SIMULATION OF HYSTERETIC BEHAVIOR AT DYNAMIC MOISTURE RESPONSE

Peter Mihalka, Ing.*, Olga Koronthalyova, PhD.*, Peter Matiasovsky, PhD.*,
Juraj Veselsky, Assoc. Professor [+], Daniel Szabo, MSc. [+], Anton Puskar, Professor [+]

* Institute of Construction and Architecture, Slovak Academy of Sciences, Dubravska 9, 845 43 Bratislava, Slovakia. e-mail: *usarmipe@savba.sk*, *usarkoro@savba.sk, usarmat@savba.sk*

[+] Slovak Technical University, Faculty of Civil Engineering, Radlinskeho 11, 813 68 Bratislava, Slovakia

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SUMMARY:
Simulation tool for solving coupled heat and moisture transfer involving the effect of a hysteresis was developed. A numerical simulation of the dynamic moisture behaviour of autoclaved aerated concrete was compared with the experimental results. Parameters of the used model of hysteresis were determined and applied in the simulation.

INTRODUCTION

For a correct simulation of the dynamic moisture behavior of building structures it is necessary to know not only the basic hygric parameters determined from the measurements under steady state conditions but to determine also a possible differences between the steady and non-steady behaviour.

In most of simulation tools, the process of simultaneous water vapour adsorption and desorption is controlled by unique function, usually main adsorption isotherm. In hysteretic materials, the process of adsorption and desorption is not the same. The equilibrium moisture content during desorption process is higher than the moisture content during adsorption at the same relative humidity.

Simulation tool for solving coupled heat and moisture transfer involving the effect of a hysteresis was developed. The simulation of the dynamic moisture response of a hygroscopic material under different dynamic boundary conditions was performed, results of simulation were confronted with results of laboratory tests.

The tests were done for the autoclaved aerated concrete (AAC) plate, the pore structure of which is characterised by two pore subsystems, consisting of 30 % volume of micropores and 50 % volume of macropores [3]. For this material a hysteretic moisture behaviour is typical [2].

EXPERIMENTS

The main adsorption isotherm of the material was determined by conditioning the samples in desiccators under a constant relative humidity and temperature (23 °C) until the steady equilibrium was achieved [2]. The estimation of main desorption isotherm was done by an analysis of previous measurements of AAC samples [1]. Two primary scanning desorption curves were determined starting from the equilibrium moisture contents corresponding to 94 % and 75 % RH. The water vapour

permeability was measured by standard dry-cup (0 – 53 % RH difference maintained by the silica-gel and the climatic chamber) and wet-cup (100 – 53 % RH difference maintained by the water and the climatic chamber) methods.

The dynamic tests were performed in a climatic chamber. The tests were performed under three different regimes of the cyclic RH step changes between 49/79, 45/80, 56/79 % relative humidities, lasting 8/16, 24/48 and 48/96 hours respectively. The temperature during the tests was kept at constant value of 23.0 ± 0.5 °C. The relative humidity changes in the chamber were controlled by the dry and wet air streams. The relative humidity near the sample was monitored by the capacitative RH sensor with ± 1.5% RH precision. The temperature was measured by the electric resistance sensor Pt 100. The specimens were sealed on all but two surfaces by the epoxy resin in order to guarantee 1D water vapour flow. Simultaneously two specimens with the dimensions of 200 x 120 x 39.5 mm were tested (the area of the active surface was 0.096 m^2). A mass of the samples was weighted by the balance with the accuracy of 0.1 g. The mass of the samples, the temperature and the relative humidity in the chamber were registered in hourly intervals. The air flow velocity near the samples varied from 0.05 to 0.15 m/s that corresponded to common interior conditions. A detailed description of the experiments and their results is in [2].

SIMULATION MODEL

The developed simulation model is based on solution of the coupled 1D equations for the heat conduction and the water vapor diffusion through a structure.

1D non-steady heat transfer is described by the Fourier`s equation of heat conduction:

$$\rho \cdot c \cdot \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \cdot \frac{\partial \theta}{\partial x} \right) \tag{1}$$

Where:
θ – temperature (°C)
ρ – density (kg/m^3)
c – specific heat capacity (J/kg.K)
λ – thermal conductivity (W/m.K)
t – time (s)
x – coordinate (m)

1D non-steady water vapour diffusion is described by the Fick`s equation:

$$\frac{\partial w_c}{\partial \varphi}(\varphi) \cdot \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(\delta_p(\varphi) \cdot \frac{\partial (p_{sat} \cdot \varphi)}{\partial x} \right) \tag{2}$$

Where:
φ – relative humidity (-)
w_c – water content (kg/m^3)
δ_p – water vapour permeability (s)
t – time (s)

x – coordinate (m)

p_{sat} – water vapour saturation pressure (Pa)

$\partial w_c / \partial \varphi$ – moisture capacity

In hysteretic material the moisture capacity is given by scanning curves, which lie always between the main adsorption and desorption isotherms. The description of scanning curves was done by simple empirical model originally used by Pedersen [5]. The moisture capacity in the hysteresis region is represented by slope of the scanning curves:

During adsorption:
$$\xi_{hys} = \frac{\gamma_a \cdot (u - u_{adsorption})^2 \cdot \xi_{desorption} + (u - u_{desorption})^2 \cdot \xi_{adsorption}}{(u_{desorption} - u_{adsorption})^2}$$

(3)

During desorption:
$$\xi_{hys} = \frac{(u - u_{adsorption})^2 \cdot \xi_{desorption} + \gamma_d \cdot (u - u_{desorption})^2 \cdot \xi_{adsorption}}{(u_{desorption} - u_{adsorption})^2}$$

(4)

Where:

ξ_{hys} - the moisture capacity (slope of scanning curve) at given relative humidity

u – water content (kg/kg)

$u_{adsorption}$ – the water content calculated from main adsorption isotherm (kg/kg)

$u_{desorption}$ – the water content calculated from main desorption isotherm (kg/kg)

$\xi_{adsorption}$ – the moisture capacity at given relative humidity calculated from main adsorption isotherm

$\xi_{desorption}$ – the moisture capacity at given relative humidity calculated from main desorption isotherm

γ_a, γ_d – the parameters of hysteresis

The numerical solution of equations (1) and (2) using Control Volume Method with 1-D model and implicit time scheme [4] was performed. In the simulation volume elements with constant thickness 1mm were used. The time step was 10 min. The material parameters dependent on moisture content were recalculated during every time step. Every volume element was considered as a material with its own sorption-desorption past.

MATERIAL PROPERTIES

The main adsorption and desorption isotherms of tested AAC were described by the following expression [2]:

$$u_{HANSEN} = u_h \cdot \left(1 - \frac{\ln \varphi}{A}\right)^{-\frac{1}{n}}$$

(5)

where: u_{HANSEN} is the moisture content (kg/kg), φ is relative humidity (-), u_h is the hygroscopic moisture content (kg/kg), A and n are approximation parameters.

The used approximation parameters for main adsorption and desorption isotherms are in tab.1. The main storage functions are in Fig.1a.

Table.1: Approximation parameters for main adsorption and desorption isotherms of tested AAC

	Adsorption	Desorption
u_h	0.4	0.4
A	0.000 04	0.001 5
N	3.43	2.4

The moisture capacity in a hygroscopic relative humidity range was expressed by the following formula:

$$\frac{\partial u}{\partial \varphi}(\varphi) = u_h \cdot \frac{\left(1 - \dfrac{\ln(\varphi)}{A}\right)^{-\frac{1}{n}}}{n \cdot \varphi \cdot A \cdot \left(1 - \dfrac{\ln(\varphi)}{A}\right)} \tag{6}$$

In simulation of the moisture uptake and release, the water vapour permeability moisture dependence was approximated by the relation:

$$\mu(\varphi) = \frac{1}{0,13 + 0,003 \cdot e^{5 \cdot \varphi}} \tag{7}$$

The dependence of the vapour diffusion resistance factor on the relative humidity of the AAC is shown in fig.1b.

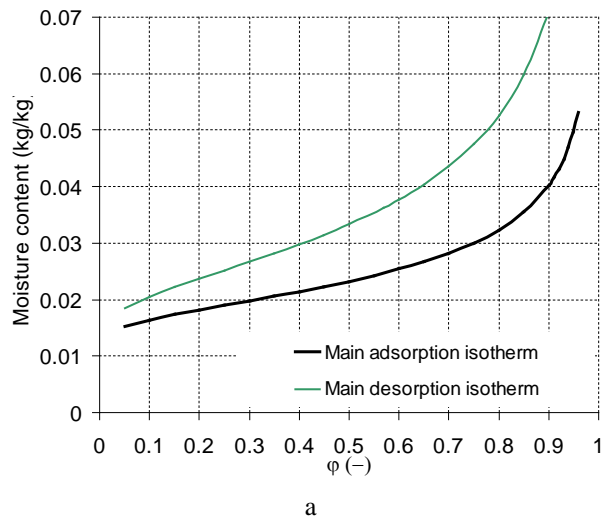a   b

Fig.1: Approximated material parameters of AAC: a- main moisture storage functions, b – vapour diffusion resistance factor

APPROXIMATION PARAMETERS OF USED HYSTERESIS MODEL

In equations (3) and (4) the coefficients γ_a and γ_d are the parameters of used empirical model. The water vapour content during a scanning between the equilibrium adsorption and desorption can be approximated as [2]:

$$u = u_o + \xi_{hys} \cdot \Delta\varphi \tag{8}$$

or:

during adsorption: $u = u_o + \Delta\varphi \cdot \left(\dfrac{\gamma_s \cdot (u - u_{sorption})^2 \cdot \xi_{desorption} + (u - u_{desorption})^2 \cdot \xi_{sorption}}{(u_{desorption} - u_{sorption})^2} \right)$ (9)

during desorption: $u = u_o + \Delta\varphi \cdot \left(\dfrac{(u - u_{sorption})^2 \cdot \xi_{desorption} + \gamma_d \cdot (u - u_{desorption})^2 \cdot \xi_{sorption}}{(u_{desorption} - u_{sorption})^2} \right)$ (10)

The measurements of primary scanning desorption from 94 % and 75 % were done [2]. The parameters of hysteresis were approximated by fitting the measured primary scanning desorption curves by equation (4). The best value for the primary scanning desorption process is $\gamma_d = 0.97$ for the desorption started at 94 % relative humidity and $\gamma_d = 0.87$ in case of the desorption started at 75 % relative humidity. Primary scanning adsorption has not been measured. Considering the second parameter of hysteresis the value $\gamma_s = 0.97$ was used. Convenience of the value will be shown in following analyses.
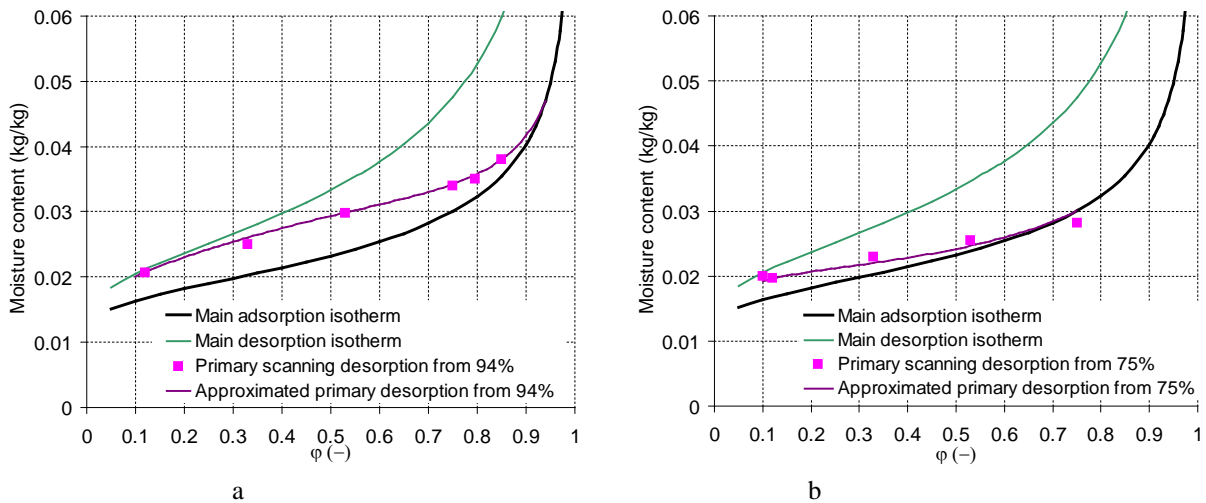

Fig.2: Experimental determination of the hysteresis parameters. a) desorption from 94 % - γ_d =0.97, b) desorption from 75 % - $\gamma_d = 0.87$

RESULTS

The tests were performed under three different regimes of the cyclic relative humidity step changes: Test # 1: 8/16 hours - 49/79 % changes (6 steps), Test # 2: 24/48 hours - 45/80 % changes (2 steps), Test # 3: 48/96 hours - 56/79 % (2 steps).
Two independent simulations were done:
-   by using the main adsorption isotherm
-   by using the described empirical hysteresis model

In all tests an evident gradual moisture uptake step by step occurred.

Test # 1: 8/16 hours intervals with relative humidity changes 49/79 %. During the first moisture uptake the simulations with the main adsorption isotherm and the hysteresis model correspond to the measurements. It is caused by the fact that initial moisture content corresponded to the main adsorption isotherm at the beginning of simulation and measurement, moisture capacity during adsorption was controlled by the main adsorption isotherm.

A significant difference occurred during the first desorption, the water vapour desorption is no more controlled by the main adsorption isotherm. The hysteresis model with the estimated parameters gave results closed to the measured values. After 5th desorption process, a lower water vapour release occurred, with the difference approx. of 0.3 g, thereafter a higher moisture content was calculated after 6th adsorption process. The simulation with main adsorption isotherm reached the quasi-steady state after 3rd step, the measurement and the hysteresis model did not stabilize during measurement.

Test # 2: 24/48 hours intervals with relative humidity changes 45/80 %. Like in the previous test, the first moisture uptake corresponded to the measurement. The hysteresis model fits the desorption process better than than a calculation with the main adsorption isotherm. During 2nd adsorption a significant difference of the mass occurred.

Test # 3: 48/96 hours intervals with relative humidity changes 56/79 %. The simulation with hysteresis fits the measurement also very well. The calculation with main adsorption isotherm shows large deviations during the desorption process.
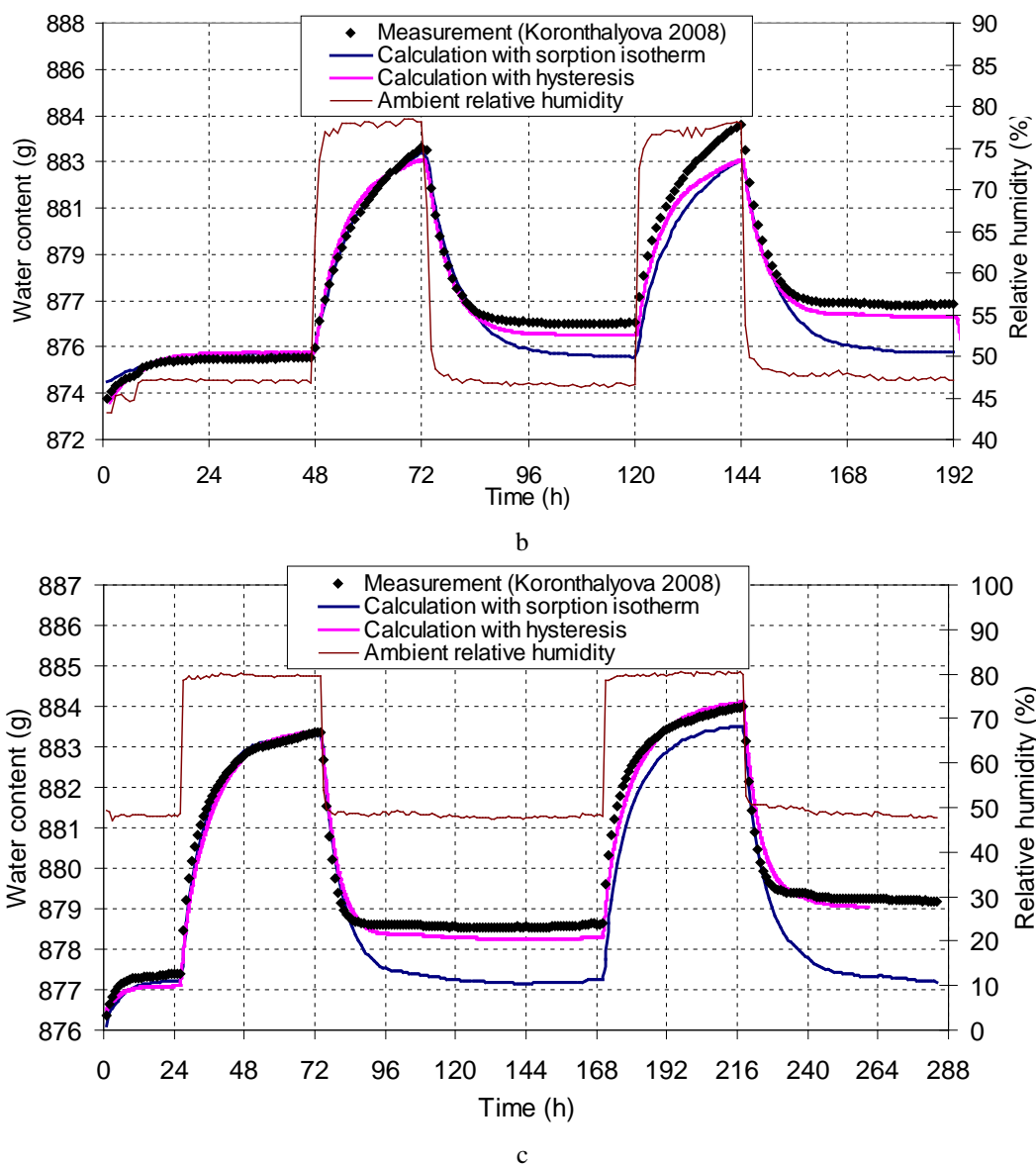

a

b

c
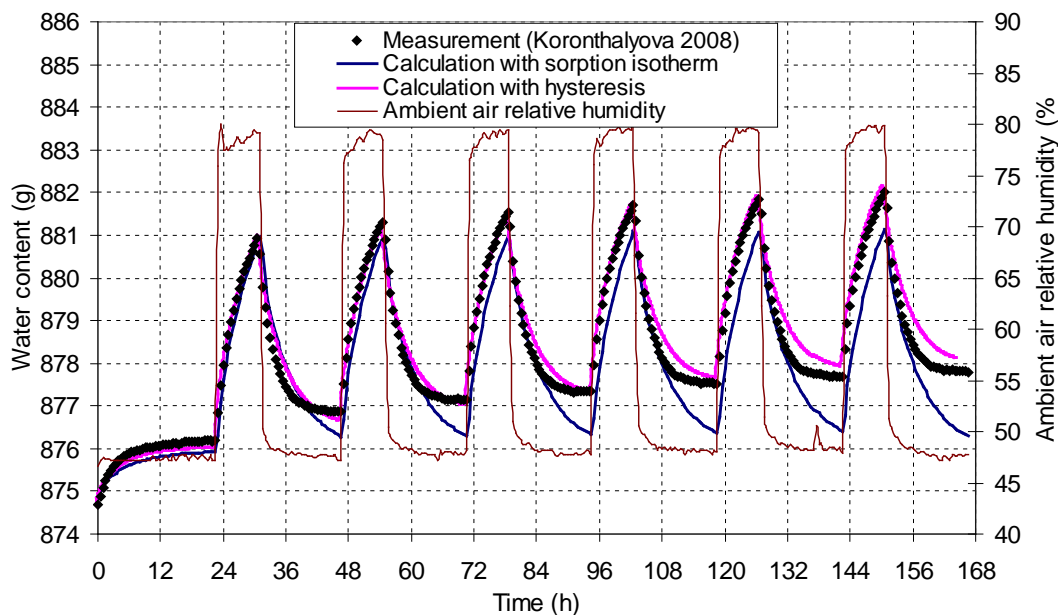
Fig.3: Measured and simulated mass change during the relative humidity change test, a) Test #1 8/16 - 49/79 %, b) Test #2 24/48 - 45/80 %, c) Test #3 48/96 - 56/79 %.

In fig. 4 there is a visualization of the calculated process of forming the scanning curves for Test # 1 (8/16 h - 49/79 %). The influence of the boundary conditions change delays towards the specimen`s core. After 5th ad/desorption step, a stabilization of the scanning curve on the surface began.
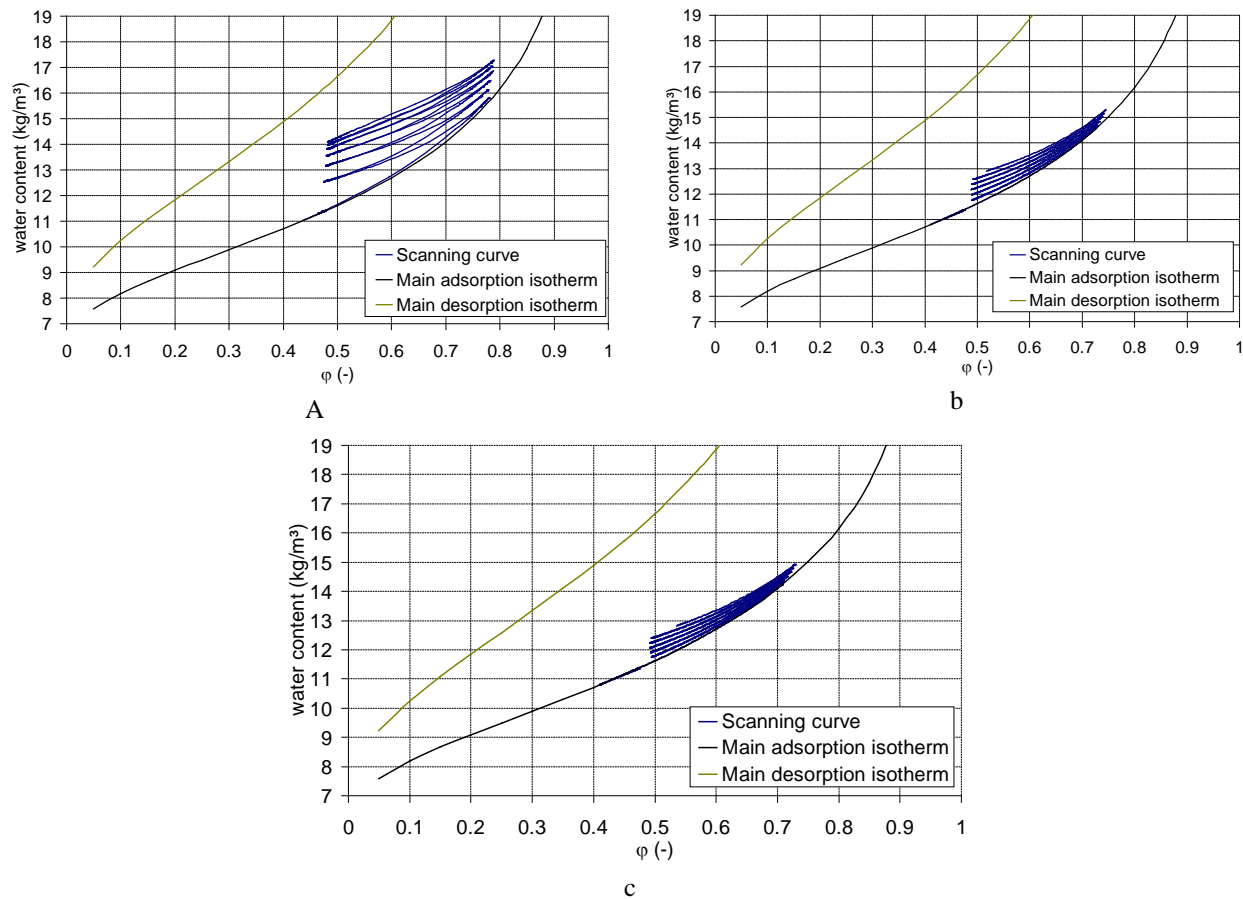
Fig.4: Process of forming scanning curves during adsorption and desorption, Test # 1 - 8/16 h - 49/79 %, a) surface element, b) 1 cm under the surface, c) 2 cm under the surface (middle of the specimen)

CONCLUSIONS

The dynamic hygric behaviour of the autoclaved aerated concrete was simulated under three different step cyclic regimes. The simulations analysed previous experimental work. The analysis of a hysteretic behaviour modelling and its comparison with a commonly used assumption of the one-storage function curve was done. In all analysed cases the simulations with the main adsorption isotherm fits the measurements during the first adsorption process, a significant deviation occurred during the desorption process, subsequent adsorption processes never reached the measured moisture content again. The simulation with the considered hysteresis model gives results close to the measurements. In general the analysis was very sensitive to the uncertainty of the measurement.

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