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Lattice modeling of rapid chloride migration in concrete

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ABSTRACT

Test methods which use external voltage are commonly used to assess resistance of concrete to chloride ion penetration. In order to facilitate fast chloride ingress, electrical voltage (typically 10–60 V) is applied across the concrete specimen. These methods have also been used on microcracked and cracked specimens in order to study the influence of cracking on chloride ingress. Chloride migration transport mechanism is fundamentally different from the diffusion process usually occurring in practice. To study the behavior during the test, a model is proposed, based on the transport lattice modeling framework. First, the accuracy and computational aspects of the proposed model are discussed. Then, the model is applied to study the transport in heterogeneous concrete (i.e. on the meso-scale). Also, chloride migration in microcracked, notched, and cracked concrete is simulated. The findings show that the proposed model can successfully reproduce experimentally observed behavior.

1. Introduction

Chloride induced corrosion of reinforcing steel is an important deterioration mechanism affecting reinforced concrete structures [1]. It is triggered by ingress of a sufficient amount of chloride ions to the level of the reinforcement. Concrete cover of sufficient quality and depth can, however, ensure its protection. It is therefore necessary to ensure high quality of the concrete cover if a long service life is to be expected. This can be attained by good workmanship and concrete mix design.

Numerous laboratory tests are developed to help in the process. For chloride penetration resistance, tests which involve artificial acceleration of the process by means of electrical voltage are mostly used due to their relatively short duration. Even though reliable from an engineering point of view, research is still needed to fully understand these rapid tests and how their results correspond to naturally occurring diffusion.

Better understanding of these testing procedures is to be found through synergy between experiments and numerical modeling. Numerous models have been proposed recently, aiming to provide more insight into the underlying processes. Most of these models have focused on studying transport of different ions present in the pore solution (e.g. Na^+, K^+, OH^-, in addition to Cl^-) during a migration experiment. These so-called multi-species models use complex formulations based on the Nernst-Planck [2] and Poisson-Nernst-Planck equations [3,4], which take into account the effect of applied voltage and ionic interactions. Using finite difference [2] and finite element methods [3,4], spatial distribution of ionic species is resolved in time. However, all of these models are one-dimensional, and don't take heterogeneity of concrete into account. A step further in this respect was made by Liu et al. [5], who modeled ionic transport of multiple species in concrete, allowing for its heterogeneous nature. They considered concrete as an assembly of impermeable spherical inclusions (aggregates) and mortar. Their two-phase model revealed some features which cannot be found from one-dimensional models.

The model developed herein aims to further enrich the understanding of these experiments. A single-species model is used [6], as the emphasis of the study lies on the chloride migration in heterogeneous and cracked/notched specimens. First, main mechanisms driving chloride ingress into concrete and some testing methods are briefly addressed and discussed. Then, a description of the developed model is given. The proposed model is then validated against the analytical solution and experimental data. Finally, some conclusions are drawn.

2. Method

2.1. Chloride penetration into concrete

2.1.1. Chloride transport mechanisms

Chloride ions are transported through concrete by several physical and chemical mechanisms. Relative importance of each transport mechanism in a given case depends on the concrete pore structure, (micro) environmental conditions, moisture state of concrete, and temperature,

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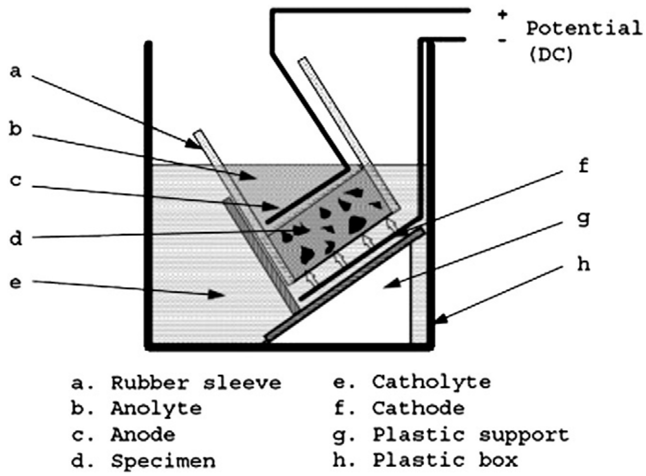

Fig. 1. Rapid chloride migration test setup [11].

among other things. Concrete cracking, due to e.g. mechanical load or shrinkage, can significantly alter local transport properties. Transport mechanisms of chloride in concrete can, in general, be categorized as [7]:

1. Diffusion, where ionic transport is driven by a concentration difference in various zones. Chloride ions move from zones with higher concentration to zones with lower concentration.
2. Permeation, where a difference in hydraulic pressure in various zones drives the movement of chloride ions.
3. Migration, where the transport of ions is driven by a difference in electrical potential. Chloride ions migrate to zones with lower electrical potential.
4. Convection or capillary suction, where the chloride transport is caused by a difference in moisture content (capillary pressure). In non-saturated concrete, water containing chloride ions moves towards zones with lower moisture content due to surface tension in the capillary pores.

In practice, any of these mechanisms (or their combined action) can govern the ingress of chloride ions into concrete.

2.1.2. Testing of chloride penetration resistance of concrete

Performance based approach to service life design is increasingly replacing the deterministic approach. This means that, instead of the deemed-to-satisfy demands for concrete quality (minimum cement content or maximum water-to-cement ratio), performance of each concrete mix needs to be proven by a certain test. This has led to researchers proposing a number of tests in past two decades.

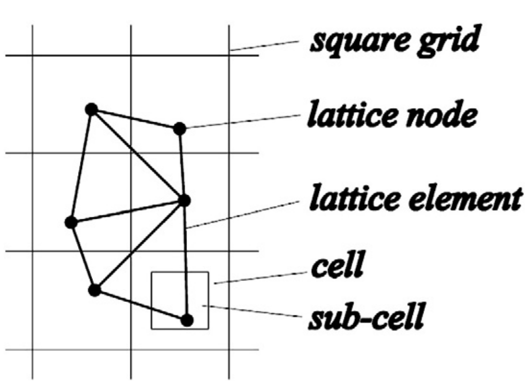

Fig. 2. Node placement procedure in two-dimensions.

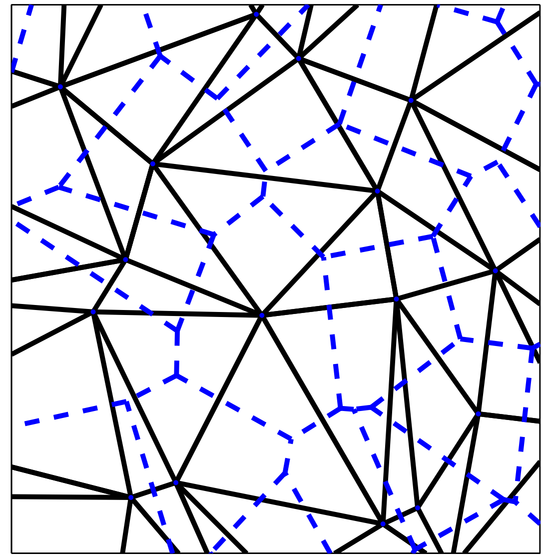

Fig. 3. Meshing procedure in two-dimensions. Solid, lattice; dashed, Voronoi cells.

In general, these can be divided into three groups:

1. tests based on natural diffusion, such as the salt ponding test (AASHTO259 [8]) or the bulk diffusion test (NT BUILD 443 [9]).
2. tests which use DC voltage to assess the chloride ion penetrability, like the Rapid Chloride Permeability Test (AASHTO T277 [10]), or to accelerate the movement of chloride ions due to the migration transport mechanism, such as the Rapid Chloride Migration test (NT BUILD 492 [11]).
3. different indirect measurement techniques, such as the electrical resistivity or sorptivity, which try to correlate these values to resistance of concrete to chloride ingress.

Due to their relatively short duration compared to the natural diffusion tests, the second group is mostly used in engineering practice and research. A comprehensive review of most common testing procedures can be found in Ref. [12].

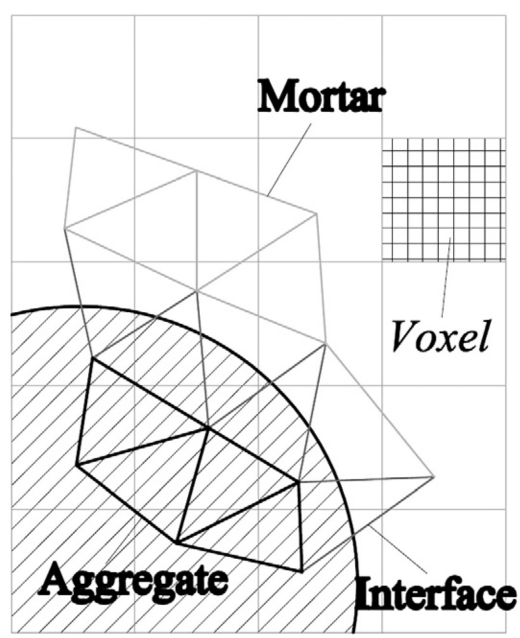

Fig. 4. Particle overlay procedure in two dimensions.