Mechanical, Thermal and Hygric Properties of Buildings Materials

Edited by
Eva Vejmelková, Jan Zatloukal and Pavel Reiterman

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Mechanical, Thermal and Hygric Properties of Buildings Materials

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Preface

This book summarizes selected papers of student conference focused on the study of properties of building materials. Presented papers deal with investigation of materials properties of conventional and also innovative building materials. The knowledge of particular material properties is essentially for successful design of structures, that is the reason why studies of basic physical, chemical, mechanical, thermal, hygric, technological and transport properties were included into this book. Experimental programs of present contributions were performed according standard system of EN and ISO but for the design of building structures is important to predict behaviour of used materials on the end of their supposed lifetime which could be number of decades. That is the reason why nowadays is necessary to apply advanced numerical and computation methods to determine of long-term durability. Last mentioned sophisticated instrument based on the theoretical principals is important to be verified in real conditions; science would be extremely boring and sterile without an experiment. Presented papers bring wide database of testing methods and materials properties which could be used in all branches of civil engineering.

Pavel Reiterman

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Analysis of Thermal Conductivity of Lime Plaster with Pozzolanic Addition by Different Homogenization Techniques

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Keywords: lime-pozzolan plaster, thermal conductivity, moisture content, effective media theory, transient impulse method, homogenization formulas

Abstract. Thermal conductivity of lime-pozzolan plaster is analyzed in the paper. At first, determination of basic physical properties of tested material is done for its basic characterization, as well as for the assessment of input parameters in the subsequent analysis of measured data by different homogenization techniques. The measurements of thermal conductivity are performed in dependence on moisture content from the dry state to the fully water saturated state using transient pulse method. Among the homogenization techniques based on effective media theory, Lichtenecker's and Dobson's models are used. The measured data presented in this paper can find utilization in practical applications of the studied plaster. The analyzed homogenization techniques are found to be applicable for a rapid evaluation of moisture dependent thermal conductivity.

Introduction

Thermal conductivity as the main parameter describing the heat transport in building materials appears to be of particular importance for their practical applications. For their use in building structures there is necessary to take into account that their thermal performance is strictly dependent on total pore volume, distribution and cross connections of pores. In materials research, thermal conductivity of dry materials is mainly studied. However, absolutely dry materials never occur in the conditions of building sites. Also the materials already inbuilt in the structures and exposed to the climatic loading exhibit the dependence of their properties on moisture changes. If the material is wet, heat transferred by moisture in the capillaries adds to the density of heat flow rate. Thermal conductivity of water is approximately 0.560 W/mK [1] which is more than 20 times higher than of the air (0.025 W/mK). Therefore, if water is present in the pore space, its effect competes with the effect of air, and the thermal conductivity of a composite material can be considered as a result of this competition, together with the effect of the solid matrix. On this account, from the practical point of view, there is necessary to have information on the dependence of thermal conductivity on moisture content.

Experimental measurement of thermal conductivity of several samples having different moisture content is quite time consuming and in consequence expensive, new approaches for the assessment of moisture dependent thermal conductivity have to be explored and tested in materials research.

Homogenization theories working with the concept of an effective medium have proven very useful in a variety of applications in mechanics and in the theory of electricity and magnetism where they already belong to well established treatments (see, e.g., [2, 3]). Within the last couple of years, some references appeared on using the effective media theories for estimation of thermal conductivity of refractory materials, foams, and polymer-based composites. In spite of very promising results, the use of homogenization theory for the assessment of thermal conductivity of lime-based composite materials is still exceptional until now.

In this paper we refer about application of homogenization techniques for the assessment of the moisture dependent thermal conductivity of lime-pozzolan plaster. The measured values of thermal conductivity are analyzed using homogenization formulas originally derived for application in electromagnetic field theory taking into account the limiting bounds.

Experimental

Lime-pozzolan plaster that should find use in restoration and reconstruction of historical buildings was the analyzed material. The plaster was composed of lime hydrate, silica sand (fraction 0 – 2 mm), metakaolin and batch water. Composition of studied material is given in Table 1.

Table 1. Composition of studied plaster

Lime hydrate (kg)	Water (kg)	Metakaolin (kg)	Silica sand (kg)
4.8	4.8	0.8	14.4

Studied plaster was characterized by bulk density, matrix density and total open porosity, whereas these material properties served also as input data for homogenization. Bulk density was determined on gravimetric principle, matrix density using helium pycnometry. Total open porosity was then calculated from these two quantities [4]. The experiments were done on 5 cubic samples of side 70 mm. The relative expanded uncertainty of applied testing method was expected 5%. The measured values of basic material parameters are given in Table 2.

Table 2. Basic physical properties of tested plaster

Bulk density (kg/m^3)	Matrix density (kg/m^3)	Total open porosity ($\% \, m^3/m^3$)
1 695	2 620	35.3

For thermal conductivity measurement, the commercially produced device ISOMET 2114 (Applied Precision, Ltd.) was used as a representative of transient pulse methods. The measuring device applies a dynamic measurement method which enables to reduce the period of thermal conductivity measurements to approximately 10 - 15 minutes [5]. The measurement is based on analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. The measurement accuracy is in thermal conductivity range 0.015 – 0.70 W/mK 5 % of reading + 0.001 W/mK and 10 % of reading in measurement range 0.7 – 6.0 W/mK. The measurements were done in laboratory conditions at average temperature 23 ± 1°C using surface circular sensor. The material samples were first dried and after that exposed to liquid water for specific time intervals. In this way, the different moisture content of the studied samples was reached. The sample size for thermal conductivity measurement was 70 x 70 x 70 mm.

Homogenization – theory, principles, applied models

In terms of effective media theory, a porous material can be considered basically as a mixture of three phases, namely solid, liquid and gaseous phase. In the lime-based plaster studied in this work, the solid phase is represented by the products of joint hydration of lime hydrate, metakaolin and silica sand, the liquid phase by water and the gaseous phase by air. On this account, the homogenization procedure presented in this work was performed in two steps. The first task was the estimation of thermal conductivity of the lime-pozzolan based matrix λ_m using the genetic algorithms estimating fitting parameters k or/and β (see Eqs. 2, 3) in interval [-1; 1] and λ_m respecting thermal conductivity of silica aggregates λ_s = 3.5 W/mK and thermal conductivity of hydrated lime – calcium carbonate λ_c = 5.5 W/mK. Thermal conductivity of metakaolin λ_m is not presented in literature, but it was supposed to lie in the interval [3.5, 5.5] W/mK.

The second step within the homogenization procedure represents evaluation of the effective thermal conductivity of the whole material, where the mixing is performed for solid matrix, air, and water. As stated in literature, the function of effective thermal conductivity cannot exceed the bounds given by the thermal conductivities and volumetric fractions of its constituents. Several different bounds were already formulated and tested, especially in the theory of electromagnetic field. In this paper, we used for the verification and validation of obtained results Wiener's bounds [6]. For the evaluation of the effective thermal conductivity of the whole material several different homogenization techniques can be used. In this paper we have used formulas proposed by Lichtenecker and Dobson with coworkers [7]. The Lichtenecker's formula is expressed by Eq. 2

$$\lambda_{eff}^k = \sum f_j \lambda_j^k , \tag{2}$$

where f_j (-) is the volumetric fraction of the particular phase ($f_1 + f_2 + ... + f_n = 1$) and λ_j its thermal conductivity. Eq. 2 represents straightforward generalization of Wiener's formula, whereas the parameter k varies within a closed interval [-1, 1]. The bounds of the interval correspond to the Wiener's parallel and serial model where k may be considered as an anisotropy transition from k = -1 (parallel) to another anisotropy k = 1 (serial) that describes a different spatial arrangements of porous building materials consisting of matrix, air and water layers [7].

Because of the large difference between the thermal conductivity of free and bound water in porous medium, Dobson with coworkers extended the Lichtenecker's power-law formula. They arrived at the following relation

$$\lambda_{eff}^{\beta} = w_{fw}\left(\lambda_{fw}^{\beta} - \lambda_a^{\beta}\right) + w_{bw}\left(\lambda_{bw}^{\beta} - \lambda_{fw}^{\beta}\right) + (1-\psi)\lambda_s^{\beta} + \psi\lambda_a^{\beta} , \tag{3}$$

that takes into account the effect of partial water bonding on the pore walls and contribution of thermal conductivity of bound water to the effective thermal conductivity of partially wetted materials. In Eq. 3, w_{fw} (m^3/m^3) is the amount of free water, w_{bw} (m^3/m^3) the amount of water bonded on pore walls, λ_{bw} the thermal conductivity of bound water (the bound water can be assumed to have the same thermal conductivity as ice, so near -20°C it is equal to 2.4 W/mK), λ_{fw} the thermal conductivity of free water (0.56 W/mK), λ_a the thermal conductivity of air (0.025 W/mK), ψ (-) the total open porosity, and β (-) is an empirical parameter. The amount of bound water was taken from measured sorption isotherm [8] of studied material (w_{bw} = 0.026 m^3/m^3).

Results and discussion

The results calculated by means of Lichtenecker's formula are presented in Fig. 1. The coefficients k and λ_m were accessed within the optimization procedure that was carried out to find the modeled data with the best agreement to the measured data. The procedure of optimization was performed for k parameter in interval [-1; 1] and λ_m interval extended from the expected λ_m value laying in interval [3.5, 5.5] W/mK to [2, 6] W/mK. The best agreement of modeled data compared to the measured data was reached by the application of Lichtenecker's model with $k = 0.1$ and λ_m = 4.9 W/mK. One can see that the optimized thermal conductivity of matrix λ_m lies in the expected interval [3.5 - 5.5] W/mK. Root mean square error (RMSE = 0.054) is relatively low, so the modeled data are in a good accordance with the measured data.

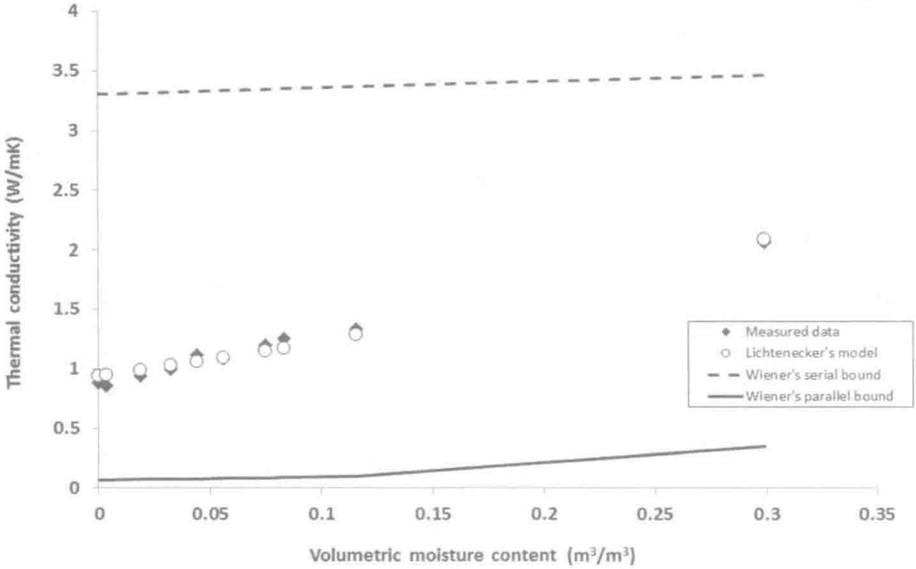

Fig. 1: The best fit of Lichtenecker's model: $k = 0.1$; $\lambda_m = 5.1$. RMSE = 0.054

Fig. 2 presents the results obtained by application of Dobson's four phase model.

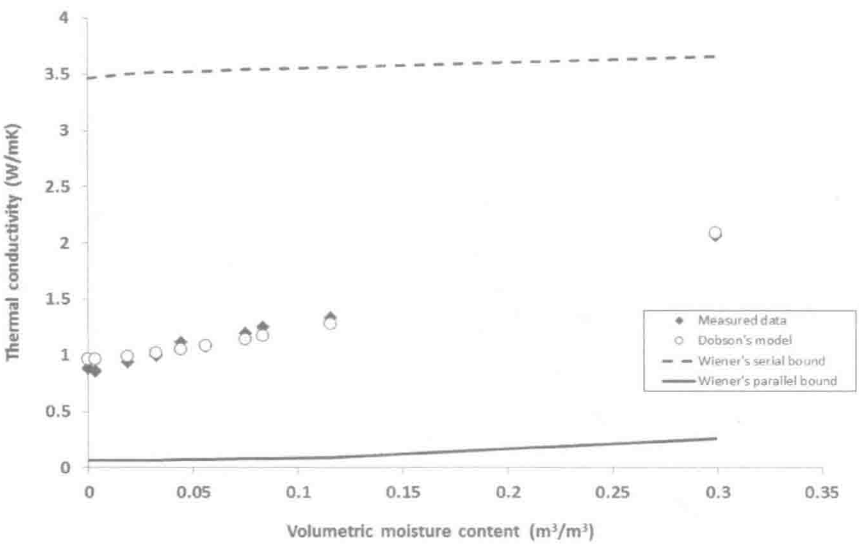

Fig. 2: The best fit of Dobson's model: $k = 0.1$; $\lambda_m = 5.4$. RMSE = 0.063

In this case, based on the parameter β and amount of bound water, good agreement between measured and calculated data was obtained even though the Lichtenecker's model was more accurate. Optimized parameter $\beta = 0.1$ is equal to the Lichtenecker's parameter k, whereas the thermal conductivity of matrix ($\lambda_m = 5.4$) is not significantly higher. Dobson's model predicts higher thermal conductivity values for low moisture content compared to the Lichtenecker's model.

Conclusions

Thermal conductivity of lime-pozzolan plaster was analyzed both experimentally and theoretically using the concept of effective media theory. The measured moisture dependent thermal conductivity data can find use in practical application of the studied lime-based composite plaster and gives information on material's behavior within its exposure to moisture action. The applied homogenization techniques were found to be applicable for evaluation of moisture dependent thermal conductivity, although the optimization was necessary in order to get sufficient agreement between measured and modeled data.

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Moisture Transport Properties of Hydrophilic Mineral Wool

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Keywords: hydrophilic mineral wool, fiber orientation effect, water transport, water vapor transport

Abstract. Mineral wool materials are widely used for thermal insulation of buildings due to their low thermal conductivity and high fire resistivity. On this account, they are popular materials for passive fire protection of buildings. Thermal insulation boards are usually provided with hydrophobic admixtures that ensure their functional properties even in the contact with moisture. In this paper we focused on investigation of hygric transport properties of hydrophilic mineral wool materials that could find application in interior thermal insulation systems as well as in desalination and drying of salt laden materials and building structures. The obtained results give evidence of the effect of fiber orientation on studied material properties and reveal that fiber orientation perpendicular to board surface is a perspective way of materials development.

Introduction

Mineral wool based materials are frequently used in various applications. Probably the most widespread use of mineral wool products is their application in building industry in the form of thermal insulation boards. However, they can also be utilized for acoustic insulation, fire protection, cement reinforcement, pipe insulation and as synthetic soils for plant growing. Many mineral wool products are provided with hydrophobic substances because the presence of water in the material is undesirable for the majority of applications. The main argument for hydrophobization is the fact that water in mineral wool increases its thermal conductivity several times, which leads to the loss of thermal insulation properties [1].

Hydrophilic additives are seldom used in mineral wool products. Practically the only notable application of hydrophilic mineral wool (HMW) is in the form of synthetic soils for plant growing, where water saturation of the material is necessary for its proper function. In paper [2], authors reported about application of HMW in green roofs as a water reservoir. However, the capability of fibrous materials with hydrophilic substances to transport rapidly liquid water could make them desirable for a variety of other applications where such favorable hydric properties could be conveniently employed. In building industry, the HMW based materials can find use for drying and/or desalination of building structures within their renovation due to the excessive moisture and salt content. Application of any type of poultice for removing of salts is often used technique for renovation treatment of salt-laden structures. Desalination by poulticing consists in the extraction of water soluble salts through the application of a moistened absorbing material on the surface on the structure to be treated [3]. Here, especially cellulose and wool cotton poultices are used. However, HMW can be applied in similar way, whereas its durability is much higher compared to above given materials. Recently, HMW finds a use in interior thermal insulation system without water vapor barrier. In these applications, HMW ensures uniform distribution of condensed moisture and its evaporation back to the interior environment [4].

Among the material properties of mineral wool based products, thermal properties appear to be of particular importance for their practical applications. Therefore, practically every catalogue list of any material producer contains thermal conductivity, sometimes also specific heat capacity, but they give only single characteristic values mostly. Moisture transport properties of mineral wool products are not so frequently presented as thermal properties in the scientific literature. Hygric properties of HMW were studied only seldom until now. The work [1] belongs to one of very few exceptions. The apparent reason is their very rare application in practice. However, for these types of materials the lack of knowledge of these parameters has much worse consequences than for common mineral wool products. On this account hygric properties of HMW products with different fiber orientation are studied in order to get information for their wider application in building practice.

Experimental

HMW materials analyzed in this paper were produced by Rockwool, Inc., Czech Republic. The materials differed in density and their fibers were originally manufactured parallel with the board surface. The specimens were cut from the material boards delivered by the producer. The size of the specimens for the determination of water absorption coefficient was 50 x 50 x 50 mm. For water vapor diffusion measurements, the cylindrical specimens with the diameter of 110 mm and thickness of 20 mm were used. The specimens were prepared in such a way that the effect of fiber orientation could be analyzed.

For characterization of researched materials, measurement of basic physical properties was done. Bulk density was determined from the measurement of sample sizes and its dry mass. The matrix density was accessed by helium pycnometry and the total open porosity was calculated on the basis of the knowledge of these two parameters [5]. The relative uncertainty of the applied method is 5%.

Liquid water transport in the studied materials was described by sorptivity. Sorptivity concept is the simplest way to describe uptake of water by porous materials. For soft materials as mineral wool this concept is very suitable because the deformation of the samples during the measurements can be avoided in a relatively easy way, which is for instance not the case of moisture diffusivity determination from moisture profiles measured on rod samples. Sorptivity S [m/s$^{1/2}$] is defined as

$$I = S \cdot t^{1/2}, \tag{1}$$

where I [m] is the cumulative absorption of water and t [s] the corresponding time. Eq. (1) is a simplification of the general expression for the cumulative mass of moisture in terms of the square-root-of-time rule that is commonly employed in the diffusion theory, which is obtained by dividing the original equation

$$i = A \cdot t^{1/2}, \tag{2}$$

by the density of water, ρ_w. In Eq. (2), i [kg/m^2] is the cumulative mass of water and A [kg/m^{2}s$^{1/2}$] the absorption coefficient of water

$$A = S \cdot \rho_w . \tag{3}$$

For the sorption tests, 5 cubic samples of side 50 mm were used. The lateral sides of the particular dried samples were waterproof insulated in order to guarantee the 1-D water transport. After that, the samples were put in contact with water and the quantity of absorbed moisture was measured at chosen time intervals. The water level was not more than 5 mm above the base of the specimen. The absorption coefficient was determined from the straight line obtained by plotting the cumulative mass of water absorbed per unit area against the square root of corresponding time. The expected relative uncertainty of the applied method is 5%.

The cup method in dry-cup and wet-cup arrangements was employed for measurement of water vapor transport properties. The circular specimens were water and vapor proof insulated by silicon rubber on lateral side, put into the cup and sealed by silicon sealant. In the wet-cup arrangement, the sealed cup containing saturated K_2SO_4 solution (the equilibrium relative humidity above the solution was 97.8%) was placed into air-conditioned room with 25% relative humidity and weighed periodically. The measurements were done at 23 ±1°C in a period of one week. The steady state values of mass loss determined by linear regression for the last five readings were used for the determination of water vapor diffusion coefficient. In the dry-cup arrangement, the sealed cup contained dried silica gel (the equilibrium relative humidity above the desiccant was 5%). Otherwise the measurement was done in the same way as in the wet-cup arrangement. The water vapor diffusion coefficient D [m^2/s] was calculated from the measured data according to the equation

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_p}, \tag{4}$$

where Δm [kg] is the amount of water vapor diffused through the sample, d [m] the sample thickness, S [m^2] the specimen surface, τ [s] the period of time corresponding to the transport of mass of water vapor Δm, Δp_p [Pa] the difference between partial water vapor pressure in the air under and above specific specimen surface, R [J/mol K] the universal gas constant, M [kg/mol] the molar mass of water, T [K] the absolute temperature.

Using the results of the water vapor diffusion experiments, the water vapor diffusion resistance factor μ [-] was calculated as

$$\mu = \frac{D_a}{D}, \tag{5}$$

where D_a is the diffusion coefficient of water vapor in the air.

For measurement of sorption and desorption isotherms, dynamic vapor sorption device DVS-Advantage (Surface Measurement Systems Ltd.) was used, whereas the measurements were done at 20°C [6]. Before the measurements, the sample of studied material was dried at first, and maintained in desiccator during cooling. Then, the sample was put into the climatic chamber of the DVS-Advantage instrument and hung on the automatic balances in the special steel tube. The particular samples were exposed to the following partial water vapor pressure profile: 0; 20; 40; 60; 80; and 98% of relative humidity.

Results and discussion

Basic physical properties of studied materials are given in Table 1. We can see high difference in materials bulk density and corresponding high values of total open porosity that give to the studied HMWs low thermal conductivity and thus good thermal resistance.

Table 1. Basic physical properties of studied materials

Material	Bulk density (kg/m^3)	Matrix density (kg/m^3)	Total open porosity (%m^3/m^3)
HMW1	172	2 602	93.4
HMW2	80	2 602	96.9

Water sorptivity data is given in Table 2. Here, the data measured for fiber orientation parallel as well as perpendicular to the original mineral wool board surface is presented.