Thermal Properties of Lime-Pozzolan Plasters for Application in Hollow Bricks Systems

Z. Pavlík, M. Čáchová, E. Vejmelková, T. Korecký, J. Fořt, M. Pavlíková, R. Černý

Abstract—The effect of waste ceramic powder on the thermal properties of lime-pozzolana composites is investigated. At first, the measurements of effective thermal conductivity of lime-pozzolan composites are performed in dependence on moisture content from the dry state to fully water saturated state using a pulse method. Then, the obtained data are analyzed using two different homogenization techniques, namely the Lichtenecker's and Dobson's formulas, taking into account Wiener's and Hashin/Shtrikman bounds.

Keywords—Waste ceramic powder, lime-pozzolan plasters, effective thermal conductivity, homogenization techniques.

I. INTRODUCTION

PLASTERS are used as final protective layer of building structures from ancient times. Many varieties in plasters composition and technological application were developed and used in order to meet the requirements of building designers, engineers, as well as buildings occupants. Presently, besides the architectural significance the plasters must meet demands on mechanical resistivity, long-term durability, thermal insulation function, etc. Moreover, the production of plasters must be highly effective from the point of view of materials costs, whereas the plasters must be produced environmentally friendly with limited consumption of natural raw materials. On this account, application of secondary raw materials coming as by-products from industry is a very often studied subject of present materials research [1], [2].

In this paper we focused on the investigation of effective thermal conductivity of newly developed lime-based plasters that should find use in hollow brick systems. In the composition of researched materials, the hydrated lime, used as primary binder, is partially replaced by fine ground ceramic powder coming from production of ceramic brick blocks.

II. MATERIALS

The composition of analyzed materials is given in Table I. Here, control reference mixture is denoted as LP R. Plasters modified by ceramic powder are denoted as LP CP1, LP CP2, LP CP3, LP CP4. Hydrated lime CL 90 S was used as primary binder. It was partially replaced by fine ground ceramic powder coming from production of ceramic brick blocks.

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TABLE I
COMPOSITION OF STUDIED PLASTERS

Material	Lime (kg)	Ceramic Powder (kg)	Sand (kg) 0.3-0.6	0.6-1.2	1.2-4.0	Water/dry mixture ratio
LM R	3.75	0.0	3.75	3.75	3.75	0.2
LM CP1	1.8	1.95	3.75	3.75	3.75	0.2
LM CP2	1.2	2.55	3.75	3.75	3.75	0.2
LM CP3	3.0	0.75	3.75	3.75	3.75	0.2
LM CP4	2.4	1.35	3.75	3.75	3.75	0.2

III. EXPERIMENTAL

A. Basic Physical Properties

The measurement of basic material properties, such as bulk density, matrix density and total open porosity was done at first to get necessary input data for homogenization. Bulk density was measured by gravimetric method. For measurement of matrix density, water vacuum saturation method was used. From the measured data, the total open porosity was calculated [3]. The samples for determination of the basic material parameters had cubic shape of side length of 50mm. For the measurement 5 samples were used.

B. Measurement of the Effective Thermal Conductivity

Thermal conductivity belongs together with thermal diffusivity and specific heat capacity to the most important material parameters describing the thermal properties of a material or component [4]. The thermal conductivity can be experimentally determined either by steady-state methods or transient methods. A measurement method has to be selected depending on the following criteria: possible sample size and shape, temperature range (limited for individual techniques), and thermal-conductivity range (low-conductivity materials like insulating materials or foams need different methods than high-conductivity materials such as metals).

For our measurements, the commercially produced device ISOMET 2104 (Applied Precision, Ltd.) was used as a typical representative of transient pulse methods. The measurement is based on analysis of the temperature response of the analyzed material to heat flow pulses. The basic measuring uncertainty of ISOMET 2104 for thermal conductivity measurement is 3% of reading + 0.001 W/mK. The measurements in this paper were done in laboratory conditions at an average temperature of $(23 \pm 1)°C$. The material samples were first dried, and after that exposed to liquid water for specific time intervals. In this way, the different moisture contents of the studied samples were reached. The sample size for effective thermal conductivity measurement was 70mm x 70mm x 70mm.

IV. HOMOGENIZATION PRINCIPLES AND USED MODELS

In terms of a homogenization, a porous material can be considered basically as a mixture of three phases, namely, solid, liquid and gaseous (in four-phase systems, the effect of bound water can be included) that form the solid matrix and porous space of the material. The liquid phase is represented by water and the gaseous phase by air. In the case of a dry material, only the solid and gaseous phases are considered. The volumetric fraction of air in a porous body is given by the measured total open porosity. In case of penetration of water, a part of the porous space is filled by water. For evaluation of the thermal conductivity of the whole material (i.e., the effective thermal conductivity), the thermal conductivities of the particular constituents (water, air, matrix) have to be known [5], [6].

In this paper, thermal conductivity of the solid matrix of the particular plasters was calculated using the Rayleigh mixing rule on the basis of the thermal conductivity measurement of fully dried materials. The Rayleigh formula modified for the effective thermal conductivity of a fully dried material is formulated as

$$\frac{\lambda_{\text{eff}} - 1}{\lambda_{\text{eff}} + 2} = f_{\text{m}}\left(\frac{\lambda_{\text{m}} - 1}{\lambda_{\text{m}} + 2}\right) + f_{\text{a}}\left(\frac{\lambda_{\text{a}} - 1}{\lambda_{\text{a}} + 2}\right), \qquad (1)$$

where λ_{eff} (W/mK) is the effective thermal conductivity measured by pulse method, λ_{m} (W/mK) thermal conductivity of solid matrix, and $\lambda_{\text{a}} = 0.026$ W/mK thermal conductivity of air.

The effective thermal conductivity λ_{eff} of a multi-phase composite cannot exceed the bounds given by the thermal conductivities and volumetric fractions of its constituents. The upper bound is reached in a system consisting of plane-parallel layers disposed along the heat flux vector. The lower bound is reached in a similar system but with the layers perpendicular to the heat flux. These bounds are usually called Wiener's bounds, according to Wiener's original work [7] and can be expressed by the following relations:

$$\lambda_{\text{eff}} = \frac{1}{\dfrac{f_1}{\lambda_1} + \dfrac{f_2}{\lambda_2} + \dfrac{f_3}{\lambda_3}}, \qquad (2)$$

$$\lambda_{\text{eff}} = f_1\lambda_1 + f_2\lambda_2 + f_3, \qquad (3)$$

where (2) represents the lower limit and (3) the upper limit of the effective thermal conductivity (f_i is the volumetric fraction of the particular phase, λ_i its thermal conductivity).

Together with Wiener's bounds, Hashin/Shtrikman formulas were also applied for verification and certain limitation of the effective thermal conductivity values. These bounds were originally formulated for the theoretical determination of the effective magnetic permeability of macroscopically homogeneous and isotropic multiphase materials. However, in [8] authors concluded that for reasons of the mathematical analogy, the Hashin/Shtrikman bounds also hold for dielectric constant, thermal conductivity, electrical conductivity, and mass diffusivity of such materials. The lower limit of the effective thermal conductivity can be according to Hashin/Shtrikman theory expressed as

$$\lambda_{\text{lower}} = \lambda_1 + \frac{3\lambda_1}{\dfrac{1}{\displaystyle\sum_{i=2}^{n} f_i \dfrac{\lambda_i - \lambda_1}{2\lambda_1 + \lambda_i}} - 1}, \qquad (4)$$

and the upper limit as

$$\lambda_{\text{upper}} = \lambda_n + \frac{3\lambda_n}{\dfrac{1}{\displaystyle\sum_{i=1}^{n-1} f_i \dfrac{\lambda_i - \lambda_n}{2\lambda_n + \lambda_i}} - 1}. \qquad (5)$$

In (4) and (5), $f_1 - f_n$ are the volumetric fractions of the particular phase ($f_1 + f_2 + ... + f_n = 1$), and $\lambda_1 - \lambda_n$ are their thermal conductivities, whereas $\lambda_1 < \lambda_2 ... < \lambda_n$.

For the determination of the effective thermal conductivity as a function of moisture content, the three-phase form of the Lichtenecker's equation and its four-phase modification which is commonly denoted as Dobson's model were used.

Lichtenecker's equation [9]

$$\lambda_{\text{eff}}^k = \sum f_i \lambda_i^k, \qquad (6)$$

is a straightforward generalization of Wiener's formulas. The parameter k in (6) varies within the [-1, 1] range. Thus, the extreme values of k correspond to the Wiener's boundary values. The parameter k may be considered as describing a transition from the anisotropy at $k = -1.0$ to another anisotropy at $k = 1.0$.

Dobson et al. [10] extended Lichtenecker's power-law formula and arrived at the relation

$$\theta = \frac{\lambda_{\text{eff}}^{\beta} - \theta_{\text{bw}}(\lambda_{\text{bw}}^{\beta} - \lambda_{\text{fw}}^{\beta}) - (1-\psi)\lambda_{\text{m}}^{\beta} - \psi\lambda_{\text{a}}^{\beta}}{\lambda_{\text{fw}}^{\beta} - \lambda_{\text{a}}^{\beta}}, \qquad (7)$$

where θ (m^3/m^3) is the moisture content, θ_{bw} (m^3/m^3) the amount of water bonded on pore walls, λ_{bw} is the thermal conductivity of bound water (according to [11], 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·m^{-1}·K^{-1}), λ_{fw} is the thermal conductivity of free water λ_{a} is the thermal conductivity of air (0.026 W·m^{-1}·K^{-1}), ψ is the total open porosity, and β is an empirical parameter.

V. RESULTS AND DISCUSSION

Basic material properties of investigated materials are summarized in Table II. We can see that due to the application of ceramic powder the total open porosity of the analyzed

composites systematically increased. This finding is positive from the point of view of thermal insulation properties of the developed plasters.

Material	Bulk density (kg/m³)	Matrix density (kg/m³)	Total open porosity (%)
LM R	1 811	2 554	29.1
LM CP1	1 759	2 615	32.7
LM CP2	1 758	2 627	33.2
LM CP3	1 765	2 597	32.0
LM CP4	1 762	2 613	32.6

The measured data and bounds of the thermal conductivity vs. moisture content functions are presented in Figs. 1 and 2. One can see a decrease of thermal conductivity with the increasing amount of ceramic powder in the mix, which is in accordance with the open porosity results in Table II. For all three tested materials a very significant dependence of thermal conductivity on moisture content was observed.
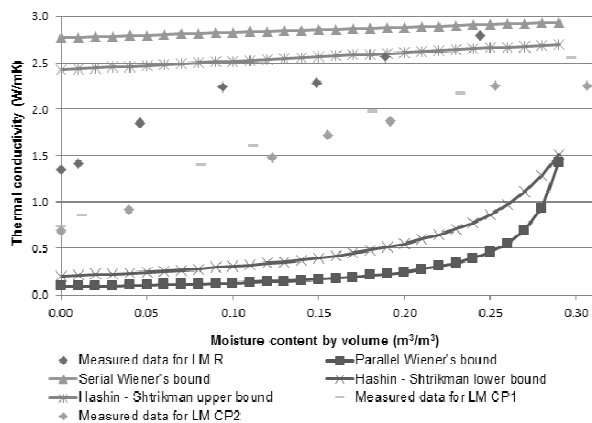
Fig. 1 Measured thermal conductivity and limiting bounds for LM R, LM CP1, LM CP2
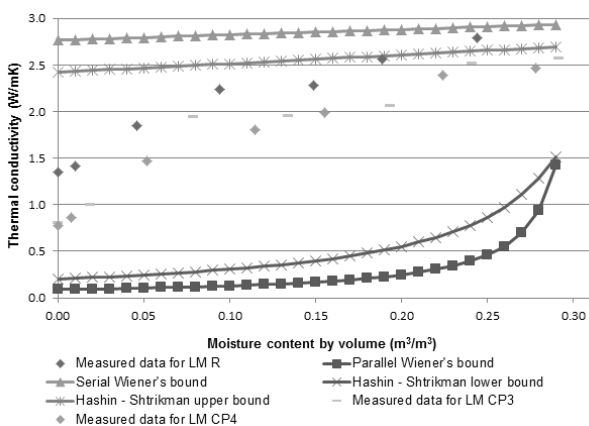
Fig. 2 Measured thermal conductivity and limiting bounds for LM R, LM CP3, LM CP4

Figs. 3-11 show the thermal conductivity vs. moisture content functions which were calculated using the three-phase Lichtenecker's model and four-phase Dobson's model.
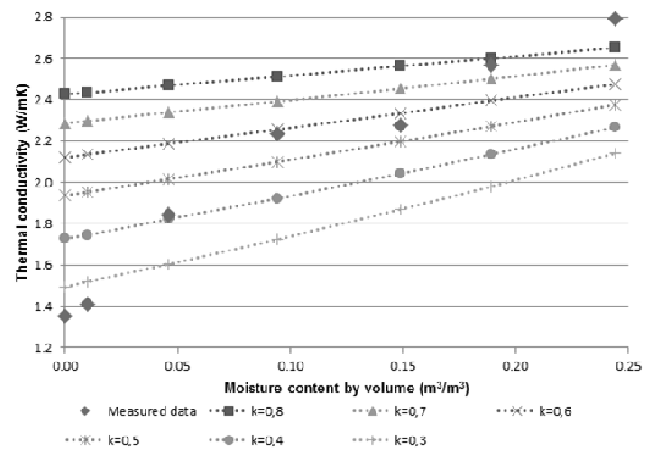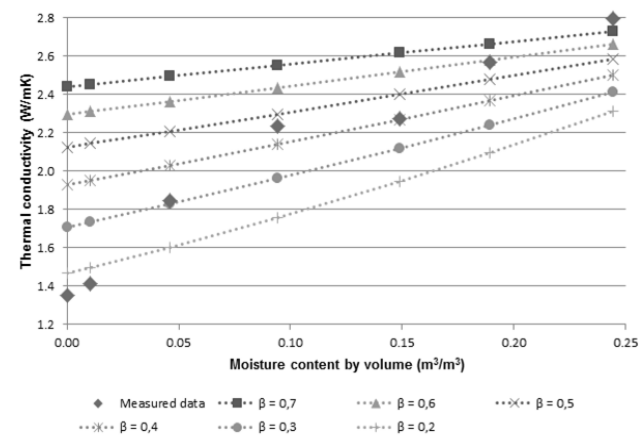

Fig. 3 Results of Lichtenecker's model for LM R

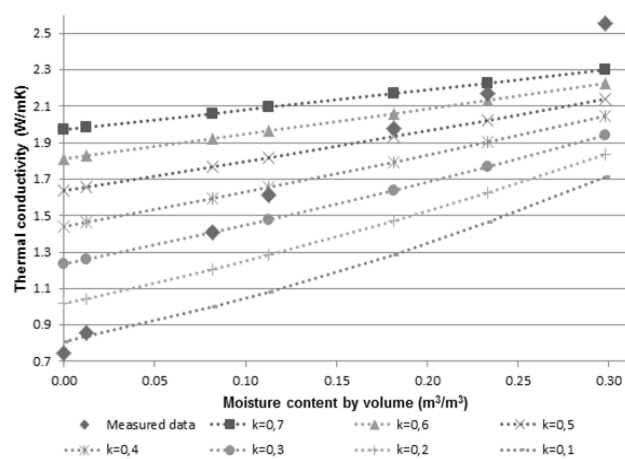

Fig. 4 Results of Dobsons's model for LM R

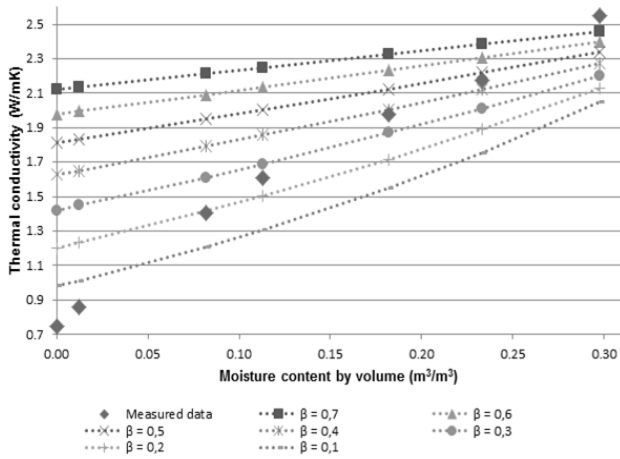Fig. 5 Results of Lichtenecker's model for LM CP1

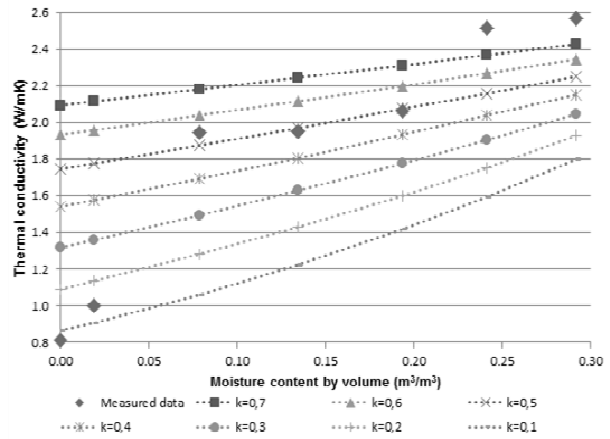Fig. 6 Results of Dobsons's model for LM CP1

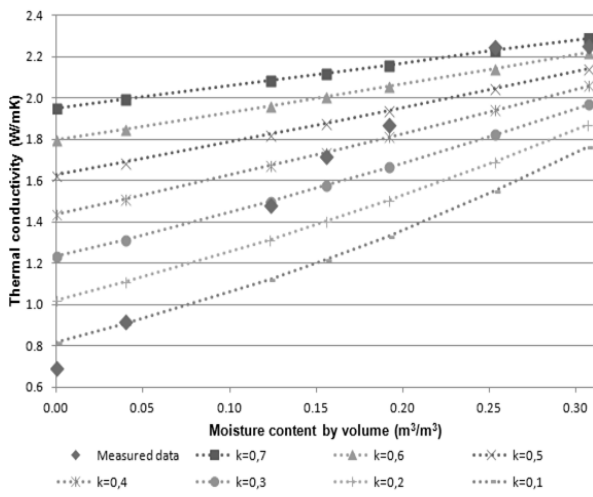Fig. 9 Results of Lichtenecker's model for LM CP3

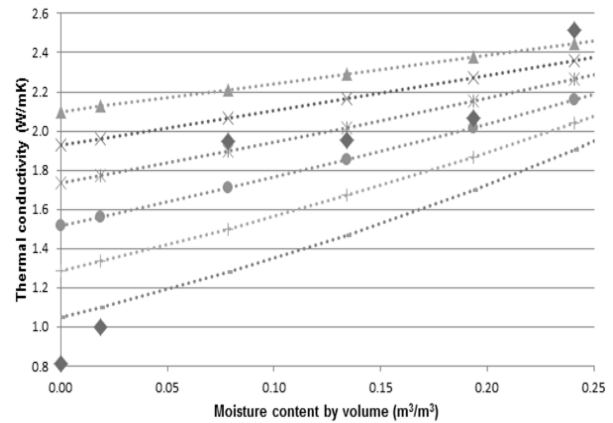Fig. 7 Results of Lichtenecker's model for LM CP2

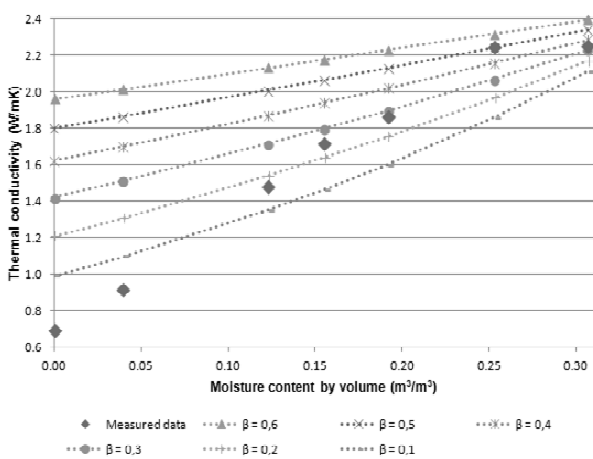Fig. 10 Results of Dobson's model for LM CP3

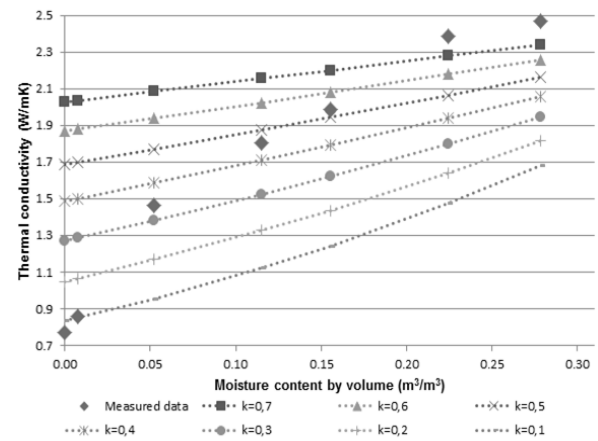
Fig. 8 Results of Dobsons's model for LM CP2

Fig. 11 Results of Lichtenecker's model for LM CP4
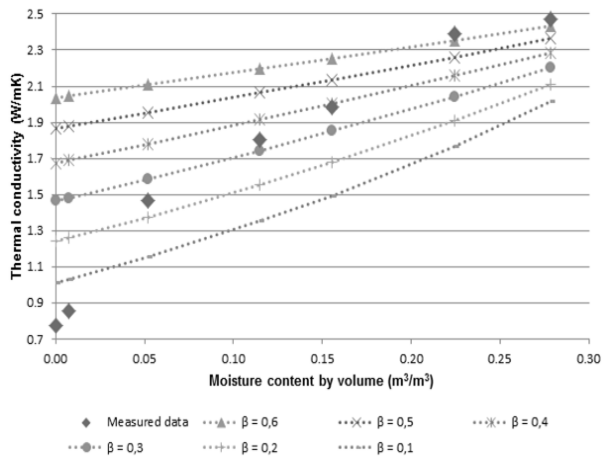
Fig. 12 Results of Dobson's model for LM CP4

Looking at the obtained data, there is quite obvious that different fitting parameters k and β were used to model the behavior of the particular materials. Apparently, for low moisture contents, the agreement was poor for all applied k and β values. On the other hand, satisfactory results were obtained for higher moisture contents, but without any possible generalization for all the studied materials. For example, Lichtenecker's formula provided relatively good agreement between measured and calculated data for LM CP2 for $k = 0.4$ at moisture range $0.13 - 0.22$ m^3/m^3, for LM CP4 for $k = 0.5$ at moisture content range $0.12 - 0.17$ m^3/m^3. Dobson's model gave satisfactory results for example for LM CP4 for $\beta = 0.6$ at moistures > 0.2 m^3/m^3, and for LM CP3 for $\beta = 0.5$ at moisture range $0.07 - 0.18$ m^3/m^3. Similar behavior was observed also for other plasters; the measured effective thermal conductivity functions could be expressed by different values of fitting parameters in limited ranges of moisture content only.

VI. CONCLUSIONS

Experimental results presented in this paper pointed out to the applicability of waste ceramic powder as partial hydrated lime replacement in mortar composition. The usage of waste ceramic powder yielded a higher porosity of the lime-pozzolan plasters. This led to the decrease of effective thermal conductivity, which is beneficial from the point of view of assumed application of the tested materials in hollow bricks walling systems.

The application of the three-phase Lichtenecker's model and four-phase Dobson's model for the calculation of thermal conductivity as a function of moisture content was not found quite successful. While in the range of higher moistures the agreement of modeled data with the experimental results was acceptable, for low moisture contents both models failed. Therefore, some other types of homogenization models are to be analyzed.

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