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Long-term chloride migration coefficient in slag cement-based concrete and resistivity as an alternative test method

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HIGHLIGHTS

- Slag cement properties influence concrete resistivity and chloride migration coefficient (D_{RCM}).
- A linear correlation is found between the D_{RCM} and concrete conductivity (resistivity inverse).
- Resistivity determination can be treated as a simple alternative to the chloride migration tests.
- A vast database on the correlation between the resistivity, conductivity and D_{RCM} is presented.

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ABSTRACT

This article reports on investigations of the resistivity and chloride migration coefficient (D_{RCM}) obtained in the accelerated Rapid Chloride Migration test for slag cement-based concretes. Determinations of the resistivity and D_{RCM} were performed on 47 different concrete compositions, up to the age of 182 days. The obtained results demonstrate that, within the investigated age of concrete, factors such as cement fineness, slag origin, w/c ratio and cement and effective water contents clearly influence concrete resistivity and D_{RCM} values. Moreover, a linear trend is observed between D_{RCM} and conductivity. Based on this trend, resistivity determination is proposed as an alternative method for more laborious and time consuming chloride ingress test methods.

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1. Introduction

Carbonation and chloride ingress are not detrimental to concrete itself [1], however due to their impact on steel reinforcement, most service life predictions models such as the ones given in the *fib* Model Code on Service Life Design [2], Life 365 [3] and DuraCrete [4], focus on carbonation and/or chloride ingress. In these chloride transport models a certain critical chloride concentration at the depth of the steel reinforcement is seen as the limit state (rebar corrosion initiation). The important role given to chloride-induced corrosion in these models indicates that for a reliable service life prediction, the ingress of chlorides under different conditions needs to be accurately modeled.

The resistance of concrete against chloride ingress is a function of its permeability, i.e. the pore structure (tortuosity and constrictivity) and the fraction of capillary pores. The w/c ratio strongly influences the capillary porosity of hydrated cementitious systems, i.e. lower w/c ratios result in a better resistance against the penetration of deleterious substances. Moreover, the binder composition is a well-recognized influential factor on concrete permeability. Blending of ordinary Portland cement (OPC) with supplementary cementitious materials (SCM), such as ground granulated blastfurnace slag (GGBS), fly ash or silica fume, results in a binder that produces a denser microstructure compared to a pure OPC system. According to Gulikers [5], the damage of concrete due to chloride-induced rebar corrosion reported in the Netherlands is limited, although a significant number of structures have reached an age in excess of 50 years. The main factor causing

Abbreviations: GGBS, Ground granulated blastfurnace slag; OPC, Ordinary Portland Cement; PSD, Particle Size Distribution; RCM, Rapid Chloride Migration test; RCPT, Rapid Chloride Permeability Test; SCM, Supplementing Cementitious Materials; TEM, Two Electrodes Method; w/c, water/cement ratio; XRD, X-Ray Diffraction.

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List of symbols

Roman

A	surface area [m^2]
a	parameter
b	parameter
D_{app}	chloride diffusion coefficient obtained in bulk chloride diffusion tests [m^2/s]
D_{RCM}	chloride migration coefficient obtained in the RCM test [m^2/s]
l	length [m]
L	thickness [mm]
R	electrical resistance [Ω]
t	time duration [s] or [h]
T	temperature [°C]
U	voltage [V]
x_d	average depth of penetration [mm]

Greek

ρ	electrical resistivity [Ωm]

improved durability is the common use of blended cements in the Dutch infrastructure, especially slag cements with a GGBS content of over 50% (e.g. CEM III/B). A proper curing of fresh concrete is also of great importance as it reduces surface microcrack development. Carbonation, cracks, quality of the concrete surface, freeze/thaw damage and temperature are further influencing parameters on the chloride penetration resistance [6]. Chloride binding by the hardened cement paste also hinders chloride penetration [7–10] and it is known that certain cement types have higher chloride binding capacities compared to OPC, e.g. slag cements or cements rich in C_3A phase [11,12].

The chloride diffusion coefficient is the most commonly used parameter in models quantifying the chloride ingress rate into concrete, since diffusion controls the chloride transport in saturated concrete. Chloride diffusion tests can be grouped based on the nature of the prevailing chloride transport mechanism, either natural diffusion driven only by concentration gradients such as in bulk diffusion tests (e.g. CEN/TS 12390-11 [13] or NT Build 443 [14]), or migration where transport is accelerated through the application of an electrical field. Test methods relying on an accelerated chloride transport mechanism have the big advantage of notably shortening the otherwise long testing period (from the scale of months to hours or days), and are less laborious than the bulk diffusion test. In recent years, use of the accelerated Rapid Chloride Migration test (RCM) according to NT Build 492 [15] has become wide-spread, especially in Europe. The output value of this test is the chloride diffusion coefficient D_{RCM}, also often referred to as D_{CTH}, D_{ns}, D_{nssm} or "migration coefficient" (also in this study), to differentiate it from the diffusion coefficient obtained in bulk diffusion tests [16]. The ASTM C1202 Rapid Chloride Permeability Test (RCPT) [17] is also a commonly used accelerated test, though its output value is not a chloride diffusion coefficient but the total charge passed through the concrete sample within a pre-defined time period, which is directly related to concrete permeability. Bulk chloride diffusion tests, with the apparent chloride diffusion coefficient D_{app} being the test output value, are generally regarded to more accurately represent the mechanism of chloride ingress into concrete under real environmental conditions. However, as presented in [18,19], the D_{app} and D_{RCM} can be linearly correlated, which suggests that the RCM test can be treated as a valid alternative for the long-term and laborious diffusion tests, despite the fundamental differences between these two tests.

A proper service life design for concrete infrastructure exposed to chloride is very important for minimizing construction, early repair and maintenance costs. In the current design codes that follow the so-called deemed-to-satisfy approach (e.g. [20]), the concrete mix composition and cover depth are prescribed based on empirical observations of laboratory and field concrete performances [5]. However, these codes do not differentiate between different binders' performances and are often considered too conservative [5,21]. Therefore, this shortcoming triggered the development of performance-based durability design approaches. These approaches use mathematical modelling to quantify chloride ingress into concrete, and differentiate between different binders. In the European DuraCrete project [4] a model was proposed to correlate the chloride ingress rate, represented by the chloride migration coefficient D_{RCM}, with concrete cover thickness. This model has later been employed in other codes such as the fib Model Code [2] or the Dutch CUR guideline [22].

Despite the apparent improvement of the concrete service life design compared to the deemed-to-satisfy approach, the performance-based approaches experienced serious and well-supported criticism. For example, it has been pointed out that, due to some oversimplifications, the chloride transport model is not sound [23,24]. Additionally, it is very unlikely that the chloride transport properties in concrete develop along the same trend during long time periods (e.g. 50 years) as assumed in these models [1,5,25]. Research has proven that after some time (e.g. 10 years) the chloride diffusion coefficient does not decrease anymore [26]. In the DuraCrete model for corrosion initiation, the effect of concrete handling (e.g. curing and compaction) on the chloride diffusion coefficient as measured in laboratory conditions is taken into account by introducing factors. The influence of binder type on the chloride transport properties is also considered, and expressed by an aging coefficient, that represents the development of the apparent chloride diffusion coefficient with time. The employed factors and parameters were obtained using a fitting procedure in order to achieve a satisfactory agreement between the observed chloride ingress and model calculations [21]. However, due to a lack of data (especially for blended cements), the fitting factors in the DuraCrete model could not be reliably quantified [21,24,25]. This is why some service life calculations based on the DuraCrete model result in very counterintuitive and doubtful outcomes, especially for blended cements, while the models can predict the chloride ingress in OPC-based concretes fairly well, at least up to a certain concrete age [23]. As an example, Gulikers [5] demonstrated that using the CUR guideline [22], the predicted service life of an OPC-based concrete with 20–30% fly ash addition would increase from 50 years to 200 years by increasing the concrete cover depth by only 3 mm. Hence, due to the lack of data, potentially unrealistic outcomes and generally poor understanding by the engineers, performance-based concrete design models are rarely used. In order to improve the reliability of performance-based durability design for concrete, much more reliable parameter values as well as long-term performance information are needed.

The popularity of the RCM test in Europe is mainly caused by its use in performance based service life models, combined with the relatively simple test execution and short duration [27]. Nevertheless, there is an ongoing discussion in the literature on the test's

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