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Experimental determination and fractal modeling of the effective thermal conductivity of autoclaved aerated concrete: Effects of moisture content

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ABSTRACT

Autoclaved aerated concrete (AAC) has widely been utilized as a lightweight, porous insulation material for energy-efficient buildings. The knowledge on the thermal conductivity of AAC is required for thermal design of building envelopes. The effective thermal conductivity of AAC is strongly dependent on the moisture content. Such dependence, however, is not well documented in available literature. In this work, AAC bricks with three different bulk densities of 415, 520, and 630 kg/m^3, were obtained as the raw materials, and the samples were prepared by humidification to a set of moisture content levels up to 100% by mass. The effective thermal conductivity of the moisturized samples was measured by means of the transient plane source technique. Meanwhile, fractal models for predicting the effective thermal conductivity were proposed based on construction of the porous structure of AAC by self-similar Sierpinski carpet. A two-phase fractal model was first proposed for dry AAC samples, and then an extension to a three-phase model was developed by considering the presence of water phase in the pores for unsaturated, moist samples. It was shown that the thermal conductivity increases with increasing the moisture content, by a factor up to 3.8 over the studied range of moisture content, following a two-section piecewise linear variation. A high-to-low slope change was found to be around a moisture content of 15% for all the AAC samples. A correlation was proposed for the measured thermal conductivity as a function of both moisture content and porosity. Appropriate parameters for the two-phase model were determined by comparing the predicted results to the measured data at dry state. The three-phase fractal model was exhibited to be able to predict the hygric dependence of thermal conductivity. The discrepancy among the predictions by the three-phase model with different geometric parameters was discussed in relation to the constructed pore structures. The predicted results by the two configurations of the three-phase model, i.e., with and without considering the presence of connected water bridges in the pores, were also presented. A reasonable elimination of the presence of connected bridges was shown to lead to better predictions in the low moisture content regime.

1. Introduction

The availability of a high-performance building envelope is identified as one of the crucial issues to be addressed towards design and development of energy-efficient buildings [1]. A building envelope, separating the indoor and outdoor environments of a building, consists of a variety of components such as walls, roofs, fenestration, and foundation, among which walls account for a predominant portion [2]. The thermal performance of a building envelope has direct impact on control of indoor thermal and hygric conditions, which in turn determine the energy utilization and occupant comfort levels. Obviously, the knowledge on physical, thermal, and hygric properties of candidate materials for a building envelope is key to simulation, prediction, and optimization of its energy consumption.

There are many physical, chemical, and geometrical factors influencing thermal properties of porous building materials, including density (porosity), temperature, moisture content,

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Nomenclature

c	moisture content by mass (%)
C	side length of the central matrix
D	fractal dimension
f	volume fraction (%)
k	thermal conductivity (W/mK)
K	dimensionless thermal conductivity
L	side length of the Sierpinski carpet
m	mass (kg)
n	number of iteration
Q	heat flux (W/m^2)
r	thickness of surrounding water layer
R	thermal resistance (K/W)
S	saturation degree
t	width of virtual thermal resistances
V	volume (m^3)
w	width of connected water bridges

Greek symbols

α	dimensionless side length of the central matrix, defined by C/L
β	dimensionless thickness of surrounding water layer, defined by r/L
ϕ	porosity (%)
κ	ratio of matrix to dry air thermal conductivity
ρ	bulk density (kg/m^3)
τ	dimensionless width of virtual thermal resistances, defined by t/L
ω	dimensionless width of connected water bridges, defined by w/L

Subscripts

a	air
b	connected water bridges
d	dry
l	lower
m	matrix
p	pores
s	surrounding water layer
u	upper
w	water

microstructure, and composition as well. During the service life of porous building materials, liquid water may easily be absorbed into and then transport and store in the pores. Water vapor could also adsorb, penetrate, and condense in the pores. The presence of water leads to increased effective thermal conductivity of moist porous building materials to a great extent from their dry state, in view of the fact that the thermal conductivity of liquid water is orders of magnitude higher than that of air. Hence, the hygric dependence on the effective thermal conductivity of common porous building materials, such as concrete with various functionalities/compositions [3–8], hemp-based composites [9], wood [10] and wood-based composites [11–13], lime- and calcium silicate hydrate (C-S-H)-based composites [14,15], and thermal insulation materials [16–19], is of great significance for accurate prediction of their thermal responses.

A porous, lightweight concrete, autoclaved aerated concrete (AAC) has widely been projected as a promising building material in structural, partition, and thermal insulation walls with desired attributes [20]. A great number of efforts have been dedicated to characterization of the structure and properties of AAC, among which the thermal conductivity is considered as the major thermal property of interest [21–31]. Although a growth factor from 2 to 7, upon increasing the moisture content from dry state to relatively low levels, has been reported for the thermal conductivity of AAC by some of the previous efforts [21,26,29], however, the hygric dependence has not yet been well documented over a wide range of moisture content, especially at relatively high moisture contents. Due to the diversity in composition and structure, the measured data scatter significantly. Moreover, great experimental uncertainties are expected to exist as a result of water migration and evaporation upon heating during steady-state thermal conductivity measurements.

On the other hand, there is a lack of models for predicting the effective thermal conductivity of AAC as a function of moisture content over a wide range. In view of the success of using fractal theory for modeling the effective thermal conductivity of porous media, either structured or randomly distributed [32–34], a few fractal-based thermal conductivity models have been established for porous building materials, like wood [35] and concrete [36], at dry state. The fractal theory has also been employed to analyze multiscale pore structure of building materials, including earth-based materials [37], cement pastes [38,39], and concrete [40] as well. In particular, as inspired by fractal modeling of the effective thermal conductivity for unsaturated, three-phase porous media [41,42], the fractal theory seems to be promising for establishment of a thermal conductivity model for moist AAC.

In this work, both experimental and modeling efforts will be made to address the above-mentioned concerns about the existing studies. First, the thermal conductivity of moist AAC with various porosities will be measured experimentally by means of a transient approach, as opposed to the steady-state methods adopted in many previous studies. Another major contribution of the present work is to propose a three-phase fractal model for prediction of the thermal conductivity of moist AAC as a function of moisture content, which will be validated against available experimental results, both from the present work and relevant literature.

2. Experimental

2.1. Preparation and characterization of AAC samples

The AAC materials were manufactured and provided by Zhejiang Kaiyuan New Building Materials Co. Ltd., P.R. China. Three types of AAC were sampled from the product line with the standard product number of B04, B05, and B06 in the China market, indicating that the nominal bulk density is 400, 500, and 600 kg/m^3, respectively. The AAC samples were randomly cut from bulk products to a uniform rectangular shape having dimensions of approximately $100 \times 100 \times 30$ mm^3. For each type of the AAC samples, multiple specimens were prepared for parallel tests. Prior to thermal conductivity measurements, the AAC samples at dry state were characterized on their structural and physical properties of interest. The dry samples were prepared in a vacuum oven that was heated at 105 °C for more than 72 h until the relative mass variations were less than 0.1% over a 24 h duration, followed by cool-down to the ambient temperature in the oven that was maintained at a vacuum condition. The samples were weighed on an electronic balance with an accuracy of 0.01 g.