

Thermal conductivity based mix design of cementitious materials



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ABSTRACT

While cement-based materials are the most consumed materials in the construction industry, low or high thermal conductivity may be desirable for these materials depending on the application purposes such as embedded floor heating systems, building envelope or using as structural elements. The procedure of presenting prediction models for thermal conductivity of cementitious composites by considering different variables such as constituent materials, porosity and moisture content is described in this paper. The prediction model can be used for thermal conductivity based mix design of cementitious materials. Based on the desired accuracy, two methods for predicting the thermal conductivity are presented.

Key words: Mix Design, Modelling, Thermal Conductivity, Cement-based Materials.

1. INTRODUCTION

Thermal conductivity is an important material property in the energy design process of buildings. While cement-based materials are the most consumed materials in the construction industry, a wide range of thermal conductivity may be desirable for these materials depending on the application purposes. Indoor surfaces such as embedded floor heating systems or cementitious materials mixed with phase change materials, may demand high thermal conductivity. On the other hand, materials with low thermal conductivity may be desirable for using as a part of heat insulation or for thermal bridge calculations as well as structural elements.

Moisture content, porosity and constituent materials are the main parameters affecting thermal conductivity of cement-based materials. Thermal conductivity of water is more than 20 times bigger than thermal conductivity of the stagnant air and replacement of air by water can make a significant change in the thermal conductivity of porous materials. While changes in constituent materials and porosity may be neglected after concrete curing for thermal conductivity determination, the moisture content is expected to have considerable changes during lifetime of most cementitious materials. This means that considering one certain value for thermal conductivity of such types of materials may give low accuracy when considering the material performance during the service life of the material. Calculating thermal conductivity as a function of main effective variables such as moisture content, porosity and constituent materials based on semi-empirical models can be a practical solution to this challenge. The thermal conductivity of dry material can be adjusted in the mix design based on the concrete technology knowledge on porosity and constituent materials. Variations in this material property due to moisture content can be estimated based on the saturation degree. Moreover, the water sorption can be controlled by modifying the pore structure as well as internal or surface hydrophobation [1,2]. The proposed model can for example be

introduced to building physic tools, where the thermal conductivity can be updated based on the existing climate conditions.

2. PARTICLE-MATRIX MODEL FOR THERMAL CONDUCTIVITY DETERMINATION

2.1 Matrix

The main factors affecting thermal conductivity of the matrix can be considered as variables in a multiphase composite model. Baghban et al. [3] presented a three-phase model for predicting thermal conductivity of hardened cement pastes (hcps):

$$\lambda^n = m\lambda_w^n + (\varepsilon_{tot} - m)\lambda_a^n + (1 - \varepsilon_{tot})\lambda_s^n \quad (1)$$

Where λ , λ_w , λ_a and λ_s are the thermal conductivity of the hcp, water, air, and solid structure of the hcp, respectively. ε_{tot} is the total porosity, m is the volumetric moisture content and n is a constant value. While λ_w and λ_a are known, a proper estimation needs to be done for λ_s and n based on experimental investigation.

The graph on the left in Fig. 1 illustrates the thermal conductivity of plain hcps at different total porosities and volume fraction of water. Unknown parameters are determined based on experimental investigations and introduced to Eq. 1, which is in agreement with the results obtained from the laboratory (See Fig. 1- right). Since thermal conductivity of solid structure of the matrix, λ_s , may vary due to changes in constituent materials such as presence of pozzolanic materials, fibers or changes in the cement chemistry, λ_s can be determined as a function of these variables by laboratory research. Furthermore, changes in the thermal conductivity of the fluid phase due to variations in the pore structure or different fluid chemistries can also be investigated by the same procedure.

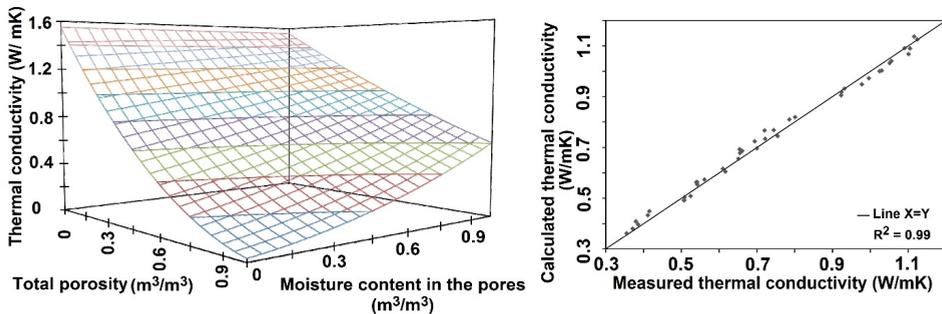


Figure 1 – Thermal conductivity of plain hcps at different total porosities and volume fraction of water calculated from Eq. 1(left), comparison of the measured and calculated thermal conductivities (right)[3]

2.2 Particle

Stone aggregates are the most commonly used particle types in cementitious composites. These aggregates have usually a low porosity and the effect of moisture sorption may be neglected for many practical applications. On the other hand, multiphase prediction models can also be presented for the particles in case of using aggregates with considerable porosity, such as using light weight aggregates.

Fine particles in the size range of the matrix particles can be considered as a part of the matrix. Moreover, the coupling effects such as effect of interfacial transition zone can also be defined as a function of the surface area of the particles in the mix.

2.3 Prediction models for cementitious composites

Semi-empirical model

Individual determination of the thermal conductivity of the particle and the matrix phases makes it possible to determine the thermal conductivity of the cementitious composites using a two-phase model. Furthermore, the accuracy of the model can be adjusted based on the considered accuracy in predicting the thermal conductivity of individual phases.

$$\lambda_{composite}^n = v_1 \lambda_{matrix}^n + v_2 \lambda_{particle}^n \quad (2)$$

v_1 and v_2 are the volume fractions and n is a constant value determined by experimental investigation.

Simplified estimation using Hashin-Shtrikman bounds

While the above mentioned semi-empirical model can be used for thermal conductivity based mix design as well as estimation of thermal conductivity of existing cement-based composites with a reasonable accuracy, a simplified method can be used for predicting the upper and lower limits of this material property. The Hashin-Shtrikman (H-S) lower (λ_l) and upper (λ_u) bounds for two material phases with $\lambda_1 \geq \lambda_2$, are given by [4]:

$$\lambda_l = \lambda_1 + \frac{v_2}{\frac{1}{\lambda_2 - \lambda_1} + \frac{v_1}{3\lambda_1}} \quad (3)$$

$$\lambda_u = \lambda_2 + \frac{v_1}{\frac{1}{\lambda_1 - \lambda_2} + \frac{v_2}{3\lambda_2}} \quad (4)$$

As the difference between thermal conductivity of matrix- and particle phases becomes lower, the two-phase H-S bounds become tighter and a reasonable estimation of thermal conductivity of cement-based composites is possible without conducting experimental investigation for predicting n value in Eq. 2. The same procedure can be used for predicting the thermal conductivity of matrix- or particle phases separately, for example in the case of submerged hcps where most of the air which has low thermal conductivity is replaced by water which has a thermal conductivity value closer to the thermal conductivity of solid structure of the hcp (Fig. 2).

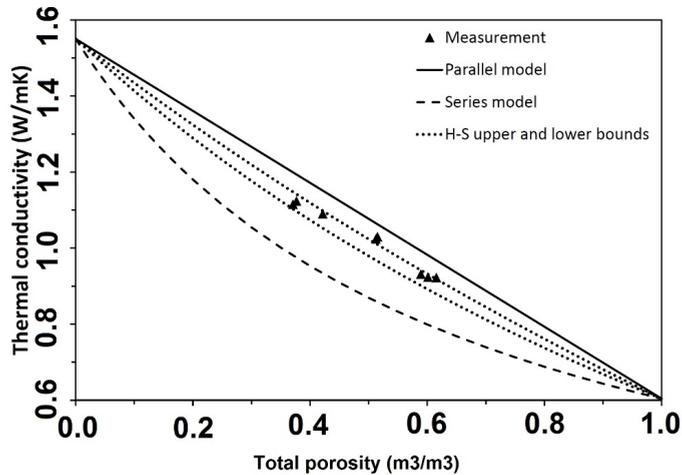


Figure 2– Measured thermal conductivity of plain hcps submerged in water and analytical bounds [3]

The expected porosity and moisture content of the cement-based materials can be estimated and adjusted by using the knowledge of concrete technology and building physics. Consequently, by introducing appropriate constituent materials, a particle-matrix model in the form of semi-empirical model or two-phase H-S bounds can be used for thermal conductivity based mix design of cementitious materials with desirable accuracy.

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