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Sensitivity of the rapid chloride conductivity index test to concrete quality and changes in various test parameters

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ABSTRACT

This study assessed the robustness of the chloride conductivity test with respect to the effect of concrete quality on its sensitivity to selected test parameters. Experiments were carried out to assess the sensitivity of the test to changes in the following parameters: (i) test duration (10, 40 and 120 s), (ii) concentration of the NaCl solution (3M and 5M), and (iii) variation of capillary voltage (7, 10 and 15 V). Concrete test specimens were made using three w/b ratios (0.40, 0.50 and 0.60) and three binder types (CEM I 52.5N (PC – Portland cement), 70/30 PC/FA (FA – fly ash) and 50/50 PC/GGCS (GGCS – ground granulated Corex slag)). One parameter was varied at a time. The results show that concretes with high chloride conductivity index (CCI) values (>~0.8 mS/cm) are generally sensitive to changes in concentration of NaCl solution, capillary voltage across the test specimen, and test duration. For such concretes, the CCI increases with increase in capillary voltage, CCI decreases with decrease in salt concentration while the effect of a longer testing duration on CCI appears to be random. Even though it is not stipulated in the test standard, this study recommends that the test duration (i.e. the duration the capillary voltage is passed across the specimen once the electrical circuit of the test set-up is closed) is limited to <10 s.

1. Introduction

The need to design for durable concrete structures has seen a progressive shift from the traditional prescriptive approaches which limit various design parameters such as w/b ratio towards performance-based approaches which take into account both the severity of the exposure environment and concrete quality in the design process. In order to specify and achieve concrete durability targets in a performance-based approach, it is imperative to have in place robust, repeatable and reproducible tests to assess the concrete before and after construction. Several tests are used to assess concrete resistance to chloride ingress including, among others, the ASTM C1202-12 rapid chloride penetration test [1], Bulk diffusion (Nordtest NTBuild 443) test [2] and AASHTO T259 (salt ponding) test [3]. Even though these tests have been criticised on various fronts e.g. overheating of test specimen in the ASTM C1202-12 test and measurement of concrete resistivity rather than concrete resistance to chloride ingress, they still remain applicable, at least at present, in assessing the potential chloride penetration resistance of various concretes for purposes of service life design [4,5].

In South Africa, a suite of durability index (DI) tests, each related to a transport process in concrete, comprising of the oxygen permeability index (gaseous diffusion), water sorptivity index (water absorption) and chloride conductivity index (ionic diffusion) are used to assess the quality of the cover concrete. This paper focuses on the chloride conductivity index test.

The recent adoption of the chloride conductivity index (CCI) test in South Africa as a standard test [6,7] to assess the potential durability of concrete has been a major step towards the implementation of performance-based design approaches in South Africa. Prior to its incorporation into the South African National Standards, the test which has been in use in South Africa for a long period of time has undergone various improvements; these are summarized in a recent paper by Otieno and Alexander [8]. Even though the test has now been standardized, the standard [6] does not address potential sources of error in the test. This is the focus of this paper. It assesses the robustness of the CCI test to variation in selected test parameters. It does not assess the effect of various factors on concrete quality (or CCI) such as w/b ratio, binder type, curing, age of concrete, specimen pre-conditioning, etc. Some of these have been extensively investigated and can be readily found in the literature [9–13]. For example, a previous study by Alexander and Streicher [12] on mortar specimens (w/b = 0.50) found that

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conductivity was relatively insensitive to small changes in the NaCl concentration at high concentrations (see Fig. 2). Their findings guided the choice to use the high (5M) NaCl concentration in the test. The high NaCl concentration is also used in order to ensure that the test assesses the resistance of the concrete microstructure to passage of chloride ions, rather than the inherent conductivity of the pore solution [14]. However, the study by Alexander and Streicher [12] does not indicate whether this trend holds for concretes made using different binders and w/b ratios. In addition to other selected test parameters, the paper assesses the sensitivity of the CCI test to variations in selected test parameters for different concretes (binder type and w/b ratio). The underlying objective is to improve the test specifications especially with respect to validity and variability of test results. The following section presents a brief summary of the CCI test.

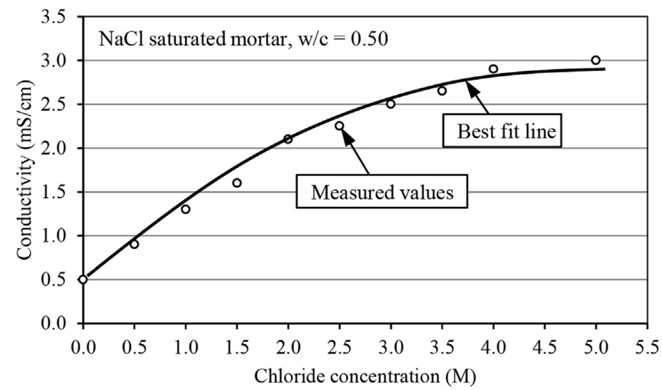

Fig. 2. Conductivities of mortar samples saturated with various chloride solutions [12].

1.1. Brief description of the chloride conductivity test and its application

The chloride conductivity test [6], is a rapid chloride conduction test used to assess the intrinsic potential of a given concrete (or mortar) to resist the ingress of chlorides by diffusion. However, in the test, chlorides penetrate the test specimen by migration due to a potential difference induced in the test set-up. The two transport mechanisms (diffusion and migration) can be related by the Nernst-Planck equation [15,16] i.e. $J = (D \times zF/RT) \times (dU/dx)$ where J is the unidirectional flux of the ionic species (mol/cm^{2}s), D is the diffusion coefficient of the ionic species (cm^2/s), z is the electrical charge of ionic species (ionic valence), F is Faraday's constant (96500 C/mol), T is the absolute temperature (K), U is the potential difference (voltage) across the sample (V), x is a distance variable (cm) and R is the universal gas constant (8.314 J/mol·K).

A schematic of the chloride conductivity test rig is shown in Fig. 1. In the test, four nominally 70 ± 2 mm diameter, 30 ± 2 mm thick concrete discs are prepared for each concrete, typically from cored specimens. Prior to testing, the specimens are dried in an oven at 50 °C oven for at least 7 days and not more than 8 days. The specimens are then vacuum-saturated with 5M NaCl solution before being placed in a test rig with a cell filled with the same salt solution on either side. A 10 V potential difference is applied across the specimen and the corresponding current through the specimen is measured, in a very short time (typically 10 s).

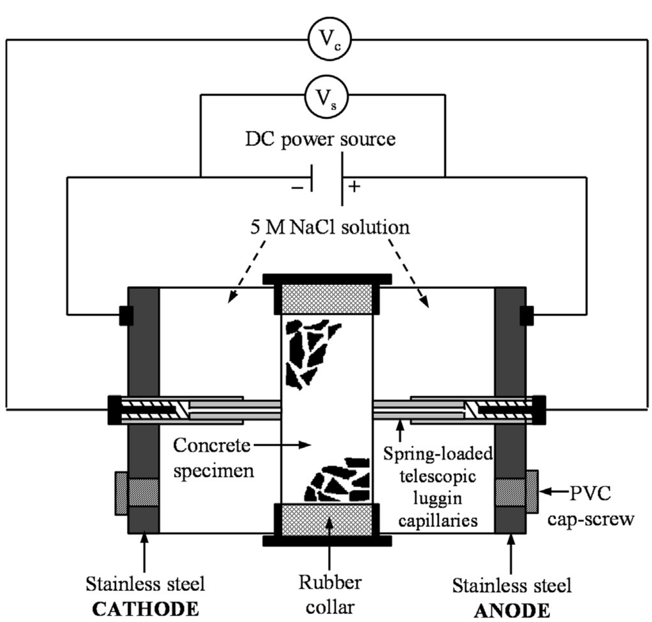

Fig. 1. Chloride conductivity testing cell circuitry set-up [6].

The CCI (σ, mS/cm) is calculated using the formula $(id) \times (VA)^{-1}$ where i is the electric current through the specimen (mA), V is the voltage difference across the specimen (V), d is the average specimen thickness (cm), A is the cross-sectional area of the specimen (cm^2). The resistance of a concrete to chloride penetration increases with a decrease in CCI and vice versa. Typical values of CCI range from <0.5 mS/cm for dense chloride-resistant concretes to >2.5 mS/cm for very penetrable concretes. The chloride conductivity is fundamentally related to steady state diffusivity (D_s) by the Nernst–Einstein equation which relates the conductivity of a bulk material to its D_s by the equation [16,17] $Q = D_s/D_o = \sigma/\sigma_o$ where Q is the diffusivity ratio, D_s is the steady state diffusivity of chloride ions through concrete (m^2/s), D_o is the diffusivity of chloride ions in the equivalent pore solution (m^2/s), σ is the conductivity of concrete (S/m) and σ_o is the conductivity of the pore solution (S/m). However, in reality, non-steady-state conditions exist, and the chloride diffusion is represented by an *apparent diffusion coefficient* (D_a). This limits the application of the Nernst–Einstein equation. Therefore, the CCI (σ) is empirically related to the (apparent) chloride diffusion coefficient (D_a) which is used in service life design [18].

The empirical relationship between CCI and long-term (time-dependent) apparent chloride diffusion coefficient is based on experiments by Mackechnie and Alexander [18] using laboratory-based and field-based specimens. The specimens used covered a range of binder types, w/b ratios and curing regimes. From the correlations obtained thereof, empirical relationships between the CCI value and short-term apparent diffusion coefficient (D_i) were developed for commonly used binder types (100% CEM I 42.5N (PC), 50/50 PC/GGBS and 70/30 PC/FA) and marine exposure environments in South Africa – (a) extreme: marine tidal and splash zone; structure exposed to wave action, (b) very severe: marine tidal and splash zone; structure exposed to little wave action, and (c) severe: marine spray zone. For example, the empirical relationships between CCI and the D_i corresponding to the age of concrete used to determine CCI for 50/50 PC/GGBS and 70/30 PC/FA concretes exposed to very severe marine conditions are expressed as follows:

For 50/50 PC/GGBS concretes:

$$D_i = \left(1.1072 \times 10^{-3}\right) e^{0.8999\mathrm{CCI}} \mathrm{cm}^2 \Big/ \mathrm{s} \quad (1)$$

for 70/30 PC/FA concretes:

$$D_i = \left(1.3689 \times 10^{-3}\right) e^{0.9499\mathrm{CCI}} \mathrm{cm}^2 \Big/ \mathrm{s} \quad (2)$$