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Investigations of equilibrium moisture content with Kelvin modification and dimensional analysis method for composite hygroscopic material

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HIGHLIGHTS

- The modified Kelvin equation has been proposed based on V-shaped cone model.
- A dimensional equation of equilibrium moisture content is presented.
- An effective coefficient of equilibrium moisture is put forward.
- The major influential factors of equilibrium moisture content are analysed by dimensional analysis method.
- Deviation in results of dimensional equation is modified by compressive strength.

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ABSTRACT

This paper proposes a V-shaped cone model to modify the Kelvin equation and thus obtaining an accurate connection between the effective aperture of hygroscopic material and its governing factors. A dimensional equation of equilibrium moisture content is presented based on the modified Kelvin equation. A series of experiments assessing the pore feature, mechanical property, performance of adsorption/desorption and MBV (moisture buffering value) of homemade hygroscopic material are conducted. The effective aperture of hygroscopic material is accurately modified by the angle θ of the V-shaped cone model. A dimensional equation of equilibrium moisture is established by the specific surface area, temperature and humidity, and an effective coefficient of equilibrium moisture is put forward. Deviation between the calculated results of dimensional equation and the tested results of $MBV_{practical}$ are modified by compressive strength. This research mainly contributes to establishing a significant basis for selection and application of hygroscopic material and providing boundary conditions for further Computational Fluid Dynamics (CFD) study.

1. Introduction

It is significantly important to control the humidity environment of residential buildings, which is of great concern for indoor air quality and building energy conservation. Since the hygroscopic material possesses good performance on moisture adsorption/desorption when environmental humidity is too high/low without consuming extra energy, it gradually becomes an economical choice for controlling indoor humidity environment and there are more and more researchers devote their efforts to this area.

There are lots of research on the mechanism of heat and mass transfer. Langmuir [1] derived the single molecule layer adsorption on the basis of kinetic theory. It was demonstrated that there were adsorption sites just like seats in the theater on the solid surface, which were able to adsorbed molecules or atoms. Based on this research, Brunauer, Emmett and Teller [2] studied a multilayer adsorption model and established an adsorption isotherm equation. In 1934, Luikov [3,4] put forward one-dimensional control equation for moisture transfer of porous material based on Darcy's law, Fick's law and Fourier's law, which explained the impact of temperature on moisture transfer. The widely used model for coupled heat and moisture transfer is Philip-Devries model [5], which describes moisture and heat transfer in porous materials under combined moisture and temperature gradients. However, the moisture content in the boundary surface of different material is ignored. Florida Solar Energy Centre (FSEC) in America [6] conducted study on the connection between humidity and balanced moisture content of building material. Mendes [7] made research on the impact of latent heat during the heat transfer and moisture transfer process of porous building wall. Based on the fundamental thermodynamic relations, Lu [8] developed an accurate model for

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predicting heat and moisture transfer in building including building envelope and indoor air. N. Mendes [9] presented a mathematical model, indicating that moisture content gradients can be used as driving forces for heat and moisture transport calculation through the interface between porous materials with different pore size distribution functions. Presented to predict heat and moisture transfer through porous walls, the model did not take into account convection and radiation heat transfer in the pores, neither did the sensible heat transferred by the liquid phase [10–12]. Samuel Dubois [13] proposed a simple moisture transfer model to predict the moisture uptake/release behavior during the MBV tests. However, the samuel's model highly depends on the model's parameters (i.e. vapor resistance), which result in relatively poor robustness. And the simulation results of Ge [14] verified that materials' adsorption performance was related with its moisture capacity and vapor permeability, but the environment factors were ignored.

Meanwhile, many researchers focused on studying the structure and properties of hygroscopic material and composite material. Ioannis [15] analysed the mechanism of capillary adsorption for aerated concrete in water. Many studies [16–25] did experiment on vapor adsorption in the pore of different materials, such as brick, fibre plants and sepiolite. It was found that the mesopore in the material contributed a lot to adsorption. Thus the mesoporous material has good performance on adsorption. Simonson [26] tested indoor hygroscopic performance of wooden structure building. It is concluded that hygroscopic wooden structures reduces relative humidity about 35% to the utmost when indoor humidity is high. Meanwhile, it is able to increase relative humidity for about 15% when indoor humidity is low. Jiang [27] conducted experiments on the performance of zeolite and diatomite, including the aperture distribution, specific surface area and adsorption/desorption capacity. Combined with the adsorption/desorption curve, the connection between microstructure and hygroscopic performance was studied.

Many investigations on the testing method of the performance of hygroscopic material were also carried out. Concept [28] and Padfield [29] put forward a new method to test the moisture buffering property of material. Hameury [30] and Woloszyn [31] studied how the moisture buffering property of indoor material influenced indoor environment and building energy consumption. Osanyintola [32,33] found that the moisture buffering capacity of two spruce specimens was related with the boundary conditions, initial conditions and thickness. The research on the performance of indoor moisture buffering was based on cellular material, improved cellular material, breathing wall and ventilated wall [34–41], which would contribute to buffering indoor relative humidity when it was too high or too low, thus improving indoor air quality. Furthermore, there are three classification methods for moisture buffer potential of building materials, which are the available water (A_w) proposed by Padfield [29], the ideal moisture buffer value (MBV_{ideal}) proposed by the NORDTEST project [42] and the ultimate moisture buffering value proposed (UMBV) by WU [43,44].

Most of the research is still carried out by phenomenological macroscopic models, introducing heuristic laws relating to thermodynamic forces to flux through moisture and temperature dependent transport coefficients. Although some of them depend on time-consuming experimental procedures, they can be conveniently applied to standard material properties. However, they ignore the influence of the surrounding environment and structural characteristics on the moisture capacity of hygroscopic material. The Kelvin equation [45–47] assumed that the material pores is cylindrical. All the pores are divided and ordered according to its size and the quantitative relationship between aperture and relative pressure was proposed when the capillary condensation phenomenon occurs. In this paper, the Kelvin equation is modified and a V-shaped cone model is developed based on experiment, which focuses on the mortar performance of structural characteristic and adsorption/desorption. A dimensional equation of equilibrium adsorption/desorption capacity is established, which combines the structural property of hygroscopic material with its performance of adsorption/desorption. The main goal of this paper is to evaluate how the structural property of hygroscopic material, ambient temperature and humidity influence the adsorption/desorption performance.

2. Experiment

2.1. Specimen

In this paper, a series of materials are compared and finally a homemade hygroscopic material, named WSE, is chosen in the experiments. The WSE is mainly composed of wood fibre, sepiolite and expanded perlite, which helps to improve the quality of mortar and reduce the chance of cracking and coarsening. As is shown in Table 1, five groups of WSE with different mixing proportion are applied in the experiments. It is found that both group II-4 and II-5 are qualified, but the required amount of water in II-4 is more than that of II-5. Consequently, the mixing proportion in the II-5 is taken as the optimal choice in the experiments, in which three kinds of lightweight thermal insulation aggregate are mixed according to the ratio of 1:2:4, named WSE.

The mix ratio of cement mortars applied in the experiments is shown in Table 2. The WSE is obtained according to the calculated mixing proportion before experiments. The mortar sample B-1 is obtained by adding redisposition powder ($4\ kg/m^3$) to WSE. The mortar sample B-2 is obtained by adding polypropylene fibre ($3\ kg/m^3$) to B-1. The mortar sample B-3 is obtained by adding zeolite ($12\ kg/m^3$) to B-1.

2.2. Microstructure characterization

The structure characteristic parameters of hygroscopic material are specific surface area, pore volume and aperture distribution. The internal structure of hygroscopic material is analysed by experiment. Scanning Electron Microscopy (SEM) is used to examine the microstructure of the distribution of wood fibre, sepiolite and expanded perlite in specimen. Brunauer–Emmett–Teller (BET) surface area analyzer and Barret–Joyner–Halenda (BJH) method are used to describe the pore features of the specimen.

2.3. Mechanical property

Compressive strength is tested to meet the requirement of thermal insulation products. According to the Chinese standard GB/T5486.2, $100\ mm \times 100\ mm \times 100\ mm$ cube specimens are moulded for testing compressive strength, taking the average of 10 groups of measurement. All specimens are cured in a moist environment at temperature of 105 °C ± 2 °C. Weight change is less than 0.01% for three days.

2.4. Equilibrium moisture content

The isothermal curve of adsorption/desorption is the basis of dynamic analysis of moisture process, which refers to the equilibrium moisture content of material [48]. It is determined by the component, structure and the corresponding environment. It is the special characteristic of the material in statistic adsorption/desorption.