



Spatial variability of chloride in concrete within homogeneously exposed areas



Ueli M. Angst^{a,b,*}, Rob Polder^{c,d}

^a ETH Zurich, Institute for Building Materials (IB), ETH Hönggerberg, CH-8093 Zurich, Switzerland

^b Swiss Society for Corrosion Protection (SGK), Technoparkstrasse 1, CH-8005 Zurich, Switzerland

^c TNO Technical Sciences, P.O. Box 49, 2600 AA Delft, The Netherlands

^d Delft University of Technology, Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, The Netherlands

ARTICLE INFO

Article history:

Received 16 April 2013

Accepted 30 October 2013

Available online xxxx

Keywords:

Pore solution (B)

Permeability (C)

Transport properties (C)

Chloride (D)

ABSTRACT

The concept of variability is increasingly considered in service life predictions. This paper reports experimental data on the spatial distribution of chloride in uncracked concrete subjected to homogeneous exposure. Chloride concentrations were measured with potentiometric sensors embedded in concrete exposed to chloride ingress by cyclic wetting and drying. The sensors allow highly localised, non-destructive measurements. Six different concrete mixes were tested, each with more than 20 sensors embedded within a plane at constant depth. The resulting dataset is discussed with respect to causes for the observed spatial variability of chloride as well as implications for service life predictions and experimental methods. It is concluded that the observed spatial chloride variability is a true property of chloride penetration into concrete and not an uncertainty arising from limited measurement precision. The primary cause was identified to be the presence of coarse aggregates rather than w/c ratio, cement type or exposure conditions.

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1. Introduction

Chloride ingress into concrete may lead to reinforcement corrosion, which is a major cause of deterioration of reinforced concrete structures [1,2]. A variety of standard methods thus exist to quantify the chloride content in concrete, e.g. Refs. [3–5]. Also numerous attempts have been made to predict chloride ingress into concrete for service life modelling purposes, as recently reviewed in Ref. [6].

It is well recognised that chloride penetration through concrete occurs in a non-homogeneous manner and does not lead to a uniform chloride front even within areas of homogenous exposure [7–12]. While chloride profiles may differ pronouncedly across a concrete structure due to differences in exposure conditions and microclimate (splash zone, height above sea-level, orientation with respect to wind direction, etc.), the present paper addresses the spatial variability of chloride concentrations within areas of presumed homogeneous exposure. Corresponding experimental data has in the literature primarily been reported on the macroscopic scale where typically numerous chloride profiles were determined on samples taken within concrete areas of the order of magnitude of ca. 1 m². The sampling consisted of drilling and collecting the powder directly (at different depths) or from taking cores with a subsequent cutting or grinding procedure to allow determining profiles. This leads to samples of dimensions of comparable or higher order of magnitude as the aggregates; the analysed chloride

content corresponds thus to the average chloride content over a concrete volume of several cm³.

In Refs. [8,9] the acid-soluble chloride content was determined on both cores (Ø75–100 mm) and drilled powder samples taken from columns of Danish highway road bridges after 10–30 y exposure. The coefficient of variation (CV = ratio of standard deviation to mean value) of the chloride content within areas of presumed homogenous exposure was found to be in the range 15–50% for both the cores (cut/ground slices) and the drilled powder samples. Thin section analysis revealed significant variability also for material properties such as local w/c ratio and local cement content. It was suggested that the inhomogeneous concrete microstructure is the main cause for the observed spatial chloride variability.

Data from the macroscopic scale is also available from measurements performed in The Netherlands [13]. This data will be further analysed in the present paper. Six marine structures with ages between 18 and 41 years were sampled a.o. for chloride penetration. Over test areas of 1 m × 1 m surface, cores of 50 mm diameter were taken and cut in 10 mm thick slices; these were ground and the powder was dissolved in nitric acid. The filtrate was analysed for chloride by Volhard titration. The result was expressed as percentage of chloride by mass of cement, assuming that all acid-soluble mass was hardened cement paste (after acid digestion, residual aggregates were weighed and taken into account) and that 18% of the mass was hydration water. Chloride ingress was found to be subject to considerable scatter. Fig. 1 shows two examples from structural members with comparable exposure (marine splash zone), comparable concrete (containing slag) and

* Corresponding author. Tel.: +41 44 633 40 24.
E-mail address: uangst@ethz.ch (U.M. Angst).

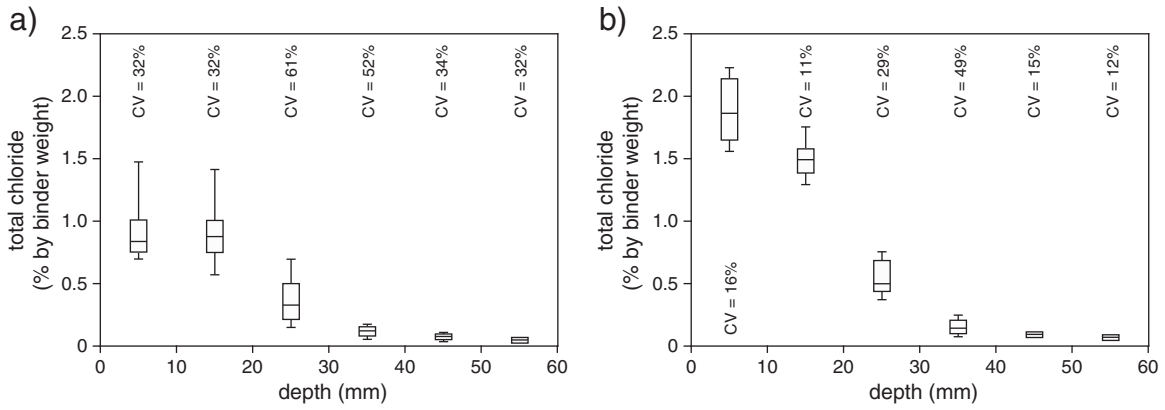


Fig. 1. Chloride profiles from the Eastern Scheldt Barrier in The Netherlands from two structural members in marine splash zone; a) pier at +1 m above sea level (after 22 y), b) upper beam at +4 m above sea level (after 17 y). The boxes represent the 25%, 50% (median) and 75% percentiles and the whiskers the minimum and maximum values; each based on 6 profiles measured within an area of 1 m × 1 m. CV = coefficient of variation. (Data from investigations described in Ref. [13]).

comparable age. The two sampled areas differed only by their height above sea level: one was at about +1 m, and the other at about +4 m above sea level. Considering the small size of the test areas (suggesting homogeneous exposure) and the good material homogeneity as observed from microscopy, no clear explanations were available for the variation of chloride profiles within each (individual) sampled area.

Experimental data on the chloride variability on the microscopic level, on the other hand, is scarce. Silva et al. [14,15] used a method based on laser ablation and inductively coupled plasma mass spectroscopy to scan the concrete along the steel/concrete interface in order to determine the chloride concentration in concrete. The laser beam that ablates material had a spot size in the range of 300–400 μm, thus enabling a resolution on the micrometre or meso-scale. The studied specimens were laboratory cast and exposed reinforced concrete specimens with a cover depth of typically 10 mm and maximum aggregate diameter of 16 mm. The chloride concentration was found to vary by up to one order of magnitude within a distance of 10 mm.

The present paper shows experimental results on the spatial variability of the free chloride ion activity in the concrete pore solution arising from homogeneous laboratory chloride exposure of uncracked concrete. The results are discussed with respect to the factors giving rise to a dispersion of the penetrating chloride front. Implications for measurement methods and for service life predictions are also addressed.

2. Experimental

2.1. Materials and specimens

Concrete specimens were cast in the laboratory with the dimensions shown in Fig. 2. In addition to reinforcement steel bars that were embedded for corrosion experiments (the results of which are discussed elsewhere [16,17]), each specimen also contained 6 ion selective electrodes (ISE) as well as a manganese dioxide reference electrode (Force Technology, ERE20). The ISEs are Ag/AgCl electrodes produced as silver wires (diameter <0.5 mm) coated with silver chloride; in the tip region,

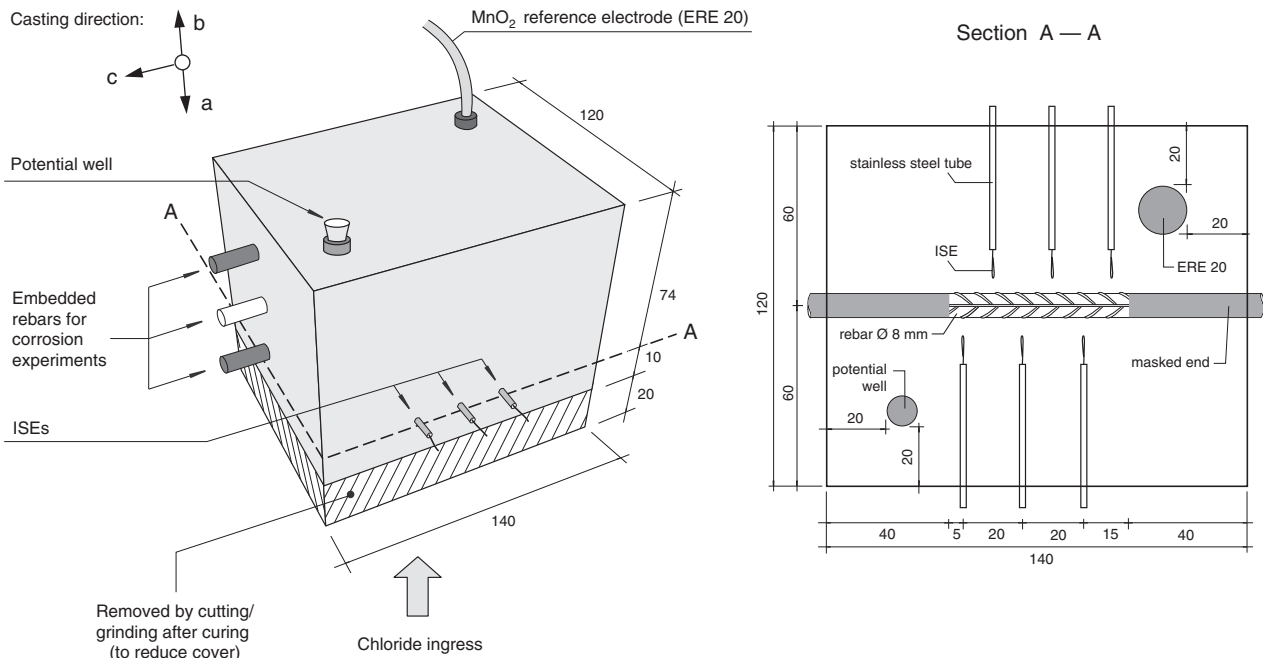


Fig. 2. Specimen geometry (dimensions in mm). Concerning the casting direction, normally the one indicated by letter a was used, with the exception of mix PC-05, where all three directions indicated by letters a, b, and c were used.

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