

# HYSTERESIS AND TEMPERATURE DEPENDENCY OF WATER VAPOR SORPTION

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Moisture in porous building materials plays an important role in almost all durability problems. The sorption characteristics of building materials exhibit hysteresis in the way the equilibrium curves develop between adsorption and desorption. The sorption curves are also somewhat temperature-dependent. These facts are most often neglected in models for combined heat and moisture transport in materials. This study provides the sorption isotherm and its hysteresis of different porous building materials. The paper seeks to contribute to the knowledge base about such sorption characteristic by presenting some new measurements of hysteresis and temperature dependency of the moisture sorption characteristics of different porous building materials: concrete, porous concrete, cement plaster, limes cement plaster, brick, and spruce. Scanning curves are measured for all materials where periods with adsorption and desorption interrupt each other intermittently between 0% and 97% of relative humidity.

*Keywords:* Material, Moisture, Water sorption, Hysteresis, Temperature dependency.

## 1 INTRODUCTION

Adsorption-desorption processes taking place in construction materials basically indicate the nature of mechanical, physical, and molecular bonds between materials and water or its vapor. In designing and construction practice, it is customary to relate adsorption-desorption calculations with the air-dry materials. Usually, the permitted moisture content, estimated strength, thermal conductivity, swelling, shrinkage and other physical and mechanical values are indicated within the limits of material hygroscopic moisture (EN ISO 12571 2000, Miniotaite 2001). The sorption curve for a material is most often represented as a unique curve that gives a direct translation between relative humidity (RH) and moisture content (Hansen 1986). In reality the curve should really be shown as a set of curves representing different temperatures at which they are determined. The warmer the temperature, the lower the equilibrium moisture content at the same RH.

The following stages of material humidity state are predetermined by adsorption-desorption processes: material moisture content when the walls of capillaries and pores of the material are covered with water molecules; material moisture content when vapor is prevailing in pores and capillaries; material moisture content at the beginning and during intense development of capillary condensation, i.e., such air conditions are shown when water and not vapor prevails in the capillaries of the material maintained. The equilibrium moisture content depends on the history of humidity exposure to which

the material has been exerted. As the material comes from a dry environment and is gaining moisture, the temporal equilibrium will establish at a lower moisture content at a given RH compared to a situation when the material comes from a humid environment and is being desiccated. Considering both temperature effect and hysteresis, the sorption characteristics of a material should be represented as a sorption volume in a three-dimensional space giving the relation between moisture content, RH, and temperature (Rode and Clorius 2004).

According to the physical data on the above stages, one can determine the ratio of moistening and drying velocities, destruction of the material in the area of microcapillaries and micro-cracks, softening of the material, and swelling-shrinkage deformations and “fatigue” of the material.

## 2 INVESTIGATION METHOD

The data on adsorption-desorption processes found in literature are fragmentary, not exhaustive, and characterize only the limit or typical values of the abovementioned properties of some traditional materials (Rode and Clorius 2004). Standard methods intended for the determination of adsorption-desorption were insufficient for the investigation of adsorption-desorption processes and therefore had to be essentially improved in the course of investigation.

The main point of the developed adsorption-desorption method is the carrying out of experiments in three stages (Miniotaite 2006). At the first stage, the sorption isotherm of the investigative material is drawn at all 7 points of ambient air humidity  $\phi$ . At the second stage, a reverse action is applied, i.e., the desorption isotherm of the same specimen is drawn. At the third stage, desorption process is at some moment discontinued; coming back to sorption, physical coordinates of such moment are fixed: the RH  $\phi$  of ambient air and specimens moisture content  $u$ .

When an adsorption-desorption experiment at 20°C is completed, the investigated materials are placed in a vessel and dried again; an analogous experiment is carried out at 5°C.

It was found in the literature that only approximate data existed on sorption moisture content of materials in case of temperatures below zero, even though surface layers of walls are under action of the environment of temperatures below zero for a long period of time (on average, 100.3 days per year in Lithuania). With the data on adsorption-desorption processes at 20°C and 5°C, a more precise recalculation of sorption moisture content at low temperatures is possible on the basis of Clausius-Clapeyron's equation.

Adsorption-desorption investigations of the materials were carried out at 20°C and 5°C according to the improved methods of sorption investigation. Then sorption isotherms were recalculated in isotherms at 10°C, 0°C and -10°C.

## 3 RESULTS AND ANALYSIS

Graphic and summarized passport-cards of adsorption-desorption investigations of all tested materials were created, indicating a structural group of materials corresponding to the similarity of moisture-caused deformations, the name of material, and the main adsorption-desorption parameters. The passport-cards constitute a respective data bank of adsorption-desorption of construction material.

A typical example of such passport-card is given in Figure 1. It should be noted that at temperatures below zero, significant differences between the experimental results and the literary data is observed. According to literary sources, material moisture content  $u$  increases with a drop in temperature, whereas, according to the experimental results, at high values of air RH and temperatures below 0°C, the material moisture content  $u$  is substantially less than that of isotherms at temperatures above 0°C.

Generalizing the nature of changes in adsorption-desorption isotherms, it was determined that no distinct limits exist between individual forms of material humidity states, i.e., one humidity form gradually transfers to another, and therefore consecutively expressed isotherms of adsorption and desorption possess a flexible S-shaped view. Each material possesses only for its characteristic such sorption curve.

More detailed examination of the curves showed that a triple moisture-material link exists. The length corresponding to ambient air RH  $\phi$  from 0% to ~10% is of a slowing rise. In this case, water vapor molecules cover the walls of material pores and capillaries initially with the layer of monomolecular thickness, and then with the layer of multi-molecular thickness until a water (aqueous) film is formed. Forces of molecular attraction act between the material and vapor molecules; therefore, wet films acquire some properties of a solid body: They do not move or freeze easily, and would not evaporate at standard drying temperature  $\Theta = 105^\circ\text{C}$ . The length corresponding to ambient air RH  $\phi$  from 10-12% to 45% is still of a slowing rise. Thus adsorbed, vapor molecules maintain thermodynamic equilibrium and move easily. If the pressure of water vapor in the capillaries of the material is higher than ambient vapor pressure, they are evaporated at 105°C. The above processes also take place in the length of a rising straight line from 45% to 55%. The length corresponding to ambient air RH  $\phi$  from 55% to 100% is of a quickened rise, i.e., material moisture content growth picks up speed. In this sorption area, the thermodynamic equilibrium of vapor molecules is destroyed, because a part of the vapor is condensed in capillaries and then capillary condensation starts. In the length corresponding to ambient air RH  $\phi$  from 58% to 75-80% the above action is slow; when humidity exceeds 80%, the process is intense or very intense. At this time, a part of the moisture contained in the material is of a liquid aggregative state. This must be taken into consideration when calculating moisture content and heat exchange in the walls. Thermal conductivity and moisture-caused deformations of the material significantly increase in this sorption area.

The investigations indicated that for many materials, the initial point of intense capillary condensation was rather distinct. However, for other materials, the capillary condensation increase is approximately proportional to the increase in ambient RH ( $\phi, \%$ ). Material moisture content values ( $u, \%$ ) at the end of intense capillary condensation stand in contrast – the beginning of intense evaporation (drying) practically coincide with the exception of below-zero temperatures, irrespective of hysteresis size and ambient temperature.

### 3.1 Group of Fine-Grained Structure Materials

This consists of cement plaster, lime cement plaster, masonry mortar, and silicate brick.

The value of maximum sorption moisture content  $u_{max}$  is up to 6% (silicate brick). Figure 1 shows adsorption-desorption isotherms of lime cement plaster.

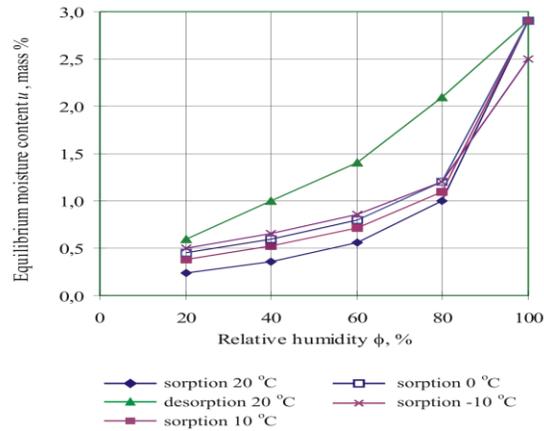


Figure 1. Adsorption-desorption isotherms of lime cement plaster,  $\rho = 1700 \text{ kg/m}^3$ : experimental,  $\Theta = 20^\circ\text{C}$ ; calculated,  $\Theta = 10^\circ\text{C}, 0^\circ\text{C}, -10^\circ\text{C}$ .

The maximum adsorption-desorption hysteresis  $\Delta u_\Theta$  is up to 120% in comparison with the sorption isotherm. It corresponds to the range of RH of air  $\phi = 75\text{-}80\%$  (i.e., fast moistening, slow drying).

The increase of material moisture content from temperature is up to 0.30 mass % when the temperature drops from  $20^\circ\text{C}$  to  $-10^\circ\text{C}$ ; RH  $\phi = 40\text{-}60\%$ .

### 3.2 Group of Porous Materials

This group consists of sub-groups of porous concrete and porous silicate. The use of cement and lime bonding material has some specific features. When cement is used as a bonding material, hysteresis of adsorption and desorption is 2 times larger than in case of lime use. The most favorable air humidity  $\phi$  environment for the hysteresis of cement articles is 75%. In the case of lime materials it is 40-60%. The above phenomenon is also observed in case of the articles of a different structure containing lime. The use of lime decreases the hysteresis, and the most favorable environment for its formation is a drier ( $\phi \leq 60\%$ ) environment.

A summary of the investigation results:

- Maximum sorption moisture value  $u_{max}$  is up to 20%;
- Maximum adsorption-desorption hysteresis in the case of the cement sub-group is in the 75-80% RH  $\phi$  environment, and  $\Delta u_\phi$  up to +80%. In the case of the lime sub-group it is 40-60%  $\phi$  in the environment,  $\Delta u_\phi$  from +9% to +20% (fast drying);
- The influence of the temperature in the environment of  $\Delta u_\Theta$ , 40-80% RH ( $\phi$ ) is practically the same and does not exceed +12% (i.e., is insignificant).

Figure 2 shows adsorption-desorption isotherms of porous concrete.

### 3.3 Group of Coarse-Grained Structures Materials

The above group consists of concrete and expanded-clay concrete. The bonding substance is cement. The value of maximum sorption moisture content  $u_{max}$  is up to 8% (expanded-clay concrete). Figure 3 the shows the adsorption-desorption isotherms.

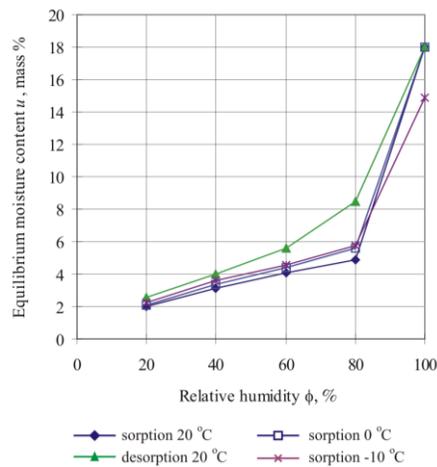


Figure 2. Adsorption-desorption isotherms of porous concrete,  $\rho = 600 \text{ kg/m}^3$ : experimental,  $\Theta = 20^\circ\text{C}$ ; calculated,  $\Theta = 10^\circ\text{C}, 0^\circ\text{C}, -10^\circ\text{C}$ .

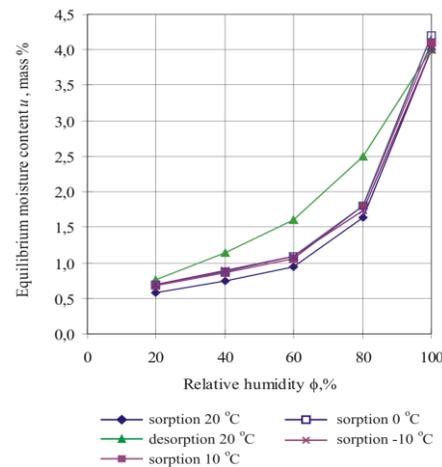


Figure 3. Adsorption-desorption isotherms of concrete,  $\rho = 2400 \text{ kg/m}^3$ : experimental,  $\Theta = 20^\circ\text{C}$ ; calculated,  $\Theta = 10^\circ\text{C}, 0^\circ\text{C}, -10^\circ\text{C}$ .

The maximum adsorption-desorption hysteresis  $\Delta u_\Theta$  is up to 95% in comparison with the sorption isotherm. It corresponds to the range of RH of air  $\phi = 40\text{-}70\%$  (i.e., fast moistening, slow drying). The increase of material moisture content from temperature is up to 0.50 mass % when the temperature drops from  $20^\circ\text{C}$  to  $-10^\circ\text{C}$ ; RH  $\phi = 60\text{-}75\%$ .

### 3.4 Group of Ceramics

The value of maximum sorption moisture content ( $u_{max}$ ) is up to 2.5% (Figure 4).

The maximum adsorption-desorption hysteresis  $\Delta u_\Theta$  is up to 225% in comparison with the sorption isotherm. It corresponds to the range of RH of air  $\phi = 60\text{-}75\%$  (fast moistening, slow drying).

The increase of material moisture content from the temperature is up to 0.14 mass % when the temperature drops from  $20^\circ\text{C}$  to  $-10^\circ\text{C}$ ; RH  $\phi = 50\text{-}65\%$ .

The maximum adsorption-desorption hysteresis  $\Delta u_\Theta$  is up to 25% in comparison with the sorption isotherm. It corresponds to the range of RH of air  $\phi = (30\text{-}80)\%$  (fast moistening, slow drying). The increase of material moisture content from the temperature is up to 1.8 mass % when the temperature drops from  $20^\circ\text{C}$  to  $-10^\circ\text{C}$ ; RH  $\phi = 30\text{-}80\%$ .

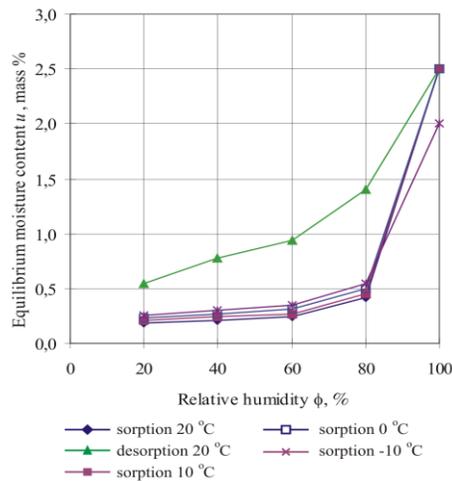


Figure 4. Adsorption-desorption isotherms of ceramics,  $\rho = 1700 \text{ kg/m}^3$ : experimental,  $\theta = 20^\circ\text{C}$ ; calculated,  $\theta = 10^\circ\text{C}, 0^\circ\text{C}, -10^\circ\text{C}$ .

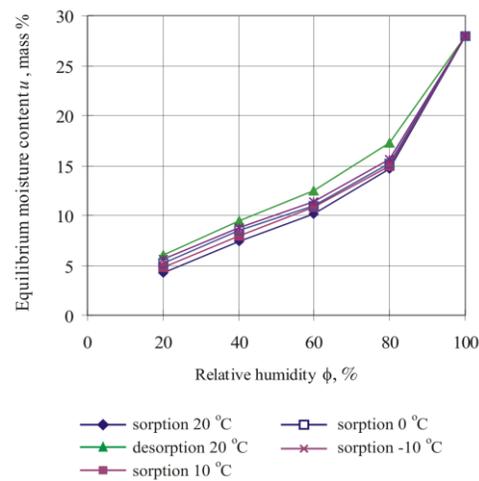


Figure 5. Adsorption-desorption isotherms of spruce,  $\rho = 500 \text{ kg/m}^3$ : experimental,  $\theta = 20^\circ\text{C}$ ; calculated,  $\theta = 10^\circ\text{C}, 0^\circ\text{C}, -10^\circ\text{C}$ .

#### 4 CONCLUSIONS

The highest hysteresis in materials of fine structure and porous concrete exists before the beginning of an intense process of capillary condensation, at a relative humidity of the ambient air  $\phi = 70\text{-}80\%$ . In the case of materials of fine-grained structure containing 30-35% and more lime in its bonding material, the mark of the highest hysteresis shifts to the left by 10-15%; in the case of coarse-grained materials, by 15-20%, and in the case of materials of organic nature by 40-50%.

The temperature influence upon the adsorption-desorption process in the case of all materials is the highest at relative humidity of the air close to the humidity of the beginning of capillary condensation. The absolute value of temperature influence depends on the nature of the framework of material. The above influence is highest in the case of coarse-grained, porous, and organic materials, 30-35%. In all cases, sorption moisture increases with decreases in temperature. At high relative humidity values, and temperatures below  $0^\circ\text{C}$ , the material moisture  $u$  is lower than in isotherms at temperatures above  $0^\circ\text{C}$ .

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