Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)
ⓒ 2010 Korea Concrete Institute, Seoul, ISBN 978-89-5708-181-5

Life cycle management of concrete structures with respect to reinforcement corrosion and concrete deterioration
Part I: birth certificate

T.F. Mayer
S+R Sensortec GmbH, Munich, Germany

C. Sodeikat & A. Schiessl-Pecka
Ingenieurbuero Schiessl Gehlen Sodeikat GmbH, Munich, Germany

ABSTRACT: On the background of scarce public resources, life cycle management of infrastructure systems has gained increasing importance. This paper presents the core components of a state-of-the-art life cycle management system for newly-completed structures. A service life design is one of the key elements. Depending on the governing deterioration mechanisms, it can be carried out on different levels of detail. Quality control tools during construction and after completion allow for an assessment of the actual quality of the structure. The results of the design and construction stage are then summarized in a so-called birth certificate which forms the basis for future inspection and maintenance planning. The use of monitoring data gathered during the use of the structure to update the original service life design is demonstrated in part II of this paper.

1 INTRODUCTION

The repair of damages on infrastructure systems, which are due to an inadequate concrete cover, inappropriate choice of construction materials or neglecting of the actual exposure conditions, causes annual costs of more than 250 Mio. € in Germany alone. Despite the major importance of durability aspects for the maintenance of structures, the durability design of newly built structures is still chiefly carried out according to empirical 'deemed-to-satisfy' approaches. However, the development of full-probabilistic service life models nowadays allows for a durability design with consideration of both the actual environmental stresses and the material resistances (Gehlen 2000). The parameters to describe the material resistance can be determined during compliance testing and the uniformity of the concrete can be checked continuously during the construction stage and after the structure is completed. The material resistance parameters together with inspection results during the use of the structure, which will yield additional information on the structure-environment interaction, can then be implemented to update and improve the original service life prognosis.

Service life design, quality control during the construction and after completion, cyclic inspections during the use and planning tools for scheduling of maintenance/repair measures are the core elements of modern life cycle management systems (LCMS) for reinforced concrete structures (Gehlen et al. 2008). The different steps to be carried out during planning and construction stage are displayed in Figure 1 and will be described in detail in the following sections. Their results will be summarized in a so-called birth certificate which forms the basis for future inspection and maintenance planning.

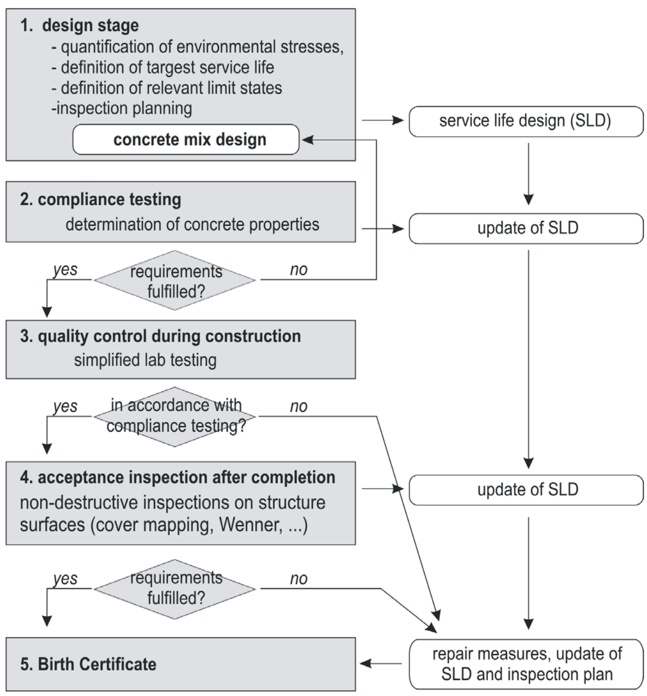

Figure 1. Flowchart for the development of a birth certificate.

2 CORE ELEMENTS OF A LIFE CYCLE MANAGEMENT SYSTEM

2.1 *Service life design*

The service life design forms the core element of every LCMS. Depending on the complexity of the structure, the deterioration mechanism and the owner's requirements it can be carried out on different levels of detail, as for instance:

- full probabilistic service life design
- semi probabilistic service life design (partial safety factor approach)
- ‚deemed to satisfy' approach
- avoidance of damage/environmental stresses

Further information on the different levels of detail can for instance be found in the fib Model Code for Service Life Design (2006). For deterioration mechanisms as ASR or freeze-thaw-attack a service life design can only be carried out according to 'deemed to satisfy' approaches or by avoiding any environmental loads, as there are currently no adequate deterioration models available. For carbonation-induced and chloride-induced reinforcement corrosion however, sufficiently well validated, full probabilistic design approaches are available. They have already been applied successfully over the last decade, as for instance for the Western Scheldt tunnel in the Netherlands, the parking garage of the Allianz Arena in Munich or currently the Qatar-Bahrain-Causeway, an appr. 40 km long bridge system between Qatar and Bahrain which is scheduled to be executed within the next few years (Breitenbücher et al. 1999, Mayer et al. 2008). Accordingly, the main focus of this paper is set on these full probabilistic service life design approaches. As a result, for every limit state under consideration (i.e. depassivation of reinforcement due to chloride ingress) these approaches will yield a certain failure probability p_f and a corresponding safety index ß over the remaining service life. The failure probability p_f indicates the probability that this specific limit state will be exceeded at time t.

The following example is intended to illustrate the general procedure of full probabilistic service life modelling: The parking deck of a parking garage was constructed with concrete (CEM I, w/c = 0.50) without any additional surface coatings. This concrete displays a comparably high chloride migration coefficient of appr. 15.8×10^{-12} m²/s and thus a relatively low chloride diffusion resistivity. The parking deck was constructed with a nominal concrete cover of c_{nom} = 55 mm and an average scatter of the concrete cover of s = 6 mm (normal distribution). The chloride load can be assumed from comparable structures to be app. 2.0 M.-%/cem (Raupach et al. 2007, Gehlen et al. 2008). The limit state under consideration is the depassivation of the reinforcement surface due to chloride ingress. The model of Gehlen (Gehlen 2000) is applied to model the time-dependent chloride ingress into the concrete. This model yields a probability that the limit state will be exceeded (i.e. that the reinforcement will be depassivated and start to corrode) of 47 % at the end of the target service life of 50 years. The development of the failure probability p_f and the reliability index ß with time are displayed in Figure 2.

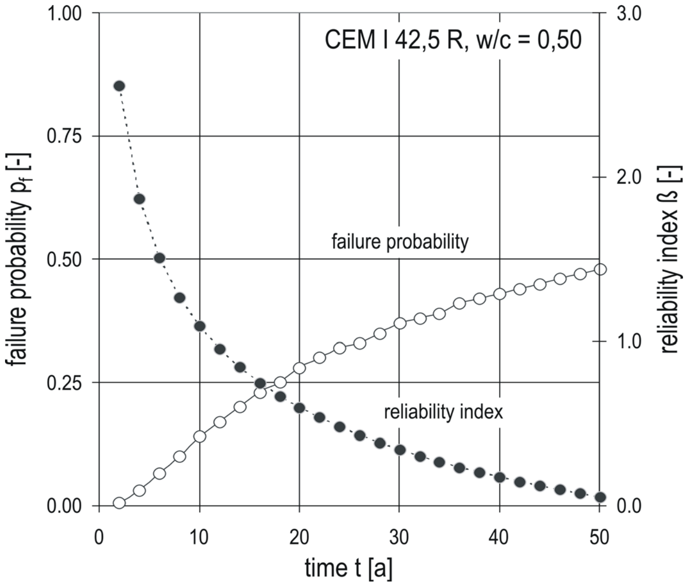

Figure 2. Reliability index and failure probability with respect to chloride induced corrosion (CEM I, w/c = 0.50).

For the limit state under consideration a reliability index ß ≥ 0.5 is normally postulated at the end of the target service life (Gehlen et al. 2009). As the postulated reliability index is not obtained, the next step in the durability design would be an increase of the chloride diffusion resistance by changing the concrete composition, increasing the concrete cover or reducing the chloride load by means of constructive measures (e.g. surface coating).

2.2 *Potentials of concrete composition optimization*

One of the major advantages of the approach presented in this paper is the opportunity to assess the effects of changes of the concrete composition on the expected service life and thus exploit the optimization potentials offered by concrete composition optimization. As an example the influence of the binder type and the water/binder ratio on the chloride migration coefficient – the key parameter to describe the chloride transport into concrete – is displayed in Figure 3 (Schiessl & Lay 2004).

Assessment tools like this are gaining increasing importance, as the high CO_2 emission for the portland cement clinker production is leading to an increased use of CEM II and CEM III cements rather than pure CEM I portland cements. The effects that a change of the binder in the above example (use of a Portland composite cement CEM II/B-M (S-LL) or a Portland slag cement CEM III/A instead of a Portland cement CEM I) would have on the reliability index are displayed in Figure 4. Even the comparably low slag contents of a CEM II/B-M (S-LL) will lead to a significant increase of the reliability.

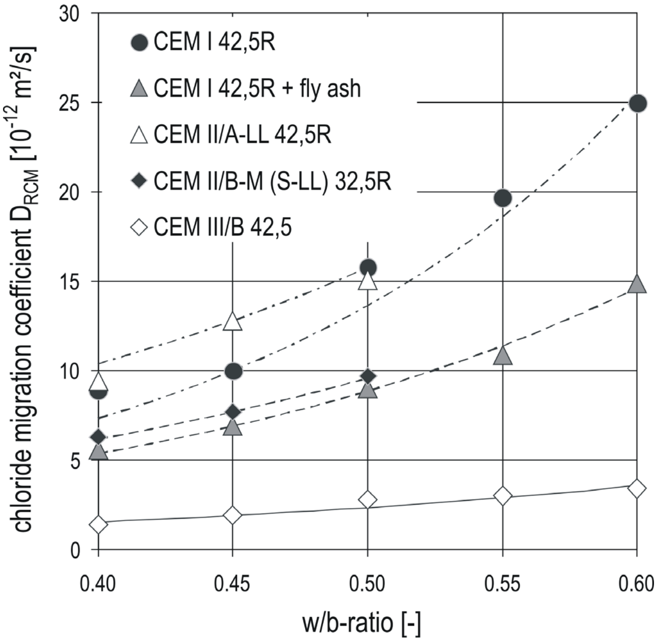

Figure 3. Influence of binder type and water/binder ratio on the chloride migration coefficient $D_{RCM,0}$ at t = 28 d (Schiessl & Lay 2004).

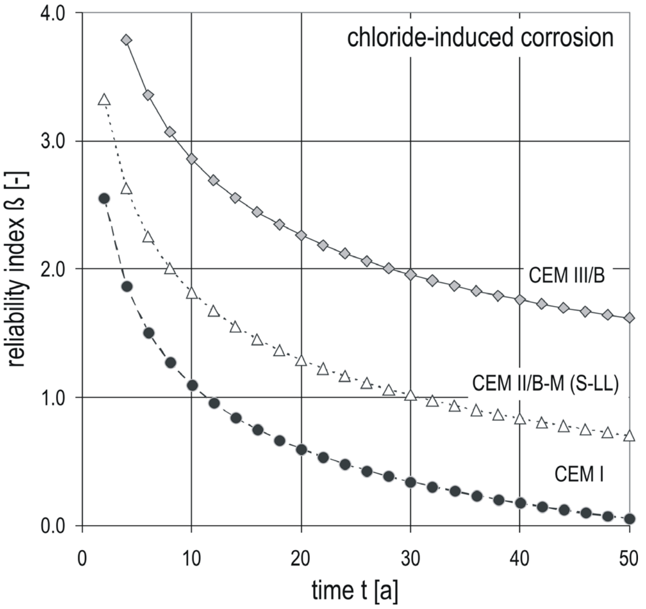

Figure 4. Influence of the binder type on the safety index ß with respect to chloride-induced corrosion.

It has to be kept in mind that the optimisation of the concrete composition can only be carried out under consideration of all durability aspects. Large fractions of pozzolanic or latent-hydraulic components in the binder may lead to an increase of the chloride diffusion resistance or the resistance towards chemical attack, but on the other hand to a decrease of the carbonation resistance or the freze-thaw-resistance. The influence of the binder type on the reliability index ß towards carbonation induced corrosion is displayed in Figure 5 for the three different types of binders (CEM I, CEM II/B-M (S-LL), CEM III/B). One possible result of the concrete optimization is the choice of a concrete composition that will safeguard an adequate durability with respect to all possible environmental stresses.

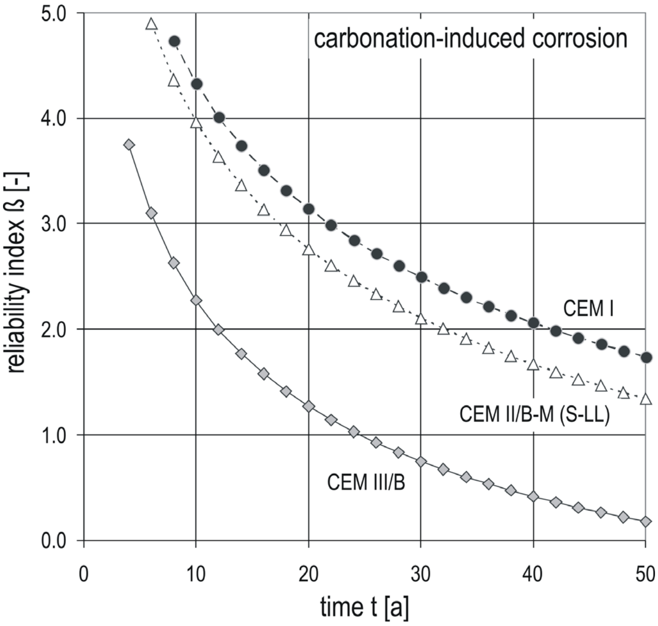

Figure 5. Influence of the binder type on the reliabilty index with respect to carbonation-induced corrosion.

2.3 *Compliance testing*

The service life design has been based on assumptions both concerning the environmental stresses and the relevant material parameters. However, even for cements of the same type, but from different cement plants these parameters can vary significantly. Therefore it is advisable to determine the governing concrete properties of the concrete mix to be used and check their compliance with the target values postulated during the design stage. This stage is referred to as 'compliance testing'. Test methods used for compliance testing are intended to give a direct and reliable quantification of the concrete characteristics. Therefore, indirect test methods such as electrolytic resistivity measurements in order to quantify the chloride diffusion properties of concrete are considered to be inadequate. However, the slow progress of deterioration mechanisms as for instance carbonation calls for accelerated test methods in order to gain reliable results within a comparably short time period. Therefore, rapid chloride migration testing and accelerated carbonation testing have been established as standard procedures for quantification of chloride migration and carbonation properties respectively (Gehlen 2000, Tang 1996). For freeze- and freeze-thaw-exposure CDF- ('capillary suction of de-icing solution and freeze thaw test') and CIF-test ('capillary suction, internal damage and freeze thaw test') appear to be adequate test methods. Due to the lack of deterioration models for these mechanisms, durability design with respect to freeze- and freeze-thaw-impact is still limited to 'deemed-to-satisfy' approaches (Schiessl & Mayer 2007).

The results of compliance testing can be used for a first update of the original deterioration prognosis. If the concrete properties determined in the tests are not sufficient to satisfy the requirements specified during design stage, an adjustment of the original concrete mix design has to be made or changes in the structural design itself (increase of concrete cover, application of coating) have to be considered. The integration of a monitoring system will not directly lead to an increase of the structural reliability, but it will enable the owner to continuously observe the current condition state of the structure while it is in use. In case the monitoring results indicate an unwanted condition state, corresponding rehabilitation measures can be scheduled in time. Therefore monitoring can be considered as an alternative, as well. Further information on this topic can be found in part II of this paper.

2.4 *Inspection planning*

Another major advantage of the predictive life-cycle-management approach developed in this paper is the possibility to regularly update the original service life design with the results of inspections carried out directly after the structure is completed or during the service life of the structure. While the inspection directly after completion will only render information on structural and material properties, the inspections while the structure is in use will enable the owner to assess the actual environmental loads and the structure-environment interactions. Thus, inspections and inspection planning play a vital part in the life cycle management.

The inspection plan has to be formulated during the design stage already. It contains specifications concerning the parameters to be assessed, the inspection methods and the inspection intervals. The use of non-destructive testing methods as for instance corrosion potential mapping, concrete cover mapping or the determination of carbonation depth and chloride profiles is essential for a predictive life cycle management, as visual inspections alone - as they are still common today – will only allow to identify potential damages once they are already visible on the concrete surface. At this stage, the range of possible rehabilitation measures is normally already very limited.

There are two possibilities for the definition of inspection intervals:

Adaptation of the inspection intervals according to the predicted condition state development of the structure,

1. Constant inspection intervals and adaptation of inspection methods/extent according to the predicted condition state development of the structure.

The second approach appears to be more reasonable, as the responsibilities for the inspections are defined more clearly. In Germany, the normal inspection intervals according to the German standard DIN 1076 are three and six years, respectively. In order to reduce the inspection costs, a multi-stage procedure is most cost-effective (Schiessl et al. 2007). During the first stage, comparably simple inspection methods with a small inspection extent are chosen. These tests are for orientation purposes, so fairly conservative threshold values should be applied to make sure that no critical state of the structure can be missed. If these threshold values are not exceeded, no further inspections are necessary. If they are exceeded, more sophisticated and complex test methods (and correspondingly less conservative threshold values) should be applied on the next stages.

In addition to cyclic inspections of the structure monitoring systems can be installed. Monitoring sensors are particularly useful in areas which can only be inspected with a considerable effort, or in structural elements which require closer attention either because they are subjected to very high environmental loads or they are of major structural importance. There are both sensor systems for the installation during the construction phase and for the installation while the structure is already in use. Further information on the sensor systems, the use of the sensor data for the update of the service life design and examples for monitoring systems as elements of a life cycle management system are presented in part II of this paper.

2.5 *Quality control during the construction phase*

Compliance testing is used to verify that the concrete meets the requirements when produced and tested under lab conditions. Unfortunately, the properties of the concrete produced in the concrete plant or on site can differ significantly from concrete produced in the lab. To become a valuable tool for the quality control during construction, the birth certificate also has to provide test methods in order to control the regularity of the concrete used on site.

It is obvious that for quality control purposes simple, easy-to-use test methods have to be chosen that can be included in the regular control procedures which have already been established for compressive strength testing. Electrolytic resistivity measurement appears to be an adequate test method as it can be conducted on the same concrete cubes already produced for compressive strength testing. Even though the electrolytic resistivity was classified as inappropriate for compliance testing, it is sufficient to assess the regularity of the concrete production. Test series conducted earlier indicated that once the characteristic properties of the concrete with respect to the prevailing exposure classes have been identified, the electrolytic resistivity can be used as a conformity indicator for concretes exposed to chloride ingress, carbonation, freeze- and freeze-thaw-attack. Different test methods can be used for the determination of the electrolytic resistivity. Among them, the Wenner-probe-method and the two-electrode-method are the most common ones (Büteführ et al. 2006, Polder 2001).

In order to gain a correlation between the resistivities measured on site, the results of the quality control during construction and the results of the compliance testing, the actual moisture content of the concrete at the time of measurement has to be taken into account. For this purpose, Figure 6 displays a possible test procedure which consists of five test stages:

1. Electrolytic resistivity measurement on lab specimens during compliance testing (water stored),
2. Electrolytic resistivity measurement on lab specimens during quality control (water stored),
3. Electrolytic resistivity measurement on lab specimens at time of acceptance inspection (lab specimens stored under water for 28 days and on site afterwards – test series A),
4. Electrolytic resistivity measurement on lab specimens at time of acceptance inspection (lab specimens stored under water for the required curing period and on site afterwards – test series B) and comparison with the results of test series A in order to determine the influence of curing,
5. Electrolytic resistivity measurement on surfaces of the structure at time of acceptance inspection (test series C) and comparison with results of the test series B in order to determine the influence of the execution quality.

This quality control procedure is comparably time-consuming and expensive, but it gives a complete control and documentation of the execution quality. If these measurements yield deviations from the expected quality, corresponding rehabilitation measures can be taken even before the structure is in use.

2.6 *Quality control after completion*

The inspections carried out after the completion of the structure resemble the classical acceptance inspection. The major difference is that the deterioration modelling carried out during the design stage allows for a more durability-oriented inspection planning. In contrast to inspections performed while the structure is already in use, quality control directly after completion yields no information about the environmental stresses that the structure is subject to or structure-environment interactions, so that only the structural resistance can be assessed. Therefore, a number of inspection techniques as for instance potential mapping, determination of chloride profile etc. cannot be used at this early stage in the life cycle of the structure. Depending on the exposure of the structural elements, non-destructive techniques to be used for quality control are for instance concrete cover mapping, electrolytic resistivity measurements or crack mapping. As concrete cover is one of the key parameters for the time until depassivation both due to chloride ingress and carbonation, large parts of the concrete surfaces should be inspected. If for some reason this is not possible, at least small fractions of every element should be checked to make sure that systematic errors can be excluded.

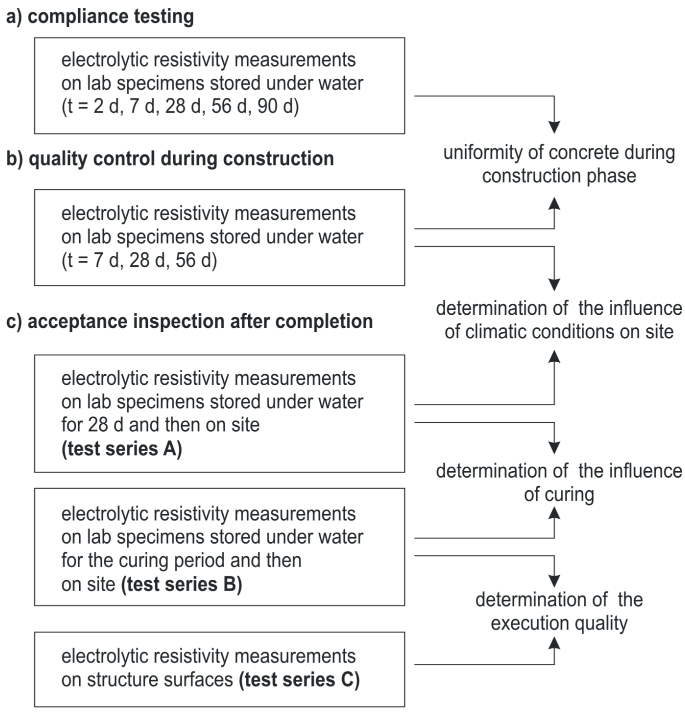

Figure 6. Electrolytic resistivity test procedure to determine the execution quality during and after construction.

The use of the torrent permeability test to assess the surface quality is confined to very dry surfaces. Besides, even very small surface-near cracks can strongly influence the test results. Despite these drawbacks permeability measurements are used extensively for instance in Switzerland for the evaluation of the cover concrete quality of bridge structures etc. (Roelfstra et al. 2004).

Visual inspections yield no quantitative results for the update of the deterioration prognosis. Still, they form an important part of the acceptance inspection as they help to identify potential 'hot spots' due to cracking, risk of ponding or other irregularities. The results of the acceptance inspections can be used to update the original prognosis. If the update leads to a significant decrease of the expected life time for single elements or the visual examination shows damages as described above, remedial measures have to be taken or an intensified inspection plan to monitor the future development has to be agreed upon.

2.7 *Birth certificate*

Throughout all the realization stages all the relevant information with respect to durability - from the original service life design, inspection plan and results of compliance testing and quality control to the results of the acceptance inspection and the update of the service life design - is collected and summarized in a central document, the so-called Birth Certificate. This Birth Certificate forms the basis for all the maintenance activities during the future use of the structure. The inspection plan will be updated after every inspection and defines future inspection intervals, methods and extent depending on the predicted condition state development. The Birth Certificate itself will be updated continuously with the results of inspections and documentation of maintenance measures. This way, all the relevant information for the life cycle management of the structure is always available even in case the owner of the structure changes.

3 CONCLUSIONS

The need to maintain ageing building stocks with scarce budget resources has caused an increasing need for life cycle management systems. In this context, the “birth certificate” can form a valuable tool for the life cycle management of newly completed structures. Ideally, life cycle management already starts during the planning stage, as most of the crucial decisions concerning durability (e.g. geometry of the structure, concrete cover or concrete mix design) have to be taken at this early stage and can thus be assessed by means of preliminary durability calculations. This way, different durability concepts can be compared quantitatively and the optimization potentials of concrete mix optimization can be utilized. Compliance testing employing accelerated test methods allows for a first update of the original calculations and an evaluation whether the materials intended for use are suitable or not. During the construction phase, simple and easy-to-use test methods should be integrated into the quality control procedures. Electrolytic resistivity measurements have been proven to yield sufficiently good information on the regularity und uniformity of the concrete used on site.

After completion of the structure, the acceptance inspection renders important information on the actual construction quality. Possible non-destructive inspection techniques are for instance concrete cover mapping, electrolytic resistivity measurements, permeability testing and visual inspections. As the structure has not been subjected to environmental loads, potential mapping or chloride profiles cannot be used at this early stage. As a result of the acceptance inspection, a second update of the reliability calculations can be conducted and an inspection plan for the structure can be developed.

REFERENCES

Breitenbücher, R.; Gehlen, C.; Schießl, P.; Hoonard van den, J.; Siemes, T. (1999). Service Life Design for the Western Scheldt Tunnel. In: Durability of Building Materials and Components. NRC Research Press, Ottawa.

Büteführ, M., Fischer, C.; Gehlen, C.; Menzel, K. & Nürnberger, U. 2006. On-site investigation on Concrete Resistivity – a parameter of durability calculation of reinforced concrete structures. Materials and Corrosion, Vol. 57, Issue 12, pp. 932 – 939.

Gehlen, Ch., 2000. Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken. Deutscher Ausschuss für Stahlbeton, Issue 510, Berlin, Beuth-Verlag.

Gehlen, Ch.; Mayer, T.F. & Schießl, P. (2008). Von Bausteinen eines nachhaltigen Lebenszyklusmanagements für Ingenieurbauwerke. Proceedings of the Bauwerksdiagnose 2008, DGZfP, Berlin.

Gehlen, Ch., Schießl, P. & Schießl-Pecka, A. (2009). Hintergrundinformationen zum Positionspapier des DAfStb zur Umsetzung des Konzeptes von leistungsbezogenen Entwurfsverfahren unter Berücksichtigung von DIN EN 206-1, Anhang J, für dauerhaftigkeitsrelevante Problemstellungen. Beton- und Stahlbetonbau 103, issue 12.

Mayer, T.; Schießl, P.; Zintel, M. (2008). Birth Certificate as an Important Tool for Public-Private-Partnership-Projects. Proceedings of the 1st International Symposium on Life Cycle Management, Varenna, Italy.

Polder, R. 2001. Test methods for on site measurement of resistivity of concrete – a RILEM TC-154 technical recommendation. Construction and Building Materials, Vol. 15, pp. 125 – 131.

Raupach, M., Harnisch, J. & Wolff, L. (2007): Praxisnahe Untersuchungen zur Vorhersage des Chlorideindringens in unbeschichteten Parkbauten. Research report F936, ibac, RWTH Aachen.

Roelfstra, G.; Hajdin, R.; Adey, B. & Brühwiler, E. 2004. Condition evolution in bridge management systems and corrosion-induced deterioration. Journal of Bridge Engineering, Vol. 9, Issue 3, pp. 268 – 277.

Schiessl, P. & Lay, S. (2004). Influence of Concrete Composition on Reinforcement Corrosion. In: Böhni, H. (ed.): Corrosion in reinforced concrete structures. Cambridge, Woodhead Publishing Ltd.

Schiessl, P. & Mayer, T.F. 2007. Lebensdauermanagementsystem. Deutscher Ausschuss für Stahlbeton, Issue 572, Berlin, Beuth-Verlag.

Schießl, P., Schießl-Pecka, A.& Mayer, T.F. (2007): Monitoring als Bestandteil des Lebensdauermanagements von Betonbauwerken. 11. Münchner Massivbau-Seminar.

Tang, L. 1996. Chloride Transport in Concrete – Measurement and Prediction. Dissertation, Chalmers University of Technology, Gothenburg.