

THERMAL CONDUCTIVITY OF MORTARS AND FRACTAL PROPERTIES OF THEIR MICROSTRUCTURE

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Abstract

ABSTRACT: Commonly manufactured mortars and plasters were analysed from the aspect of the relationships among their composition, microstructure and dry thermal conductivity. The thermal conductivity analysis of the considered materials was done in order to find the most appropriate model of the configuration of particular components in a heat flow path. The dry thermal conductivity of plasters and mortars depends on the thermal conductivity of used aggregate, binder and fillers and on the porosity and its fractal properties. In case of unsatisfactory information on the material composition and the components properties a simple microstructural model of thermal conductivity enables to estimate the effective thermal conductivity from the total porosity of a material.

Key words: thermal conductivity,

1 Introduction

Most of the building materials are composites and their thermal parameters represent the effects resulting from the properties of their particular phases and components. The components of the solid phase can be differentiated according to their function in a material. Usually the composite consists of the bonding matrix, aggregate and the pore space. The thermal properties of dry porous materials are predominantly given by the properties of the solid phase as a whole and the pore volume. The known relationships among the solid phase properties, the pore structure parameters and the material thermal parameters enable to model, predict and develop the thermal properties of the porous materials only from the knowledge of properties of the solid phase and the pore space. In practice the parameters of the porous composite material always represent the complex and mutual interaction of the solid and gaseous phases in the heat transport process. Therefore it is difficult to produce the pure dense single solid phase component material for testing which would have the properties identical with the properties of the solid in the real porous composite. The simplest way how to determine the solid phase properties for modelling is still to measure the thermal parameters of real porous materials and to analyse them using a standard information on the composition and pore structure. Also the determination of the thermal and microstructural properties and solid phase composition of porous composites and then application of an appropriate thermal

conductivity model enable to estimate the required solid phase conductivity with satisfactory reliability.

In order to analyse the microstructure - thermal conductivity relationships dry thermal conductivities of 16 various mortars, plasters and insulation boards were determined. Besides the thermal conductivity also the pore structure parameters and composition of the analysed material were determined. From the aspect of their chemical properties the considered plasters and mortars can be characterised as the calcium silicate hydrates (CSH) based composite materials with a certain content of calcium carbonate or gypsum.

2 Theory

Considering the links between microscopic material parameters, microstructure and macroscopic parameters the basic material parameters for modelling are the parameters of the solid or its components and the pore space parameters.

Generally the relations between micro- and macro- structural porous material parameters can be expressed by a model in which the thermal conductivity of the *ith* material component or pore volume fraction λ can be approximated according to the relation (Meng 1994, Sahimi 1996):

$$\lambda = \lambda_i (\Phi_i - \Phi_{i,crit})^{n_i} \quad (1)$$

where: $n_i = 1 + FD$, λ_i is the thermal conductivity of the fraction unit volume, Φ_i is the volume fraction, $\Phi_{i,crit}$ is a critical volume needed for a connected network to be formed through the material, the term $\Phi_i - \Phi_{i,crit}$ is a relevant volume portion considered.

- The *critical volume* is also known as the critical threshold volume for connectivity percolation. The critical volume value is specific for particular transport processes. The volume participates on the transport only if some critical minimum part of the volume is present. If $\Phi_i < \Phi_{i,crit}$, the component volume portion or the pore volume fraction is not percolated in the material volume. In such a case it is necessary to take into consideration the dispersion of the component or pore volume fraction with other components or pore volume fractions.

- FD is *the fractal dimension* of the component or pore volume fraction. In case of the pore volume the pore size distribution curve in a double logarithmic representation can be divided into the pore space fractions characterized by a constant slope and indicating the ranges of self-similarity. The slope of each fraction gives the fractal dimension of the pores in the fraction. The exponent n_i expresses the deviations of real component from a parallel model: variable cross-sectional shape, variable cross-sectional size, tortuosity, connectivity of the component network, existence of the insulated components, abrupt changes of cross-sectional shape.

Particular component and pore volume fractions can have different dominant configuration in material volume. For the continuous high conductivity components fractions with the discrete low conductivity components the macroscopic transport coefficient can be obtained by the summation of all particular components fractions:

$$\lambda = \sum_i \lambda_i (\Phi_i - \Phi_{i,crit})^{n_i} \quad (2)$$

where $n_i = 1$ in the case of parallel configuration of the components.

In case of the discrete high conductivity components in the continuous low conductivity or pore volume fractions the following relation can be applied:

$$\lambda = \frac{1}{\sum_i \frac{(\Phi_i - \Phi_{i,crit})^{n_i}}{\lambda_i}} \quad (3)$$

where $n_i = 1$ in the case of serial configuration of the components.

3 Analysis of measurements

All the analysed materials are composites and their solid phase generally consists of the bonding matrix, reinforcement, aggregate or lightweight filler.

The thermal conductivity of the analysed plasters and mortars was measured by the guarded hot plate method (Klarsfeld 1984). The dry bulk density of the considered materials was in the range of $\rho = 200 - 1725 \text{ kg/m}^3$. The measured samples had

Table 1. Components volume portions and dry thermal conductivities of particular materials

Material	Aggregate [-]	Binder [-]	Light- weight filler [-]	Total porosity [-]	Thermal conductivity [W/m.K]
ZM	0.43	0.28		0.29	0.77
710	0.39	0.33		0.29	0.56
KM	0.43	0.17		0.31	0.50
PM02	0.41	0.19		0.41	0.52
PM04	0.41	0.15		0.44	0.37
MSS20	0.3	0.18		0.52	0.28
720	0.11	0.26		0.63	0.204
EP-B		0.2	0.80	0.71	0.155
EP-T		0.18	0.82	0.74	0.13
Sanova	0.1	0.14		0.76	0.146
EPS-T	0.039	0.11	0.57	0.85	0.075
EPS-B	0.04	0.07	0.73	0.89	0.076
250		0.10		0.90	0.085
1100		0.09		0.91	0.066
1100M		0.09		0.91	0.067
200		0.07		0.93	0.063

the dimensions of 0.50x0.50x0.04/0.08 m. The mean sample temperature was ca 22°C and the temperature difference was ca 6 K during the measurements. The samples were conditioned under the laboratory conditions: 19°C temperature and 45% relative humidity and they can be practically considered to be dry. The pore volume portions of particular components for each material (Bagel 2002) and the corresponding results of the thermal conductivity measurements are in Table 1.

In principle the thermal conductivity – microstructure relationship in case of porous materials assumes that the thermal conductivity of the material correlates with the thermal conductivities and the volume portions of particular phases. The possible

thermal conductivity values intervals for particular components of mortars/plasters are in Table 2 (Khan 2002, Koronthalyova & Matiasovsky, 2003, Marshall 1972, Xu & Chung , Missenard 1965). It results from the table that the thermal conductivity of aggregate is always significantly higher in comparison with thermal conductivity of the other mortars/plasters components.

Table 2. Considered thermal conductivities of mortars and plaster components

Material	Thermal conductivity [W/m.K]
Cement paste	0.66 – 1.2
Gypsum	0.66
Quartz	2.90 – 5.18
Limestone	3.15 – 3.23
Calcium silicate hydrate	1.00

The correlations between the measured thermal conductivities and the volume portions of the particular components as well as of the porosities were analysed. For mortars, plasters and insulation boards the best correlation is between the thermal conductivity and the total porosity and the dependence can be expressed by the following formula:

$$\lambda_{dry} = \frac{1}{\frac{\Phi^2}{0.064}} \quad (4)$$

where Φ is the total porosity [m^3/m^3]. In Figure 1 the measured dry thermal conductivity values for materials with different total porosities given in Table 1 is shown.

4 Discussion

The determination of the effective dry thermal conductivity by a microstructure model is usually accompanied by the problem of the lack of reliable information on the thermal conductivity of particular components. In this situation the data from other sources are usually used. However such data are characterized by their high variability resulting either from the material properties variability or from the variability of the measurement methods used.

Plaster and mortar are typically viewed as two-phase composite materials consisting of discrete aggregates dispersed in a continuous porous cement paste matrix. However the influence of aggregates on the microstructural development of the cement paste and thus the ultimate properties of the mortars/plasters cannot be neglected. The aggregate causes that the pore structure of paste in mortar near the aggregate is quite different from that of plain cement paste. The paste near the cement paste-aggregate interfaces – the region within 50 μm of the aggregate surface contains more porosity than the bulk paste far away from the aggregate. Also the pores in this zone are generally larger than

those in the bulk material. This region has been classified as the interfacial transition zone (Winslow et al 1994).

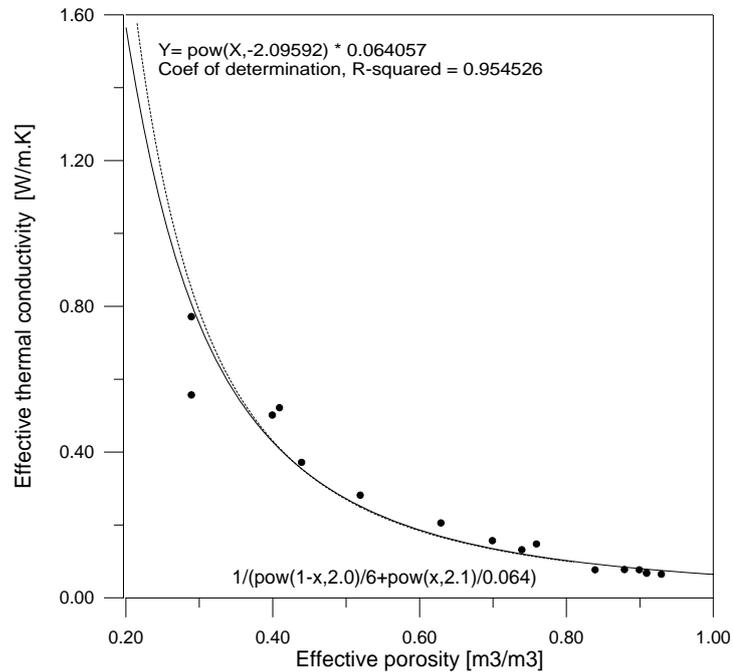


Figure 1 Effective thermal conductivity of mortars, plasters and insulation boards vs. total porosity, comparison of calculated and measured values [m³/m³]

Considering that in the dry mortar cement paste the region of the interfacial transition zone (ITZ) and the region of the bulk material can be distinguished and the model of the thermal conductivity of mortars should issue from the following assumptions:

- In general the mortar/plaster consists of three different zones: aggregate, bulk paste, porous interfacial transition zone including total porosity.
- The most conductive zone – aggregate is discontinuously dispersed in the paste. The bulk paste and aggregate are practically disconnected by the continuous porous interfacial zone.

For the thermal conductivity of the mixture of two components: the continuous ITZ and the discontinuous bulk paste and aggregate the model of coated spheres assemblage is typical. For creating this model it is necessary to define the volume portion of the interfacial zone.

The volume portion of interfacial zone is dependent on the volume portion of aggregate and total porosity. From the analysis of the relationship between the interfacial zone volume portion and the total porosity for mortars with total porosity from ca 20% to ca 35% it was found out that about 40% of the paste volume belongs to the interfacial zone and the interfacial zone volume fraction represents 10% of the total porosity in average (Winslow et al. 1994). Furthermore we can assume that the binder volume portion of interfacial zone is decreasing with the increasing total porosity.

Considering the character of particular components/zones configuration the resulting effective thermal conductivity of the mortars, plasters and insulation boards λ [W/m.K] can be then expressed as a serial configuration of the high and low conductivity (including porosity) solid regions of the particular components by the relation:

$$\lambda = \frac{1}{\frac{(\Phi_{aggregate} + \Phi_{paste} - \Phi_{pasteITZ})^{n_1}}{\lambda_{aggregate}} + \frac{(\Phi + \Phi_{pasteITZ})^{n_2}}{\lambda_{ITZ}}} \quad (5)$$

where: λ_{ITZ} is the thermal conductivity of interfacial zone including its porosity [W/m.K], the influence of bulk paste is relatively negligible. The whole volume of porosity and interfacial zone paste portion $\Phi + \Phi_{pasteITZ}$ is not strictly in serial configuration which is expressed by the exponents higher than 1.0. The exponents in relation (5) express the fractal character of the pore structure – Eq. (1). From the fractal analysis of the considered materials the fractal dimensions of porosity and solid phases ca 1.0 has been obtained, which gives the value of the exponents n_1 and n_2 equal to 2.0. The fractal dimensions were determined from SEM pictures of the considered materials by a box counting method (Zmeřkal et al, 2001).

As the thermal conductivities of the bulk paste and mainly the aggregate in the relation (5) are significantly higher than thermal conductivity of the interfacial zone including porosity the relation has practically the form of the approximation (4) obtained from measurements. The thermal conductivity of the interfacial zone 0.064 W/m.K in relation (1) corresponds to the values measured for the pure CSH – xonotlite (Koronthaljova & Matiasovsky, 2003).

Considering the thermal conductivity of aggregate in the interval 3.0 – 6.0 W/m.K and the thermal conductivity of cement paste 1.0 W/m.K the model expressed by relation (5) gives for different total porosity values the values of thermal conductivity close to the measured values, considering the thermal conductivity of quartz aggregate equal to 6 W/m.K (Fig. 3).

There are a lot of models for the evaluation of the thermal conductivity of porous composite materials (Marshall 1972, Khan 2002). Most of them are based on the combination of parallel and serial configuration of particular phases and components. The problem of empiric factor of each model is to determine the adequate portion of the serial components. Simultaneously the aggregate thermal conductivity is significantly variable which increases the uncertainty of the model used.

The results were compared with the lower bounds of thermal conductivity (Fig. 1):

- Wiener bounds (Wiener 1912):

$$\lambda = \frac{1}{\frac{\Phi_1}{\lambda_1} + \frac{\Phi_2}{\lambda_2}} \quad (6)$$

- Hashin-Shtrikman (HS) bounds (Hashin 1983):

$$\lambda = \lambda_2 + \frac{\Phi_1}{\frac{1}{\lambda_1 - \lambda_2} + \frac{\Phi_2}{3 \cdot \lambda_2}} \quad (7)$$

where $\lambda_1 = 6.0$ and $\lambda_2 = 0.064$.

Also the HS bounds underestimate the thermal conductivities of low porosity materials.

The model formulated by the relations (1)–(5) tries to prevent these uncertainties. It estimates the resulting composite thermal conductivity from two relatively easily measurable parameters – the total porosity and pore size distribution. From Figure 1 it can be seen that the relationship (5) satisfactorily fits in the whole

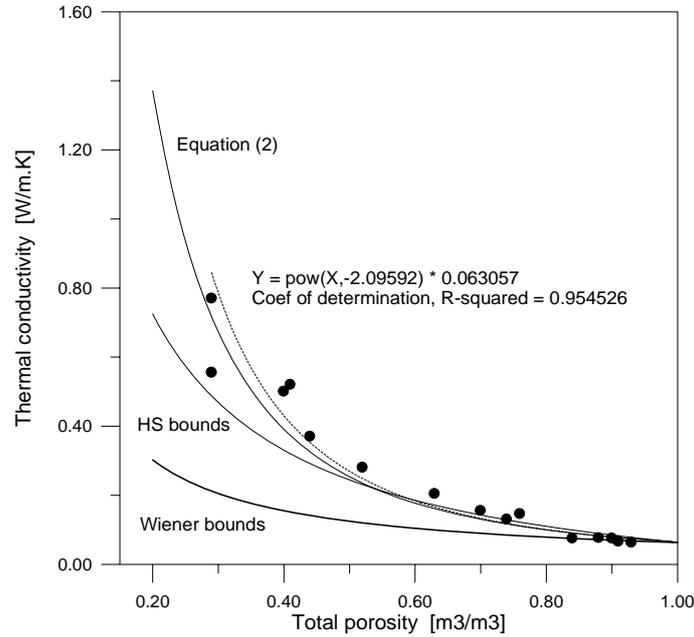


Figure 2 Effective thermal conductivity of mortars and plasters vs. total porosity, comparison of measured values with Wiener and HS bounds

porosity range and by its analysis the thermal conductivity of aggregate (from the fitted curve position along a vertical coordinate) can be estimated.

4 Conclusion

The effective thermal conductivity of dry CSH-based mortars, plasters and insulation boards can be modelled by the serial configuration of the aggregate with bulk paste and the interfacial transition zone conductivities, weighed by the power functions of their volume fractions. The exponents include fractal dimension of particular components and correspond to a degree of percolation of the configuration of particular elements and pore volume fractions in the materials.

Thermal conductivity of mortars and plasters is in the first approximation proportional inversely to the second power of their total porosity.

The approximation of the measured results by the proposed model enables to estimate the thermal conductivity of particular components or zones fitting the optimum thermal conductivity dependence curve shape and the position along a vertical coordinate.

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