

# P5: Drying-wetting cycles: effects on moisture transport within cementitious materials

Zhidong ZHANG, Véronique BAROGHEL-BOUNY, Mickaël THIERY (IFSTTAR, Paris, France)



A native of China, Zhidong got his MS in Hydraulics at the Beijing Normal University in China in 2009. He started to work at IFSTTAR (former LCPC) 1<sup>st</sup> April 2011.

## Introduction

Durability of reinforced cement-based structures is controlled by diffusion of aggressive species through the concrete cover whose quality may be jeopardized due to the cyclic drying-wetting (shrinkage and swelling effects). Drying-wetting cycles also affect hydration at early age and may reduce early strength. The purpose of this research is to study the moisture transfer occurring during weathering cycles and to propose a modelling of the couplings between hydration and moisture transfers by taking into account of effects of hysteresis and of temperature variations.

## General isothermal drying model

At the macroscopic scale, drying of cementitious materials can be described continuously in time and space by a set of partial differential equations which are mass balance equations for liquid water ( $l$ ), water vapor ( $v$ ) and dry air ( $a$ ):

$$(1) \frac{\partial[\rho_l \phi S_l]}{\partial t} = -\text{div } \mathbf{w}_l - \mu; \quad \frac{\partial[\rho_v \phi(1-S_l)]}{\partial t} = -\text{div } \mathbf{w}_v + \mu; \quad \frac{\partial[\rho_a \phi(1-S_l)]}{\partial t} = -\text{div } \mathbf{w}_a$$

The flux of liquid water is expressed by the generalized Darcy's law for unsaturated conditions, which reads:

$$(2) \quad \mathbf{w}_l = -\rho_l \frac{K_l}{\eta_l} k_{rl}(S_l) \mathbf{grad } p_l$$

The movement of water vapor and dry air are both governed by advection of the gaseous mixture and by molecular diffusion. Advection can be described by Darcy's law. Moisture diffusion in the form of water vapor is driven by a gradient of molar fraction according to the first Fick's law. The expressions of water vapor and dry air fluxes are given by as follows (where  $i = v$  or  $a$ ),

$$(3) \quad \mathbf{w}_i = -\rho_i \frac{K_g}{\eta_g} k_{rg}(S_l) \mathbf{grad } p_g - \frac{M_i p_{atm}}{RT} f(\phi, S_l) D_{va} \mathbf{grad } \left( \frac{p_i}{p_g} \right)$$

**Hysteretic properties:** A two-parameter analytical function which has been proposed by van Genuchten [1] is used to simulate sorption curves.

**Intrinsic permeabilities:** An indirect method, generally used by means of fitting experimental drying kinetics (mass loss vs. time) through inverse analysis [2] is used in this research to determine  $K_l$ .

**Relative permeability:** We use a comprehensive numerical model proposed by Mualem [3] to predict the relative permeability of a porous medium by means of an integration of the capillary pressure curves.

## Drying properties

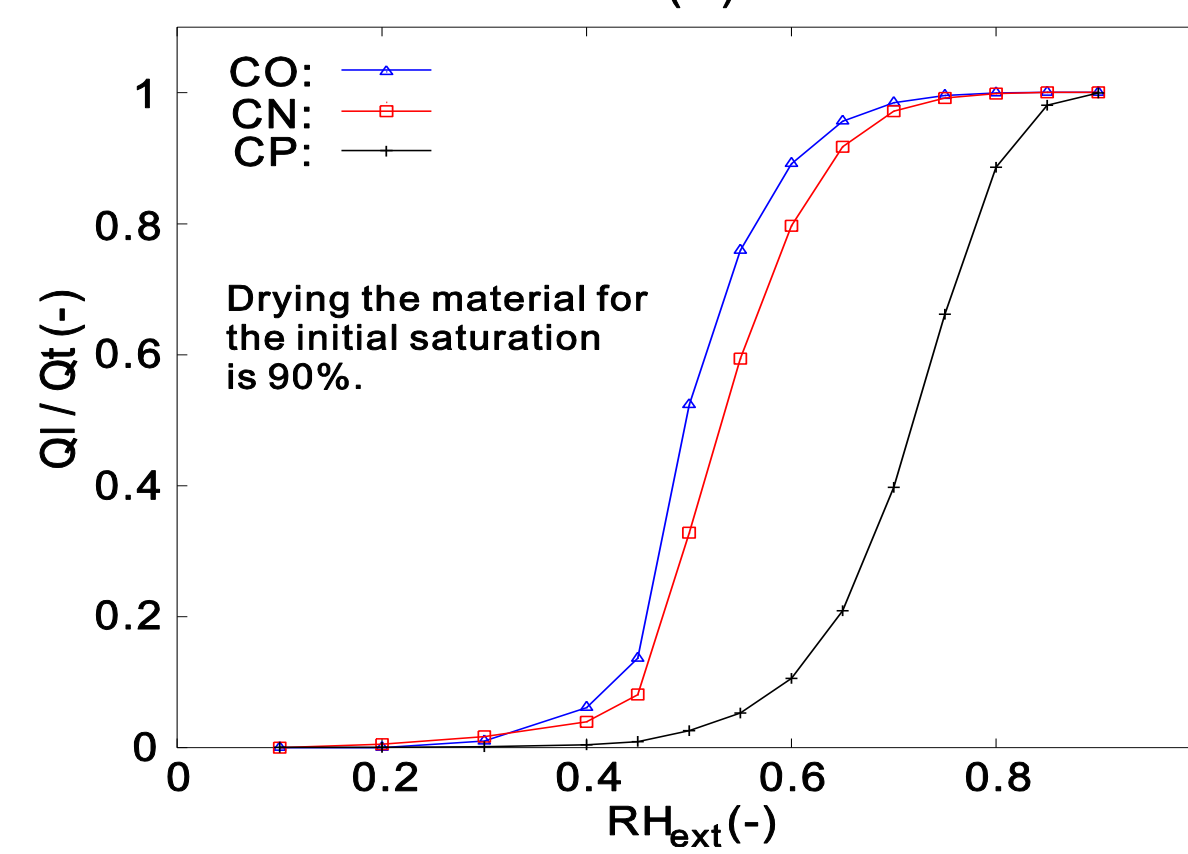
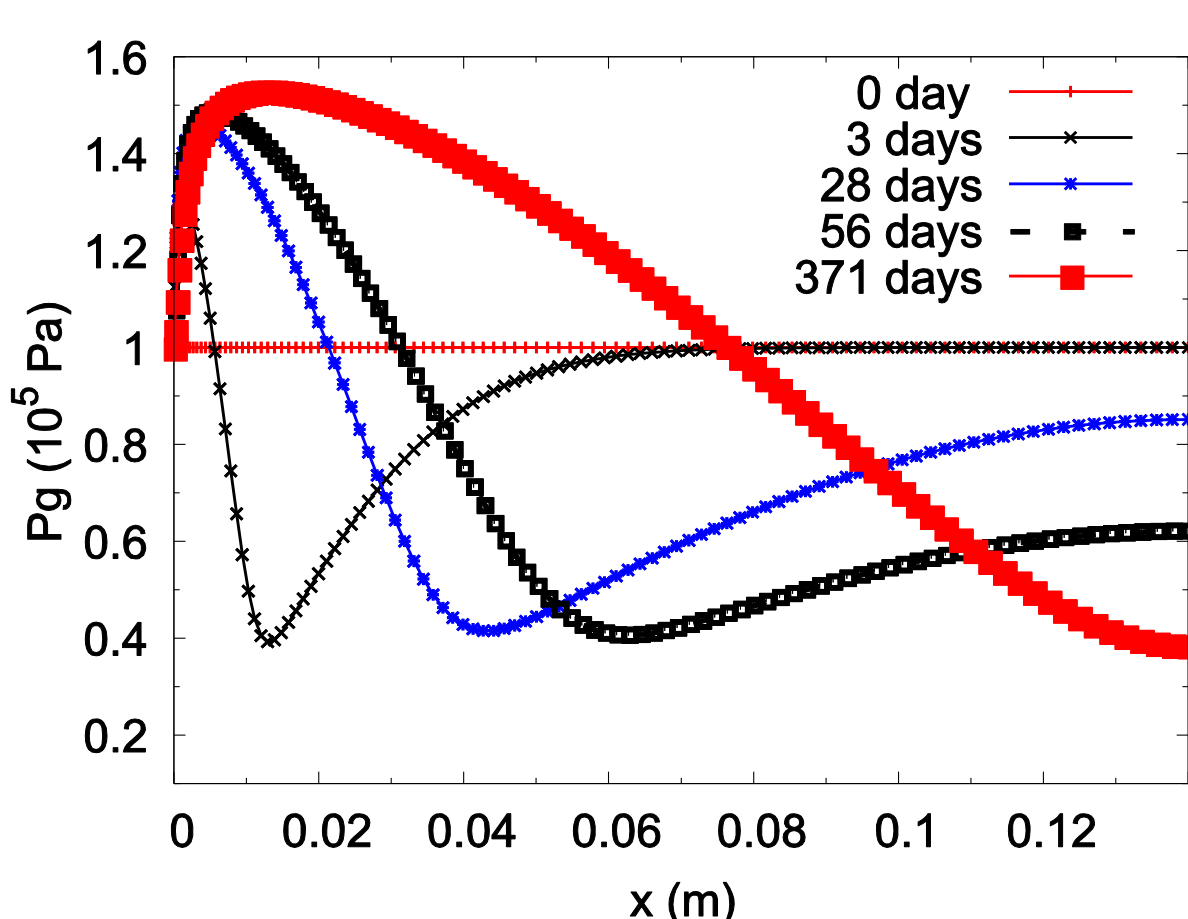
### Gas pressure properties

Simulation of gas pressure profiles during drying at initial  $S_l=99\%$  shows that a significant gas overpressure appears at the border layer. The vapor pressure is limited by the saturating vapor pressure as the upper bound, which is much lower than the gas overpressure. When the evaporated water vapor is forced to diffuse toward the surrounding air, the diffusion of dry air entries and takes the place of water vapor simultaneously [4]. Drying a high initial  $S_l$  material shows an obvious gas depression. On one hand, liquid water movement is significant due to the high gradient of capillary pressure. On the other hand, the diffusion coefficient of vapor is lower because of the high water content, so that the diffusion of vapor is restricted.

### Moisture transfer modes

Drying process is mainly controlled by two modes: (1) liquid water in the material is transported to the boundary and then evaporates; and (2) liquid water evaporates within the material and then diffuses to the surrounding environment.

From the liquid water movement contribution figure, we can see: (1). At low values of external RH, water vapor dominates the mass loss which is due to the high vapor diffusion, while for the high external RH, it is liquid water movement which dominates because of capillary transport. (2). CP always has the least contribution of liquid water than CN and CO owing to a larger porosity.



## References

- [1]. M.Th. van Genuchten, *Soil Sci. Soc. Am. J.*, (1980). [2]. V. Baroghel-Bouny, *CCR*, 37(2007). [3]. Y. Mualem, *Water Resour. Res.*, 12(1976). [4]. M. Mainguy, *J. Eng. Mech.*, 88(2001). [5]. X.S. Li, *Com. And Geo*, 32(2005). [6]. C. Wei, *Water Resour. Res.*, 42(2006).

## Drying-wetting cycles

For a modelling of moisture transport during drying-wetting cycles, hysteresis is one of essential factors we need to consider. The key issue is how to describe the hysteretic path for each calculating point in the material.

### Simplified concept

Assuming all paths remains on the main curves. At the end of drying, all points within the sample are switched directly from the main desorption curve to the main adsorption curve. Modelling results (right figure) show it is only valid for wetting at saturated state. One reason is that after the switching, some points are still undergoing drying in the sample.

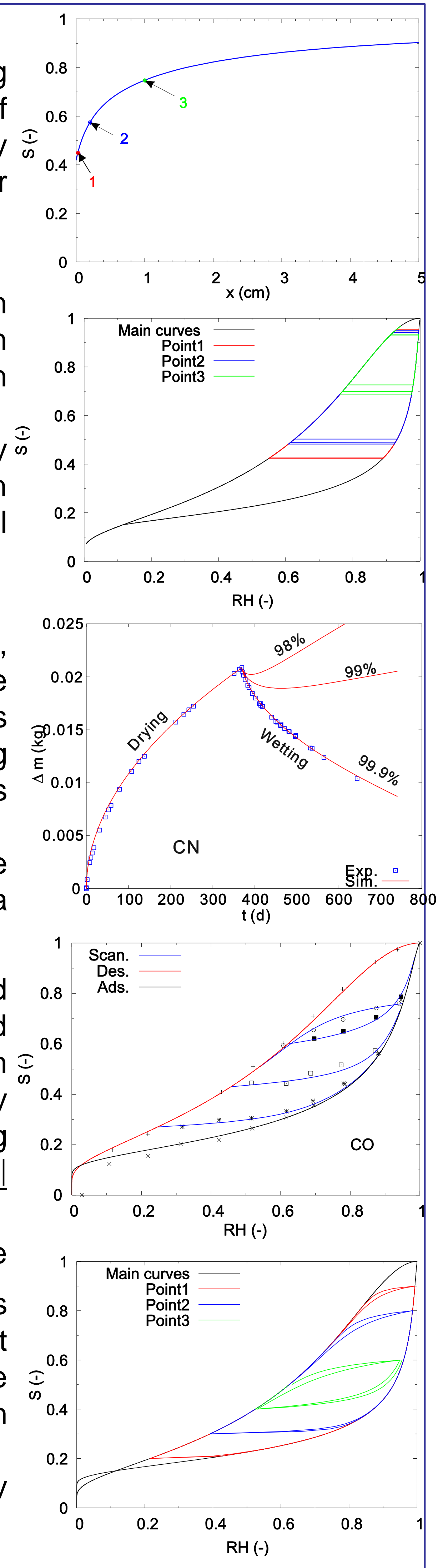
### Standard method

For drying (or wetting) from equilibrium state, we can assume all hysteretic paths follow the main curve. After that, when the sample is exposed to wetting (or drying), scanning curves will be used describe hysteretic paths for each calculating point.

**Main curves:** VG function is used to simulate main curves, which can fit experimental data very well:  $p_c(S_l) = \alpha(S_l^{-\beta} - 1)^{1-1/\beta}$ .

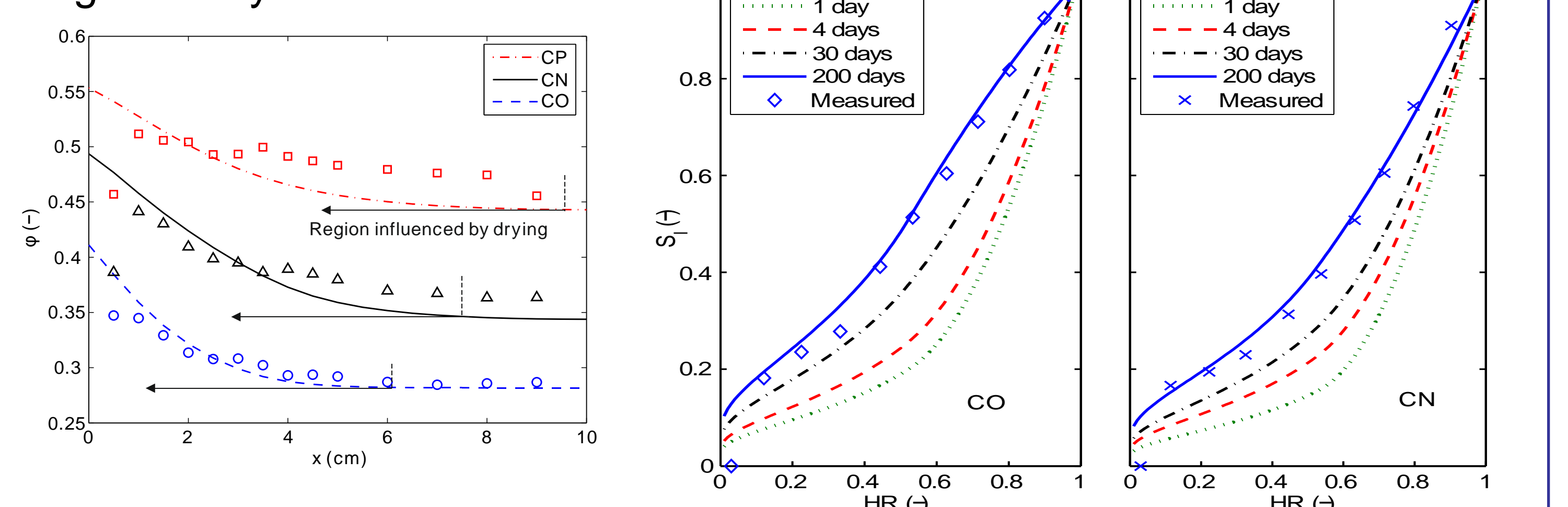
**Scanning curve:** An incremental method improved from the literature [5, 6] is employed to predict the scanning curve, through controlling the slope of scanning curve by assuming the relation between the scanning curve and main curves:  $K^w = K^{ad} + \frac{c|p_c^s - p_c^{ad}|}{p_c^{de} - p_c^{ad}}$

(wetting),  $K^d = K^{de} + \frac{c|p_c^s - p_c^{de}|}{p_c^{de} - p_c^{ad}}$  (drying). The parameter  $c$  determines the initial slope and is related to the current position of the initial point ( $S_l$ , RH, drying or wetting etc.). When the scanning curve reaches the main curve, both of them have the same slope. Relative permeability is also calculated by integrating the scanning curve ( $P_c \sim S_l$ ).



## Coupling with hydration

Cyclic external RH can change water content in the material and influence hydration at early-age. On the contrary, hydration can affect moisture transport properties by changing microstructure. A coupled model will describe those interactions with expressing transport coefficients (porosity, sorption curves, intrinsic and relative permeabilities) as functions of the degree of hydration.



Profiles of the porosity after 200-day drying. Simulations (lines) and experiments (symbols).

Desorption curves for CO and CN at different ages.