DANISH EXPERT CENTRE FOR INFRASTRUCTURE CONSTRUCTIONS

Newsletter no. 2, September 2012

Introduction

The Danish Expert Centre for Infrastructure Constructions was established ultimo 2010 as a performance contract signed between the Danish Ministry of Science, Technology and Innovation and the Danish Technological Institute. The contract runs until the end of 2012 and involves a close cooperation between Danish Technological Institute and DTU·Byg (Technical University of Denmark).

All the research activities carried out in the Expert Centre is essentially concerned with durability aspects of reinforced concrete subjected to severe environmental conditions, e.g. bridges and tunnels exposed to seawater.

This second newsletter summarizes the most important findings and activities undertaken in the Expert Centre since the first newsletter was published in September 2011.

Development of properties

In 1977, Freisleben-Hansen and Pedersen [1] proposed a function that is able to compute a maturity index based on a recorded temperature history of a hardening concrete. The function – commonly referred to as the maturity function – allows for a conversion of the actual age of the concrete to an equivalent maturity age at a reference temperature (20°C). Since the function was introduced in the late 1970’s it has been extensively used in Denmark for predicting the development of properties of hardening concrete.

However, as a consequence of advances in concrete technology, mainly the introduction of supplementary cementitious materials such as fly ash, silica fume and slag in almost every concrete composition used for civil engineering structures, the underlying data for the Maturity function has become outdated. A comprehensive test series has been undertaken in order to investigate the applicability of the maturity concept to modern concretes exposed to aggressive environments. This involved an examination of the influence of the curing temperature on the development of properties such as compressive strength and resistance against chloride ingress.

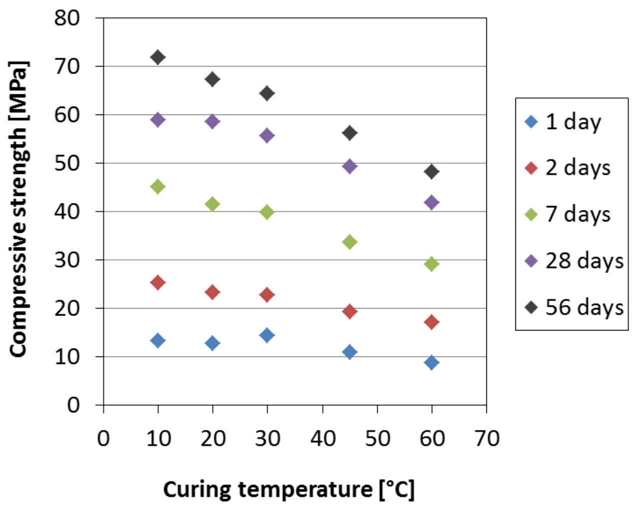

Figure 1: Compressive strength as a function of curing temperature and curing age (in maturity days) for concrete with a binder of sulphate-resistant Portland cement (CEM I, 42.5 N). The measured data for each maturity age would lie on a horizontal line in the case of a perfect match between the measured data and the strength development predicted by the maturity function of Freisleben-Hansen and Pedersen [1].

The main experimental program involved the curing of five types of concrete at five different temperatures (10, 20, 30, 45, and 60 °C). The five examined concrete types were based on the following binders:

- Portland cement (CEM I, 52.5 N)
- Sulphate-resistant Portland cement (CEM I, 42.5 N)
- Portland cement (CEM I, 52.5 N) + 25% fly ash

- Sulphate-resistant Portland cement (CEM I, 42.5 N) + 25% fly ash
- Slag cement (CEM III/B)

Preliminary results have shown that the measured development of compressive strength for concrete cylinders cured at the five above-mentioned temperatures does not correspond well with the strength development predicted by the maturity function, at least not for compressive strengths above approx. 35 MPa or a curing temperature of 60 °C.

As an example, Figure 1 displays the measured strength development for concrete with a binder consisting of sulphate-resistant Portland cement. The observed discrepancy between measured and predicted strength development is not equally pronounced for all of the studied binder systems, but the obtained results generally indicate that the original maturity function probably needs to be revised in order to be consistent with the types of concretes used nowadays.

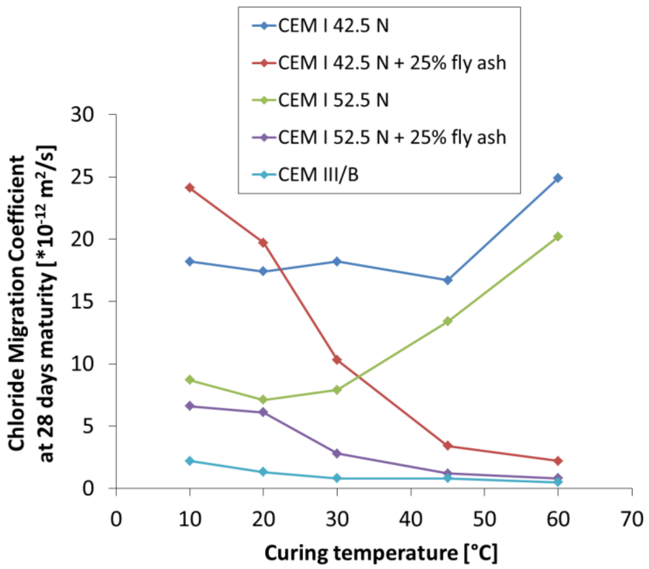

Figure 2: Chloride migration coefficient (at 28 days maturity) as a function of curing temperature for five different binders. The migration coefficients where obtained according to the procedure in NT Build 492.

The investigations have also revealed some very interesting and surprising behaviour regarding to the chloride migration coefficient (CMC): For pure CEM I concretes, the CMC at similar maturity increases with increasing curing temperature, whereas the opposite is observed for the fly ash concretes, i.e. the resistance to chloride ingress is greatly improved for fly ash concrete by high-temperature initial curing (Fig. 2).

Currently, a supplementary test series is being carried out with the purpose of validating the findings from the initial test series.

Chloride binding

It is well-known that when chloride ions ingress into concrete (Fig. 3) part of the penetrating ions becomes fixed to the cement paste hydrates. This phenomenon is commonly referred to as chloride binding and is important in connection with chloride-induced reinforcement corrosion, since the binding of chlorides reduces the amount of free chlorides available in the pore solution for initiation of reinforcement corrosion.

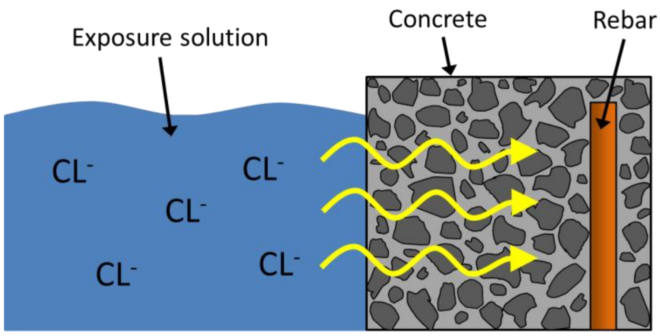

Figure 3: Schematic illustration of the ingress of chloride ions from an exposure solution (e.g. seawater) into a reinforced concrete structure.

A modeling tool for quantification of chloride binding and for prediction of pore solution chemistry in concrete has been developed in the Expert Centre. The prediction tool is based on an existing model, which was originally developed in a PhD project at DTU [2]. However, the work carried out in the Expert Centre has resulted in a significant expansion of the model, which can now be applied to a much wider range of binder compositions, e.g. binders with a high content of fly ash or ground granulated blast-furnace slag.

The model allows a ranking of different binder systems in terms of the ability to ensure a low $[Cl^-]/[OH^-]$ ratio in the pore solution, a parameter generally known to be very important for the initiation of reinforcement corrosion.

Currently, a series of experiments is being carried out in our laboratory, which will hopefully result in a validation of the developed prediction tool. In these experiments samples of crushed concrete with various binder compositions are mixed with artificially prepared pore solutions containing different concentrations of chloride and alkali (Fig. 4).

After mixing the samples are left for approximately three months in order for equilibrium conditions to be achieved. At this point the chemistry of the pore solution will be measured and subsequently compared to prediction from the modeling tool. These measurements are scheduled for October 2012.

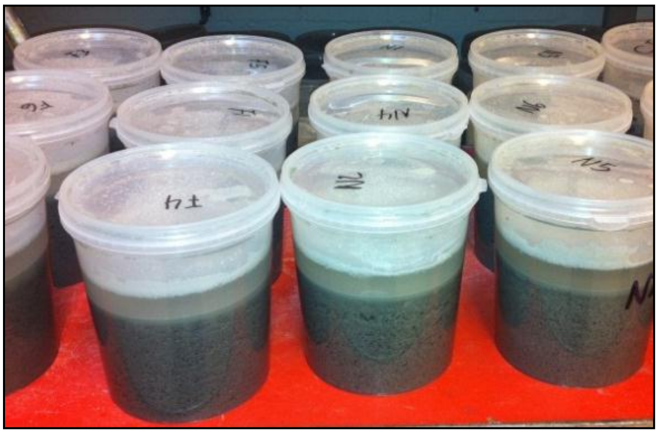

Figure 4: Samples of crushed concrete mixed with artificial pore solutions prepared with different concentrations of chloride and alkalis.

Chloride threshold values

A crucial input parameter for modeling of the service lifetime of reinforced concrete structures is the so-called chloride threshold value, which may be defined as the minimum concentration of chloride at the depth of the reinforcement that is able to initiate corrosion of the steel. Without an experimentally determined chloride threshold value, engineers are generally forced to make rather conservative estimates of this value, thus potentially underestimating the service lifetime significantly.

Part of the research carried out at the Expert Centre is focused on the experimental determination of chloride threshold values for reinforcement corrosion, and the Centre is currently participating in a Round Robin test of a newly proposed method from a RILEM group (TC 235 CTC) working on the development of a commonly accepted test method for determination of chloride threshold values.

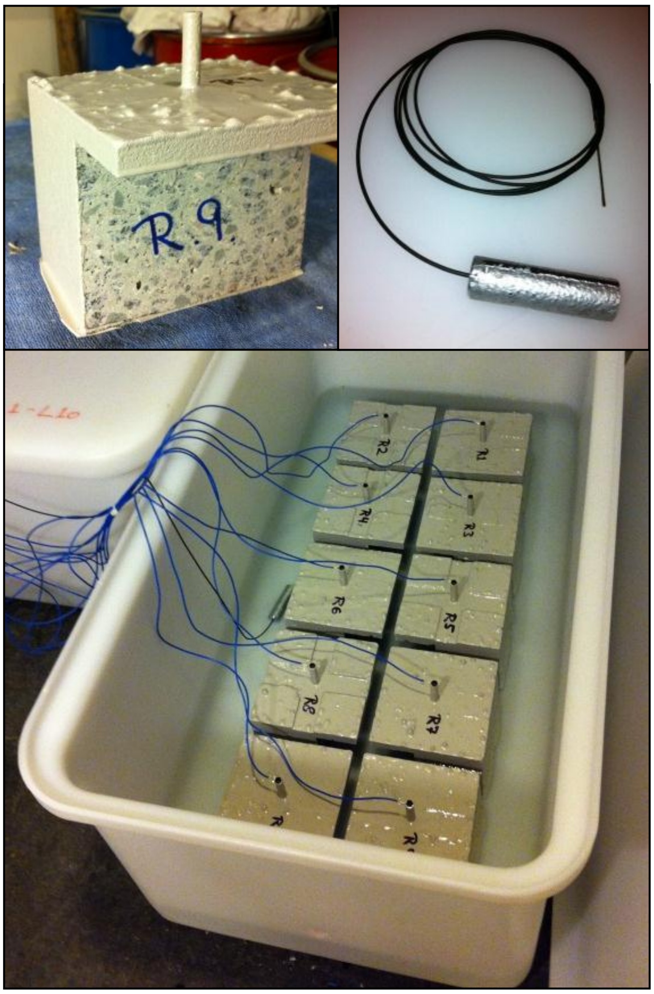

Figure 5: Example of partially epoxy-coated concrete specimen with a cast-in rebar (top left), reference zinc electrode for measurement of electrochemical potentials (top right), and experimental setup with ten concrete specimens exposed to at 3.3 wt% NaCl solution in a plastic tank (bottom).

The basic concept of the proposed test method is to expose a series of concrete specimens, each containing a reinforcement bar, to a chloride solution (Fig. 5) and continuously measure the electrochemical potential of the reinforcement bars against a common standard reference electrode. Onset of reinforcement corrosion is identified by a significant drop in the measured potential.

The concrete specimens were exposed to the chloride solution in the beginning of February 2012 and initiation of reinforcement corrosion was originally expected to occur within a few months. However, initiation of corrosion has not been detected at the time of writing, despite an exposure time of more than seven months.

Most recently, a student from DTU has initiated his MSc thesis project, which primarily will focus on the development of an accelerated test method for determination of chloride threshold values in concrete. The basic idea is to develop an experimental setup in which high pressure is utilized to accelerate the ingress of chloride in concrete samples with cast-in rebars. The project arose out of discussions between Rambøll A/S and the Expert Centre.

It should also be mentioned that initiation of reinforcement corrosion has recently been detected on instrumented concrete blocks at the marine exposure site at Rødbyhavn (see description below). The content of chloride at the depth of the reinforcement has been measured shortly after the detection of corrosion, thus giving the chloride threshold value for the exposed concrete. The results from these investigations will be available on the Expert Centre's website (www.concreteexpertcentre.com) in the near future.

Long-term durability of concrete

Another important part of the Expert Centre's activities involves the investigation of the long-term durability of concrete structures in marine environments. In this connection, cored samples from a number of Danish bridges (e.g. Old Little Belt Bridge, Vejlefjord Bridge, Alssund Bridge, the Farø Bridges and the Øresund Bridge) have been collected and investigated by various microscopic methods. In addition, detailed chloride profiles have been measured by profile grinding.

The results from these investigations are currently being evaluated and will be presented at the forthcoming meeting with the reference group in November 2012.

The over-all aim of the study is to understand and quantify the chemical processes that take place during long-term exposure to a marine environment, and to use this knowledge to validate the interpretation of short term observations for the predictions of long-term performance.

Exposure site at Rødbyhavn

In connection with the planned Fehmarn Belt Fixed Link between Denmark and Germany an exposure site has been established in 2010 at Rødbyhavn harbour in Denmark for long-term testing of various types of concrete exposed to sea-water (Fig. 6). This offers a unique opportunity to study and compare the influence of seawater exposure for a wide spectrum of concrete types.

Results from microscopic investigation of the partially submerged concrete blocks at the exposure site are used as an integrated part of the research in the Expert Centre.

Figure 6: Series of concrete blocks partially submerged in seawater at the exposure site at Rødbyhavn habour in Denmark.

So far, the study has revealed the occurrence of three discrete zones when examining the specimens from the exposed concrete surface and inwards. Generally speaking, the zones are characterized by being enriched in magnesium, sulphate and chloride, respectively. This phenomenon has been observed for all the investigated types of concrete.

Presently, samples collected after two years of exposure are being thoroughly examined, e.g. by various microscopic techniques. The results from these investigations will appear on the Expert Centre's website (www.concreteexpertcentre.com) in the near future.

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Critical details during construction

As reported in the previous newsletter, a testing program has been carried out with the purpose of investigating the influence of casting defects and unavoidable structural weaknesses on durability, e.g. cold and "warm" casting joints, poker vibrator tracks and reinforcement spacers.

A leaflet (in Danish) presenting the results from these tests has recently been prepared (Fig. 7). If you are interested, the leaflet can obtained by contacting:

Anita Rasmussen, DTI, Tel: +45 7220 2227 or e-mail: anc@teknologisk.dk.

Figure 7: The results from a testing program regarding the influence of critical details on concrete durability has been summarized in a leaflet, which is now available for requisition.

DTU projects

Developing service life modeling of concrete

The DTU group of the Concrete Expert Centre is mainly focusing on the development of advanced service life models for concrete. The research conducted in the group will bring DTU·Byg among the leading research institutes of this area. Broad collaboration is sought with international research institutes and industry partners.

The DTU group is currently working together with colleagues from Stanford University, USA and NTNU, Norway to discuss how to meet future problems in maintenance of concrete structures. Some of the outermost visions discussed in the group is e.g. monitoring of the "structure health" to feed service life models and keep them updated in a real-time approach, as seen in e.g. seen airplane maintenance programs.

Another idea is the use of extended BIM models as a base for complete life cycle modeling and analysis. The ideas discussed in this forum reflect ambitious visions of how to manage large infrastructure concrete structures in the future.

Modeling of chloride diffusion and 50 other important ions in concrete pore solution![1]

Chloride diffusion and binding is often detailed described in service life prediction but often the interaction with the complex pore solution is neglected. Some of the interactions are studied in the PhD project "A Coupled Transport and Chemical Model for Durability Predictions of Cement Based Materials" and combined in an advanced service life prediction model with a high level of detail.

The new service life model is based on the well-established hybrid mixture theory, which is a modern tool used within descriptions of porous media. The model is based on an extended version of the Poisson-Nernst-Planck equations, where each constituent in the pore solution is described individually, by diffusion properties, migration properties and chemical reactions. Chemical equilibrium among the constituents is established by defining an unlimited number of reaction schemes together with their solubility products. At this stage of the project more than 50 ionic complexes are used in the test simulations. The

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solid matrix is similarly described using reaction schemes, in order to determine the chemical degradation over time, more than 30 solid constituents are included and more will be added in the future, to improve the accuracy of the model.

Chloride binding described by electrical double layer theory
Chloride binding is a chapter on its own within concrete technology, a new promising research results in this respect have been developed by the leading research team at Taiheiyo Cement, Japan, together with researchers at Université de Bourgogne. In this work, part of the chloride binding is considered to be in the electrical double layer of the CSH surface. A set of surface reaction sites determines the surface charge to which the chloride ions are bound. Using this model approach enables the account for Na and K interactions which in many cases are neglected. The ions bound in the double layer are assumed immobile and therefore not considered in the mass transport calculation.

Partial saturation and sorption hysteresis modeling
The degree of saturation in concrete is controlled by the sorption hysteresis effect, which is a time/history depended function. The saturation degree is of great interest with respect to the constituent concentration and further the effect on the chemical equilibrium state. Sorption hysteresis is taken onto account by a set of measured boundary isotherms, making it possible to model the scanning curves within these boundaries.

The outcome of the PhD project will be a complete coupled model as an attempt to make physically based predictions, using a multi-physics modeling. The model used in this PhD project link a number of specialist models into a single model in order to evaluate the status, need and capability of multi physical models within concrete science. We believe that this kind of multi physics model will play an important role within service life prediction in the future.

Numerical Modeling of Reinforcement Corrosion in Cracked Concrete[2]

One of the most important, but not fully understood, deterioration mechanisms in concrete structures is reinforcement corrosion. Consequently, vast investments are made to ensure the durability of concrete structures, particularly with regard to reinforcement corrosion. To better understand reinforcement corrosion and thereby the durability of concrete structures the PhD project "Numerical Modeling of Reinforcement Corrosion in Cracked Concrete" was established. The work is focusing on the modeling of mechanically induced cracks in order to describe the initiation stage of corrosion. Also further developing of an existing deterministic corrosion model, which primary describes the propagation stage, is a focus area in the project.

Modeling of corrosion-induced cracking
Corrosion-induced cracking has been studied to a great extent. Although it is seen in experiments that the corrosion products form unevenly around the re-bar and penetrates into the concrete, the majority of the current models do not take this phenomenon into account. Therefore the existing corrosion model, which simulates the radial expansion of uniform corrosion and the propagation of a predefined corrosion-induced crack, is being taken a step further by including these mechanisms in the modeling scheme.

So far the penetration of the corrosion products has been included in the model and currently the non-uniform formation of corrosion products is being modeled. As a first step the modeling of non-uniform corrosion is simplified to investigate the influence of this mechanism on the time until the predefined crack reaches the surface. Later a probabilistic description of non-uniform corrosion as well as the initiation and propagation of more than one crack will be included.

Modeling crack formation induced by static and/or dynamic loads
The influence of structural defects on corrosion, including defects on the surface of the re-bar and cracks in the concrete are also to be studied as it is by now widely recognized that defects in the re-bar/concrete interface have a profound influence on the susceptibility of the rebar to corrosion.

It is believed that particularly the debonding between reinforcement and concrete, appearing where reinforcing bars cross a concrete crack, has a significant influence on the risk of corrosion initiation and propagation and therefore the mechanical modeling has been initiated with a study of the debonding length. The theory of the fictitious crack is used to describe the crack propagation in the concrete and at this point the results show that there is a non-trivial relationship between the debonding length and the crack mouth opening displacement (CMOD) and therefore the CMOD cannot be used alone as corrosion risk indicator which is the current assump-

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tion. This study is ongoing and simulations will later be verified with experimental results.

Perspective

By using the information of the propagation of mechanically induced cracks as boundary conditions in the corrosion modeling a probabilistic service life model for cracked reinforced concrete will be established. The idea is to use the established model for development of a basis for a new service life design approach for reinforced concrete structures as the included mechanisms contribute to the understanding of the durability of a structure. The basic concept for this new framework is to define service life from a critical corrosion condition or a critical corrosion rate rather than a critical chloride concentration, which forms the basis of existing service life models.

Future activities

The research activities of the Expert Centre will terminate at the end of 2012. However, Danish Technological Institute and DTU Byg intend to continue the established collaboration regarding concrete durability in some yet to be defined format, possibly through a EU-funded project under Horizon 2020.

The next and final meeting with the reference group is scheduled for November 30, 2012.

Contact

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Website

For further information about the activities carried out in the Expert Centre, please visit our website at:

www.concreteexpertcentre.dk.

References

[1] Freisleben-Hansen, P. and Pedersen, J. Maturity Computer for Controlled Curing and Hardening of Concrete. Nordisk Betong, 1, 1997, 19-34.

[2] Nielsen, E.P. The durability of white Portland cement to chemical attack. PhD thesis R-084, DTU·BYG, 2004.