Chloride transport in concrete: Specification, testing and modelling

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There is widespread consensus among the concrete industry, that the most common and serious cause of deterioration in structural concrete members is corrosion of reinforcing steel induced by chloride ion ingress and oxygen ingress into reinforced concrete.

Therefore, any improvement in the reliability of predicting the timing and the extent of required maintenance will result in considerable cost savings. Developments in test methods and reliability modelling of chloride transport through the concrete cover, an essential part of any life-time prediction model, are of ongoing concern to concrete technologists. Owing to the severity of this issue, the ICT held a half-day seminar at University College London in September 2014, to discuss this topic.

Six papers were presented by leading academic and industrial experts. The topics examined the latest research and industrial case studies on the testing and modelling of chloride transport in concrete, including:

- performance specification of concrete in chloride environments
- laboratory methods to determine chloride transport parameters
- site methods for assessing the chloride transport resistance of concrete

**Reinforcement corrosion**
Steel in a moist concrete is protected against corrosion by the high alkalinity of the pore solution in the concrete. At these high pH levels, a passive film of ferric oxide forms on the surface of the steel, protecting it from further corrosion (Figure 1). This ferric oxide layer can be damaged as a result of reduced pH in the cover concrete caused by the presence of chloride ions.

Chloride ions can be present in concrete as a result of the application of de-icing salts, exposure to a marine environment, airborne salt, or from the concrete constituents (eg, historical application of calcium chloride added as an accelerator to the concrete).

As a consequence of corrosion problems in service, most countries now prohibit the use of calcium chloride in reinforced and prestressed concrete. In Europe, the maximum permissible total chloride ion levels in fresh concrete are 0.4% (by weight of cement) for reinforced concrete and 0.1% for prestressed concrete. These limits apply irrespective of whether or not the concrete is exposed to external chlorides.

Once corrosion has commenced, the rate of corrosion is controlled by the ease at which oxygen enters the concrete and by the availability of moisture. The corrosion product forms a volume two to four times the volume of steel before it oxidises. Thus internal stresses can be induced in the concrete, eventually leading to cracking along the lines of the reinforcement, spalling of the concrete, loss of bond and reductions in the serviceability of a structural member.

**Performance specification**
In his presentation, ‘Performance Specification of Concrete in Chloride Environments’, John Broomfield discussed how the corrosion of steel in water solution was a function of hydroxide ion (OH–) concentration and pH level. He noted that chloride ions do not significantly affect the concrete chemistry, but at the steel surface they compete with OH– ions, that are vital to the formation of the passive layer.

In areas where voids in cement paste exist and OH– ion concentrations are low, corrosive pits can form. As illustrated in Figure 2, the threshold for corrosion is estimated to lie somewhere between 0.2 and 0.4% chloride by weight of binder, which is reflected within the current Standards.

There was a discussion on the latest formation of the European Standards for reinforced concrete durability. This highlighted how chloride durability specification to BS 8500-112 and the maritime works Code BS 6349-112 differ. Thereafter, the need to harmonise both Codes in order to promote a performance-based specification for chloride durability, stimulated great debate.

**Laboratory methods**
Michael Grantham of Sandberg discussed laboratory test methods that are used to determine chloride transport parameters in ‘Laboratory Methods to Determine Chloride Transport Parameters’. He outlined how the mechanisms of ingress can consist of absorption, permeation or diffusion, with the driving force consisting of surface tension, pressure or concentration gradient.

Both natural and electrically accelerated test methods were discussed and the usefulness of the measurements they derive, in characterising the performance of concrete in resisting chloride ingress, was summarised.

Discussions of immersion and migration test methods, and how they can be used to evaluate alternative concrete mix designs at the design stage, were presented. However, with respect to in-situ structures, it was noted that the determination of chloride ion profiles is key to evaluating the corrosion potential of steel reinforcement. Lastly, it was noted that these multi-point chloride contents can be used to generate a chloride profile. Thereafter, by a process of non-linear curve-fitting of this profile to Fick’s second law of diffusion, surface chlorides and a diffusion coefficient can be obtained. This coefficient can then be used in a ‘service life model’ for the structure and to estimate the time for chloride to reach the steel ‘initiation period’.

**Chloride transport resistance**
Mohammed Bashier of the University of Leeds explained in ‘Site Methods for Assessing the Chloride Transport Resistance of Concrete’ how an electric field hastens the ingress of chloride ions. Here it was outlined how this knowledge can be applied to carry out in-situ accelerated chloride migration testing of concrete, without the need to core
or drill for dust samples. The advantages and disadvantages of extracting dust samples as opposed to resistivity-type test methods, or the embedment of chemical sensors into new concrete structures, was discussed. It was outlined how the former allows for ‘multi-point’ sampling to be obtained but how the latter only facilitates a ‘single-point’ sample, while sensors can provide data at the steel–concrete interface.

Suggestions were made that single-point measurements of chloride content are useful for relative evaluation; however, for determining the rate of ingress of chloride ions, chloride profiles using multi-point measurements are preferable. Thereafter, a convective zone (0–20mm), as illustrated in Figure 3, needs to be given consideration while collecting dust samples and the method can only be performed on structures that have been exposed to chloride environments.

With respect to accelerated chloride migration tests, these can be performed on both new and existing structures. Limitations do exist with these types of test methods and if applied on-site, they are not ‘non-destructive’. Finally, with respect to the application of indirect test methods, such as the ‘Wenner four probe’ resistivity test method or the use of ‘embedded electrical sensors’, unless the pore structure is fully saturated, the data are not very useful.

**Modelling of chloride transport**

Sreejith Nanukuttan of Queens University Belfast described in ‘Modelling of Chloride Transport and Implications to Service Life Predictions’, the complex process of modelling chloride durability of concrete and how it is now possible to do this with reasonable accuracy. He discussed how researchers are aiming to reduce the need to use up-to 40 different input variables, to a number that will make models more user-friendly to the practicing engineer (Figure 4). In conclusion, he stated that provided the model used is validated, then porosity, chloride-binding parameters, diffusivity, temperature and surface chloride concentrations are the most critical parameters.

**Industrial case studies**

Drawing on the previous presentations, David Dunne of AECOM outlined in his presentation ‘Industrial Case Studies’ how industry is applying the latest technologies, to ensure that the infrastructure that is designed today can withstand the test of time. He initially presented typical chloride-induced durability defects associated with highway structures (Figure 5), costs, and issues associated with ongoing intervention measures. Thereafter, case studies of three recently completed chloride durability specifications were discussed and compared. Their geographical locations are presented in Figure 6.

He noted how premature deterioration of reinforced concrete structures, in salt-laden environments, has resulted in a lack of confidence in deemed-to-satisfy design codes. However, he also noted that while modelling is a useful tool to support the decision-making process, it will only fully develop in usefulness as greater knowledge of its input parameters evolve, rendering prescriptive measures less necessary. Furthermore, he explained that deterministic models can be deceptive in this respect as they give a single output value, often expressed with a high degree of precision, but in reality carrying a low degree of accuracy.

On a positive note, he concluded that by working collaboratively, the structural
and material engineers can ensure that the new structures of today will be there for generations to come.

**Challenges for characterisation**

The final presentation – ‘Challenges for the Characterisation of Chloride Transport of Novel Cement Systems’ – by Yun Bai of University College London, discussed the challenges of characterising the chloride transport properties of novel cement systems. Expanding on the previous presentations, he noted that the measurements obtained from migration-type tests are not only dependent on the pore structure of cementitious materials but also on the electrical conductivity of the pore solution. This is of particular importance when using novel cement systems, where they usually have different raw materials, hydration mechanisms and pore solution chemistries to that of Portland cement-based systems.

He presented a pH cement toolbox (Figure 7), which outlined the pH differences of these non-Portland-cement-based systems. He posed two interesting unanswered questions to the delegates: (i) are migration-type accelerated test methods suitable when comparing the performance of Portland cement-based cementitious materials to that of novel cement systems; and (ii) are migration-type accelerated test methods suitable when comparing the same novel cement system with different formulations?

**Concluding remarks**

Overall, when considering the volume of reinforced concrete structures worldwide, concrete infrastructure is performing well. However, due to the important nature of its applications, any durability issues that result in visual defects, or require intervention works, will continue to impact upon end users and operators. This will only drive the perception that reinforced concrete structures are failing to service the requirements of the industry and, no matter how large or small a defect may be, overall discernment will remain.

In promoting a sustainable approach to design and construction within the industry, seminars such as these are vital to ensure that knowledge from all fields of civil engineering is disseminated to those at the front line in industry. These knowledge transfer activities will help ensure that future infrastructure maintenance needs and associated costs will continue to be reduced.

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**References**
