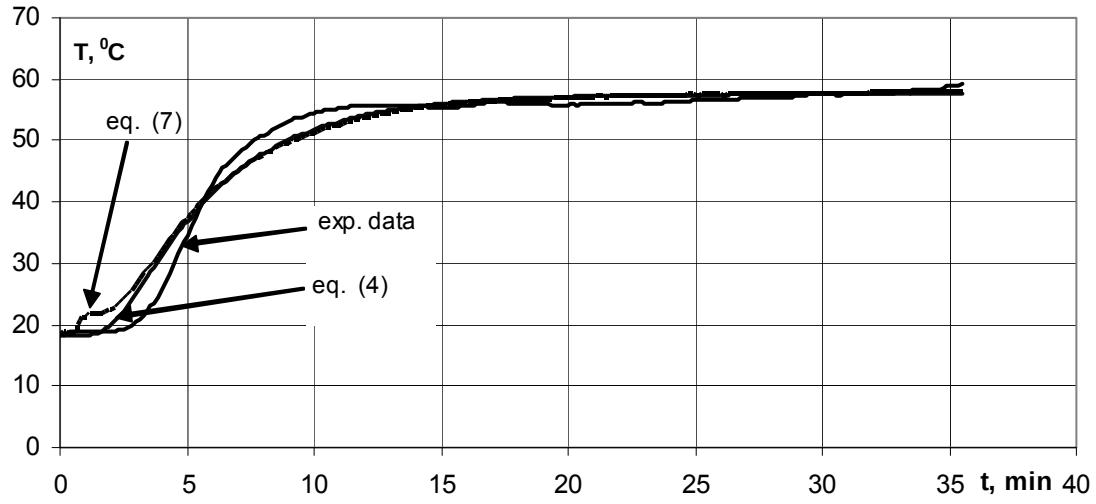

Figure 4: Experimental temperature changes and temperature changes calculated theoretically with Eq(4) and (7) depending on time on sample surface x = d of foam gypsum with density of 332 kg/m^3 and depth d = 0.04 m.

The difference in time between temperature increase on surface (x=d) and surface (x=0) can be calculated using index exponent of Eq(4). For example, at the offset time $t_1 = 3/(a \cdot \mu_1^2)$ on surface (x = d) 95 % of the maximum possible temperature increase will be reached. Inserting numbers $a = 7.74 \cdot 10^{-7}$ m^2/s, $\mu_1 = 74.87$ m^{-1}, we obtain $t_1 = 11.5$ min, which matches well with the temperature offset in time on sample surface (x = d) demonstrated in Figure 4. Theoretically the calculated temperature dependencies in Eq(4) and (7) mutually differ from time relatively slightly. The average offsets from experimental temperature process do not exceed 4 °C, which conforms to temperature measurement error. This means that temperature process in fire side (x = 0) included in the theoretical model with temperature increase delay by 1.2 min, which is demonstrated in Figure 3 has no significant effects and temperature dependency from time at coordinate (x = d). Thus the theoretical temperature dependency from time will further on be solved according to the simplest formula Eq(4). According to temperature increase displayed in Figure 4 about 11.7 min from the beginning of the process temperature stabilizes for a definite period of time. It is related to the fact that time t in result Eq(4) becomes sufficiently large and index

$$exp\left(-a\mu_k^2 t\right) \to 0 \tag{8}$$

near zero without any limitations and result (4) simplifies as expression

$$T(t;x) = T(x) = T_1 - \frac{(T_1 - T_0)}{1+b} \cdot \frac{x}{d}, \tag{9}$$

which depends only on coordinate x. It is easy to acquire coherence from Eq(9) between “stabilization” temperature on sample external surface (x=d) and the sample depth (Figure 5), because volume b contains the sample depth (10),

$$T = \frac{T_0 + T_1 \frac{\lambda}{\alpha d}}{1 + \frac{\lambda}{\alpha d}}. \tag{10}$$

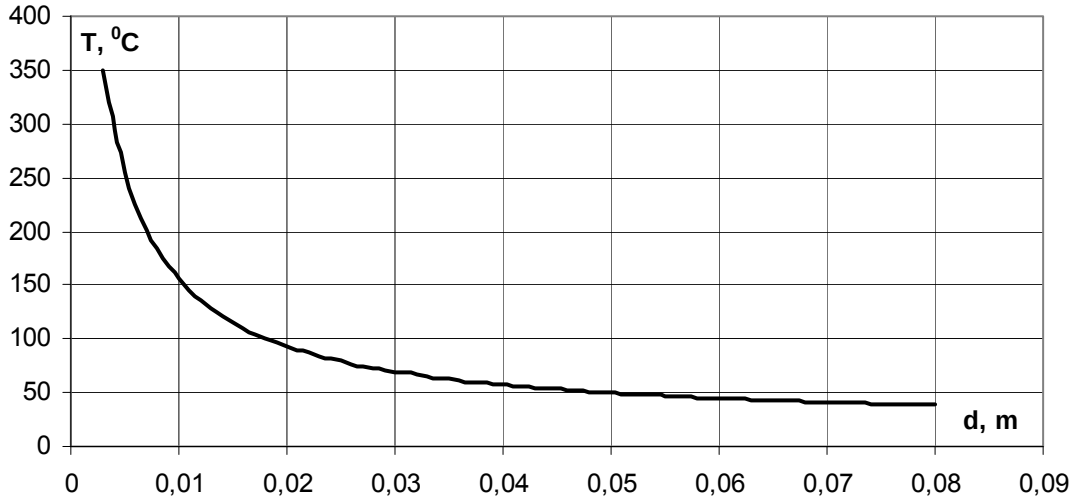

Figure 5: Dependency of stabilization temperature from sample depth of foam gypsum with density of 332 kg/m^3 calculated with Eq(10). α = 40 W/(m^2 K); λ = 0.0794 W/(m K); T_1 = 850 °C; T_0 = 18 °C

As provided in Figure 5 graph at the sample depth of about 0.01 m the surface (x=d) temperature reaches 150 °C, which is close to the maximum increase of fire protection. Thus this is the lowest admissible depth of foam gypsum fire protection layer.

To experimentally determine the temperature change according to time inside the foam gypsum board, thermocouples were inserted in the sample in accordance with scheme (Figure 2b). The temperature divisions at four coordinates x, which were experimentally measured and acquired from the theoretical model are demonstrated in Figure 6 depending on time. Qualitatively the progress of our temperature measurements in foam gypsum is similar to analogue studies in the paper about plasterboard (Ghazi et al., 2007). It should be noted that temperature in the cold surface of foam gypsum sample with density of 288 kg/m^3 at layer depth of d = 60 mm, after 100 min in the opposite side of the fire does not exceed 32 °C. It is obvious that the results of the simplified model that we offer on the surface (x = 0.06 m) match well with the experiment data. But inside the sample at coordinates x = 0.045 m, x = 0.030 m and x= 0.015 m) the difference between the experimentally acquired temperatures and temperatures calculated according to the theoretical model Eq(4) is significant. According to our opinion it is related to the fact that the latent heat of foam gypsum dehydration has not been taken into account in the theoretical model. Paper (Kontogeorgos et al., 2010) widely analyses studies of various authors about both dehydration reactions of gypsum in the temperature range from 90 °C to 250 °C with extraordinary energies of dehydration 400 - 500 kJ/kg. Such energy values are significant and can be compared to the extraordinary energy of water crystallization (334 kJ/kg). Of course, foam gypsum with density of about 300 kg/m^3 will not have such dehydration energy, but Figure 6 demonstrates that dehydration process in foam gypsum during the heating of it is significant, and its consideration in the theoretical model could provide significantly better theoretical calculation and matching of experimental results.

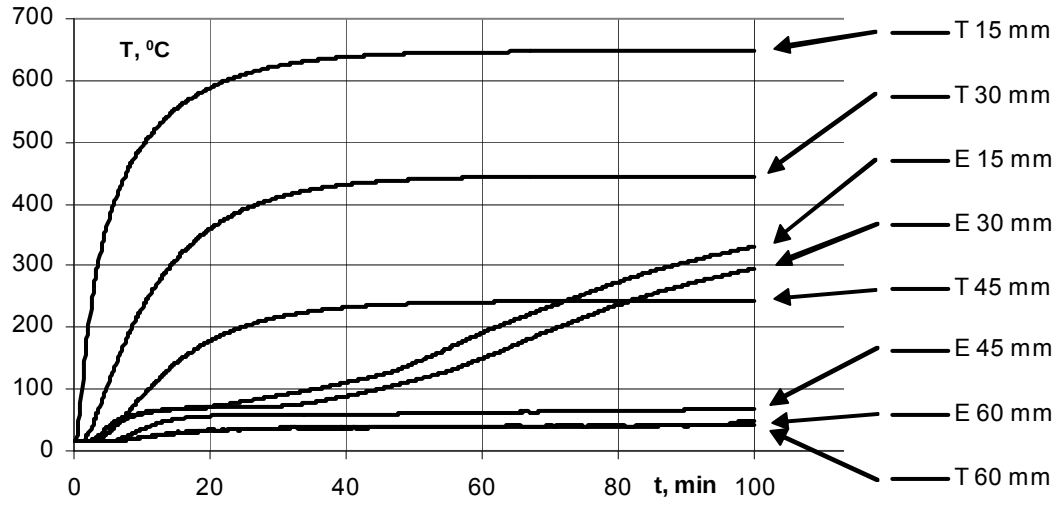

Figure 6: Comparison of experimentally measured (E) and theoretically with expression (4) calculated (T) temperatures according to time in various sample depth. Foam gypsum sample density 288 kg/m^3; α = 30.8 W/(m^2 K); λ = 0.0706 W/(m K); a = 5.77·10^{-7}m^2/s; d = 0.06 m. E 60 mm and T 60 mm is used as boundary temperature on the cold side

Conclusions

1. In laboratory studies the foam gypsum provides very high fire protection qualities (Figure 6), which indicates to wide possibilities of using this material in fire protection solutions and the necessity to develop the foam gypsum products further.
2. With the help of the developed small-size laboratory experimental device it is possible to test the fire resistance of materials before standard testing of structures.
3. Using relatively simple mathematical model it is possible to predict the temperature on sample ambient surface depending on the sample depth (Figure 5), which further on provides the opportunity to predict the foam gypsum fire resistance.
4. In further theoretical description of foam gypsum fire resistance model the energy absorbed by the dehydration process must be considered.

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