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Thermo-wet Physical Properties of Porous Materials

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The thermal and wet physical properties of porous materials are discussed. Through physical performance testing methods, the performance of porous materials under wet and hot conditions is analysed, and the optimal heat exchange coefficient, heat-moisture coupling transfer rate and diffusion coefficient are obtained, and the SiON coefficient, equilibrium humidity and thermal performance coefficient are optimized. The results show that the thermal and wet physical properties of porous materials are closely related to the environment. The thermal and wet physical properties of porous materials can be improved by adjusting the thermal and wet properties. Therefore, the thermal and wet physical properties of porous materials are of great significance to the development of modern construction industry.

1. Introduction

HVAC (Heating, Ventilation and Air Conditioning) as a part of the construction project has a certain regulation function on the indoor and outdoor environment. There are acoustic, thermal and humid environments in the building. In the application process of building materials, it is required to gain an insight into the physiological needs of the human body and make effort to do anything required by the owners. Porous building material features water absorption, thermal conductivity and permeability, etc. The surrounding building structures are susceptible to the mixture at different ratios of various materials. In the application of new envelope structure, the climate effect requires to be considered, and the parametric conditions for building materials are studied based on the heat and humidity coupling theory and the relevant computation and verification methods.

This paper explores the humidity properties of porous building material to seek the material moisture balance based on the heat and humidity coupling theory and other relevant algorithms by taking the envelope structure as the study object. As for specific operations, it is required to clarify the boundary conditions, diffusion coefficient and equilibrium humidity of porous material, and analyze how the application effect of it with thermal and moisture behaviors.

2. Literature review

With the rapid development of the world economy, the demand for energy has increased sharply, the energy reserves have become increasingly scarce, and the contradiction between energy supply and demand has become increasingly prominent (An et al., 2017; Fan et al., 2017; Li et al., 2018; Liu, 2018; Qin, et al., 2017; Rudra and Chakraborty, 2017; Dell'Isola et al., 2012). Therefore, the energy issue is a major social problem faced by all mankind. Among them, building energy consumption is also an important part of energy structure. With the development of national economy and the further improvement of people's living standard, urban construction in China will be further accelerated (Guo, 2016). Therefore, the implementation of sustainable development strategy, in order to build a harmonious society for the purpose of achieving national building energy efficiency, low-carbon economy, can effectively alleviate the energy crisis people are facing.

The thermal conductivity of building materials is one of the most important parameters to represent the heat transfer performance of materials. Porous building materials are widely used in building structures. Most of the porous building materials used in practice have a certain moisture content, and their heat transfer performance will change after moisture content (Camaraza-Medina et al., 2018). However, in the current calculation methods and software of building cooling and heating load, it is often approximated that the physical properties of porous building materials are constant, ignoring the influence of moisture change on

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thermal conductivity of materials, which will cause errors in heat transfer of envelope structure and calculation of building energy consumption.

Scholars at home and abroad have done a lot of research on porous building materials, and these research results have played an active role in the actual social and economic production. Tonini and Cossali established a one-dimensional coupled heat-moisture transfer equation in a multi-layer wall driven by temperature gradient and water vapor density in order to study the change of temperature and vapor density inside the wall in outdoor hot-humid climate. Under the periodic change of outdoor temperature and steam density, the scalar equation was modified by Fluent software to solve the coupling equation (Tonini and Cossali, 2016). Considering the effect of phase transition and solar radiation in the wall, Kontoleon and Giarma modified the Budaiwi model by using air moisture content and temperature as driving force, which made up for the omissions in the mass transfer equation (Kontoleon and Giarma, 2016). Based on the study of gas transport mechanism in porous media, Takahashi and Ishida proposed a test method for testing high performance and long-term concrete permeability by improving pressure gradient reasonably (Takahashi and Ishida, 2016). Based on the mechanism of gas diffusion, Alnaggar et al. deeply analyzed the influencing factors of gas diffusion in concrete, and proposed a calculation model of effective gas diffusion coefficient, which regarded the compressive strength of concrete as the main parameter and took into account the comprehensive influence of environmental temperature and humidity (Alnaggar et al., 2017). Liang et al. carried out experimental analysis on thermal conductivity of materials with different pore size distribution. It was found that pore size distribution and rarefied gas in the pore had important effects on thermal conductivity of micro-nano materials (Liang et al., 2017). Ramazani et al., combined with simple modal analysis of one-dimensional lattice system, carried out theoretical analysis of non-equilibrium molecular dynamics simulation of atomic-scale thermal resistance at solid-liquid interface. It was considered that the interaction strength between solid atoms and liquid molecules was the key to the analysis of interfacial thermal resistance (Ramazani et al., 2017). Asako and Hong analyzed the flow and heat transfer characteristics near the solid-liquid interface in the thin liquid film region of microchannels. It was found that velocity and temperature slip occurred on the wall of the thin liquid film region and the relationship between temperature slip and velocity slip parameters was given (Asako and Hong, 2017). Imamura et al. analyzed the heat transfer process of solid-liquid interface in thin liquid film region using molecular dynamics simulation method in micro solid-liquid heat transfer space. It was found that there were several micro-liquid thermal resistive layers with molecular thickness between the solid-liquid interface (Imamura et al., 2017). For porous materials with geotechnical structure, Różański and Stefaniuk simplified solid particles into ellipsoids, and considering their shape factors, established a calculation model for effective thermal conductivity of two-phase porous materials (Różański and Stefaniuk, 2016). Based on the two-phase porous material model, Zhou et al. introduced water saturation, and combined with experimental analysis, established a three-phase effective thermal conductivity calculation model with empirical constants (Zhou et al., 2017).

In summary, the above research work mainly focuses on the one-dimensional coupled heat-moisture transfer equation, Budaiwi model, effective gas diffusion coefficient of porous media and thermal conductivity of materials with different pore size distribution in multi-layer walls. However, there are few studies on thermal-wet physical properties. Therefore, based on the above research status, the thermal and wet physical properties of porous building materials are mainly studied. The rules of energy and mass transfer in the process of heat and mass transfer of building envelope structure are put forward. A theory of heat and moisture hazard is introduced based on the deduction of representative voxel. The software of heat and moisture coupling based on the theory as framework is validated, which lays the foundation for further studying the heat and mass transfer of building envelope structure with porous materials.

3. Method

3.1 Boundary conditions

How thermal mass balance between the material and the external environment, as well as the heat-moisture absorption and desorption behaviors seem like depends largely on the convective heat transfer (surface heat exchange coefficient) and the surface mass exchange coefficients between the material surface and the surrounding environment, the radiation heat transfer coefficient between indoor surfaces and the absorption coefficient of wall surfaces for solar radiation, etc (Wang et al., 2018).Among them, surface heat exchange and mass transfer coefficients are most important. When liquid water such as rainwater directly acts on the surface of the porous material for the enclosure structure, it is required to determine the flow rate of the boundary liquid water. Under the third type of boundary conditions in the heat-moisture coupling transfer model, its assignment of surface heat exchange co efficient follow sempirical data and for mulasas recommended by aloto fliter ature. In the building energy simulation software ENERGYPLUS, the convective heat transfer coefficient are given as indoor and outdoor types. The simple algorithm assumes that the outdoor convective heat transfer coefficient of the material has a bearing on the material roughness and is in a quadratic relationship with the air flow velocity. The roughness coefficients D, E, and F take the values as shown in Table 1 below:

Table 1: Values of roughness coefficients D, E and F

Roughness	D	E	F	Material examples
Very rough	11.58	5.894	0.00	Plaster
rough	12.49	4.065	0.028	brick
Medium rough	10.79	4.192	0.0	Concrete
Medium smooth	8.23	4.0	-0.057	pine
smooth	10.22	3.1	0.0	Smooth plaster
Very smooth	8.23	3.33	-0.36	Glass

The coarseness coefficients R_f are shown in Table 2 below:

Table 2: The value of coarse excess coefficient

Roughness	R_f	Material examples
Very rough	2.17	Plaster
rough	1.67	brick
Medium rough	1.52	Concrete
Medium smooth	1.13	pine
smooth	1.11	Smooth plaster
Very smooth	1.00	Glass

The governing equations that allows for heat-moisture coupling transfer of air permeability are a set of second-order partial differential equations with many variable coefficients, which have strong nonlinearity and mutual coupling, so that it is very difficult to solve them. According to different parameters to be determined, there are two types: positive and inverse problems. Given all the physical properties of materials, it is required to know the heat and moisture distribution through the material as the so-called positive problem solution. Given the heat and moisture distribution of materials, it is required to know the physical properties of the materials, that is, to solve the inverse problem.

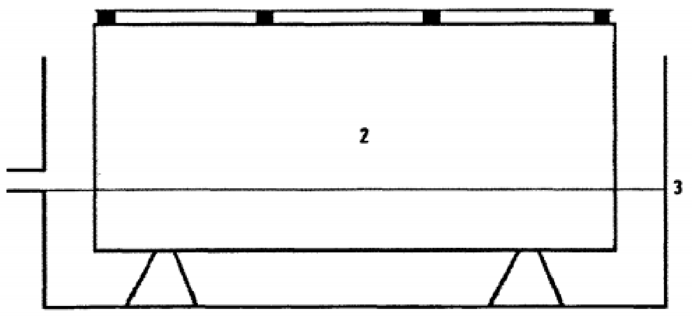

Figure 1: Test principle of local wetting method

3.2 Diffusion coefficient of porous building materials

At the time of thermodynamic equilibrium, as the relative humidity of the ambient air to which the porous materials are exposed increases, the relative humidity of the gas phase in the porous material also increases accordingly. When the relative humidity rises to a certain stage, capillary condensation will occur. At this point, the liquid water will first accumulate in the tiny pores.

To obtain the liquid water diffusion coefficient in the material, the maximum diffusion coefficient of the material must be determined experimentally, or estimated based on the water absorption coefficient, and then the numerical calculation method can be used to determine the specific correction coefficient. Here the

experiment measurement requires relatively high equipment, but the accuracy is not guaranteed. Therefore, this paper chooses the estimation method using the water absorption coefficient. This requires to test the water absorption coefficient of the material to describe howit changes with the time when the material is in contact with water. A local infiltration method is used hereof. For the test piece 2, there is a moisture-proof materialused to treat with it on the side, and only the upper and lower surfaces are exposed to the atmosphere. It is also required to ensure that the height of the test piece immersed in water is 5±2mm.
The test is conducted in accordance with the international standard IS015148, as shown in Table 3.

Table 3: Environmental requirements for water absorption coefficient test

	Temperature (°C)	Relative humidity
Test permissible condition	18～28	0.4～0.6
Test allowed fluctuation range	±2	±0.05

3.3 Determination of parameters such as equilibrium humidity and thermal properties

The equilibrium moisture content in the porous material for the building envelope structure should be dynamically balanced with the humidity of the air surrounding the material. The humidity balance represents the moisture capacity of the porous material for the building envelope structure under the equilibrium state, which is only relevant to the composition and structure of the material itself. For the material that has reached equilibrium humidity, when its temperature rises up, the dehumidification occurs; when its temperature swoops, moisture absorption occurs. In order to make the test piece reach the balance as soon as possible, and let it fully represent the basic properties of the tested material, the size of test piece used to measure the wet balance curve is 5X5X2cm square test piece. In order to obtain a regression curve, the equilibrium moisture content of the test piece of the material under different relative humidity conditions must be tested. The thermal property parameters of the material refer to physical quantities closely bound up with the heat conduction process of the material, such as the specific heat and thermal conductivity. The specific heat of a material refers to the heat absorbed or released by the substance every time the unit mass temperature increases or decrease by one degree. In general, the specific heat of the material varies slightly with temperature. The heat conduction in the porous medium is different from that in the general dense material. In wet-bearing porous building, the heat transfer mechanism is particularly complex, including thermal conduction through the framework material, molecular heat conduction through the air in the pores, heat conduction through water vapor and liquid water, radiant heat in the pores, evaporation and condensation heat in the closed pores, etc. Therefore, it is very cumbersome to accurately describe the effects of various parts of the wet-bearing material on the overall heat transfer. In general, it can be determined by experimental methods.

4. Analysis of results

From the perspective of whether physical properties is subjected to change with heat and humidity transfer, the physical parameters of building envelope materials can be divided into two types: structural and hot wet parameters, the former mainly include geometrical parameters such as porosity, specific surface, tortuosity, solid particle size, void size and density, and others that can be determined by geometrical parameters and constant throughout the heat and moisture transfer process; the latter includes the thermal conductivity, the specific heat, the equilibrium humidity, the water vapor diffusion coefficient, the liquid water diffusion coefficient, and other physical properties that are subject to the heat and moisture transfer. The bulk density test is to first dry the material in a vacuum oven and then measure its mass and volume. (See Table 4 for details)

Table 4: Density test results

Sample number	1	2	3	4	5
Dry weight (g)	74.666	72.882	71.71	70.646	73.036
V (mm3)	106306	104283	102264	99747	103509
Density (kg/m3)	702.369	698.887	701.224	708.252	705.600
Average density (kg/m3)	703.266				
average error	0.13%	0.63%	0.29%	-0.70%	-0.33%

The material density is 703．266 kg/m3. The average error of several samples used for testing the density is only 0.70%, which shows that the material is prepared uniformly and may adequately represent the physical properties of the material under test. The porosity test is to completely immerse the five samples to be tested in water. After about 10 days, the poresare completely filled with water. Table 5 gives the porosity results of the materials measured by the infiltration method.

Table 5: Porosity test results

Sample number	1	2	3	4	5
Dry weight（g）	74.666	72.882	71.71	70.646	73.036
Wet weight（g）	121.5	119.423	117.296	115.673	119.842
V（m3）	1.06E-04	1.04E-04	1.02E-04	9.97E-04	1.04E-04
Vp（m3）	4.68E-05	4.65E-05	4.56E-05	4.50E-05	4.68E-05
porosity	0.441	0.446	0.446	0.451	0.452
Average porosity	0.447				
average error	1.52%	0.21%	0.33%	-0.92%	-1.09%

5. Conclusion

Test results show that the limits of the indoor temperature basically fit the moisture transfer through the wall, which suggests that the numerical computation method of the thermal model and the thermal-moisture coupling software used in this paper has been proven to be effective, so that it allows an accurate survey on the heat and moisture transfer of the envelope structure. In terms of the impact of physical parameters on heat and moisture transfer, the porous material in the epidermis climate layer has an optimal porosity at low relative humidity, while the porosity is not excessive under saturated humidity; the relative humidity is low, whenever possible, the impact of moisture on the thermal conductivity of material should be reduced. When the relative humidity is high, this impact has an optimum value.

This paper conducts a test only for the basic physical properties and moisture transfer property of a thermal insulation mortar. it still needs to further study how to simplify the test procedure and design a new test to shorten the test period, to improve the method for determining the moisture transfer coefficient, thus providing the clues for the country to establish a new database for thermal physical properties of building materials.

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Reference

Alnaggar M., Di L.G., Cusatis G., 2017, Modeling time-dependent behavior of concrete affected by alkali silica reaction in variable environmental conditions, Materials, 10(5), 471, DOI: 10.20944/preprints201704.0094.v1

An Y., Zhang Q., Shen R., 2017, Simulation for separation and conversion energy consumption of shale gas, Chemical Engineering Transactions, 61, 295-300, DOI: 10.3303/CET1761047

Asako Y., Hong C., 2017, On Temperature Jump Condition for Slip Flow in a Microchannel with Constant Wall Temperature, Journal of Heat Transfer, 139(7), 072402, DOI: 10.1115/1.4036076

Camaraza-Medina Y., Rubio-Gonzales Á.M., Cruz-Fonticiella O.M., García-Morales O.F., 2018, Simplified analysis of heat transfer through a finned tube bundle in air cooled condenser, Mathematical Modelling of Engineering Problems, 5(3), 237-242, DOI: 10.18280/mmep.050316

Dell'Isola M., D'Ambrosio Alfano F.R., Giovinco G., Ianniello E., 2012, Experimental analysis of thermal conductivity for building materials depending on moisture content, International Journal of Thermophysics, 33(8-9), 1674-1685, DOI:10.1007/s10765-012-1215-z

Fan Y.V., Lee C.T., Klemeš J.J., 2017, Challenges for energy efficiency improvement anaerobic digestion (ad), Chemical Engineering Transactions, 61, 205-210, DOI: 10.3303/CET1761032

Guo K., 2016, Empirical Study on Factors of Student Satisfaction in Higher Education, Revista Iberica de Sistemas e Tecnologias de Informacao, E11: 344-355

Imamura K., Yoshida H., Ozaki M., 2017, Field-induced dynamics of liquid crystal/liquid crystal micro-particle composites, Molecular Crystals and Liquid Crystals, 646(1), 125-131, DOI: 10.1080/15421406.2017.1285097

Kontoleon K.J., Giarma C., 2016, Dynamic thermal response of building material layers in aspect of their moisture content, Applied Energy, 170, 76-91, DOI: 10.1016/j.apenergy.2016.01.106

Li S., Zhao J., Shao Y., 2018, Energy storage and flame retardance of building organic composites, Chemical Engineering Transactions, 66, 571-576, DOI: 10.3303/CET1866096

Liang Q., He Y.L., Zhou Y.P., 2017, Study on lattice thermal conductivity of silicon thin film with aligned nano-pores, Energy Procedia, 105, 4915-4920, DOI: 10.1016/j.egypro.2017.03.981

Liu X., 2018, Study on the temperature characteristics of phase-change energy storage building materials based on ansys, Chemical Engineering Transactions, 66, 385-390, DOI: 10.3303/CET1866065

Qin Z., Tang K., Wu X., Yu Y., Zhang Z., 2017, Product-based carbon constraint energy planning with pinch analysis for sustainable methanol industry in china, Chemical Engineering Transactions, 61, 103-108, DOI: 10.3303/CET1761015

Ramazani A., Reihani A., Soleimani A., 2017, Molecular dynamics study of phonon transport in graphyne nanotubes, Carbon, 123, 635-644, DOI: 10.1016/j.carbon.2017.07.093

Różański A., Stefaniuk D., 2016, Prediction of soil solid thermal conductivity from soil separates and organic matter content: computational micromechanics approach, European Journal of Soil Science, 67(5), 551-563, DOI: 10.1111/ejss.12368

Rudra J.P., Chakraborty M., 2017, Increase in lifetime by harvested energy and analysis of RC5 along with efficient energy consumption in WBAN, Environmental and Earth Sciences Research Journal, 4(2), 39-44, DOI: 10.18280/eesrj.040203

Takahashi Y., Ishida T., 2016, Modeling of Chloride Transport Resistance in Cement Hydrates by Focusing on Nanopores, Journal of Advanced Concrete Technology, 14(11), 728-738, DOI: 10.3151/jact.14.728

Tonini S., Cossali G.E., 2016, One-dimensional analytical approach to modelling evaporation and heating of deformed drops, International Journal of Heat and Mass Transfer, 97, 301-307, DOI: 10.1016/j.ijheatmasstransfer.2016.02.004

Wang Y., Ma C., Liu Y., Wang D., Liu J., 2018, Effect of moisture migration and phase change on effective thermal conductivity of porous building materials, International Journal of Heat and Mass Transfer, 125, 330-342, DOI: 10.1016/j.ijheatmasstransfer.2018.04.062

Zhou J., Putz A., Secanell M., 2017, A mixed wettability pore size distribution based mathematical model for analyzing two-phase flow in porous electrodes I. Mathematical model, Journal of The Electrochemical Society, 164(6), 530-539, DOI: 10.1149/2.0381706jes