Service Life Demonstration Based on Simulated Exposure and Numerical Modelling

by N. R. Buenfeld

Synopsis:

Modelling chloride transport is usually an integral part of demonstrating that a concrete structure in a chloride-rich environments will have the required service life. Ideally this should take account of spacial and temporal variations in exposure environment and concrete properties. This paper describes how this may be approached through a combination of simulated natural exposure and numerical modelling. This approach helps to reduce the errors associated with coupling different transport processes.

The example taken is a reinforced concrete tunnel exposed to chloride-contaminated groundwater. In a laboratory experiment, opposite faces of specimens of tunnel lining concrete were exposed to the maximum hydrostatic head (30m) of groundwater and the minimum relative humidity (35%) expected inside the tunnel and water outflow and chloride accumulation were monitored over a 3 year period. Water vapour diffusion, chloride binding and porosity measurements were made on parallel specimens. The measurements were used as inputs to a numerical model of water and chloride transport to extrapolate from the measured chloride profiles to predict future chloride profiles. The results were very sensitive to ground water chloride concentration and chloride threshold level, but relatively insensitive to hydrostatic head.

Keywords: cement; chloride; concrete; life prediction; numerical modelling; simulated exposure

Nick Buenfeld is Professor of Concrete Structures at Imperial College London. Specialising in the durability of concrete structures, he aims to advance understanding of deterioration processes to develop more effective methods of design, assessment and repair. He has worked on major projects worldwide, has authored/coauthored over 100 refereed publications and holds several patents.

INTRODUCTION

Major civil engineering projects commonly require demonstration that the required service life is highly likely to be achieved. Modelling chloride transport is usually an integral part of this in chloride-rich environments. Fick's 2nd law of diffusion (describing diffusion of an unreactive species into a semi-infinite medium) is commonly used to represent chloride penetration, the variables being the apparent diffusion coefficient (D_a) and surface chloride content (C_s). D_a and C_s values are often determined by curve fitting to chloride profiles measured on existing structures. Even though chloride *does* react with cement paste and diffusion is rarely, if ever, the only transport process in situations where chloride-induced reinforcement corrosion is a concern, this empirical method has its attractions. It is simple to implement and recent developments have included allowing D_a and C_s to be time-dependent and represented by mean, standard deviation and distribution type such that the predictions are probabilistic (1).

However, in situations where transport processes other than diffusion are expected to dominate, where elements are relatively thin (so that the semi-infinite assumption is invalid) or where properties vary with depth, numerical modelling may be more appropriate. A concrete-lined tunnel below the groundwater table with an internal relative humidity of less than 100% is a good example of such a situation and is the case study in this paper.

NUMERICAL MODELLING

Numerical modelling of transport usually involves the concrete member being divided into a series of laminae, each parallel to the exposed surfaces and attributed with relevant physical and chemical properties. Initial boundary conditions are set at the exposed surfaces and the equations governing transport are then solved for each lamina for a small step forward in time; the resulting values are used in the next time increment. In this way, each transport process is modelled individually using continuum mechanics and is then coupled with the other transport processes. The method depends on being able to describe each process by an equation or look-up table involving measurable coefficients.

INGRESS is a finite difference model of water and chloride transport into concrete developed at Imperial College (2). The main processes modelled and the governing relations and coefficients are listed in Table 1. The corresponding modelling equations and their solutions for different scenarios are presented in Ref. 2. Where possible, numerical solutions have been compared to analytical solutions (2). Matched asymptotics have been used to test the accuracy of the finite difference solutions for wick action (water absorption and water vapour diffusion in series) as this model is too complex to solve using purely analytical techniques (3).

All of the transport processes listed in Table 1 are involved in the common scenario of a concrete lined tunnel with an internal relative humidity of less than 100%, located below the ground water table. In theory, all of the coefficients could be measured separately on concrete specimens and then used as inputs to *INGRESS* to predict overall chloride build up due to the combination of processes. However, experience shows that this is not the best approach. First, not only are there at least 6 coefficients required, but several of these vary with time and so a very large number of measurements would be needed. Second, the main assumption in a numerical model of this kind is that transport by the different processes occurs to the same extent in the same porosity. This is almost certainly not the case, with transport by convection not occurring to the same extent as diffusion in the smaller pores. Where time is available and the exposure environment is appropriate, a more effective approach, which is demonstrated here, is to apply simulated natural exposure to specimens in the laboratory, monitoring water and chloride transport and then use the numerical model to extrapolate forward in time based on a more limited number of additional measurements.

APPLICATION

Tunnel construction and exposure

The tunnel (which cannot be named to retain confidentiality) is formed from 250 mm thick precast concrete segments, with steel reinforcement protected by 40 mm of concrete cover at each face. The concrete has a binder content of 400 kg/m^3 of which 30% is fly ash and a free water-cementitious materials ratio of 0.34. The segments are exposed to up to 30 m head of groundwater containing typically 2 g/l chloride and up to 3.5 g/l chloride. The air inside the tunnel is at around 20 degC and 35% relative humidity, whilst the temperature of the ground is around 16 degC. All of the processes listed in Table 1 are expected to contribute to, or influence, chloride penetration.

Measurements

At an age of 28 days, 100 mm diameter 250 mm long cylinders of tunnel lining concrete were vacuum saturated with distilled water (to provide a more clearly defined starting moisture state) and were then subjected to simulated natural exposure. This involved applying 30 m head of chloride contaminated groundwater (3.5 g/l chloride) to the extrados (external surface) and monitoring the outflow of water at the intrados (internal surface), which was held at 35% RH. The results that follow are for one particular specimen. The outflow of water with time is shown in Fig. 1.

It can be seen that the rate fell during the test. Over the 1000 days of exposure there was a total outflow of only 21.3 g and parallel tests showed that a major contribution to the early water outflow was drying of the concrete close to the intrados with the total inflow being only around 10.3 g. By the end of the test the flow rate was around 0.006g/day. If this flow rate is attributed entirely to the pushing effect of 30 m head of groundwater, with no pulling contribution from wick action (4), this final flow rate equates to a coefficient of permeability of 1.84 x 10^{-14} m/s, an extremely low value. In fact, wick action will have contributed to flow and so the permeability will be even lower than this.

After simulated exposure, the cylindrical specimen was subjected to a range of tests. The total chloride profile was measured and is shown by the closed symbols in Fig. 2. Chloride penetrated to a depth of only around 10 mm: the hump at 9 mm is probably the result of a higher cement paste content at this location. Discs cut parallel to the intrados face were tested using 3 gravimetric methods to estimate the porosity contributing to transport; methanol exchange porosity ranged from 5.0 to 5.3% and the empty porosity after drying to 35% relative humidity was around 4%. The chloride binding isotherm, shown in Fig. 3, was measured using the equilibrium method (5). The x-axis of Fig. 3 represents the free chloride content of both the groundwater and of the concrete pore solution.

Modelling

INGRESS was used to fit a curve to the 1000 day chloride profile measured in the simulated exposure test (Fig. 2). INGRESS inputs were lining thickness (250 mm), applied head (30 m), groundwater chloride concentration (3.5 g/l), water inflow vs time (Fig. 1 - note this results from pressure-induced water flow and wick action), effective porosity (5%), chloride binding isotherm (Fig. 3) and background chloride content (0.003% chloride by weight of concrete).

Chloride diffusion coefficient was used as the fitting variable such that the total amount of chloride predicted as entering the concrete was equal to the measured amount, less the background content. This resulted in a diffusion coefficient of 3 x 10^{-12} m^2/s. One of the reasons that it was chosen for fitting was that recent research shows that the chloride diffusion coefficient measured using conventional methods is subject to errors, that are currently impossible to accurately quantify, due to membrane potential effects (6). It was therefore necessary to quantify chloride diffusion under conditions as closely simulating the exposure environment as possible.

The fitted profile is shown by the open symbols in Fig. 2. The surface chloride content in the fitted profile is entirely dependent upon the chloride binding isotherm and is slightly lower than the measured value. This was expected and is a consequence of the higher cement paste content of the surface concrete in relation to the bulk.

The fitted profile for 1000 days of exposure formed the basis for the prediction of future chloride profiles. To be conservative (safe) it was assumed that the water inflow and chloride diffusion coefficient remained constant at their 1000 day values of 0.006 g/day and 3×10^{-12} m^2/s, rather than reducing with further hydration. The same porosity (5%) and chloride binding isotherm (Fig. 3) were also assumed and predictions were based on the 250 mm thick section being divided into 250 one mm thick elements.

Fig. 4 shows the predicted effect of groundwater chloride concentration on chloride profiles at 120 years, the required service life of the tunnel. It can be seen that chloride penetration is confined to within 100 mm of the extrados surface such that both chloride precipitation at the position of water evaporation near the intrados and release of bound chloride due to carbonation at the intrados can be ignored.

Fig. 5 shows the predicted effect of hydrostatic head on chloride profiles at 120 years, making the assumption that all of the water flow is associated with wick action. Despite this assumption, it can be seen that the effect of head is very slight. At first sight this may be surprising, but these results are consistent with the simulated exposure results which showed this concrete to have extremely low permeability.

Time to corrosion

To predict the time to corrosion of embedded steel requires information concerning the cover depth and the amount of chloride necessary to initiate corrosion, the chloride threshold level (CTL). The tunnel linings under investigation have reinforcing steel in both the intrados and extrados faces with a nominal cover depth of 40 mm. Chloride will reach the extrados steel first, but oxygen is also necessary for corrosion. If the extrados steel is electrically insulated from the intrados steel, it is likely that there would be insufficient oxygen available at the extrados steel to sustain a significant rate of corrosion and so chloride accumulation at the intrados rebar (which is embedded in partially saturated and therefore oxygen accessible concrete) would control corrosion and extremely long service lives would be predicted. In the case under consideration the intrados and extrados rebars are electrically connected and so oxygen at the intrados steel can drive corrosion of the extrados steel and it is chloride accumulation at the extrados rebar that will control corrosion. Hence the relevant cover depth is 40mm.

The most appropriate means of expressing the CTL is in terms of total (not free) chloride content (7,8). A wide range of CTL values have been reported in the literature, ranging from around 0.2 to 2.5% chloride by weight of cement (including replacements). This wide range can largely be explained by variations in the entrapped air content at the steel concrete interface (9). The lower the entrapped air content at the steel, the higher the chloride threshold level and the more corrosion resistant the lining. For design purposes (i.e. providing a margin of safety), 0.4% is the value most commonly adopted. For concrete which has a total cementitious content of 400 kg/m^3 and a density of around 2,400 kg/m^3, this is equivalent to 0.067% chloride by weight of concrete. On this basis, Fig. 3 can be used to predict the CTL above which the linings are immune to chloride-initiated reinforcement corrosion until, in the extremely long-term, the chloride concentration in the concrete pore water exceeds that in the groundwater due to back-diffusion from the point of wick action evaporation (3). For example, it can be seen in Fig. 3 that at a groundwater chloride concentration of 4 g/l the maximum achievable chloride content (without extremely long-term wick action effects) would be around 0.17 % chloride by weight of concrete (equivalent to 1.0% chloride by weight of cement), while this figure falls to around 0.09% at a groundwater chloride concentration of 2 g/l.

Fig. 4 includes lines representing the cover depth (40 mm) and CTL (0.067%). It can be seen that for a groundwater chloride concentration of 4 g/l (with 30 m head), the CTL of 0.067% chloride by weight of concrete is predicted to have penetrated to a depth of around 38 mm after 120 years of exposure. A mean time to corrosion of 133 years is predicted for a cover of 40 mm. Of course concrete properties, cover depth and environmental characteristics are stochastic variables and ideally would have been represented by statistical distributions to enable the probability of corrosion initiation at different times to be assessed; however, in this instance there was insufficient data for such an analysis.

CONCLUSIONS

- The empirical application of Fick's second law is not appropriate for modelling chloride penetration in situations where transport processes other than diffusion dominate, where elements are thin in relation to the depth of chloride penetration, or where transport properties vary with depth.

- A numerical model using continuum mechanics and measurable physical and chemical properties allows the effects of several transport processes to be combined, allows realistic boundary conditions to be applied, and allows concrete properties to be varied with time and depth.

- Numerical modelling usually requires a large amount of transport coefficient data for the concrete of interest. The number of measurements can be reduced by applying simulated natural exposure to specimens in the laboratory, monitoring the associated transport, and then using a numerical model to extrapolate forward in time based on a more limited number of additional measurements. This approach should also reduce errors arising from assumptions regarding the coupling of processes.

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Table 1. Processes contributing to, or influencing, chloride transport in concrete

Process	Governing relation	Coefficients
Chloride ion diffusion	Fick's 1st law	Chloride diffusion coefficient (m^2/s) Porosity (volume fraction)
Chloride binding	Binding isotherm	Bound vs free chloride plot
Pressure-induced water flow	Darcy's law	Water permeability (m/s)
Water absorption	Sharp wet front penetrating as $time^{1/2}$	Sorptivity ($m/s^{1/2}$)
Water vapour diffusion	Fick's 1st law	Water vapour diffusion coefficient (m^2/s)

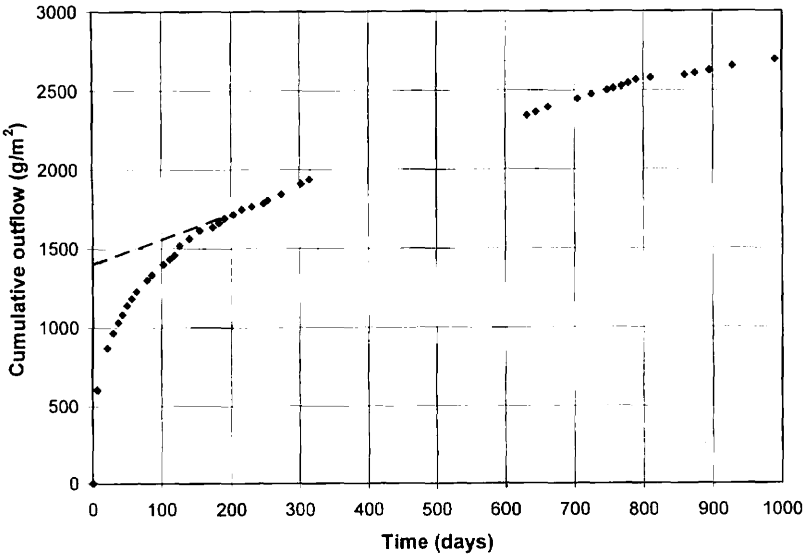

Fig. 1. Cumulative outflow of water vs. time

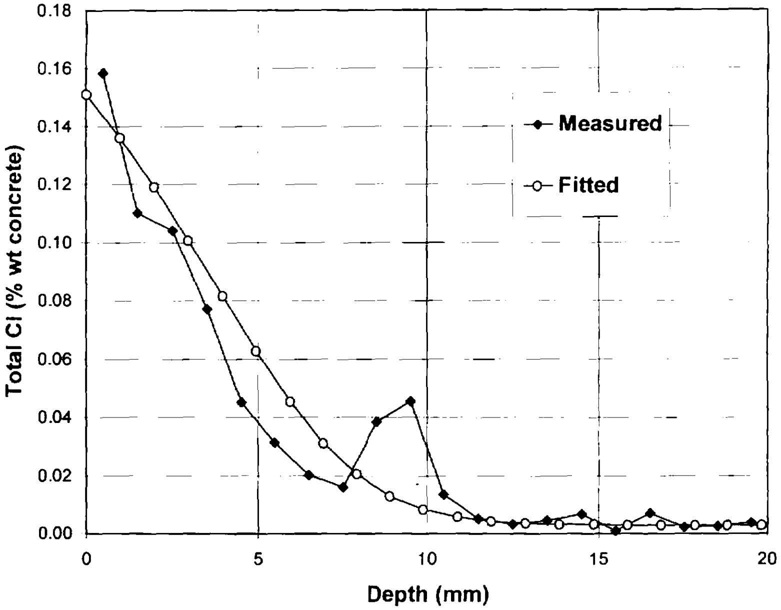

Fig. 2. Measured and fitted chloride profiles (3.5 g/l chloride in groundwater)

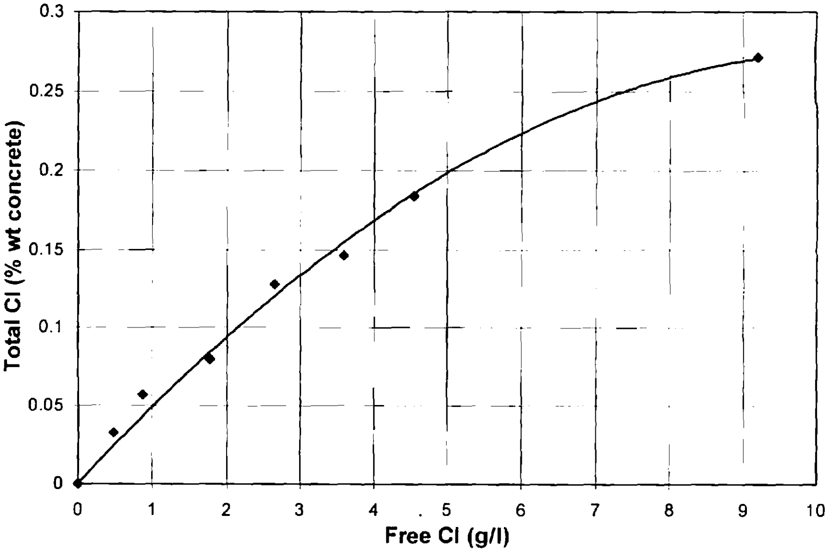

Fig. 3. Measured chloride binding isotherm

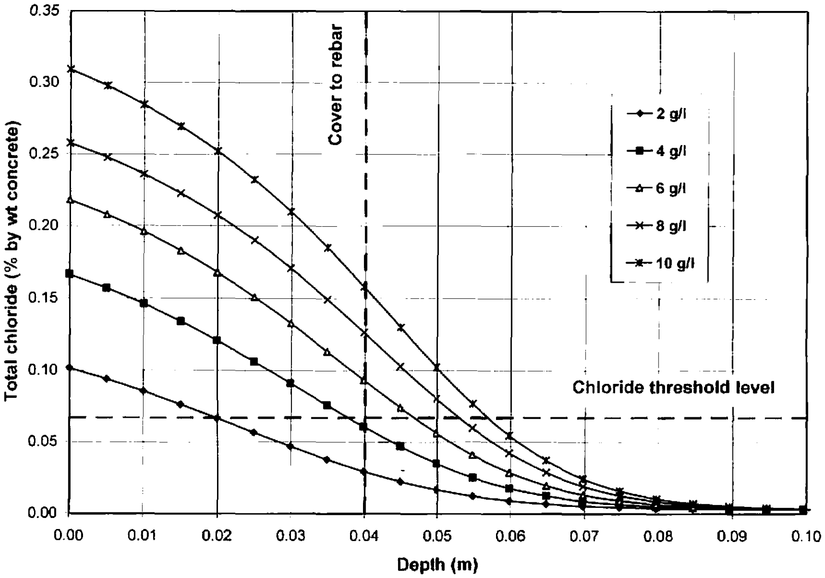

Fig. 4. Predicted effect of chloride concentration on chloride profiles after 120 years of exposure (30m head).

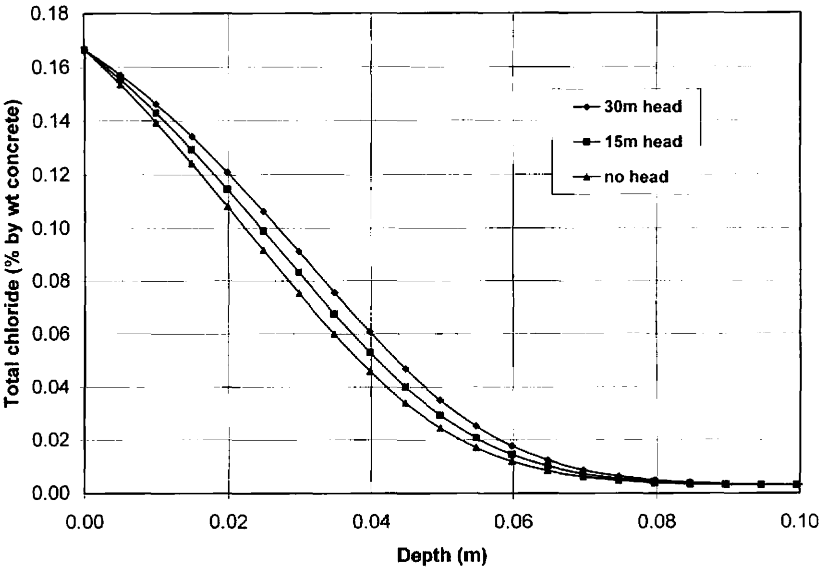

Fig. 5. Predicted effect of hydrostatic head on chloride profiles after 120 years of exposure (4.0 g/l chloride).