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Image analysis for determination of cement content in concrete to improve accuracy of chloride analyses

Carolina Boschmann Käthler[a,*], Ueli M. Angst[a,b], Matthias Wagner[c], Bernhard Elsener[a,d]

[a] ETH Zurich, Institute for Building Materials (IfB), ETH Hönggerberg, CH-8093 Zurich, Switzerland
[b] Swiss Society for Corrosion Protection, Technoparkstrasse 1, CH-8005 Zurich, Switzerland
[c] Tecnotest AG, Alemannenweg 4, CH-8803 Rüschlikon, Switzerland
[d] University of Cagliari, Department of Chemical and Geological Science, I-09100 Monserrato, CA, Italy

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ABSTRACT

The chloride content C_{cl} expressed as %Cl by weight of cement is important in condition assessment of reinforced concrete structures. Whereas standardized procedures determine C_{cl} in concrete powder, the cement content C_m is generally assumed equal to the mix design or an experience-based constant value. This work shows in concrete with maximal aggregate diameter 32 mm, C_m exhibits significant variability in 50 mm diameter cores, because the specimens are too small to be representative of bulk concrete. In such specimens, C_m might differ from the bulk cement content by a factor of up to 2. Thus, a reliable determination of C_{cl} in terms of %Cl by weight of cement requires the analysis of both C_{cl} and C_m in a concrete specimen. A procedure based on colouring the cement paste, scanning the specimen surface, and image analysis allows the practically non-destructive determination of C_m with good accuracy.

1. Introduction

Chloride ions are known to impair the service life of reinforced concrete structures, as they can cause chloride-induced reinforcement corrosion. In marine environments or when using de-icing salts chloride-induced corrosion is the most common deterioration mechanism for reinforced concrete structures [1]. Therefore, measuring the chloride concentration in concrete (C_{Cl}) is common in condition assessment of existing reinforced concrete structures. Comparing the measured C_{Cl} with the so-called critical chloride content (C_{crit}), i.e. the chloride threshold for corrosion initiation [2], is the widely accepted procedure to assess the risk of chloride-induced corrosion.

Standardized methods [3–6] for the determination of C_{Cl} include three principal steps: 1) taking a sample, 2) extraction of the chloride ions, and 3) analysis of the chloride concentration. The result is a value of the chloride concentration referred to the dry mass of concrete. Each of the steps 1–3 are performed using different procedures, thus the size of the sample, the way of extraction and the analytical method can lead to errors in the final result. Several round robin tests [7,8] in the past have shown that on a homogeneous, reasonably fine concrete powder the total chloride content C_{Cl} can be determined with good accuracy. In accredited laboratories neither the extraction method nor the method of analytical chemistry used leads to significant errors.

In engineering practice and in durability standards it is often preferred to relate C_{Cl} to the mass of cement. This representation is considered the best way to include both the aggressivity of the chloride ions and the corrosion inhibitive properties of the cement matrix at the steel reinforcement [2]. Usually, however, the cement content in the concrete is not known and may even vary between different parts in a structure. Thus, an assumption has to be made and commonly 300 kg cement per m^3 concrete as a bulk cement content is considered adequate.

In reality, concrete is not homogeneous, but a composite material consisting of three phases: cement paste, aggregates, and air voids. The aggregate volume fraction of bulk concrete typically is 60–80% of the concrete. Single coarse aggregate particles are likely of diameter ~ 30 mm, which thus have a volume of 14 cm^3 (spherical shape assumed). Concrete specimens taken from structures for measuring C_{Cl} are typically drilling cores of diameter (d_{dc}) in the range of 30 to 50 mm. These cores are typically cut or ground into slices of 5 to 10 mm thickness, which corresponds to specimen volumes of 3 to 10 cm^3 – a volume comparable to a single coarse aggregate particle. It is thus expected that the volume fraction of cement paste can vary strongly from one concrete specimen to another, depending on the presence or absence of coarse aggregate particles. As is shown in Fig. 1, the actual cement content of a concrete specimen ($C_{specimen}$) can differ from the

* Corresponding author.
E-mail address: cboschmann@ifb.baug.ethz.ch (C. Boschmann Käthler).

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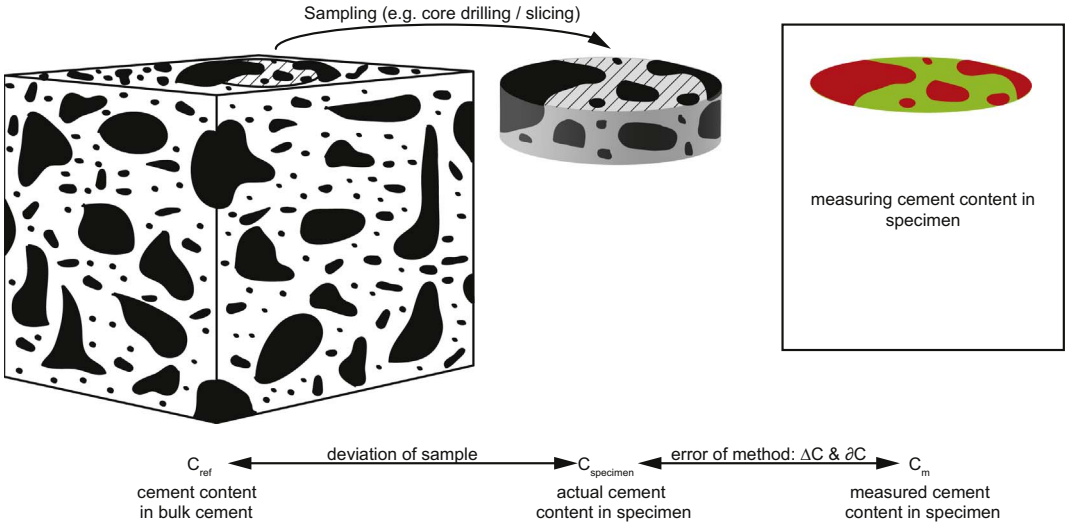

Fig. 1. Definition of error and deviation: C_{ref} is equal to the cement content according to the mix proportion (bulk concrete), whereas $C_{specimen}$ is equal to the actual cement content within a specific concrete specimen. The measured C_{Cl} within this specimen needs to be referred to $C_{specimen}$. C_m is the cement content on the specimen surface, measured with the suggested procedure including image analysis. All abbreviations are listed in Table 3.

cement content of the bulk concrete (C_{ref}). Furthermore, all methods to determine the cement content of a concrete specimen exhibit an error due to limited measurement precision. As depicted in Fig. 1, the difference between $C_{specimen}$ and the measured cement content, C_m, is termed "error of the method" (ΔC, δC).

Fig. 2 illustrates an example of two drilling cores taken from the same concrete. There are clear differences in cement paste volume fraction. To anticipate here the results of this work, the cement content in Fig. 2A is 17.5 M-% and in Fig. 2B is 5.5 M-%, thus differing by a factor > 3. When expressing the chloride concentration in concrete as C_{Cl} by weight of cement we believe that it is crucial to determine, in addition to the chloride concentration, the cement content in each specimen.

Ideally, methods to measure the cement content in hardened concrete should be reliable, quick, almost non-destructive, and applicable to a wide variety of concretes. There exists a number of methods [9–11]; some are implemented in codes [10,11]. Some methods are based on determining the mass of the filter cake after acid digestion of the concrete specimen to quantify the aggregate mass fraction [9,12,13]. However, these are only applicable to lime-free aggregates [14]. Other methods use image analysis, either of electron microscope pictures [15] or of macro scale pictures [16–21]. Image analysis benefits from the contrast in brightness or colour of the features to be distinguished (aggregates, cement paste, air voids). Thus, some methods [21–23] include etching a layer of cement paste followed by colouring the cement paste and aggregates with gypsum and black paint respectively to enhance contrast between both features. This method is laborious and therefore not convenient for practice. Ozen and Guler [20] simply used a desktop flatbed scanner for image acquisition. However, it is worth mentioning that the cement paste used by Ozen and Guler [20] is of whitish colour and therefore comparatively straightforward to differentiate from greyish aggregates without further image processing. The problem for implementation of this procedure in practice is that cement paste is itself often greyish. To account for this, Hammer [19] describes a method of staining the cement paste deep purple with Alizarinred S, without staining the aggregates [24]. After image processing, the optimal threshold is readily defined for determination of cement content in hardened concrete.

In this paper, we describe and propose a method for the reliable and almost non-destructive determination of the cement content in specimens of hardened concrete – containing partly limestone aggregates in the concrete. The method includes colouring the concrete specimen, image acquisition by a flatbed scanner and image analysis. The method will be assessed in terms of applicability in research and practice; furthermore, it is applied to concrete specimens to quantify the variability in cement content in specimens of hardened concrete; the

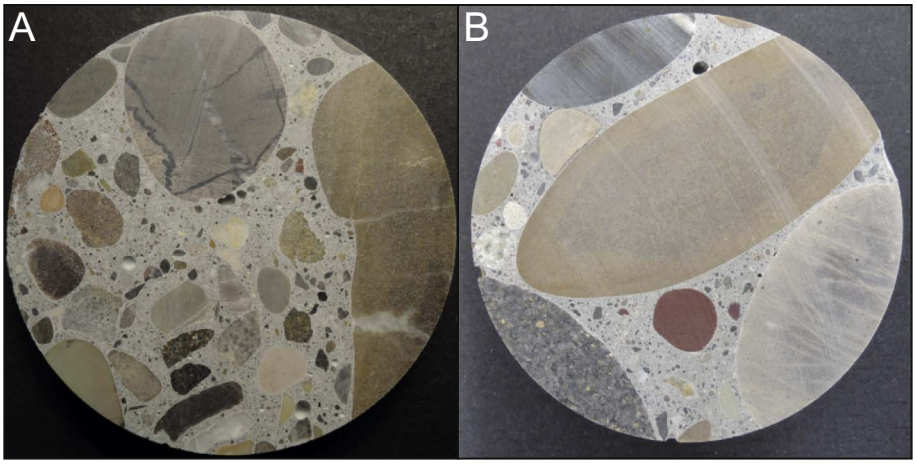

Fig. 2. Two drilling core slices (d_{dc}: 50 mm) from the same concrete mix d_{max} 32. Section A shows few coarse aggregates and has a higher cement content (17.5 M-%). Section B has more coarse aggregates and has therefore a lower cement content (5.5 M-%).