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# Modeling influence of hysteretic moisture behavior on distribution of chlorides in concrete

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ABSTRACT

Aggressive environmental conditions, such as exposure to the sea climate or use of de-icing salts, can have a considerable influence on the durability of reinforced concrete structures due to corrosion-induced damage of reinforcement. Recently, the coupled 3D chemo-hygro-thermo-mechanical (CHTM) model for simulation of processes related to the chloride induced corrosion of steel reinforcement in concrete was developed. In the model, it is assumed that for wetting and drying of concrete, the transport of water is controlled by a single sorption curve. However, it is well known that concrete exhibits a hysteretic moisture behaviour, which significantly influences the distribution of moisture and chlorides. To account for the hysteretic moisture behaviour of concrete and for simulating a more realistic time and space distribution of moisture, the CHTM model was further improved. The proposed hysteretic model is implemented into a 3D finite element code and it is validated using a numerical example, which shows reasonably good agreement with the available test results. Similar to what is observed in the experimental tests, it is shown that due to the wetting and drying of the concrete surface, the peak concentration of chloride moves progressively deeper into the concrete specimen.



## 1. Introduction

Corrosion-induced damage of concrete is a major problem for durability of reinforced concrete (RC) elements exposed to severe climate conditions. The onset of corrosion can be caused by carbonation of the concrete cover or by reaching a critical concentration of free chloride ions in the vicinity of the reinforcement bar. Here presented work is focussing on the processes related to the chloride-induced corrosion. Generally, computation of corrosion current density depends upon the following physical, electrochemical and mechanical processes: (1) Transport of capillary water, oxygen and chloride through the concrete cover; (2) Immobilization of chloride in the concrete; (3) Drying and wetting of concrete and related hysteretic property of concrete; (4) Transport of $OH^-$ ions through electrolyte in concrete pores; (5) Cathodic and anodic polarization; (6) Transport of corrosion products; (7) Creep of concrete around reinforcement bars and (8) Damage of concrete due to mechanical and non-mechanical actions [1].

In partially saturated concrete, the main physical phenomenon governing transport of chlorides in concrete are diffusion in the capillary pore water and convection due to flow of the pore water as a consequence of capillary suction and diffusion. A moisture hysteretic behaviour typical for cementitious material affects the transport of water and consequently the ingress of chlorides. For more accurate prediction of chloride's distribution in the concrete cover, binding of chlorides on the pore walls also needs to be taken into account.

Currently, there are a number of models in the literature that are able to simulate processes before and after depassivation of reinforcement in concrete [1–15]. A recently developed 3D chemo-hygro-thermo mechanical model [13–15] is able to simulate non-mechanical and mechanical processes and their interaction before and after depassivation of steel reinforcement. The model is implemented into a 3D finite element (FE) code and the results have shown that it is able to realistically replicate relevant processes before [13] and after depassivation of reinforcement [14,15]. However, in the original model, the hysteretic behaviour of concrete, which is relevant for the distribution of moisture and chlorides and consequently also for the processes related to the active

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corrosion phase, was not included. Therefore, the model was recently extended to account for this hysteretic moisture response of concrete [16].

It is well known that the transport processes important for the onset and corrosion progression of steel reinforcement in concrete are highly dependent on the pore moisture content. With the change of the environmental relative humidity (RH), the relative pore pressure is correspondingly changing and hence, affecting the water content in the concrete pores. Unsaturated conditions in concrete specimens have a strong influence on the distribution of chlorides. Convective flux of chloride ions due to moisture transport becomes more dominant compared to a slower, diffusive flux. Hence, the ingress of chlorides is more pronounced compared to the chloride attack under saturated conditions [17]. Furthermore, exposure to wetting and drying cycles can result in characteristic "peak" chloride profiles along the concrete depth [18–20], with the peak value of the total chloride content being translated away from the exposed surface progressively with the wet/dry cycling.

Assuming isothermal conditions, the water content can differ for the same relative humidity, depending on the dynamic moisture loading history [21–28]. For a constant air temperature and constant relative humidity, equilibrium conditions can be obtained in a concrete specimen, i.e. the pore pressure in the specimen becomes approximately the same as the RH of the ambient air. The relation between relative humidity and the experimentally measured water content is given by isotherm curves [22]. Usually, in the experiments for determination of isotherm curves, very small or thin specimens are used in order to quickly reach the equilibrium state, for a step-like increase or decrease of the ambient RH [25]. The main adsorption curve is obtained by plotting the values of the water content for each increase of RH, starting from a completely dry specimen. Similarly, starting from a fully saturated specimen and incrementally decreasing RH of the ambient air, the main desorption curve can be obtained.

Depending on the loading history, porous materials such as concrete, have different moisture values for the same RH. Therefore, at a constant temperature the sorption curves differ from each other, with the position of the desorption curve always being above the adsorption isotherm (see Fig. 1). The hysteretic behaviour of cementitious material for cases where the conditions change periodically from drying to wetting is described with the so-called scanning curves (see Fig. 1). They are positioned between the main adsorption and desorption curves, which are acting as envelopes [22,23,25]. Here, the main adsorption and desorption curves are given as input data, coming from experimental tests or empirical formulae.

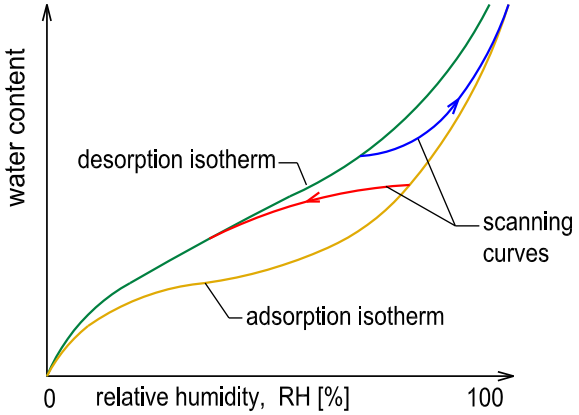


**Fig. 1.** Illustration of typical adsorption, desorption and scanning curves for a cementitious material.

In the incremental transient FE analysis, the model explicitly computes the distribution of relative humidity in the concrete and then determines the moisture content based on the sorption curves. By knowing the position on the isotherm curve from a previous time step, a new distribution of the relative pore pressure can be calculated for the current boundary conditions. Subsequently, the corresponding water content is established from a new location on the isotherm curve. In the case of static moisture conditions, i.e. constant wetting or drying, the analysis is following the main adsorption or desorption curve. This is valid only under the assumption that the initial starting condition (previously wetted or dried concrete) corresponds to the boundary environmental condition (wetting or drying). In the case of dynamic moisture conditions, i.e. with the change from wetting to drying or vice versa, the scanning curves need to be employed. In the present work they are calculated empirically, using the formulae proposed by Pedersen [23]. They differ from the main adsorption or desorption curves and behave in a loop-like manner depending on the number of wetting and drying cycles. The implemented hysteretic behaviour of concrete [16] was verified by simulating several experimental tests [25,29].

The recently improved CHTM model, which includes hysteretic moisture behaviour, is here used to compute the distribution of chloride in concrete under cyclic wetting-drying conditions. In the first part of the paper, the hysteretic model, based on the above mentioned theoretical background and its implementation into the FE code are discussed. The model is then employed in a transient numerical finite element study of concrete specimens exposed to chloride attack in a dynamic moisture environment. The chloride profiles along the concrete cover depth are computed and compared with the experimental results of Polder & Peelen [19].

## 2. Hysteretic moisture model for concrete

### 2.1. Moisture transport

During wetting and drying cycles, it is assumed that concrete is exposed only to changes in relative humidity, so the macroscopic pressure-driven liquid flow is not considered. Transport of moisture through the concrete is described as a vapour transport, which means that for nonsaturated concrete at uniform temperature, the moisture flux $\mathbf{j}_{w,mass}$(kg/m$^2$s) may be expressed as [30]:

$$\mathbf{j}_{w,mass} = -\delta_v(h)\, p_{v,sat}\, \nabla h \tag{1}$$

where $h$ is the relative humidity (dimensionless), $\delta_v(h)$ is the water vapour permeability (s) and $p_{v,sat}$ is the water vapour saturation pressure (Pa). The mass conservation condition reads:

$$\rho_w \frac{\partial \theta_w(h)}{\partial t} = \rho_w \frac{\partial \theta_w(h)}{\partial h}\frac{\partial h}{\partial t} = \nabla \cdot \left(\delta_v(h)\, p_{v,sat}\, \nabla h\right) \tag{2}$$

where $t$ is the time (s), $\rho_w$ is the density of water (kg of water/m$^3$ of water), $\theta_w$ is the volume fraction of pore water (m$^3$ of water/m$^3$ of concrete) and $\rho_w \frac{\partial \theta_w}{\partial h} \equiv \xi$ is the moisture capacity (derivative of the sorption isotherm).

For nonsaturated concrete at temperatures that are slightly different from the reference temperature of 25 °C, $\delta_v(h)$ can be approximately described by the expression [31]:

$$\delta_v(h) = a_0 f_1(h) \tag{3}$$

in which $a_0$ is the reference permeability at 25 °C and for mature paste the values of $a_0$ are in the range of $a_0 = 10^{-10}$–$10^{-14}$(s).