

Fig. 3 : Reactive aggregate supposed spherical.



Fig. 4 : R.E.V. with three different reactive aggregates



Fig. 5 : equilibrium between alkalis (Na⁺) and Ca^{2+} in solution in presence of portlandite



Fig. 6 : Sand granulometry









Fig. 8 : experimental swelling versus time



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Fig. 9 : comparison between numerical and experimental swelling

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Modelling Chloride Ingress in Concrete: A Comparative Study of Laboratory and Field Experience

by T. Callanan and M. Richardson

Synopsis:

Performance-based specifications for concrete exposed to chlorides may involve the determination of long-term material parameters by relatively short-term laboratory tests. The first generation of chloride environment durability models are likely to be based on diffusion theory, despite the fact that chloride ingress is both by absorption and diffusion. This paper compares chloride resistance values from laboratory experiments and from field trials, derived solely on diffusion-based modelling. Concrete prisms were exposed to sodium chloride solutions in laboratory tests for a period of 12 months. The trials included both continuous immersion and cyclical wetting and drying cycles. Chloride values were determined at 3, 6 and 12 months. Material variables included normal portland cement, fly ash, crushed limestone aggregate, natural sand, and natural gravels. Diffusion coefficients were derived through best-fit curves based on Crank's error function solution of Fick's second law of diffusion. It was found that the laboratory test diffusion coefficients diminished significantly with increase in test duration and stabilised between 6 and 12 months, by which time they yielded values of a similar order of magnitude to those from the structures in service. The coefficients for gravel aggregate concrete specimens were more variable than those for crushed rock aggregate concretes and could exceed the in-service values by a factor of at least two. The beneficial influence of fly ash was reflected in the results.

<u>Keywords</u>: chloride diffusivity; durability design; fly ash; performance-based specification

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Thomas Callanan is a civil engineer with consultants Parsons Brinckerhoff (Ireland) Ltd. He joined the company's Structural Investigations Group following research with the Bridge Research Group, Department of Civil Engineering, University College Dublin.

Mark Richardson is a senior lecturer in the Department of Civil Engineering, University College Dublin. His primary research interest is concrete durability. He is a former chairman of the Concrete Consultative Committee of the National Standards Authority of Ireland.

INTRODUCTION

Corrosion of reinforcement due to chloride penetration is the greatest threat to the durability of a significant proportion of the world's reinforced concrete infrastructure. A tolerable level of chloride, introduced as trace elements in aggregates or admixtures, is present in many durable concrete structures. However unacceptably high levels at the reinforcement may occur over the service life where external sources of chloride are available. The sources of chloride are from the environment, in the case of coastal and marine structures, and from de-icing salts in the case of highway structures.

Many reinforced concrete bridge structures throughout the world have been classified as defective and this has led to concern in respect of the adequacy of code recommendations. Particular concern has been expressed by Bamforth (1) in respect of the potential service life of normal portland cement concretes in chloride environments, despite compliance with code advice. This focussed attention on the issue in countries such as the Republic of Ireland where normal portland cement was virtually exclusively used in concrete throughout the last century. In relation to code advice, it is heartening that decades of work by European standards authorities and industry experts is finally coming to fruition. The introduction to practice of long-awaited European standards on cement and concrete is now in motion. Perhaps the most significant of these is EN 206-1, the standard on concrete specification, performance, production and conformity, published by the Comité Européen de Normalisation (2). The document is being progressively published in European countries as national annexes become available. The standard will replace conflicting national standards in December 2003. The specifier and producer will be faced with fundamental changes to current practice including an enhanced prescriptive approach to specification of durable concrete that involves consideration by the user of the required

service life. Perhaps of even greater significance is encouragement to introduce performance-related design methods with respect to durability.

In light of these developments, a research project was established in Ireland to examine the extent to which concern should exist in Irish concrete practice in respect of the durability of normal portland cement concretes, and to explore the introduction of performance-based specifications based on apparent chloride diffusion coefficients. The project includes concretes with secondary cementitious materials exposed to sodium chloride solutions and to seawater. This paper reports on the chloride diffusion coefficients determined for normal portland cement concretes and fly ash concretes in laboratory tests and for normal portland cement concretes from data derived from tests on structures in service.

MODELLING CHLORIDE INGRESS

Mathematical modelling of chloride ingress in concrete should, strictly speaking, take account of three transport mechanisms: diffusion, capillary absorption and, where relevant, flow under hydrostatic pressure. Diffusion allows the movement of chloride ions under a concentration gradient to any depth as long as there is a continuous liquid phase in the concrete. Capillary absorption is driven by moisture gradients and can lead to significant chloride ion take-up but does not, by itself, encourage transport of the chloride ions to the level of the reinforcing bars. Permeation may occur through hydrostatic pressure if a solution containing chloride ions is present under an applied hydraulic head on at least one face of the concrete. However, mathematical models incorporating all three modes are user-unfriendly and the use of chloride penetration models in performance-based specifications are likely to be simplified by consideration of diffusion only. Chloride diffusion into concrete therefore has generally been modelled solely by the error function solution to Fick's second law of diffusion by Crank (3). Fick's second law of diffusion for the non-steady state condition, where the concentration (C) of the medium is changing with time (t) is:

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial t^2}$$

It is only applicable to one-dimensional flow with the space co-ordinate (x) measured normal to the section. The parameter D_{eff} is the effective diffusion coefficient. The equation may be solved for a semi-infinite medium using the Laplace transformation, assuming that the surface concentration is constant (C_{θ}) , the initial concentration in the concrete is zero and the infinite point condition $C_{(x=\infty_1, >0)}$ is also zero since it is far enough away from the surface.

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Crank's error function solution, based on these assumptions is:

$$C = C_o \left\{ 1 - erf\left(\frac{x}{2\sqrt{D_{eff}t}}\right) \right\}$$

where *erf* is the error function, a mathematical construct available in tables or in many spreadsheet software packages. Diffusion theory alone may not accurately model the relevant transport mechanisms and therefore coefficients derived from Crank's error function solution are best characterised as empirical values referred to as 'apparent diffusion coefficients', based on a best fit curve between theoretical and actual performance.

EXPERIMENTAL PROGRAM

Laboratory Test Program

The laboratory program employed specimens representing eleven concrete mixes. The control concrete mixture was based on a cement content of 360 kg/m³ and W/C of 0.5 to represent the minimum requirement for a concrete to meet the composition limitation for an exposure class in the 'XS2' and 'XD2' series of I.S. EN206-1 (4). These exposure classes relate to concrete elements subject to direct contact with chlorides from seawater and other sources (such as de-icing salts) respectively. The mixtures were designated by alphanumeric codes, the structure of which is presented in Table 1. Mixture 'NG40-2', for example, represented a concrete with normal portland cement, gravel coarse aggregate, and forty per cent fly ash that was classified as 'coarse'. All specimens were 0.28m square and 0.075m deep. The dimensions were chosen to encourage unidirectional flow in the central test zone from which all samples were extracted. No edge sealing was used. The samples were prepared in accordance with the recommendations of British Standard BS 1881:Part 125:1996 (5). The mixture proportions and concrete properties are set out in Table 2 and Table 3 respectively. All specimens were cast using normal portland cement and natural sand fine aggregate. Coarse aggregate was either 10-20mm crushed limestone plus 5-10mm crushed limestone or a natural gravel. Fly ash was low lime and was categorized as either 'fine' or 'coarse'. The fine fly ash had a maximum of 12.5% retained on a 45 micron sieve whereas the corresponding value for the coarse fly ash was 60%.

Method of Test

Specimens representing the eleven concrete mixes were allowed to mature for several months before exposure to a high molar sodium chloride solution. The molarity of the solution used was 5 Mol/l, which was deemed from tests to be the maximum practical value. This test arrangement was chosen to facilitate direct correlation with similar tests using seawater, in preference to rapid chloride migration methods.

The initial condition of the specimens was standardised through immersion in a water bath (chloride concentration less than 10ppm) for 168 hours immediately prior to exposure to the chloride solutions. Testing by phenolphthalein indicator solution demonstrated that the samples had negligible carbonation depth (less than one millimetre) despite storage indoors during the maturing period. The specimens in the immersion experiment were stored in a single layer. The wetting and drying cycle experiment employed two tanks at different levels. The specimens were stored in layers in the lower tank while the upper tank acted as a reservoir for the chloride solution. The arrangement is schematically illustrated in Fig. 1. The lower tank was flooded in the first week of the experiment by gravity flow and emptied in the second week by pumping the solution back to the upper reservoir. This fortnightly pattern was repeated during the 12-month duration of the experiment. The samples were therefore allowed to dry by natural air circulation every alternate week, thus encouraging greater capillary absorption than in the immersion trials. (This arrangement was introduced to accelerate corrosion activity as part of the wider study). Average ambient air temperature during the drying cycles was 11°C and average relative humidity was 75%. These values represent typical exposure conditions in Ireland. No ponding or salt crystallisation was observed during the weekly drying cycles. However some crystallisation was apparent during the extended drying period after test completion.

The test blocks were temporarily removed from the trials at three, six and twelve months for sampling by drilling of dust samples. The blocks were replaced in the test tanks as soon as possible. Each specimen was drilled at predetermined incremental depths of 0-6mm, 6-10mm, 10-20mm and 20-28mm from the shuttered face. Three holes were drilled at each sampling location and depth interval to produce a representative sample. The chloride content of the samples were determined using the titration procedure of British Standard BS 1881:Part 124 (6). This yields a total chloride value of the sample due to the use of acid solubility.