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The performance of concrete exposed to marine environments: Predictive modelling and use of laboratory/on site test methods

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HIGHLIGHTS

- Suitability, scope and repeatability of test methods in assessing chloride ingress.
- Beneficial features of Permit ion migration test for on site assessment of concrete.
- 20 years of chloride ingress data from a marine structure.
- Modelling the chloride ingress into concrete and validation of modelling.
- A methodology for developing performance-based specifications for concrete.

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ABSTRACT

This paper reports an approach by which laboratory based testing and numerical modelling can be combined to predict the long term performance of a range of concretes exposed to marine environments. Firstly, a critical review of the test methods for assessing the chloride penetration resistance of concrete is given. The repeatability of the different test results is also included. In addition to the test methods, a numerical simulation model is used to explore the test data further to obtain long-term chloride ingress trends. The combined use of testing and modelling is validated with the help of long-term chloride ingress data from a North Sea exposure site. In summary, the paper outlines a methodology for determining the long term performance of concrete in marine environments.

1. Introduction

Premature deterioration of reinforced concrete structures due to lack of durability and subsequent poor state of their *health*, has led to a significant part of the construction budget being spent on repair and rehabilitation works. As a direct consequence, asset owners are often forced to take decisions to repair and maintain existing ailing infrastructure, as opposed to investing in new ones. Effective decision making in this regard requires systematic information about the state of health of an asset (or expected performance), an acceptable level of variance in this information and an effective maintenance strategy that is linked to its whole life value. In the case of concrete infrastructure, factors such as, for example, materials used, design and type of loading on the structure, its location and severity of the exposure condition, will all influence the decision making process as to the calculated state of health of the structure.

It is important, therefore, to specify the expected performance of a structure in addition to the guidelines given in standards, such

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as BS 8500, which detail the factors defined above. Some of the leading European and International research organisations such as RILEM Technical Committee 230-PSC, fib Task Group 8.10 and ACI Committee 365 are focusing on developing "Performance-based Specification for concrete". The final technical report by Brite EuRam III DuraCrete [1] project provides an insight into the future of such specifications. Further articles on this topic can be found elsewhere see, for example, [2–5]. As the quality of materials and exposure environments vary for different countries, it is also necessary to develop and refine the specifications so that they remain relevant to the practices of that country. The availability of test methods and understanding in the use of predictive models will also become critical in the general adoption of performance-based specification.

This paper details an approach by which laboratory and on site (*in situ*) testing can be further exploited with the help of a numerical model in order to determining the long term performance of concrete exposed to marine environments. The data presented in this paper are obtained from three research projects:

1) ChlorTest supported by European Union, Framework 5 [6];
2) PhD research by one of the authors (S.V. Nanukuttan) [7], and
3) Performance-based Testing Methodologies supported by Engineering Physical Science Research Council [8].

A range of test methods available for assessing the resistance to chloride ingress are reviewed and their repeatability compared. Numerical simulation of chloride movement into concrete is undertaken using a service life prediction model and the simulated data compared with on site data obtained from a long-term marine exposure study. The main objective of this paper is to present and summarise developments in testing and modelling of concrete for chloride ingress and to illustrate how progress could be made in developing performance-based specifications.

2. Measurement of resistance to chloride ingress in concrete

Although the primary mechanism of chloride transport through unsaturated concrete cover is absorption, the accumulation of chlorides in this layer leads to further penetration of chlorides into the cover-zone by diffusion [9]. As a consequence, diffusion becomes the dominant mechanism of chloride transport at greater depths, which can be assessed in terms of the diffusion coefficient of the chloride ion. Different test methods are available to determine the diffusion coefficient, e.g. steady-state and non-steady-state chloride diffusion. As diffusion takes time to establish and tests are often tedious, migration tests are often used to quantify the movement of chlorides in concrete. The most common migration test uses an external electrical field to accelerate the flow of chloride ions, hence the coefficient determined using such a test is termed a migration coefficient. In addition, diffusivity is recognised as a term that represents chloride transport resistance of concrete, irrespective of the mechanism used to establish the flow of chlorides.

2.1. Experimental programme

Table 1 shows mix details of 9 typical concretes used across Europe. The concrete samples (large slabs) were cast as part of the EU funded ChlorTest programme [6]. Cores of 100 mm diameter and 200 mm length were extracted from the samples and these were transported to Queen's University in a moist state and were kept at 20 °C until the test date. Samples were wrapped with moist hessian to prevent drying. All data reported in Table 1 were generated by the tests carried out at Queen's University. In addition to the mix design, the table also shows migration and electrical resistivity data from NT Build 443 [10], NT Build 492 [11] and bulk electrical resistivity [12] testing. Average chloride concentration at depths 5 mm and 10 mm from the surface from samples studied for NT Build 443 [10] are also reported. Repeatability of the tests are discussed together with the long-term performance (readers interested in reproducibility of the tests may refer to ChlorTest [6] report where inter and intra laboratory comparisons were analysed).

2.2. Relationship between chloride penetration and concrete diffusivity assessed using different lab based test methods

Figs. 1–3 present the diffusivity of concrete (assessed using different laboratory-based tests) plotted against the quantity of chloride ions measured at 5 and 10 mm depths from the exposed surface. The chloride ion concentration at these depths was determined by the potentiometric titration method using powder samples collected from concrete specimen immersed in 2.8 M NaCl solution for 35 days. Data points represent nine different concrete mixes and the test age of concrete samples was >180 days. Results presented in Figs. 1–3 indicate that the diffusivity assessed by the different test methods can be used with varying degree of accuracy to predict the chloride concentration at a particular depth.

Figs. 2 and 3 suggest that useful information about the penetration of chloride ions can be obtained using rapid test methods. NT Build 492 [11] requires, on average, 24 h to assess the diffusivity of concrete whereas electrical resistivity can be measured instantaneously. It is also worth noting that the electrical resistivity, in this case, was obtained from concrete specimens saturated with calcium hydroxide ($Ca(OH)_2$) solution. The procedure for carrying out the test can be found in references [12] and [6]. All these tests require concrete cores with a minimum thickness 50 mm to be extracted from the structure which considerably limits the number of test that can be performed as frequent testing can leave the structure badly disfigured. As a result, two on site methods were also included as part of this study which are outlined in the next section.

3. Onsite methods for assessing chloride diffusivity

3.1. Background of Permit ion migration test (Permit)

This is a unique, non-destructive, surface-based test developed on the principles of the steady state migration test. Initial developments of this test are detailed elsewhere [14] and further refinements during 2007–10 resulted in automation of the procedure and making it site/user friendly [7]. The test apparatus is shown in Fig. 4a and a brief description of the apparatus and working principle are outlined below for the benefit of readers.

The Permit comprises two concentric cylinders placed on the concrete surface with the inner cylinder and outer cylinder containing 0.55 M NaCl and de-ionised water, respectively. A potential difference is applied via a stainless steel cathode placed in the inner cylinder and mild steel anode placed in the outer cylinder. The test establishes a flow of chloride ions from inner cylinder through concrete to the outer cylinder. A conductivity sensor located in the outer cell monitors the conductivity of the electrolyte (initially de-ionised water) and this is converted to chloride concentration using relationship established by Castellote et al. [13]. The validity of conductivity/concentration relationship was established for the range of concretes using the Permit and is shown in Fig. 4b. The change in conductivity (therefore concentration) is used in the Nernst–Planck equation to obtain a migration coefficient ($D_{in\ situ}$) viz,