

Nonlinear Effect of Moisture Content on Effective Thermal Conductivity of Building Materials with Different Pore Size Distributions

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Abstract Understanding the quantitative relationship between the effective thermal conductivity and the moisture content of a material is required to accurately calculate the envelope heat and mass transfer and, subsequently, the building energy consumption. We experimentally analyzed the pore size distributions and porosities of common building materials and the influence of the moisture content on the effective thermal conductivity of building materials. We determined the quantitative relationship between the effective thermal conductivity and moisture content of building materials. The results showed that a larger porosity led to a more significant effect of the moisture content on the effective thermal conductivity. When the volumetric moisture content reached 10 %, the thermal conductivities of foam concrete and aerated concrete increased by approximately 200 % and 100 %, respectively. The effective thermal conductivity increased rapidly in the low moisture content range and increased slowly in the high moisture content range. The effective thermal conductivity is related to the moisture content of the materials through an approximate power function. As the moisture content in the walls of a new building stabilizes, the effective thermal conductivity of normal concrete varies only slightly, whereas that of aerated concrete varies more significantly. The effective thermal conductivity of the material is proportional to the relative humidity of the environment. This trend is most noticeable when the wall material is aerated concrete.

Keywords Building materials · Effective thermal conductivity · Moisture content · Moisture transfer · Nonlinear · Pore size distribution

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Nomenclature

Variables

A	Area of specimen (m^2)
a_0	Empirical constant ($W \cdot m^{-1} \cdot K^{-1}$)
a	Fitting constant ($W \cdot m^{-1} \cdot K^{-1}$)
b	Fitting constant
D	Pore diameter (μm)
D_v	Water vapor diffusivity ($m^2 \cdot s^{-1}$)
h_c	Convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
h_m	Water vapor exchange coefficients ($s \cdot m^{-1}$)
h_v	Specific evaporation enthalpy of water vapor ($J \cdot kg^{-1}$)
$j_{conv}^{m_w}$	Convective liquid (capillary) water flux ($kg \cdot m^{-2} \cdot s^{-1}$)
$j_{conv}^{m_v}$	Convective water vapor flux ($kg \cdot m^{-2} \cdot s^{-1}$)
$j_{diff}^{m_v}$	Diffusive water vapor flux ($kg \cdot m^{-2} \cdot s^{-1}$)
j_{diff}^Q	Heat conduction ($W \cdot m^{-2}$)
u_g	Specific internal energy of gas phase ($J \cdot kg^{-1}$)
u_l	Specific internal energy of liquid phase ($J \cdot kg^{-1}$)
p_v^{air}	Water vapor pressure of ambient air (Pa)
p_v^{elem}	Water vapor pressure in boundary element (Pa)
Q	Heat flow (W)
R_m	Thermal resistance of specimen without plastic film wrapping ($m^2 \cdot K \cdot W^{-1}$)
R_p	Thermal resistance of plastic film ($m^2 \cdot K \cdot W^{-1}$)
R_t	Thermal resistance of specimen with plastic film wrapping ($m^2 \cdot K \cdot W^{-1}$)
t	Time (s)
T^{air}	Temperature of ambient air (K)
T^{elem}	Temperature in boundary element (K)
u	Moisture content of material ($kg \cdot kg^{-1}$)
v	Moisture content of material ($m^3 \cdot m^{-3}$)
v_h	Hygroscopic moisture content ($m^3 \cdot m^{-3}$)
v_w	Moisture content of wall ($m^3 \cdot m^{-3}$)
x	Abscissa (m)

Greek letters

α_m	Additional value of effective thermal conductivity of moist main structural material
β_{ms}	Modification value of effective thermal conductivity of main structural material
ΔT	Temperature difference between hot and cold plates ($^{\circ}C$)
δ	Thickness of specimen (m)
δ_{EPS}	Thickness of EPS of wall (mm)
ε	Porosity
λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
λ_d	Effective thermal conductivity of dry material ($W \cdot m^{-1} \cdot K^{-1}$)

λ_m	Effective thermal conductivity of moist material ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
λ_s	Difference of effective thermal conductivity between moist and dry materials ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
ρ	Density ($\text{kg}\cdot\text{m}^{-3}$)
$\rho_{REV}^{m_{w+v}}$	Moisture (liquid+vapor) density in reference volume ($\text{kg}\cdot\text{m}^{-3}$)
ρ_{REV}^U	Internal energy density in reference volume ($\text{J}\cdot\text{m}^{-3}$)
$\sigma_{REV}^{m_{w+v}}$	Moisture sources/sinks in reference volume ($\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$)
σ_{REV}^U	Energy sources/sinks in reference volume ($\text{W}\cdot\text{m}^{-3}$)
φ_a	Mean annual outdoor relative humidity (%)

1 Introduction

Most building materials are typically porous materials. Because of the moisture adsorption of porous materials, there is a certain amount of moisture or liquid water in the internal pores of these materials. The moisture content influences the effective thermal conductivity of the materials, as determined previously [1–3]. Understanding the quantitative relationship between the effective thermal conductivity and moisture content of these materials is required to determine the envelope heat and mass transfer and building energy consumption. However, once the building objects are established, the thermophysical properties of the building materials are considered to be approximately constant. The influence of the moisture content on the effective thermal conductivity of these materials is typically ignored [4–6]. However, the effective thermal conductivity of the moist materials should be modified, and the quantitative relationship between the effective thermal conductivity and moisture content of common building materials should be studied.

Studying the effective thermal conductivity of porous materials primarily includes theoretical and experimental analyses. Many analytical models have used compound heat transfer, fractal theory, and other similar methods to predict the effective thermal conductivity of porous materials [7–10], and these models provide a theoretical basis for experimentally analyzing the influence of the moisture content on the effective thermal conductivity of building materials. Shin and Kodide [11] and Suchorab et al. [12] experimentally analyzed the influence of the moisture content on the effective thermal conductivities of normal concrete and aerated concrete. They showed that with increasing moisture content, the effective thermal conductivity of the materials increased approximately linearly. However, in the study by Alex and Suchorab, the moisture content range was relatively small, and it was difficult to accurately determine the influence of the moisture content on the effective thermal conductivity of the materials. Jerman and Černý [13] as well as Abdou and Budaiwi [14] experimentally analyzed the influence of the moisture content on the effective thermal conductivities for several types of building insulation materials. Quadratic and linear functions were used to fit the relationship between the effective thermal conductivities and moisture contents of the building insulation materials, respectively. Taoukil et al. [15] and Bal et al. [16] experimentally analyzed the influence of the moisture content on the effective thermal conductivities of concrete combined with wood and bricks with millet waste additive, respectively. Exponential and linear functions were used to fit

the relationship between the effective thermal conductivities and moisture contents of these two types of mixed materials, respectively. However, the suitability of mixed materials for comparison to other common building materials is limited.

Considering the influence of the ambient conditions on the temperature and moisture content of building materials, Pérez-Bella et al. proposed a correction factor to functionally approximate the design thermal conductivity of materials based on normative values [17]. del Coz Díaz et al. obtained the effective thermal conductivity of lightweight concrete as a function of the density and environmental relative humidity through an experimental method [18] and presented a combination of experimental and numerical methods to solve the hygrothermal behavior of lightweight concrete hollow bricks [19]. These studies provide some reference for analyzing the nonlinear effect of the moisture content on the effective thermal conductivity of building materials with different pore size distributions in this paper.

Many experiments and empirical formulas have analyzed the effective thermal conductivity of porous media. However, there are no uniform descriptions or limitations for the effective thermal conductivity of moist building materials. The effective thermal conductivity of porous materials is obtained by converting all types of heat transfer into the heat conduction of the porous materials [20–22]. Therefore, the effective thermal conductivity of a porous medium is closely related to the moisture content and internal pore structure. However, there has been little analysis on the impact of the pore size distributions on the effective thermal conductivity of moist building materials. Therefore, building materials with common porous structures were chosen as the research focus for this paper. A scanning electron microscope and a mercury injection apparatus were used to analyze the pore size distributions and porosities of the materials. The effect of the moisture content on the effective thermal conductivity of the materials was experimentally analyzed. The quantitative relationship between the effective thermal conductivity and moisture content was determined, and the results can be used to modify the effective thermal conductivity of building materials.

A new building has a large initial moisture content of the envelope and a long stabilization time of the envelope moisture content. When moisture and temperature gradients exist between the envelope and the environment, moisture transfers between both surfaces of the envelope and moist air via evaporation and condensation [23–25]. Therefore, the moisture content of the walls of a new building continuously changes over time via moisture transfer to the air. During the stabilization process, the moisture content changes significantly, which causes large variations in the effective thermal conductivity of the building materials and this process impacts the energy consumption of a building.

At present, the main research focus in the heat and mass transfer of building envelopes is determining the effects of moisture transfer on the heat transfer and energy consumption of buildings [26–29]. The effect of the moisture content on the energy consumption of buildings has been neglected. Therefore, analyzing the effective thermal conductivity of envelope materials can provide a basis for energy consumption corrections for new buildings.

CHAMPS-BES is an excellent software that analyzes the coupled heat and moisture transfer in building envelopes. This software is used to analyze the variations in the moisture content of walls in a new building over time. In this paper, based on the

quantitative relationship between the effective thermal conductivity and the moisture content of the materials, the variations in the effective thermal conductivity of the wall materials are provided. These data provide the basis for accurate calculations of the energy consumption of a new building.

2 Materials and Methods

2.1 Experimental Materials

To determine the quantitative relationship between the effective thermal conductivity and moisture content of building materials, the influence of the porous structure on the effective thermal conductivities of common building materials (i.e., normal concrete, clay brick, aerated concrete, and foam concrete) that have different pore size distributions and porosities was studied. Additionally, to compare the effect of the porosity on the effective thermal conductivity of the materials, two types of normal concrete with different porosities, aerated concrete, and foam concrete, were selected. The length, width, and thickness of the experimental samples were approximately 300 mm, 300 mm, and 30 mm, respectively.

2.2 Experimental Apparatuses

The experimental methods for determining the thermal conductivity are classified as steady-state and transient heat transfer methods. The steady-state method has the advantages of a simple principle, convenient calculation, and high measurement accuracy [30,31]. Therefore, the steady-state method is frequently used to determine the effective thermal conductivity of building materials [32,33].

The effective thermal conductivity of the moist materials was determined using a plane table thermo-conductivity meter (PTTM), which adopts the steady-state method. The PTTM comprises the principal part of apparatus, a refrigerated circulating water tank, and a monitoring system, as shown in Fig. 1. A high-precision PT100 was used as the temperature sensor to measure the temperature of the hot and cold plates.

At the center of the measurement region of the PTTM, an approximate one-dimensional heat transfer model of an infinite flat surface under steady-state conditions was established for the parallel surfaces of the uniform experimental specimens between two uniform temperature plane tables. The constant heat flux, specimen area, and temperature difference between the hot and cold surfaces of the specimen were measured under steady-state heat transfer conditions. Then, the effective thermal conductivity of the experimental materials was calculated using Fourier's law, as given in Eq. 1:

$$\lambda = \frac{Q\delta}{A\Delta T}, \quad (1)$$

where λ is the thermal conductivity, Q is the heat flow, δ is the thickness of the specimen, A is the area of the specimen, and ΔT is the temperature difference between the hot and cold plates.

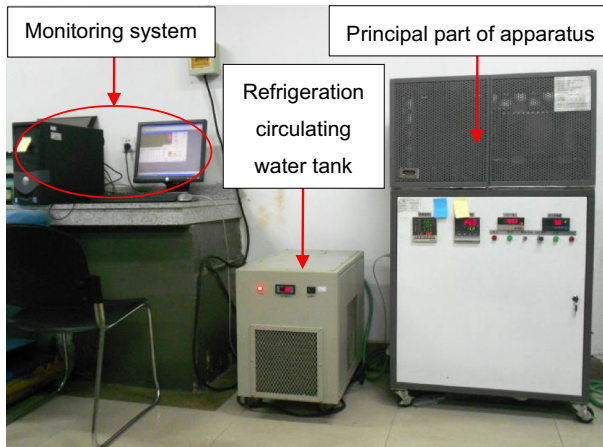


Fig. 1 Plane table thermo-conductivity meter (TPMBE-300)

The internal pore structure, specifically the pore size distribution and porosity, significantly influences the effective thermal conductivity of a material. Therefore, the pore size distribution and porosity should be known when determining the influence of the moisture content on the effective thermal conductivity of a material. There are large differences in the pore sizes of porous materials, and the typical methods for measuring porous materials include optical, mercury intrusion, and isothermal adsorption techniques. The pores of the aerated concrete and foam concrete materials, which contain many macropores, were measured using scanning electron microscopy (SEM). Then, the pore size distributions and porosities of the materials were obtained using professional image analysis software [34]. Mercury intrusion porosimeter (MIP) measures the micropores; therefore, MIP was used to test the normal concrete and clay brick.

The relevant parameters of the experimental apparatuses of the PTTM, SEM, and MIP are as follows:

- (1) The PTTM is a TPMBE-300 with a measurement range from 0.02 W/(m·K) to 1.6 W/(m·K), an accuracy of $\pm 3\%$, and a repeatability of $\pm 0.1\%$. The temperature sensor is a PT100 with a measurement range from $-200\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$ and an accuracy of $\pm 0.15\text{ }^{\circ}\text{C}$ ($0\text{ }^{\circ}\text{C}$).
- (2) The MIP is a PoreMaster GT60 with a measurement range from $3 \times 10^{-3}\text{ }\mu\text{m}$ to $1.08 \times 10^3\text{ }\mu\text{m}$ and an accuracy of $\pm 0.11\%$.
- (3) The SEM is a JSM-6510LV with a magnification factor of 5 to 3×10^5 and a resolution of 4 nm.

2.3 Experimental Procedure

The experiments consisted of two parts: (1) the measurement of the porosities and pore size distributions and (2) the measurement of the effective thermal conductivity of the moist materials.

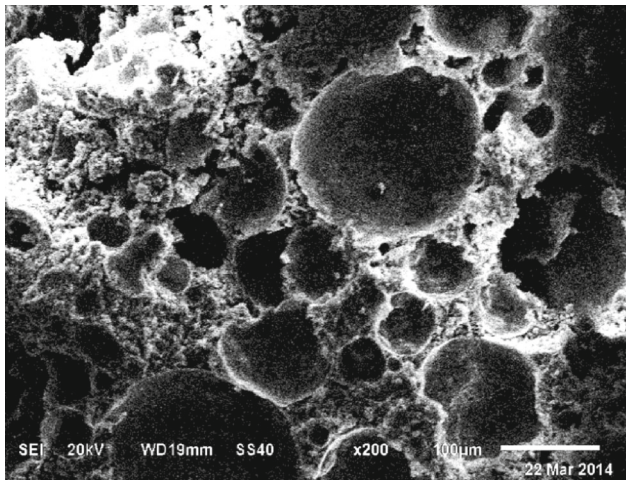


Fig. 2 SEM image of aerated concrete B (magnification factor of 200)

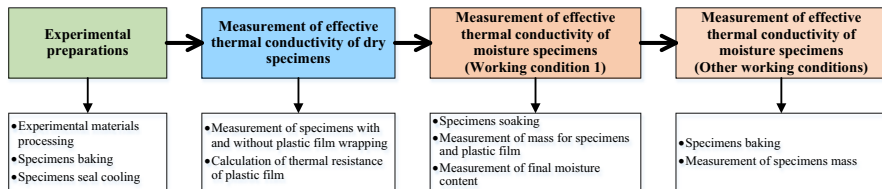


Fig. 3 Flowchart of measurement procedure of effective thermal conductivity of experimental materials

The SEM images of the aerated concrete and foam concrete (see Fig. 2) were processed and analyzed in black and white binary using image analysis software to determine the area porosity, which can be used as an approximation of the volume porosity (i.e., porosity) [34, 35]. The pore size distributions and porosities of the normal concrete and clay brick were directly measured using the MIP.

The acquisition time of a steady-state heat transfer method is relatively long. Based on the PTTM, the duration of each steady-state measurement of the experimental materials under different conditions is slightly different, and the duration is approximately 2 h. When a PTTM is used to test moist materials, the apparatus will create a temperature difference on the two sides of the moist materials to cause moisture transfer and redistribution. To prevent the moisture from diffusing into the air, the experimental materials were wrapped with waterproof plastic films during the experiments.

Figure 3 depicts a flowchart that shows the components of the measurement procedure of the effective thermal conductivity of the experimental materials.

The main experimental procedures were as follows:

- (1) The experimental materials were processed into specimens with lengths, widths, and thicknesses of 300 mm, 300 mm, and 30 mm, respectively; both sides of the surfaces were flat. The specimens were placed in an oven to bake at an operating

temperature of approximately 150 °C until the masses of the samples no longer changed.

- (2) The dry specimens were sealed in plastic bags to measure their masses. Based on the masses and volumes of the specimens, the densities were determined. The dry specimens were cooled to the indoor temperature. Then, the specimens with and without the plastic films were tested using the PTTM. According to the series formula of thermal resistance, the thermal resistance of the plastic film wrapping was calculated according to the following formula:

$$R_p = R_t - R_m, \quad (2)$$

where R_p is the thermal resistance of the plastic film, R_t is the thermal resistance of a specimen with the plastic film wrapping, and R_m is the thermal resistance of a specimen without the plastic film wrapping.

- (3) The dry specimens were soaked in water for 48 h. Then, the specimens were removed and weighed. When the difference in the mass of a specimen for the former and latter weights was less than 5% of the latter weight, the soaking process of the specimens was considered to be complete. The specimens were wrapped with the waterproof plastic films, and the masses were measured using an electronic balance.
- (4) The effective thermal conductivity of the soaked specimens with the plastic film wrapping was tested using the PTTM. Depending on the masses of the different specimens that were soaked in water, the soaked specimens were placed in an oven to change the water content. The effective thermal conductivity of the specimens was determined for the different moisture content conditions. After the tests, the masses of the specimens were measured again to determine the final moisture content, considering the water loss which is caused by the incompletely sealed specimens.

In the effective thermal conductivity measurements of the specimens, the temperatures of the hot and cold plates of the PTTM were set to 35 °C and 15 °C, respectively. The effective thermal conductivity of the specimens was determined three times under each condition.

3 Experimental Results and Analysis

3.1 Pore Size Distributions and Porosities of Materials

The pore size distributions and porosities of the materials are shown in Fig. 4 and Table 1, respectively. Figure 4 shows that the diameters of the internal pores of the normal concrete are very small, primarily from 0.01 μm to 10 μm in diameter; most of the pores are micrometer sized. The diameters of the internal pores of the clay brick and aerated concrete are primarily within the ranges of 0.1 μm to 100 μm and 10 μm to 1000 μm, respectively. The pores in the clay brick are primarily micropores and macropores, whereas those in the aerated concrete are primarily macropores.

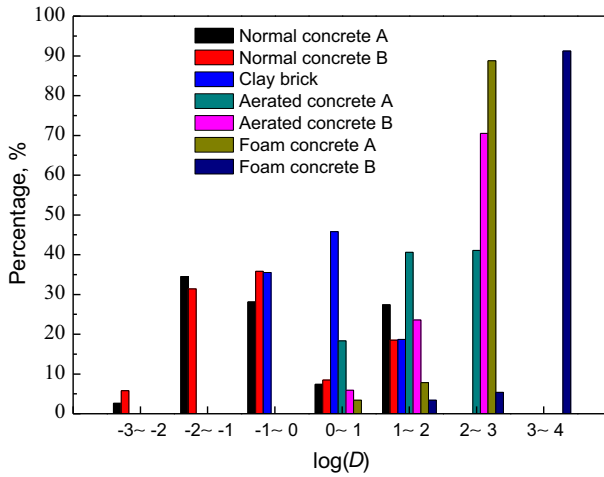


Fig. 4 Pore size distributions of experimental materials (D is pore diameter, μm)

Table 1 Porosities of experimental materials

Materials	Normal concrete A	Normal concrete B	Clay brick	Aerated concrete A	Aerated concrete B	Foam concrete A	Foam concrete B
Porosity	0.1336	0.1609	0.3187	0.5075	0.5810	0.7124	0.7739

3.2 Influence of Moisture Content on Effective Thermal Conductivity

For the experimental determination of the effective thermal conductivity of the materials, the moisture was prevented from diffusing into the air by wrapping the specimens with waterproof plastic films. However, the moisture still moved toward the cold side of the specimens, and it was difficult to determine the moisture distribution in the specimens because the specimens were thin. Therefore, the effect of the uneven moisture distribution on the effective thermal conductivity was neglected.

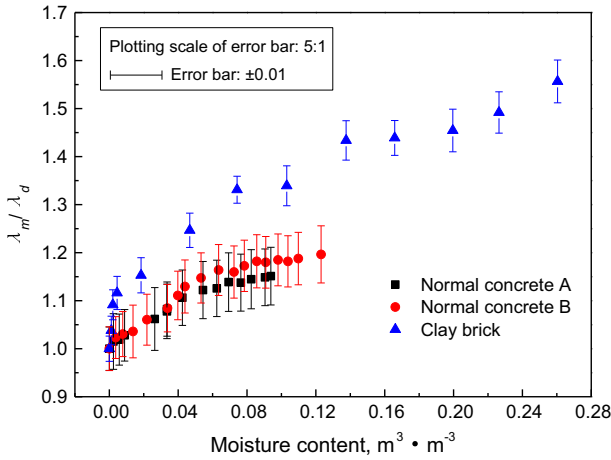
The effective thermal conductivities of the moist materials were taken as the averages of three tests under the same working conditions. When the moisture contents of the three tests were different under the same working conditions, the linear difference method was used to determine the problem. Then, based on the thermal resistance of the wrapped plastic film, the effective thermal conductivities of the specimens with different moisture contents were determined. The thermal resistances of the plastic films used to wrap the specimens are shown in Table 2.

Figure 5 shows the effect of the volumetric moisture content on the effective thermal conductivity ratios of the moist to dry materials and the errors in the effective thermal conductivity of the materials. The maximum volumetric moisture content and saturability of the experimental materials are shown in Table 3.

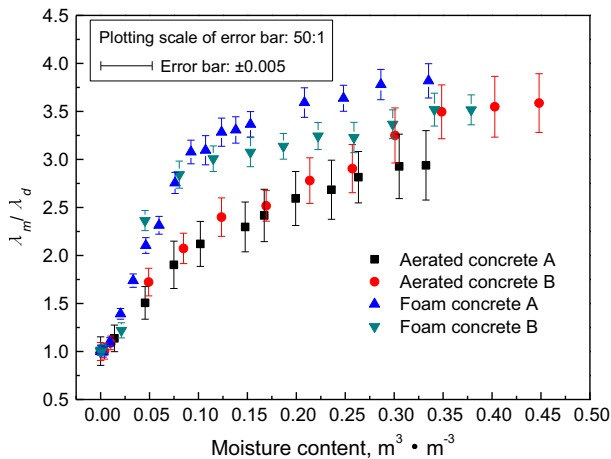
As shown in Fig. 5, the effective thermal conductivity increased with increasing moisture content of the materials, and the increasing ranges of the effective thermal

Table 2 Thermal resistances of plastic films used to wrap specimens

Specimens	Normal concrete A	Normal concrete B	Clay brick	Aerated concrete A	Aerated concrete B	Foam concrete A	Foam concrete B
R_p ($m^2 \cdot K \cdot W^{-1}$)	0.00067	0.00062	0.00071	0.00089	0.00093	0.00117	0.00104



(a)



(b)

Fig. 5 Influence of volumetric moisture content on effective thermal conductivity of experimental materials [(a) Normal concrete and clay brick, (b) aerated concrete and foam concrete]

conductivities of different types of materials were different for the same volumetric moisture content. When the volumetric moisture content reached 10%, the effective thermal conductivities of the foam concrete and aerated concrete increased by approx-

Table 3 Maximum volumetric moisture content and saturability of experimental materials

Materials	Normal concrete A	Normal concrete B	Clay brick	Aerated concrete A	Aerated concrete B	Foam concrete A	Foam concrete B
$v_{\max} (\text{m}^3 \cdot \text{m}^{-3})$	0.0938	0.1230	0.2604	0.4480	0.3325	0.3351	0.3787
Φ_{\max}	0.7023	0.7646	0.8172	0.7711	0.6550	0.4704	0.4893

imately 200 % and 100 %, respectively. However, the effective thermal conductivity of the normal concrete only increased by approximately 15 %, which is because the porosities of the foam concrete and aerated concrete are larger. When water, which has a higher effective thermal conductivity, takes the place of a gas in a material, the heat transfer of the material is significantly enhanced. However, the porosity of the normal concrete is small, and the effect of the moisture content on the effective thermal conductivity is relatively weak. Therefore, for materials with larger porosities, the influence of moisture content on the effective thermal conductivity is more noticeable.

Figure 5 also shows that the effective thermal conductivity of the moist materials increased rapidly in the low volumetric moisture content range and increased slowly in the high volumetric moisture content range. This trend is more obvious in the materials with larger porosities and pore diameters. Thus, the volumetric moisture contents of foam concrete A and foam concrete B increased from 0 % to 10 %, and the effective thermal conductivity increased by approximately 200 %. However, as the volumetric moisture content increased from 10 % to 30 %, the effective thermal conductivities of foam concrete A and foam concrete B increased by approximately 70 % and 40 %, respectively.

When the moisture content is low, the moisture is adsorbed onto the surfaces of the material framework via capillary adsorption, forming a multilayer. The adsorbed layers exhibit a good heat transfer performance. Most of the pores in the normal concrete and clay brick are micropores. Therefore, the absorbed water obviously influences the effective thermal conductivities of the normal concrete and clay brick.

Over the volumetric moisture content range from 0 % to 10 %, the effective thermal conductivities of the foam concrete and aerated concrete increase sharply. As the moisture content increases further, the effective thermal conductivities increase slowly because liquid water gradually forms in the internal pores of the materials as the absorbed water quantity increases; the small pore spaces fill with liquid water, and wedges form at the points where the frameworks touch [36]. The wedges are equivalent to liquid bridges between adjacent frameworks and these structures are beneficial to heat transfer. The porosities and pore sizes of the inner skeletons of the aerated concrete and foam concrete are relatively large, and there is less material in the skeleton joints, causing the liquid bridges to greatly influence the heat transfer in the foam concrete and aerated concrete. By further increasing the moisture content, the remaining portion is mixed with air and liquid water in the pores of the materials, which can cause the interfacial thermal resistances between the air, liquid water and frameworks to increase. Therefore, the effect of the moisture content on the heat transfer is weakened in the high moisture content range.

3.3 Error Analysis

The error bars in Fig. 5 are the standard deviations of the effective thermal conductivity of the experimental materials. The expression of the standard deviation is shown in Eq. 3:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (\lambda_i - \bar{\lambda})^2}, \quad (3)$$

where n is the acquisition time under the same working conditions, λ_i is the effective thermal conductivity of the i -th time, i is the ordinal number, and $\bar{\lambda}$ is the mean effective thermal conductivity under the same working conditions.

The ranges of standard deviations of the effective thermal conductivities of the moist normal concrete, clay brick, aerated concrete, and foam concrete are approximately 0.009 to 0.0123, 0.005 to 0.009, 0.0014 to 0.0072, and 0.0006 to 0.0036, respectively. In Fig. 5, the vertical coordinate is the ratio of the thermal conductivity of the moist and dry experimental materials. Considering the match between the error bars and the vertical coordinate, the error bars of the effective thermal conductivities of the moist normal concrete and clay brick were magnified 5 times, and the error bars of the moist aerated concrete and foam concrete were magnified 50 times. As shown in Fig. 5, the errors increased gradually as the moisture content increased because the effective thermal conductivity increased with increasing moisture content of the building materials. For the experimental determination of the effective thermal conductivity, the moisture loss also increased in the high moisture content range. Therefore, it was necessary to produce moist specimens with excellent sealing properties that could effectively improve the accuracy of the effective thermal conductivity of the materials during the experiments.

3.4 Quantitative Relationship Between Effective Thermal Conductivity and Mass Moisture Content

The empirical Eq. 4 is frequently used to express the quantitative relationship between the effective thermal conductivity and moisture content of building materials [11, 12, 14].

$$\lambda_m = \lambda_d + a_0 u, \quad (4)$$

where λ_m is the effective thermal conductivity of the moist material, λ_d is the effective thermal conductivity of the dry material, u is the moisture content of the material, and a_0 is an empirical constant.

When the moisture content range is small, the effective thermal conductivity has an approximately linear relationship with the moisture content of the moist building materials. Generally, the moisture content ranges of building materials are small, and the calculation errors of the effective thermal conductivity are small when using Eq. 4. When the moisture content range of building materials is large (such as for new buildings), the calculated errors of the effective thermal conductivity will be larger when using the linear fitting formula.

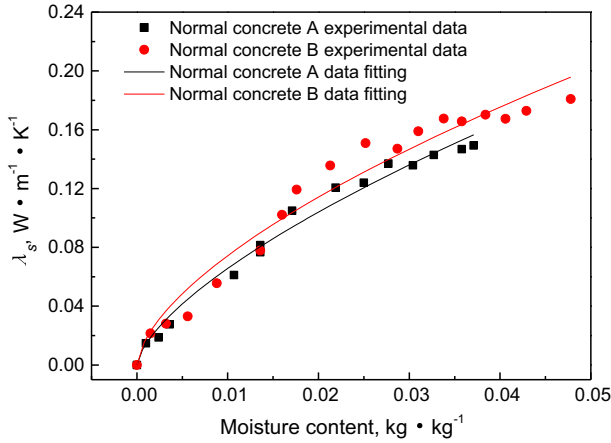


Fig. 6 Influence of moisture content on effective thermal conductivity of normal concrete

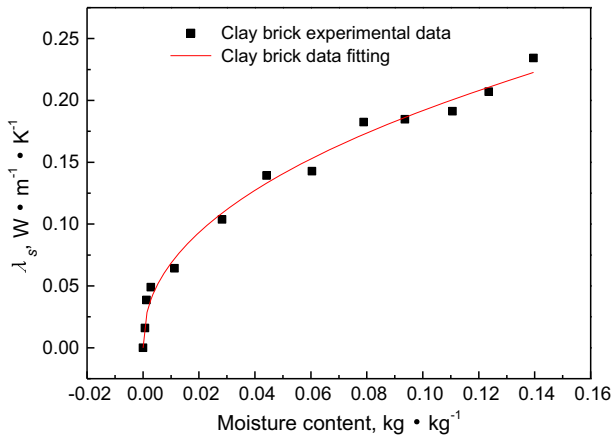


Fig. 7 Influence of moisture content on effective thermal conductivity of clay brick

According to the microscopic mechanism of liquid heat conduction, the effective thermal conductivity of a liquid is related to its density via a power function [37]. According to the literature [7,38], the theoretical models of the effective thermal conductivity of multiphase porous materials show that the effective thermal conductivity exhibits an approximate power function relationship with the proportion of each phase. Therefore, Eq. 5 is presented to fit the effective thermal conductivity and moisture content of the moist materials based on Eq. 4. The fitted curves are shown in Figs. 6, 7, 8, and 9, and the fitting constants in Table 4 were obtained using Eq. (5). The differences in the effective thermal conductivity between the moist and dry materials (λ_s) are used as the ordinates in Figs. 6, 7, 8, and 9.

$$\lambda_m = \lambda_d + au^b, \tag{5}$$

where a and b are the fitting constants.

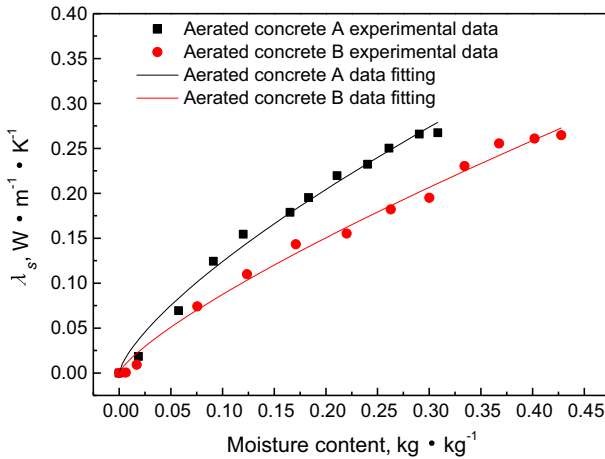


Fig. 8 Influence of moisture content on effective thermal conductivity of aerated concrete

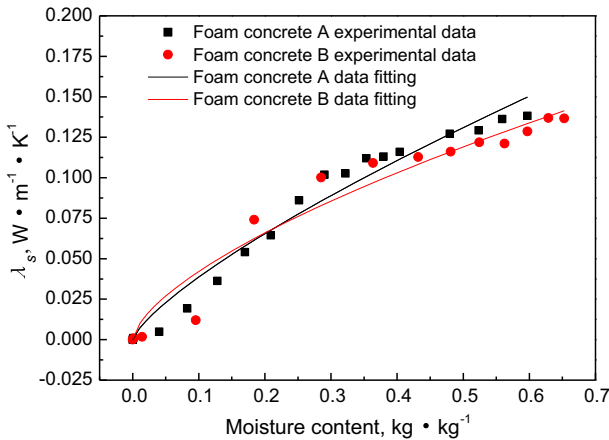


Fig. 9 Influence of moisture content on effective thermal conductivity of foam concrete

As shown in Table 4, except for clay brick, the index b of the power function relationship is in the range from 0.6 to 0.8. The constant a decreases with the porosity increases. The fitting results show that the correlation coefficient between the effective thermal conductivity and the moisture content of the materials is very high. When Eq. 4 was used to fit the effective thermal conductivity and mass moisture content of the moist materials, the correlation coefficients were 0.952, 0.911, 0.803, 0.965, 0.980, 0.914, and 0.940, respectively, which are all lower than those from Eq. 5. Therefore, Eq. 5 was applied to fit the effective thermal conductivity and mass moisture content of the moist materials, which more accurately reflects the quantitative relationships.

Table 4 Fitting constants of effective thermal conductivity of moist materials

Materials	λ_d (W·m ⁻¹ ·K ⁻¹)	a (W·m ⁻¹ ·K ⁻¹)	b	R^2
Normal concrete A	0.9873	1.3920	0.6632	0.986
Normal concrete B	0.9205	1.2870	0.6192	0.966
Clay brick	0.4208	0.5371	0.4473	0.987
Aerated concrete A	0.1387	0.6513	0.7205	0.988
Aerated concrete B	0.1023	0.5302	0.7826	0.992
Foam concrete A	0.0543	0.2214	0.7576	0.967
Foam concrete B	0.0490	0.1862	0.6454	0.958

4 Numerical Simulation Results and Discussion

Moisture transfer in porous wall materials is complex and limited by the testing equipment and technology. Determining the moisture content of each layer of the wall materials is difficult. Therefore, a numerical simulation method is often adopted to analyze the heat and moisture transfer in walls. Therefore, CHAMPS-BES was used to analyze the variations in the moisture content until the moisture content of the new building walls was stable. Then, the variations in the effective thermal conductivities of the wall materials were measured.

By analyzing the heat and mass transfer mechanisms of building envelopes, a coupled heat and moisture theory model based on the representative elementary volume (REV) was presented [39,40].

4.1 Theoretical Model

4.1.1 Moisture Mass Balance Equation

The assumptions for the moisture mass balance equation are as follows:

- (1) there is no ice;
- (2) there is an evaporation equilibrium (Kelvin-equation);
- (3) the diffusive liquid water mass flow, dispersive liquid water, and dispersive water vapor mass flow are all negligible;
- (4) there is a pressure equilibrium between all phases (resulting in well-defined capillary pressure and water retention); and
- (5) the distortions of the solid material matrix are negligible.

Based on the above assumptions, the moisture mass balance equation for REV can be written as follows:

$$\frac{\partial}{\partial t} \rho_{REV}^{m_{w+v}} = -\frac{\partial}{\partial x} \left[j_{conv}^{m_w} + j_{conv}^{m_v} + j_{diff}^{m_v} \right] + \sigma_{REV}^{m_{w+v}}, \quad (6)$$

where $\rho_{REV}^{m_{w+v}}$ is the moisture (liquid+vapor) density for the reference volume, $j_{conv}^{m_w}$ is the convective liquid (capillary) water flux, $j_{conv}^{m_v}$ is the convective water vapor flux,

$j_{diff}^{m_v}$ is the diffusive water vapor flux, $\sigma_{REV}^{m_w+v}$ is the moisture sources/sinks for the reference volume, t is the time, and x is the abscissa.

4.1.2 Energy Balance Equation

The assumptions for the energy balance equation are as follows:

- (1) there is a temperature equilibrium between all of the phases and
- (2) the difference between the internal energy and the enthalpy may be neglected.

Based on the above assumptions, the energy balance equation for REV can be written as follows:

$$\frac{\partial}{\partial t} \rho_{REV}^U = -\frac{\partial}{\partial x} \left[j_{diff}^Q + u_l j_{conv}^{m_l} + u_g j_{conv}^{m_g} + h_v j_{diff}^{m_v} \right] + \sigma_{REV}^U, \quad (7)$$

where ρ_{REV}^U is the internal energy density for a reference volume, j_{diff}^Q is the heat conduction, u_l is the specific internal energy of the liquid phase, u_g is the specific internal energy of the gas phase, h_v is the specific evaporation enthalpy of the water vapor, and σ_{REV}^U is the energy sources/sinks of the reference volume.

The expressions for each item in the equations are detailed in the literature [39].

4.1.3 Definite Conditions

(1) Boundary conditions

To determine the wall heat and moisture transfer, the third boundary conditions are used by both sides of the wall. At the two sides of the wall, the heat and moisture diffusion caused by both water vapor pressure and temperature gradients affects the heat and mass balance. According to the above analysis, the boundary conditions are given as follows:

$$j_{diff}^Q = h_c (T^{elem} - T^{air}) \quad (8)$$

$$j_{diff}^{m_v} = h_m (p_v^{elem} - p_v^{air}), \quad (9)$$

where h_c is the convective heat transfer coefficient, T^{air} is the temperature of the ambient air, T^{elem} is the temperature in the boundary element, h_m is the water vapor exchange coefficient, p_v^{elem} is the water vapor pressure in the boundary element, and p_v^{air} is the water vapor pressure of the ambient air.

The water vapor exchange coefficient uses the empirical values given by the CHAMPS-BES software in which the water vapor exchange coefficients of the interior and exterior surface are $3e-08$ s/m and $2e-07$ s/m, respectively. The convective heat transfer coefficients are based on the literature [41] in which the convective heat transfer coefficient of the interior surface is 8.7 W/(m²·K) and that of the exterior surface is 23 W/(m²·K).

The outdoor meteorological parameters include the outdoor air temperature and relative humidity. Standard meteorological data for Chinese cities from the literature

Table 5 Main thermal and moisture physical parameters of wall materials

Material	λ (W·m ⁻¹ ·K ⁻¹)	ρ (kg·m ⁻³)	ε (m ³ ·m ⁻³)	$D_v \times 10^6$ (m ² ·s ⁻¹)	v_h (m ³ ·m ⁻³)
Normal concrete	0.9205	2115.16	0.1609	0.241	0.0582
Clay brick	0.4208	1568.24	0.3187	0.558	0.0028
Aerated concrete	0.1023	597.75	0.5810	3.800	0.0121
Cement plaster	1.3400	2100.00	0.2200	2.500	0.0252
EPS	0.4000	20.00	0.9700	0.560	0.0011

[42] were taken as the outdoor meteorological parameters for the simulation calculations. According to the indoor design temperature for heating and air conditioning in China, the indoor temperatures in winter and summer were set to 18 °C and 26 °C, respectively [43]. During the transition seasons, the indoor temperature was set to 22 °C, which is the average value between the winter and summer temperatures. The indoor relative humidity was set to 60 % all year.

(2) Initial conditions

The initial conditions include the initial temperature and moisture content of the wall. The average value of the annual outdoor temperature was used as the initial temperature of the wall. The initial moisture content is provided in the following sections. The initial temperature and moisture content of the wall were considered to be uniform.

4.1.4 Thermal and Moisture Physical Parameters of the Materials

The normal concrete, clay brick, and aerated concrete walls were the typical wall types selected for this study. EPS and cement mortar were used as the insulation material and plaster for the walls, respectively. Table 5 shows that the thermal and moisture physical parameters of the wall materials were based on our experimental data and the experimental results in the CHAMPS-BES software from Syracuse University.

The relationships between the effective thermal conductivity and the moisture content for the cement mortar and EPS were based on the CHAMPS-BES software. The formulas in CHAMPS-BES were adopted, as given below in Eq. 10:

$$\lambda_m = \lambda_d + 0.6v. \quad (10)$$

4.2 Variations in Effective Thermal Conductivity of Moist Materials

Considering the annual periodic variations in the moisture transfer in walls, the moisture content is considered to be stable when the ratio of the difference in the annual volumetric moisture content to the saturation moisture content of the wall is approximately 1 %. Moreover, when the moisture content of the wall is stable, the average moisture content of the next year is described as stable moisture content.

According to the literature [29], the initial moisture content does not significantly influence the stability time and the stable moisture content of the walls. Thus, an initial

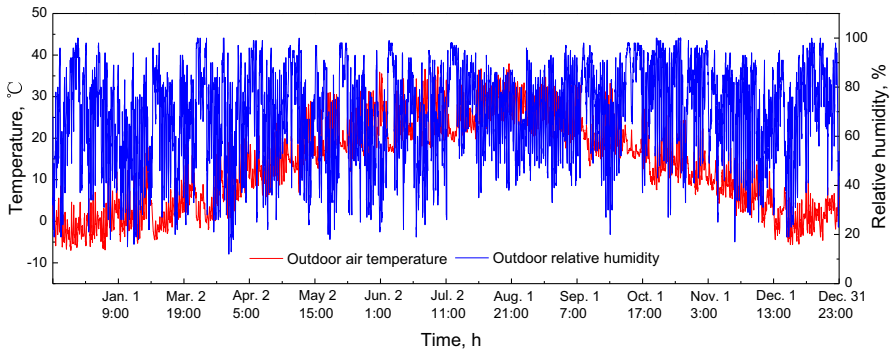


Fig. 10 Outdoor hourly temperature and relative humidity of Xi'an

moisture content of 60% was selected to analyze the changes in the moisture content and effective thermal conductivity of the wall materials.

4.2.1 Normal Concrete Wall

Taking a concrete wall of a new building in Xi'an as an example, the variations in the moisture content and its effects on the effective thermal conductivity of each layer of the wall materials were analyzed. Figure 10 shows the climatic data of Xi'an, China, in a typical meteorological year for the simulations. Figure 11 shows the variations in the moisture contents of each material layer of the normal concrete wall, except for EPS, with an initial moisture content of 60%. The structure of the wall was 20 mm cement mortar + 40 mm EPS + 200 mm normal concrete + 20 mm cement mortar. Figure 11a shows that the moisture content of the cement mortar and EPS would be highly stable one year after completing building construction using these materials, and the stable moisture content was low. During the tenth year, the moisture contents of the outside and inside cement mortar would be approximately $0.0234 \text{ m}^3/\text{m}^3$ and $0.0253 \text{ m}^3/\text{m}^3$, respectively, with a difference of approximately 7.5%. Additionally, the moisture content of the outside cement mortar fluctuated greatly due to the outside relative humidity. The set value of the initial moisture content of the EPS was zero, so the moisture content of the EPS increased quickly and then decreased due to moisture transfer from the main structure. The stable moisture content of the EPS was approximately $0.0009 \text{ m}^3/\text{m}^3$. Thus, the variations in the wall moisture content were consistent with that of normal concrete because EPS is made of hydrophobic materials with poor moisture adsorption; the moisture contents of the cement mortar and EPS were low because these layers were very thin.

The moisture content of the outer cement mortar did not significantly differ from the inner cement mortar. Thus, as shown in Fig. 11b, the average effective thermal conductivity of the outer and inner cement mortars was selected. The modified values of the effective thermal conductivity, β_m (i.e., the ratio between the effective thermal conductivities of the moist and dry materials), of the cement mortar, EPS, and normal concrete were approximately 1.0109, 1.0129, and 1.1416, respectively. Consequently, compared to the dry material, when the moisture content of the material was stable, the

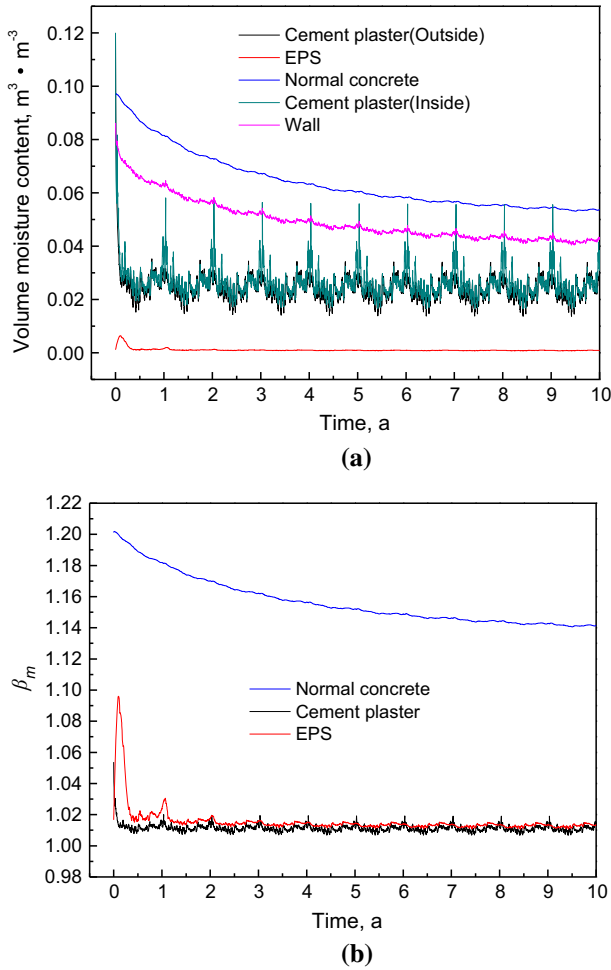


Fig. 11 Moisture content and modification value of effective thermal conductivity of normal concrete wall layers [(a) Moisture content. (b) Modification value of thermal conductivity]

effective thermal conductivities of the cement mortar and EPS increased by approximately 1.1 % and 1.3 %, respectively. The effective thermal conductivity of the normal concrete changed slightly every year. From the initial moisture content until a stable moisture content was reached, the effective thermal conductivity varied from 1.2011 W/(m·K) to 1.1416 W/(m·K), a decrease of 5.0 %. When the moisture content of the normal concrete wall was stable compared to the dry normal concrete, the effective thermal conductivity of the moist normal concrete was 14.2 % higher.

The plastering and insulating layers were thinner than the main structure of the wall; therefore, the effects of the moisture content on the building energy consumption were relatively insignificant. The effective thermal conductivity of the moist material of the main structure of the wall was analyzed, as discussed in the following sections.

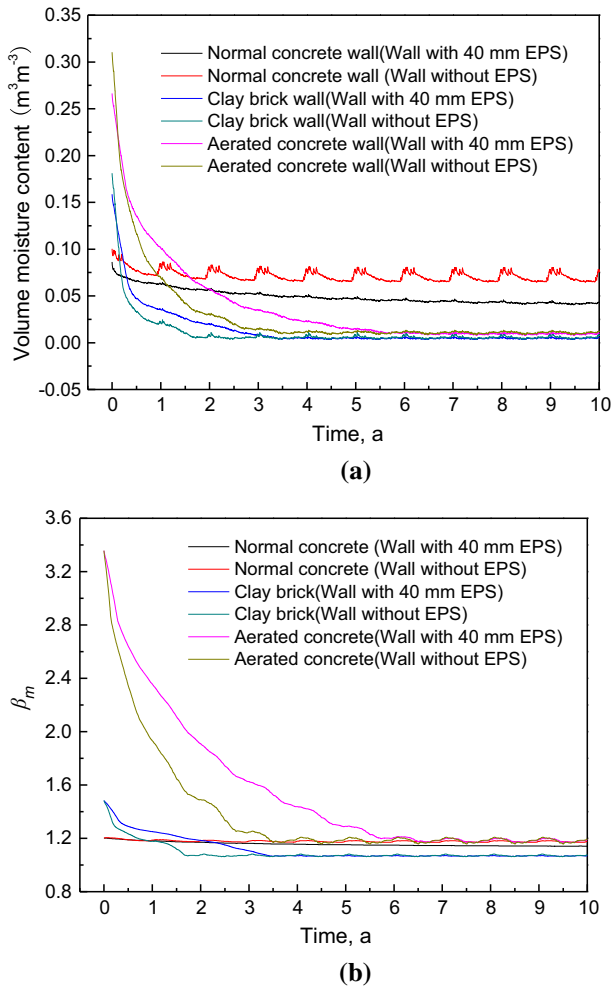


Fig. 12 Moisture content and modification value of effective thermal conductivity of different wall types [(a) Moisture content. (b) Modification value of effective thermal conductivity]

4.2.2 Types of Walls

Figure 12 shows the variations in the moisture contents and the effective thermal conductivities of the main structural materials of three wall types with and without EPS insulation for an initial wall moisture content of 60 %, except for the EPS layer. Figure 12a shows that until the moisture content of the walls stabilized, the moisture content of the aerated concrete wall changed most significantly. Compared to the walls with EPS, the moisture content of the walls without EPS decreased rapidly, which was especially obvious for the aerated concrete walls. Figure 12a and Table 6 show that the stabilization time for the moisture content of the normal concrete and clay brick walls with EPS was approximately one year longer than that of the walls without EPS, whereas the stabilization time of the aerated concrete wall was approximately 2 years.

Table 6 Stable moisture content of walls and modification values of effective thermal conductivity of wall materials

Types of wall	Normal concrete wall		Clay brick wall		Aerated concrete wall	
	With EPS	Without EPS	With EPS	Without EPS	With EPS	Without EPS
Time (a)	6	5	4	3	6	4
$v_w(\text{m}^3 \cdot \text{m}^{-3})$	0.0420	0.0698	0.0046	0.0056	0.0094	0.0108
β_{ms}	1.1416	1.1757	1.0680	1.0704	1.1834	1.1841

Figure 12 and Table 6 also show that compared to the moisture content of walls with EPS insulation during the tenth year after construction, the moisture contents of the normal concrete, clay brick, and aerated concrete walls without EPS insulation were greater by approximately 39.8 %, 17.7 %, and 13.2 %, respectively. The effective thermal conductivity of these walls was also larger by approximately 2.9 %, 0.23 %, and 0.06 %, respectively. The stable moisture content of the normal concrete wall was different when the EPS was or was not included in the wall. Additionally, when there was no EPS in the wall, the moisture content fluctuated significantly. Compared to the 60 % initial moisture content for the walls without EPS, the effective thermal conductivity of the moist normal concrete, clay brick, and aerated concrete walls with stable moisture contents were lower by approximately 2.1 %, 27.8 %, and 64.7 %, respectively. These results show that the effective thermal conductivity of the moist normal concrete varies insignificantly, whereas the effective thermal conductivity of the aerated concrete changes significantly as the wall moisture content stabilizes.

4.2.3 Outdoor Relative Humidity

The relative humidity of the environment is an important factor that impacts the moisture transfer and moisture content of walls. Figure 13 shows the modified effective thermal conductivity of a normal concrete wall (20 mm cement mortar + 40 mm EPS + 200 mm normal concrete + 20 mm cement mortar) for different outdoor relative humidities. The effective thermal conductivity changed more slowly with increasing outdoor relative humidity. When the outdoor relative humidity reached 90 %, the moisture of the wall slowly transferred to the environment. Thus, the effective thermal conductivity of the normal concrete has little variation with time.

As Fig. 14 shows, when the moisture content of the wall is stable, the effective thermal conductivity of the material is proportional to the environmental relative humidity. The trend is relatively obvious when the main structure is aerated concrete. The effective thermal conductivity of the aerated concrete increased by approximately 60.1 % when the outdoor relative humidity increased from 50 % to 90 %, and the effective thermal conductivities of the normal concrete and clay brick increased by approximately 5.7 % and 14.0 %, respectively. Based on the material adsorption curve [44,45], when the ambient temperature is approximately the same, the moisture adsorption of a material is primarily affected by the relative humidity of the environment. Therefore, the relative humidity of the environment significantly influences the stable moisture

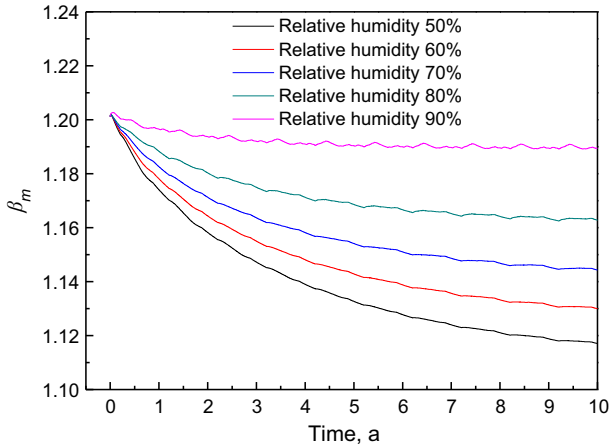


Fig. 13 Modification value of effective thermal conductivity of normal concrete in different outdoor relative humidities

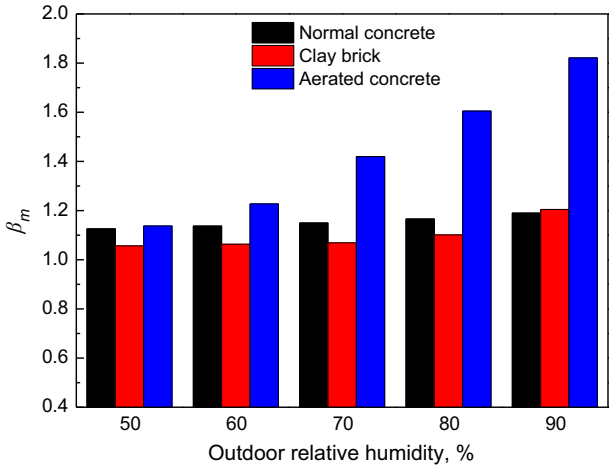


Fig. 14 Modification value of effective thermal conductivity with stable material moisture contents in different outdoor relative humidities

content and the effective thermal conductivity of the main structural material of the wall.

4.2.4 Cases of Effective Thermal Conductivity of Wall Materials in Different Climatic Regions

To analyze the differences in the modification of the effective thermal conductivity of the wall materials in different climatic regions, typical cities in China were selected. China can be divided into five climate zones according to the Chinese building thermal partition: severe cold, cold, hot summer and cold winter, hot summer and warm winter,

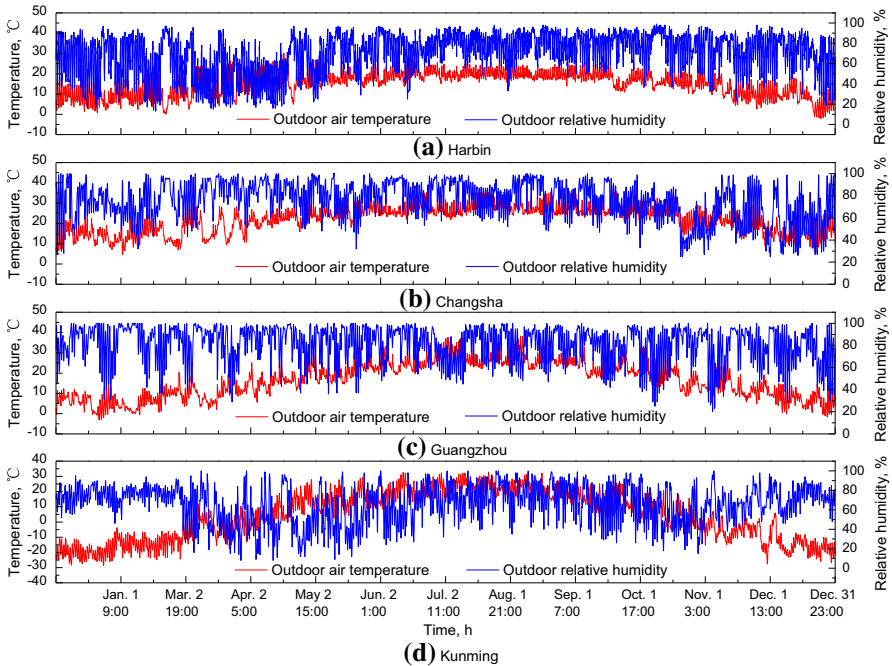


Fig. 15 Outdoor hourly temperature and relative humidity of typical Chinese cities

and temperate zones. The climate features and structural forms of the buildings vary widely. Because the climatic zones refer to extensive regional areas, Harbin, Xi'an, Changsha, Guangzhou, and Kunming were selected as the typical cities for the five climatic zones in this paper, respectively. Figure 15 shows the climatic data of Harbin, Changsha, Guangzhou, and Kunming in the Chinese typical meteorological year for the simulations.

In general, the thicknesses of the main structure and both sides of the cement mortar of the walls in all of the typical cities are the same. Based on the requirements for the limit values of the heat transfer coefficient of walls in each climate zone in the literature [46–48], the thicknesses of the insulating layers are different. The structural formations of the walls in the different typical cities are shown in Table 7.

Table 7 shows that the additional value of the effective thermal conductivity α_m ($\alpha_m = (\lambda_m - \lambda_d) / \lambda_d \times 100\%$) of the moist aerated concrete is the highest among the three wall types and that the additional values in the different cases have larger differences. Compared to case II, the effective thermal conductivity of the aerated concrete in case III was approximately 13% larger because the outdoor relative humidity had a greater influence on the moisture adsorption of the aerated concrete and the effective thermal conductivity of the aerated concrete increased more quickly with increasing moisture content. Although the stable moisture content of the normal concrete wall was the highest, the effective thermal conductivity of the moist normal concrete slightly increased with increasing moisture content. The additional value of the effective thermal conductivity of the normal concrete falls within a range of

Table 7 Additional values of effective thermal conductivity of moist materials for main structural walls in typical cities

Case	Typical city	φ_a (%)	Wall type	δ_{EPS} (m)	v_w ($\text{m}^3 \cdot \text{m}^{-3}$)	α_m (%)
I	Harbin	65.8	Normal concrete wall	0.10	0.0532	14.07
			Clay brick wall	0.08	0.0022	7.10
			Aerated concrete wall	0.02	0.0109	22.58
II	Xi'an	68.0	Normal concrete wall	0.06	0.0533	14.10
			Clay brick wall	0.04	0.0020	6.80
			Aerated concrete wall	0	0.0098	20.99
III	Changsha	81.3	Normal concrete wall	0.04	0.0757	17.40
			Clay brick wall	0.02	0.0026	7.55
			Aerated concrete wall	0	0.0206	36.79
IV	Guangzhou	76.0	Normal concrete wall	0.02	0.0658	16.00
			Clay brick wall	0	0.0023	7.12
			Aerated concrete wall	0	0.0131	26.13
V	Kunming	70.0	Normal concrete wall	0	0.0641	15.75
			Clay brick wall	0	0.0021	6.96
			Aerated concrete wall	0	0.0106	22.26

approximately 14% to 17.5%. The moisture adsorption of the clay brick is poor so that there is only a small difference in the stable moisture contents for the different cases. The effective thermal conductivity slightly increased with increasing moisture content for the clay brick, and the additional value of the effective thermal conductivity falls within a range of approximately 7% to 7.5%. The modification value of the effective thermal conductivity of the envelope materials not only is larger in the attenuation process of the moisture content but is also not negligible at the stable moisture content of the envelope, especially in the hot summer and cold winter, and hot summer and warm winter zones. Therefore, the effective thermal conductivity of the envelope materials must be amended according to the structure and moisture conditions of the envelope.

5 Conclusions

The influence of the moisture content on the effective thermal conductivity of common building materials was analyzed experimentally. The variations in the moisture contents and effective thermal conductivities of the main structural materials of walls of a common new building were obtained via numerical simulation, and the conclusions are as follows:

- (1) For moist building materials, the effective thermal conductivity increased with increasing moisture content of the materials. For large porosity materials, the effect of the moisture content on the effective thermal conductivity was more pronounced. When the volumetric moisture content reached 10%, the effective

thermal conductivity of the foam concrete and aerated concrete increased by approximately 200 % and 100 %, respectively. However, the effective thermal conductivity of the normal concrete increased by only approximately 15 %.

- (2) The effective thermal conductivity of the moist building materials increased rapidly in the low moisture content range and increased slowly in the high moisture content range. This trend was more evident for the materials with larger porosities and pore diameters. For example, the volumetric moisture content of the foam concrete with a porosity of 0.71 increased from 0 to 10 %, and the effective thermal conductivity increased by approximately 200 %. However, as the volumetric moisture content increased from 10 % to 30 %, the effective thermal conductivity increased by approximately 70 %.
- (3) The relationship between the effective thermal conductivity and moisture content of building materials was approximately represented by a power function, and the quantitative relationship was provided by the experimental analyses.
- (4) When the moisture content of the walls of a new building stabilizes, the effective thermal conductivity of the moist normal concrete varies only slightly, whereas that of the aerated concrete varies more significantly. Compared to the 60 % initial moisture content of the walls without EPS, the effective thermal conductivity of the moist normal concrete, clay brick, and aerated concrete walls with stable moisture contents were lower by approximately 2 %, 28 %, and 65 %, respectively. Based on the literature [49], it can be concluded that the stable moisture content of the aerated concrete walls without an insulation layer in Xi'an is lower than that in Miami for a new building. Compared to the Miami area, the effective thermal conductivity of the moist aerated concrete of the wall in Xi'an is approximately 10 % smaller. The average outdoor relative humidity in Xi'an is lower than that in Miami, which is located in a hot and humid climate. Another reason for the difference is that the indoor moisture gain was considered in the calculation of the heat and moisture of the wall.
- (5) The effective thermal conductivity of a material is proportional to the relative humidity of the environment. This trend is noticeable when the wall material is aerated concrete. For the stable moisture content of a wall, the effective thermal conductivity of the aerated concrete increased by approximately 60 % when the outdoor relative humidity increased from 50 % to 90 %.

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