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Recent progress on hygroscopic materials for indoor moisture buffering

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Abstract. Once in contact with the indoor air, hygroscopic materials can moderate the indoor humidity fluctuation by adsorbing or releasing water vapour, and then improve the moisture regulation and thermal management of buildings. It is desirable to explore the characterized properties of these materials about moisture buffering behaviour. In this regard, we review various hygroscopic materials used for the built environment control. The hygrothermal properties of hygroscopic materials often can be characterized by some parameters, such as water vapour adsorption/desorption capacity, water vapour adsorption/desorption rate, water vapour diffusion coefficient, and so on. To provide an insight on the existing research on humidity control materials, different research studies and the recent progress on humidity control materials have been summarized. The materials include traditional and conventional building materials, some natural materials, and novel humidity control materials. Besides, the relevant parameters are considered as well as the improvement suggestions to enhance the application of humidity control materials in building environments. Finally, new multifunctional materials and intelligent moisture control materials together with the corresponding systems are collated to summarize the latest research trends. The overview of the application of hygroscopic materials can provide current and future researchers guidelines for the science-oriented design of moisture control systems for new energy-efficient buildings.

1. Introduction

The indoor environmental quality has been widely concerned in the recent 30 years. The indoor relative humidity is an important factor to determine indoor climate conditions, which is closely related to people's health, occupants' thermal comfort, and building energy consumption [1,2]. To maintain an indoor comfortable environment, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends that indoor relative humidity should be maintained between 40% and 65%, which is the desired comfort relative humidity range for human beings [3]. The main methods to the humidity regulation highly rely on air conditioning technology, but the air conditioning system is not a kind of ecological control method to control indoor humidity. The traditional air conditioning systems require spending a large amount of energy on dehumidification, especially in high-performance buildings. Some materials can absorb or release moisture to positively mitigate the humidity fluctuation in the built environment. The utilization of humidity control materials to reasonably control indoor humidity with low energy consumption is a topic of research in hygrothermal conditions for buildings.

Humidity control materials (hygroscopic materials) can automatically regulate the relative humidity with the change of temperature and humidity of the air in the regulated space with their moisture absorption and desorption capacity. Some traditional building materials, natural materials, high-performance hygroscopic materials, and composite humidity control materials are often used in modern buildings. Many traditional and conventional building materials, such as concrete, drywall, brick, and plywood, have moisture buffering capacity for indoor humidity control [4, 5]. Many natural materials such as natural minerals and plant fibers have been studied to achieve the humidity control purpose [6,7]. They can adsorb water out of the air through the pores and functional groups on the surface to achieve humidity regulation, such as diatomite, sepiolite, vegetal fibers, stem fibers, and so on. Synthetic desiccants, such as silicates, aluminophosphates, zeolites, and inorganic salt, tend to have strong moisture absorption capacity and are widely used in civil engineering [8, 9]. To achieve the purpose of indoor comfort and health, it is often necessary to use composite humidity control materials or a multi-material assembly system to control the temperature, humidity, and indoor air pollutants of the building environment.

With people's attention to the indoor living environment, more materials and new technologies are studied, which may be applied to the building environment. But there are still many challenges in the application of humidity control materials in buildings, i.e. how to use hygroscopic materials with other functional materials to realize the multi-function adjustment and the energy saving of the built environment. This paper summarizes the existing research on humidity control materials, different research studies, and the recent progress on humidity control materials. First, several kinds of humidity control materials and their characteristics will be introduced systematically. Secondly, many humidity control materials using in the corresponding systems are collected to summarize the latest research trends. The overview of the application of hygroscopic materials can provide current and future researchers' guidelines for new buildings.

2. Humidity control mechanism and performance parameters of hygroscopic materials

The indoor humidity is mainly affected by the temperature and humidity of the surrounding environment. Hygroscopic materials can absorb/release water vapor from/to the space according to the variations of ambient temperature and humidity, and then affect the relative humidity of indoor environment [10]. Generally, there are two main principles for humidity control materials to regulate humidity. First, the properties of some solid porous humidity control materials are mainly decided by the pore structure, the diffusion of water vapor in the pores, and the material surface. The water vapor in the air interacts with the pore surface of the material so that the vapor pressure in the micro space structure is higher than that in the indoor environment, and the water vapor gathers or condenses into liquid water in the pores. Secondly, such as some inorganic salts can absorb and release water vapor from space by chemical reaction. The humidity control mechanism of hygroscopic materials is shown in Figure 1. According to the humidity control mechanism of humidity control materials, a series of parameters have been introduced to characterize the multiple humidity control performance. Generally, the amount of moisture adsorption and the rate of moisture adsorption are important evaluation parameters of hygroscopic materials.

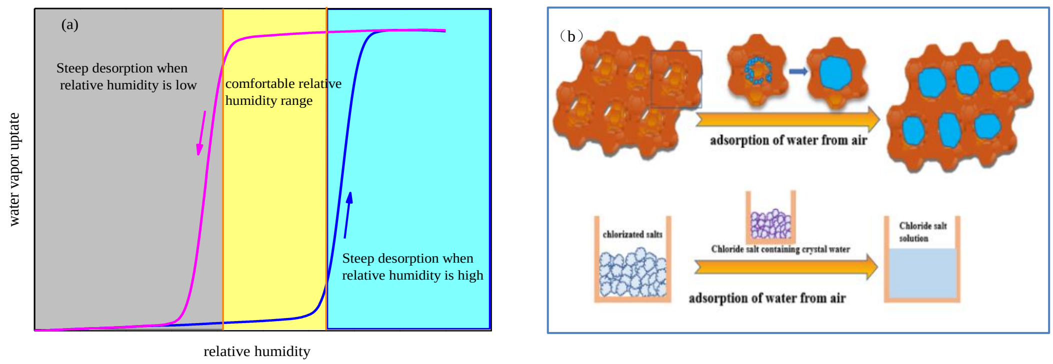

Figure 1. The humidity control mechabnism of hygroscopic materials: (a) working principle of hygroscopic materials and (b) moisture adsorption of hygroscopic materials.

3. Hygroscopic materials

3.1. Traditional building materials
With the development of science and technology, some traditional materials are still widely used in construction, such as various types of brick, wood, gypsum, and concrete. These materials also have a certain adsorption and storage capacity for the water vapour in a space and can regulate the indoor humidity properly. Some researchers have studied the moisture buffering capacity of wood, brick, gypsum, and concrete for the built environment, and the specific parameters are listed in Table 1**.** Though these traditional building materials have a certain buffering effect on the humidity in the space, their moisture adsorption capacity and buffering value is significantly lower than some novel humidity control materials and can be combined with other materials or special processes to achieve its effective humidity control function [11]. Therefore, the development of functional humidity control materials based on traditional building materials is a research hotspot in recent years.

Table 1. Sorption capacity of traditional building materials for water vapor.

Materials	Test conditions	Moisture adsorption capacity (g/g×100%)	References
Concrete	Temperature 4-30 °C, Relative humidity range 30-90%, Air speed 0.1-0.3 m/s	0.95%	[4]
Brick	Temperature 4-30 °C, Relative humidity range 30-90%, Air speed 0.1-0.3 m/s	0.24%	[4]
Unfiered brick	Relative humidity range 40-60%, Air speed 0.2-1.2m/s	0.98%	[12]
Gypsum board	Relative humidity range 45-60%	0.5%	[13]
Pine wood	Relative humidity range 40-60% Air speed 0.2-1.2m/s	1.6%	[12]
Beechwood	Relative humidity range 40-60%, Air speed 0.2-1.2m/s	1.5%	[12]
carbon-gypsum-cement compound	Average temperature23 °C, Relative Humidity range 30-95%	6.9%	[9]

3.2. Natural hygroscopic materials
In the natural environment, many natural materials can adsorb moisture in the air and regulate the surrounding environment. Natural porous minerals and plant fibers can buffer moisture in the air and can be used as humidity control materials. The natural porous minerals are usually a series of silicate solid materials with layered or micropore structures. The minerals take advantage of their hydrophilic and pore structure to adsorb and condense water molecules in a certain space, such as sepiolite, montmorillonite, zeolite, diatomite, bentonite, and so on. The diatomite, a naturally occurring porous mineral, can adsorb water content to about 10% in 80% RH [14]. Diatomite pore structure and surface further affect the humidity control performance of diatomite and diatomites from different areas show different properties in the process of humidity control. Therefore, diatomite usually requires simple chemical treatments to further improve its moisture absorption performance. Most natural porous minerals are used as a filling material with other building materials to realize the humidity control

function of building materials. The minerals are mixed as a filler with cement, gypsum, or wood to form humidity control materials. Some researchers have shown that the humidity is lower by 20% to 30% using the zeolite composite humidity control materials in the room [15]. Plant fiber is generally considered as a kind of environmentally friendly biobased material with wide sources. Plant fibers are mainly composed of sugar-based polymers and have a multi-scale structure [16, 17]. Due to the chemical composition and microstructure of the plant fiber, the strong hydrophilic behaviour of such reinforcing fibers leads to a high level of moisture absorption in wet environments. Some researchers who have studied the water absorption in cellulose showed that the amorphous phase and the highly polar carboxyl functions in plant fibers can create hydrogen bonds with the air-water [18, 19]. The moisture absorption characteristics of natural minerals and plant fibers are shown in Table 2.

Table 2. Moisture adsorption characteristics of natural minerals and plant fibers.

Materials	Test conditions	Moisture adsorption capacity (g/g×100%)	References
Diatomite	Temperature 20-30 °C, Relative humidity range 11-90%, Air speed 0.1-0.3 m/s	1-3%	[20]
Nature zeolite	Temperature 20°C, Relative humidity 0-80%	3.9%	[21]
Nature zeolite after modifying	Temperature 20°C, Relative humidity 0-80%	6.4%	[21]
Sepiolite	Temperature 20°C, Relative humidity range 30-90%	10%	[22]
Heat-treated sepiolite	Temperature 23-40°C, Relative humidity range 30-90%, surface area 145 m^2/g	15%	[22]
Modified Bentonite	Relative humidity range 33-75%	10%	[23]
Fiber of sisal	Tempsrature37°C, Relative humidity range 0-98%,	15.4%	[24]
Fiber of hemp	tempsrature37°C, Relative humidity range 0-98%,	14.4%	[24]
Fiber of nut	tempsrature37°C, Relative humidity range 0-98%,	14.5%	[24]

3.3. *Some synthetic and novel humidity control materials*

Although some natural materials can regulate the humidity in the environment, the amount of moisture absorption is limited. Some synthetic materials have good adsorption capacity and adsorption rate and can be used as hygroscopic materials for built environment. Silica gel is a kind of amorphous silica with a porous structure, which is considered an effective material for humidity control. FUMIHIKO OHASHI made some mesostructured silica products, and these materials possess a sharp increase in adsorption of water vapour when the relative water vapour pressure is located at 40–60% [25]. Wang demonstrated a full-solid-state humidity pump using the silica gel materials, which showed a humidity transfer rate of 28.38g/h for small-space humidity control application [26]. In addition, some inorganic salts can also be used as hygroscopic materials, such as $LiCl•6H_2O$, $CaCl_2•6H_2O$, NH_4CL, $NaNO_3$, $Pb(NO_3)_2$ and so on[27]. Because different concentrations of the salt solution have different saturated vapour pressure, the humidity of the surrounding space can be controlled by changing the concentration of the salt solution. Silica gel and hygroscopic salt can usually be assembled as composite humidity control materials to enhance water adsorption characteristics. Some silica gel-host composites and their properties are shown in Table 3. Organic polymer materials are also the humidity control materials reported with high humidity control capacity. In recent years, there is more and more research on polymer humidity control materials, mainly focusing on the development of materials with high moisture adsorption capacity and rapid adsorption and release of humidity to adapt to different applications. Recently, mesoporous materials such as metal-organic frameworks (MOFs) have emerged as an effective candidate for the currently used desiccants. MOFs have open frameworks with ordered structure and high surface area, which make these materials promising desiccants in the sorption-based their variable chemical structure. Many studies have been reported about the utilization of MOF materials on the humidity regulation in buildings, such as MOF-801[28], MOF-841[29], MIL-160[30], MIL-100 (Cr, Fe, Al) [11, 31] and so on. Moisture adsorption characteristics of synthetic and novel humidity control materials are shown in Table 3.

Table 3. Moisture adsorption characteristics of synthetic and novel humidity control materials.

Materials	Test conditions	Moisture adsorption capacity (g/g×100%)	References
Silica gels	Temperature 24°C, Relative humidity 0-80%, Pore diameter 10nm	30%	[21]
Mesostructured silica	Relative humidity 40-60%, Surface area 1200 m^2/g, Pore diameter 2.6 nm	35%	[25]
Silica gel–lithium chloride	Temperature 25°C, Relative Humidity 30-80%	55%	[33]
Silica gel–calcium chloride	Temperature 25°C, Relative Humidity 30-70%	32%	[33]
Silica gel–lithium bromide	Temperature 20°C, Relative Humidity 10-80%	43%	[33]
konjac glucomannan-acrylic acid copolym	Temperature 25°C, Relative Humidity 0-90%	110%	[34]
MOF-303Al	Temperature 25°C, Relative Humidity 0-40%	33%	[35]
MIL-100Fe	Temperature 30°C, Relative Humidity 30-90%	30%	[35]
MIL-101Cr-NO3	Temperature 20°C, Relative Humidity 20-90%,Surface area 1245 m^2/g	38%	[36]
MIL-101Cr-NH3	Temperature 20°C, Relative Humidity 20-90%, surface area 2690 m^2/g	90%	[36]
MIL-160Al	Temperature 30°C, Relative Humidity 0-30%, surface area 1070 m^2/g	35%	[37]
Y-shp-MOF-5	Temperature 25°C, Relative Humidity 30-80%, surface area 4549 m^2/g	39%	[38]
Cr-soc-MOF-1	Temperature 30°C, Relative Humidity 30-90%, surface area 4549 m^2/g	190%	[39]

4. Development trend of humidity control materials used in indoor environment

Since the living environment can be affected by indoor temperature, humidity, air quality, and other aspects, more new functional materials or new systems have been developed to realize the integrated control of indoor environment. Considering that a large amount of heat transferred during the process of adsorption and desorption by hygroscopic materials, the research of phase change humidity control materials (PCHCM) has become a hot spot in recent years [40]. Some composite materials such as fabric-sodium sulfate-silica gel, metal-organic frameworks-octadecane composite, and vesuvianite/sepiolite/zeolite-hydrochloric acid were reported to be used as humidity control phase change materials in some papers [41]. Qin made use of a combined HAMT (heat, air and moisture transfer model) and enthalpy model to evaluate the performance of PCHCM. The results have shown that up to 20% of the potential energy could be saved when using PCHCM in the buildings [42]. In order to further promote the use of interior decoration materials, more functional materials and humidity control materials are combined to form multi-functional composite building materials. Zhang used sepiolite and nano-TiO_2 to prepare a multifunctional powder coating material for the interior wall [43]. Qiu prepared a cemented by hydrothermal synthesis of sepiolite and calcium silicate to function both in humidity regulation and volatile organic compound removal [44].This material can not only regulate the indoor humidity but also inhibit the growth of bacteria in the indoor air and remove formaldehyde in the air. As many new materials are reported, humidity control materials also can be integrated with new materials to form a new integrated system. For example, Qin reported a new dehumidification system, which can utilize the energy highly effective during the process of water vapor adsorption and desorption by using the assembly of the refrigeration silicon chip and hygroscopic materials [45].

5. Conclusion

To date, many new hygroscopic materials have been studied and applied in building environment. Humidity control materials are developing in the direction of being intelligent, multifunctional, high performance and practical systems, which can improve the building environment and save energy to a certain degree. On the basis of current materials and various technologies, the assembly of hygroscopic materials with other technologies can not only promote the practical applications of hygroscopic materials in the built environment, but also expand the application of hygroscopic materials in agriculture, food and daily chemical products.

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