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Modelling of water and chloride transport in concrete during yearly wetting/drying cycles

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HIGHLIGHTS

- Water and chloride transport in concrete is modelled with convection and diffusion.
- Chloride transport is differentiated for the different water filled pore radii.
- Exact boundary condition for the chloride transport is still unknown, but relevant.
- When drying concrete, the surface chloride concentration can rise considerably.
- Presented model leaves room for extensions, such as crystallization or adsorption.

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ABSTRACT

The simultaneous transport of water and chloride in concrete has been modelled. The water transport is described with a concentration dependent diffusion coefficient. The chloride transport is modelled with a convective part, caused by the water transport, and a diffusive part, caused by the chloride concentration gradient in the pore water. Because the water velocity depends on the pore radius, the chloride transport is a complex pore radius dependent process. Modelling this process leads to an expression for the dispersion coefficient, for the chloride diffusion. The model equations are applied on concrete with a yearly variation of the surface water concentration. A few different boundary conditions for the chloride transport are described. The water distribution is almost homogeneous over the samples. The chloride concentration at the surface can rise considerably, when water leaves the concrete sample, while chloride stays behind. Crystallization and a few other possible model extensions are discussed.

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1. Introduction

A large threat for the durability of concrete is the corrosion process of the steel reinforcement. The corrosion is accelerated by the presence of chloride. Most often, the chloride comes from outside the concrete during the life time of the structure. An overview of the literature regarding the factors influencing the chloride transport in concrete is given by Song et al. [1]. The chloride can also be bound to the concrete. A review on this topic is the work of Yuan et al. [2].

It has been described by Baessler et al. [3] how the corrosion of the reinforcement can be measured with electrochemical devices. The corrosion process around the steel in concrete has been studied numerically by Kim and Kim [4]. Also, the bond between the reinforcement and the surrounding concrete depends on the status of corrosion of the concrete, as studied by Fang et al. [5]. The relation between the various parameters and the time to corrosion initiation of the reinforcement has been given by Zhang and Lounis [6]. How the time to corrosion depends on the surface chloride concentration has been examined by Ann et al. [7].

The reinforcement of a concrete structure can be protected against corrosion by a high quality covering layer of concrete. Very often, concrete has small cracks due to the production process or caused by mechanical stress. The chloride penetration in cracked concrete and around the cracks in concrete has been measured by Win et al. [8]. The crack width in the covering layer of concrete can be used to analyse how much the corrosion of the reinforcement has proceeded, as it has been shown by Vidal et al. [9]. The service life of repaired concrete structures under chloride environment has been studied by Song et al. [10].

An additional factor in the transport of chloride in concrete is the question whether the surface of the concrete is exposed to wetting and drying or not. During the wetting process, additional

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Nomenclature

Roman

a	specific exchanging surface area ($m^2\ m^{-3}$)
C	water concentration ($kg\ m^{-3}$)
$C_{x=0}$	water concentration at $x = 0$ ($kg\ m^{-3}$)
$C_{t=0}$	begin water concentration ($kg\ m^{-3}$)
D	diffusion coefficient of water in concrete ($m^2\ s^{-1}$)
D_m	molecular diffusion coefficient of chloride in water ($m^2\ s^{-1}$)
D_s	dispersion coefficient of chloride in concrete ($m^2\ s^{-1}$)
L	length of the sample (m)
n	mass flux ($kg\ s^{-1}\ m^{-2}$)
$n_{s,w}$	chloride flux in water ($kg\ s^{-1}\ m^{-2}$)
$n_{v,w}$	volume flux ($m^3\ s^{-1}\ m^{-2}$)
r	largest filled pore radius (m)
s	chloride concentration in water ($kg\ m^{-3}$)
$s_{outside}$	chloride concentration in the water from the outside world ($kg\ m^{-3}$)
S	chloride concentration ($kg\ m^{-3}$)
t	time (s)
v	velocity ($m\ s^{-1}$)
x	position coordinate (m)

Greek

ρ	density ($kg\ m^{-3}$)
τ	tortuosity (–)
φ	volume fraction (–)

Subscript

H	high velocity part
L	low velocity part
s	chloride
w	water

chloride can enter the concrete and stays behind when water is evaporating during the drying process. This way, the surface chloride concentration can rise to high values. There is not so much research yet on this point.

Most often, the concentration of chloride in concrete is measured with a destructive technique. However, Montemor et al. [11] showed that with Ag/AgCl electrodes the concentration can be measured in situ. Pel et al. [12] showed that NaCl concentration profiles in fired-clay brick can be measured with nuclear magnetic resonance. Climent et al. [13] presented a method to measure the diffusion coefficient of chloride in non-saturated concrete. Also, Azari et al. [14] measured the diffusion coefficient of chloride in a wide range of microsilica concrete. Measurements of Hong and Hooton [15] showed that chloride not only can enter concrete, but that it can also, to a certain extent, be washed out of the concrete with fresh water. It has been shown experimentally by Marsavina et al. [16] and by Djerbi et al. [17] that the transport of chloride in concrete is increased by the presence of cracks in the concrete. The coupled transport of water and chloride in concrete was measured by Cerny et al. [18]. The influence of wetting/drying cycles with water with a chloride concentration on the rebars of concrete was characterised by Polder and Peelen [19].

Huinink et al. [20] put forward a simple model for ion distribution in drying porous materials which was based on convection and diffusion. Oh and Jang [21] gave a model including the binding of chloride to the concrete and the water flux in concrete and compared the prediction of this model with the chloride concentration profile in concrete structures of 10 years old. The transport properties of interacting ions in unsaturated cement systems were modelled by Marchand [22]. A model for the chloride ion ingress in concrete, including the adsorption of the chloride on the concrete and the desorption from the concrete, as well as the chemical reaction of the chloride with the concrete, was given by Shin and Kim [23]. Johannesson [24] made a complex model for describing ion transport in a pore solution using the mixture theory, where the transport of moisture is taken into account explicitly also. Conciatori et al. [25] also put forward a complex model based on capillary suction and diffusion to describe the chloride ingress into concrete. A model for the ingress of chloride in concrete, including convection, drying/wetting cycles and carbonation was given by Meijers et al. [26]. The predictions of this model were compared with experimental results. Their conclusion was that models which take into account explicitly the moisture transport are better models than models which use only one diffusion coefficient for chloride transport. This conclusion was also the result of the work of Wang et al. [27]. The predictions of a model incorporating the fine or coarse network structure of the porous concrete were given by O'Neill Iqbal and Ishida [28] for a cyclic exposure with wetting and drying. The theory and experimental results about the chloride transport in concrete under the influence of an external electric field was given by Stanish et al. in respectively [29] and [30].

The models described in the preceding paragraph are very often so complex that almost always an analytical solution is impossible, and that only a numerical solution can be given. Also, the material properties, which are used in these models, can be a strong function of other parameters which makes an analytical solution impossible. For instance, the diffusion coefficient of water in concrete and the diffusion coefficient of chloride in concrete depend strongly on the moisture content.

The present paper puts forward a model for the transport of chloride in concrete that is not saturated with water. The transport of water is described with a diffusion coefficient. The transport of chloride includes the transport of chloride dissolved in the pore water migrating through the concrete and the transport of chloride caused by a gradient in the pore water chloride concentration. The first process of chloride convection through the concrete is modelled with keeping in mind that the larger water filled pores contribute (relatively) more to the chloride transport than the smaller water filled pores. It is a first simple model for a complex process. The second process of chloride diffusion is modelled with Fick's law, which is adapted for the non-ideal situation.

The model is applied on concrete with a yearly cycle of wetting and drying. The equations are solved numerically using the Crank–Nicolson method. The numerical results are given. A final discussion ends the paper.

2. Water transport

In a partially saturated porous material, the water flux, n_w, is influenced by differences in the water concentration, C. In the present work, it is assumed that the water flux is, according to Fick's first law, proportional to the concentration gradient,

$$n_w = -D\frac{\partial C}{\partial x}, \tag{1}$$

where x is the position coordinate and D the diffusion coefficient of water in concrete. It is recognised that also a presence of chloride and a gradient in the chloride concentration can influence the water transport, but in this study, these influences are ignored, because they are not well known and are probably mostly of minor importance. Using a micro mass balance and Eq. (1), the result is Fick's

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