MOISTURE DEPENDENCY OF THERMAL CONDUCTIVITY OF CERAMIC BRICKS

Olga Koronthalyova

Institute of Construction and Architecture, Slovak Academy of Sciences, Dubravska 9, 845 43 Bratislava, Slovakia. e-mail: usarkoro@savba.sk, usarmat@savba.sk

Abstract:
Measurement of thermal conductivity moisture depencency of commonly manufactured burnt clay bricks was performed using an impulse technique. The relationships between microstructure and moisture dependency of thermal conductivity were analysed. The using formely developed microstructural model for the dry composite materials was disscussed and its modiffication was suggested.

Keywords:
Thermal conductivity, moisture dependency, clay brick, porosity, model

INTRODUCTION

Porous building materials generally consist of solid, gaseous and liquid phase. The effective thermal conductivity of the porous material depends on thermal conductivities of particular phases, their volume portion, their distribution and interconnection.

Burnt clay bricks are common building material manufactured from the clay-sand mixture (the portion of the sand can be from 30 to 50%). The burning takes place at temperatures 900 - 1000°C. Their microstructure is dependent of the particle size distribution, mineralogical and chemical composition, type of burning additives and the way of burning [2, 3]. The thermal conductivity of clay brick body can also vary depending on its factual mineralogical and chemical composition.

In the previous works [5], [6] the relationship between the thermal conductivity and pore structure parameters for dry CSH-based materials and ceramic bricks was analysed. It was found out that in the first approximation the thermal conductivity of tested materials was proportional inversely to the second power of their total porosity. It was also shown that the thermal conductivity of the tested materials could be modeled by serial configuration of the high conductivity fraction (solid phase fraction) and low conductivity fraction (pore volume fraction + interfacial transition zone) weighted by the power function of their volume fractions. The exponents of the power function were determined using the particular components fractal dimensions.

In the paper the moisture dependence of effective thermal conductivity of burnt clay bricks was measured and analysed. In the first step the possibility of using the formely developed microstructural model [5], [6] was investigated. For the more precise modelling of the moisture dependence of thermal conductivity the lattice-type periodic model [9, 10] was used for an expression of thermal conductivity of moist pore volume (including the interfacial transition zone).

THEORY

Macroscopic thermal conductivity of composite material can be expressed using the thermal conductivities of particular components.

Wiener bounds

The lower and upper limits of effective thermal conductivity of moist composite material can be evaluated by Wiener bounds. Their derivation is based on assumption of strictly parallel or serial setting of particular phases [13]. In case the material consists of three phases – solid, air and water the Wiener upper bound is given by relation (1):

$$\lambda_{up} = \lambda_s \cdot (1-\Phi) + \lambda_w \cdot u_v + \lambda_a \cdot (\Phi - u_v) \tag{1}$$

and the Wiener lower bound by relation (2):

$$\lambda_{low} = \frac{1}{\frac{(1-\Phi)}{\lambda_s} + \frac{u_v}{\lambda_w} + \frac{(\Phi - u_v)}{\lambda_a}} \tag{2}$$

Where λ_s, λ_w, λ_a are thermal conductivity of solid, water and air respectively, Φ is total porosity and u_v is volume portion of moisture content.

Microstructural model of effective thermal conductivity

For the continuous high conductivity components fractions with the discrete low continuity components the macroscopic thermal conductivity can be modeled by the summation of particular components:

$$\lambda = \sum_i \lambda_i \cdot (\Phi_i - \Phi_{i,crit})^{n_i} \tag{3}$$

Where λ_i is thermal conductivity of component,
Φ_i is component volume fraction,
$\Phi_{i,crit}$ is the critical volume needed for a connected network to be formed through the material,
$n_i = 1 + FD$,
FD is the fractal dimension of the component or pore volume fraction [5].
In case of parallel configuration of the components, $n_i = 1$.

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

$$\lambda = \frac{1}{\sum_i \frac{\left(\Phi_i - \Phi_{i,crit}\right)^{n_i}}{\lambda_i}} \tag{4}$$

Where n_i =1for serial configuration of the components, $n_i > 1$ in case of dispersion of the low conductivity component.

In the previous works [5], [6] the relations between the thermal conductivities of dry composite materials and their total porosity were studied. The following empirical relation between thermal conductivity and total porosity was found out for ceramic bricks and CHS based materials:

$$\lambda = \frac{1}{\dfrac{\Phi^2}{0.064}} \tag{5}$$

It was also shown that the thermal conductivity of the tested composite materials could be modeled by serial configuration of the high conductivity fraction (solid phase fraction) and low conductivity fraction (pore volume fraction + interfacial transition zone) weighted by the power function of their volume fractions. It was supposed that the interfacial zone volume fraction represented 10% of the total porosity in average [14]. As the thermal conductivity of low conductivity zone the value λ_{low} = 0.064 W/mK, corresponding to the value measured for the pure CHS – xonotlite [4], was considered. In this highly porous material the volume portion of solid phase is also about 10%. The resultant thermal conductivities of dry material was given by following relation:

$$\lambda = \frac{1}{\dfrac{(1-1.1\cdot\Phi)^{n1}}{\lambda_{high}} + \dfrac{(1.1\cdot\Phi)^{n2}}{\lambda_{low}}} \tag{6}$$

The exponent of solid phase was estimated as $n_1 \approx 1.0$, the exponent of pore volume fraction was estimated as $n_2 \approx 2.7$ [6].

Lattice-type periodic model

In case of two-phase system created by continuous medium with thermal conductivity λ_0 and dispersed phase with thermal conductivity λ_1 and on condition that dispersed phase is created by spherical particles of the same size and they are dispersed regularly the resultant relation for effective thermal conductivity λ_{ef} can be written as [9, 10]:

$$\lambda_{ef} = \lambda_0 \cdot \left[1 + 3.844 \cdot \left(\frac{\lambda_1 - \lambda_0}{\lambda_1 + 2\lambda_0}\right) \cdot \left(\frac{\Phi_1}{\Phi_0}\right)^{2/3}\right] \tag{7}$$

Where Φ_1 is volume portion of dispersed phase and Φ_0 is volume portion of continuous medium. The equation (7) was derived on condition of simple cubic lattice, taking into account mutual interaction of dispersed phase up to fourth neighbour. It is valid for case of small dispersion, i. e. on condition that $(\Phi_1/\Phi_0)^{2/3}$ lies between 0 and 0.4 [10]. When $(\Phi_1/\Phi_0)^{2/3}$ lies between 0.4 and 1.0, the effective thermal conductivity is given by relation (8) [10]:

$$\lambda_{ef} = \lambda_1 \cdot \left[1 + 3.844 \cdot \left(\frac{\lambda_0 - \lambda_1}{\lambda_1 + 2\lambda_0}\right) \cdot \left(1 - \left(\frac{\Phi_1}{\Phi_0}\right)^{2/3}\right)\right] \tag{8}$$

Practically the same relation with slightly different coefficient (3.74 instead of 3.844) was derived in [11] for case of cylindrical lattice structure. The relations (7) and (8) has been used in [10] for expression of thermal conductivity of moist air in pore system of sand.

EXPERIMENTAL

The measurements were done for four types of burnt clay bricks.

The pore size distribution, the open porosity and the specific surface area of pores were studied using the mercury intrusion porosimetry (MIP): the high-pressure porosimeter mod. 2000 and macro-porosimeter mod. 120 (both Carlo Erba, Milan). This system enables determination of micropores with the radius from 3.7 up to 7500 nm and of larger pores with a radius up to 0.06mm. The porosimetry measurement was carried out by the fraction of broken dried (up to 105°C) samples. Specific surface area of pores was determined using the cylindrical model.

The open porosity was also determined from the suction test.

The thermal conductivity was measured by transient pulse method using the commercial device ISOMET 2104 with the surface probe API 210412. The used surface probe is suitable for thermal conductivities in the range from 0.3 to 2 W/m·K. The measurement is based on the analysis of the temperature response of the practically semi-infinite body to the heat flow impulse. The heat flow is generated by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. The declared precision of the measurement is about 5%. The mean values from five measurements were taken into account in analysis of results.

The interval of measured moisture contents of samples was form 0 to 9% (by volume). It follows that for the considered materials the maximum volume fraction of moisture in pore space was 0.23 and therefore the condition of small dispersion water in pore air was fulfilled. The samples were moistened and conditioned for at least 24 days to achieve homogeneous moisture content distribution. The moisture content was checked before and after measurement gravimetrically.

RESULTS AND DISCUSSION

The total porosity, specific surface area and pore radius median values, determined by MIP [1] as well as the values of open porosity, bulk and true density are in Tab. 1. Because for the clay bricks the values of open porosity and total porosity are practically identical [3], the values of open porosity were used in the following analysis of the relationships between the thermal conductivity and microstructure.

Table 1. Basic material parameters of tested bricks

Material	Bulk density [kg/m^3]	Total porosity (MIP) [-]	Open porosity (suction test) [-]	True density [kg/m^3]	Specific surface area [m^2/g]	Pore radius median [nm]
Brick D	1724	-	0.3	2460	-	-
Brick L	1710	0.28	0.33	2550	2.39	559.1
Brick P	1377	0.50	0.42	2370	8.07	535.1
Brick S	1426	0.43	0.44	2590	1.44	542.9

In the first step of modelling the tested bricks thermal conductivity moisture dependence the possibility of using formely developed microstructural model for the dry composite materials (relations (5) and (6)) was tested. In case of moist bricks instead the total porosity the free porosity – the difference between the total porosity and volumetric moisture content was used. In Fig. 1 the relationship between the measured thermal conductivity and total / free porosity is compared with the calculated values according relations (5) and (6). The considered thermal conductivity of the solid phase λ_{high} (thermal conductivity of clay brick body with density equal to ca 2500 kg/m^3 - see Tab. 1) was about 1.5 W/m·K [8]. As can be seen from the Fig. 1 the thermal conductivity / free porosity dependence of the tested bricks can be in the first approximation expressed by empirical relation (5) as well as by the serial model (6) similarly like in case of dry materials.

The more detailed representation of the measured thermal conductivities of particular types of moist bricks vs. their modeled values is shown in Fig. 2.

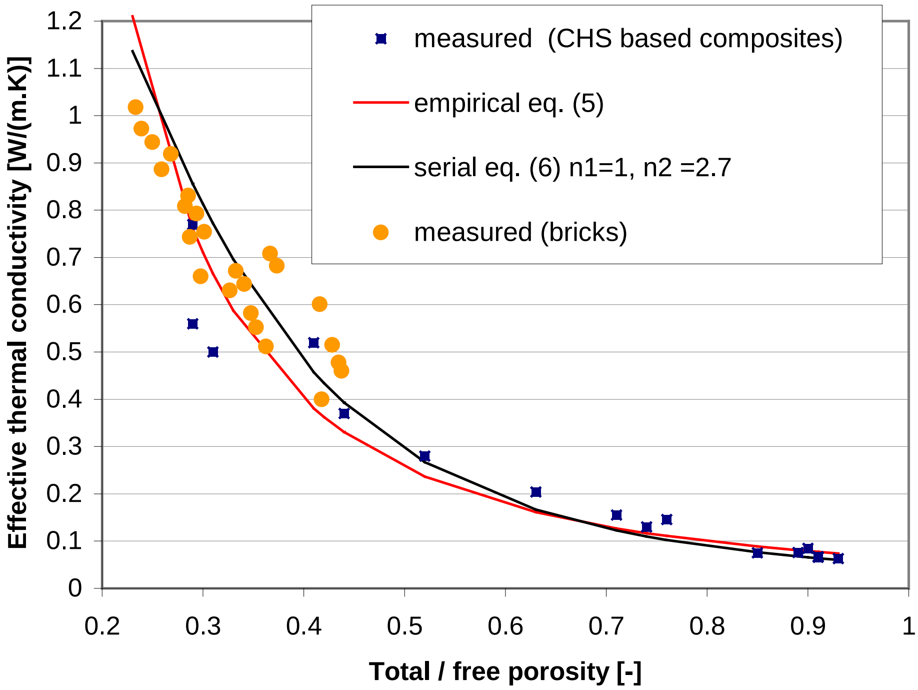

Fig. 1 Thermal conductivities of clay bricks and CHS based materials vs. total / free porosity. Comparison of the measured values with empirical approximation (5) and serial model (6)

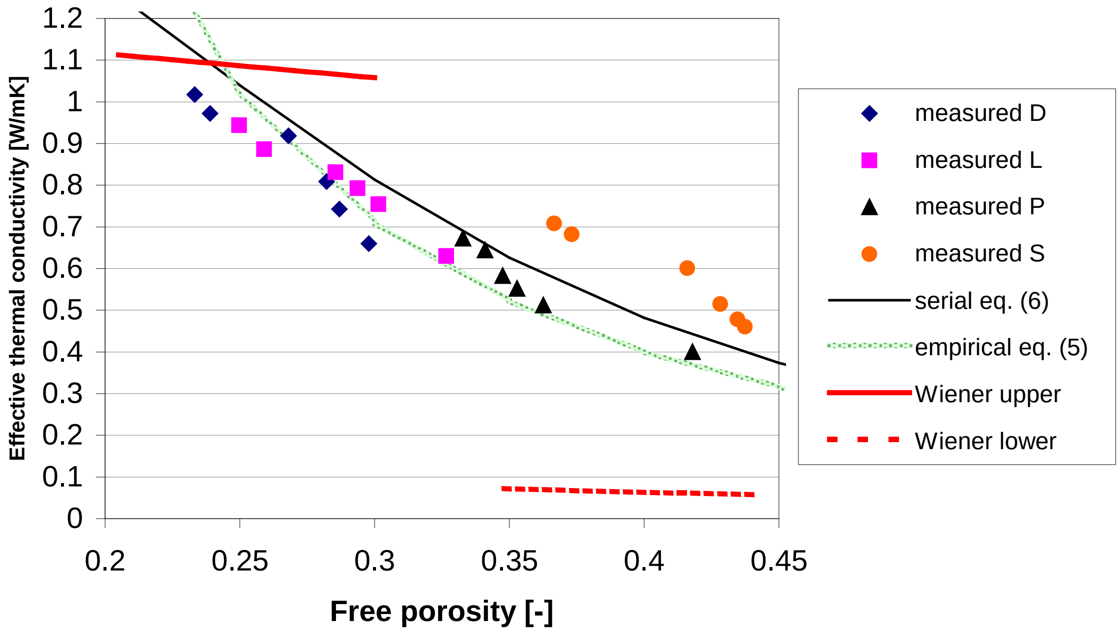

Fig. 2 Thermal conductivities of moist clay bricks vs. free porosity. Comparison of the measured values with empirical approximation (5), serial model (6) and Wiener bounds

As can be seen from the Fig. 2, in case of bricks D, L, P the measured values of clay bricks are in a relative satisfactore agreement with the relations (5) and (6) up to the free porosity value ca 0.26. For the lower values of free porosity the relations (5) and (6) predicted values are in contradiction with the upper Wiener bound (eq. 1). In case of S brick the measured values of thermal conductivity were higher than the modeled. It could be partly caused by different minearology and therefore thermal conductivity of S brick body.

The comparison of the measured and modeled thermal conductivities vs. moisture content are presented in Fig. 3 and Fig. 4. In this comparison the thermal conductivity of solid phase λ_{high} = 1.05 W/m·K for bricks D, P, L and λ_{high} = 2.5 W/m·K for brick S was considered. The serial model (6) coincides roughly with the measured values but it is not able to express the changing slope in the effective thermal conductivity vs. moisture content dependency. Similar changing slopes were noticed also by other authors – for example [10] for moist sands with porosity of 0.42 and 0.52, [12] for moist sand with porosity of 0.3 or [7] for composite material with porosity of 0.32.

With the aim to get more precise description of the moisture influence on thermal conductivity the above described lattice-type periodic model was used for thermal conductivity of moist pore space (including interfacial zone) $\lambda_{m,low}$. Because the considered moisture contents fulfill condition of small dispersion the relation (7) was used:

$$\lambda_{m,low} = \lambda_{low} \cdot \left[1 + 3.844 \cdot \left(\frac{\lambda_w - \lambda_{low}}{\lambda_w + 2\lambda_{low}} \right) \cdot \left(\frac{u_v}{1.1 \cdot \Phi} \right)^{2/3} \right] \tag{8}$$

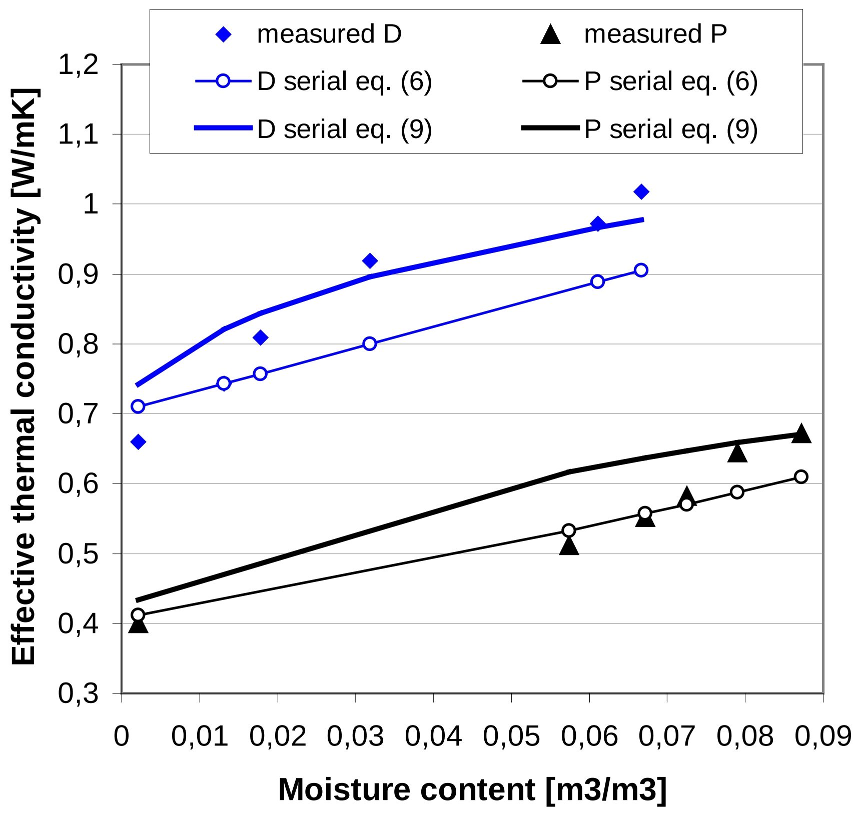

Fig. 3 Thermal conductivities of bricks D and P vs. moisture content. Comparison of the measured values and modeled values by eq. (6) and (9)

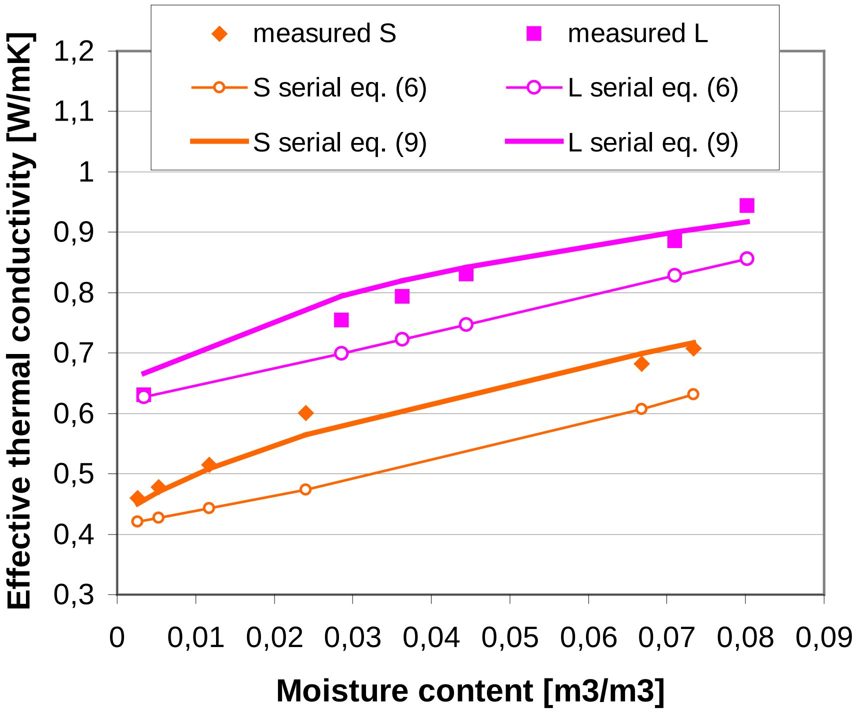

Fig. 4 Thermal conductivities of bricks S and L vs. moisture content. Comparison of the measured values and modeled values by eq. (6) and (9)

The relation (6) then changed into:

$$\lambda = \frac{1}{\dfrac{(1-1.1\cdot\Phi)^{n1}}{\lambda_{high}} + \dfrac{(1.1\cdot\Phi)^{n2}}{\lambda_{m,low}}} \tag{9}$$

The results of modelling are shown in Fig. 3 and Fig. 4. Using of the upgraded model (9) improved significantly the agreement between measured and modeled values in case of bricks D, L, S. As to the brick P, it is a material with relative high non-homogeneity. Therefore the existing discrepancies were probably caused by the higher measurement uncertainty.

CONCLUSIONS

The relation between effective thermal conductivity and moisture content was investigated for four types of burnt clay bricks.

In the range of measured moisture contents (0-9%) the first approximation of effective thermal conductivity of moist clay bricks can be modeled by serial configuration of the high conductivity fraction (solid phase fraction + water) and low conductivity fraction (free pore volume fraction + interfacial transition zone) weighted by the power function of their volume fractions**.**

Incorporating the lattice-type periodic model of moist pore space into the formely developed serial model significantly improved the coincidence between the measured and modeled values.

ACKNOWLEDGEMENTS

This paper has been supported by Slovak Grant Agency VEGA (grant No. 2/7113/27).

REFERENCES

[1] Bagel, L. (2001) Structural parameters of clay bricks. Internal report. Institute of Construction and Architecture, SAS, Bratislava (in Slovak).
[2] Cultrone, G. et al. (2004) Influence of mineralogy and firing temperature on the porosity of bricks. *Journal of the European Ceramic Society.* Vol. 24, pp. 547-564.
[3] Dondi, M. et al. (2005) Water vapour permeability of clay bricks. *Construction and Buillding Materials.* Vol. 17, pp. 253-258.
[4] Koronthályová, O., Matiašovský, P. (2003). Thermal Conductivity of Fibre Reinforced Porous Calcium Silicate Hydrate-based Composites. *Journal of Building Physics*, Vol. 26, No. 4, pp.71- 89.
[5] Matiašovský, P., Koronthályová, O. (2005) Thermal Conductivity of Mortars and Fractal Properties of their Microstructure. In *Proceedings of Thermophysics 2004*, USTARCH SAV, ISBN 80-969371-8-9. Bratislava, 2005, pp. 38-45.
[6] Koronthályová, O., Matiašovský, P. (2007) Pore structure and thermal conductivity of burnt clay bricks. In *Proceedings of Thermophysics 2007*, Vydavatelstvo STU, ISBN 978-80-227-2746-4. Bratislava, 2007, pp. 100-106.
[7] Pavlik, Z., Fiala, L., Cerny, R. (2007) Application of Maxwell mixing role in the measurement of thermal conductivity of porous building materials. In *Proceedings of Thermophysics 2007*, Vydavatelstvo STU, ISBN 978-80-227-2746-4. Bratislava, 2007, pp. 34-38.
[8] Raznjević, K. (1984) Thermophysical Tables, ALFA Bratislava, (in Slovak).
[9] Singh, R., Beniwal, R., S. and Chaudhary, D. R. (1987) Thermal conduction of multi-phase systems at normal and different interstitial air pressures. *J. Phys. D: Appl. Phys.* Vol. 20, pp.917-922.
[10] Singh, A. K., Singh, R. and Chaudhary, D. R. (1990) Prediction of effective thermal conductivity of moist porous materials. *J. Phys. D: Appl. Phys.* Vol. 23, pp.698-702.
[11] Singh, R., Sharma, P. (2008) Effective thermal conductivity of polymer composites. *Advanced Engineering Materials,* Vol. 10, pp. 366-370.
[12] Veselsky, J. (2006) Investigation of thermal properties of soil by impulse method. In *Proceedings of Thermophysics 2006*, Vydavatelstvo STU, Bratislava, 2006, pp. 115-123.
[13] Wiener, O. (1912) Die Theorie des Mischkoerpers fur das Feld des stationaren Stromung. Abh. Math – Phys. K1 Konigl. Saechs. Gesel. Wissen, 32, pp. 509-604.
[14] Winslow, D. N. et al. (1994) Percolation and pore structure in mortars and concrete. *Cement Concrete Research* 24, pp. 25-37