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Reflections on future needs in concrete durability research and development

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ABSTRACT: There is no doubt that, over the past two decades, we have made enormous advances in the understanding and practice of concrete durability. Spurred by the often experienced early deterioration of reinforced concrete structures, with high capital investment for repair and rehabilitation, conceptions of design for durability have gained an increasingly higher level of importance in recent years. Durability design is beginning to be considered of equal importance as design for safety and serviceability. Nevertheless, durability concerns remain and early deterioration still attracts much expenditure. This paper is aimed at identifying important developments made in the field of concrete durability during the past two decades. Based on current design practice and current knowledge, future research and development needs are discussed, focusing on the influences of constituent materials, deterioration prevention methods, service life modelling of reinforced concrete structures, and performance-based test methods.

1 INTRODUCTION

It is not difficult to recognise or to acknowledge the significant changes that have taken place in the field of concrete durability over the last 25 years. This period has seen an enormous growth in our understanding of the mechanisms and processes of deterioration, the ways in which to protect concrete against early deterioration and the effective utilisation of concrete-making materials that will enhance durability. Equally important has been the extent to which the advocacy of durability—as a fundamental property of concrete—has resulted in a conceptual change in the minds of those involved in the design and construction of concrete structures. For practitioners, concepts of durability are beginning to be woven into the everyday discourse of concrete technology.

In large measure, this change has been driven by the efforts of researchers throughout the world, both in developing our understanding of the theoretical issues and in making the case for greater attention to durability in the cement and concrete sector in general. In the best tradition of the path of knowledge development, the debates in the field of concrete durability have certainly been vigorous and many misconceptions or flawed theories lie on the sides of this path. However, in many areas, the issues and concerns are far from settled and the need for continuing research and development remains.

This paper therefore presents some reflections on the future research needs in concrete durability. Much of this discussion relies on observations of the extent to which researchers have addressed some of the

Figure 1. Reinforcement corrosion remains the most significant threats to the durability of reinforced concrete structures.

fundamental questions of concrete durability, influenced the practice of concrete technology, or attended to needs of technology transfer in this field. While the issues raised are intended to have general application, the reader will find something of a South African bias.

2 MATERIALS

2.1 *Influence of material properties on reinforcement corrosion*

Significant advances have been made in our understanding of the influence of concrete mixture constituents on the likelihood and rate of reinforcement corrosion. Much of this work has focused at understanding the role of cement extenders and admixtures in modifying the ionic and fluid transport properties of the concretes that we use in chloride-laden environments. Greater understanding of the notion of the 'threshold' level of chloride content in relation to the binder type has also helped to clarify much of the complexity of empirical data.

Our sense is that continued work is necessary in developing a more fundamental understanding of the physico-chemical process related to the interactions between the products of hydration and corrosion-inducing species such as chlorides or carbon dioxide. These studies should be focused on ingress, binding and flow of these materials in concrete. This is necessary in light of the rapidly changing nature of cementitious materials that are being used in concrete. Our reliance on models developed from empirical data, without fundamental understanding, limits our ability to predict the long-term performance of new materials used in concrete. Furthermore, the increasing use of combinations of supplementary cementitious materials—so called ternary blends—presents particular challenges in this context.

The past five years have also seen enormous growth in the materials and technology of concrete admixtures. However, there is little information on the effects of these new materials on the general durability and deterioration of concrete. In particular, there is a serious lack of understanding of the effects of these materials on concrete exposed to the potential of damage due to reinforcement corrosion.

In the areas of limiting the effects of corrosion of reinforcing steel, the following are some of the issues that will require attention:

- Corrosion inhibitors: future research is needed to establish long-term performance and applicability
- Service life of protective coatings
- The development of corrosion-resistant reinforcement.

There is certainly a need for an international shared database on long-term performance of concrete structures in relation to concrete mixture constituents. This will act as a touchstone for researchers to assess the suitability of proposed models against a historical knowledgebase of recorded performance. There is a special concern here regarding the potential problems with new materials such as high-performance concrete, for which long-term behaviour is unrecorded. In these materials, the likely effects of large amounts of unhydrated cement on durability (as well as long-term deformations) remain a concern.

2.2 *Other deterioration mechanisms*

While deterioration due to reinforcement corrosion remains the most significant global concern in this area, other deterioration mechanisms are also in need of research attention. Some examples of such issues are:

- Our understanding of the mechanisms and process of sulphate attack remains hazy and there is much confusion and sometimes contradiction on this phenomenon (Neville, 2006).
- In the case of alkali silica reaction, our knowledge of the strategies for prevention is fairly advanced. However, more work is clearly needed in the repair and rehabilitation of concrete damaged by this mechanism of attack.
- Soft water attack and other dissolution processes also requires further research, particularly to develop our understanding of the strategies for protecting concrete against such deterioration.

Much of the comments related to the materials research needs for reinforcement corrosion apply here in equal measure.

3 SERVICE LIFE MODELING OF REINFORCED CONCRETE STRUCTURES

3.1 *General*

For reinforced concrete structures, the most important durability considerations concern reinforcement corrosion. As a result, the modeling of the ingress of aggressive agents such as chlorides and carbon dioxides has received considerable attention on recent years. However, many questions yet have to be answered in determining reliable and practical design procedures for reinforced concrete members subjected to chloride ingress or carbonation.

Design approaches for durability can be divided into prescriptive concepts, also termed deemed to satisfy concepts, and performance-based concepts. Prescriptive concepts are based on material specification from given parameters such as exposure classes and life span of the structure. Following this approach, durability specifications in most existing codes and standards are based primarily on establishing constraints to the mix proportions of the concrete as a function of the severity of the exposure.

Durability specifications in the South African standards (SANS 2005) and the new European standards (BS EN 2004), for example, follow the prescriptive concept and are of the 'recipe' type, setting limits on w/c ratios, cement contents, and compressive strength for different exposure classes. The design for durability includes the correct choice of exposure class and compliance with material requirements, concrete cover specifications, and curing procedures.

However, durability is a concept that incorporates material properties, processing technology and environmental exposure conditions and, as such, it cannot easily be assessed through intrinsic material properties. The prescriptive approach ignores, to a large extent, the different performance of the different cement types and of the mineral components added to the cements or to the concrete itself, as well as the influences of on-site practice during the construction process.

Performance concepts, on the other hand, are based on quantitative predictions for durability from exposure conditions and measured material parameters. The resistance of the structure, measured through durability parameters of the actual concrete used, is compared against the environmental load, taking the influences of time into account. On this basis, the probability of damage occurring to the structure during its lifetime is calculated using appropriate deterioration models.

Different levels of sophistication may be applied to performance-based design for durability, including the use of durability indexes, the application of analytical deterioration models, and full probabilistic methods. At the moment, various approaches are being developed worldwide, however yet with very limited application in real projects. Of course, the added challenge of assessing such models against long-term structural performance remains as an important future research need.

3.2 *Current international developments*

The recently published fib Model Code for Service Life Design (fib, 2006) proposes a design approach to avoid deterioration caused by environmental action comparable to load design. Based on quantifiable models for the load side (environmental actions) and the resistance side (resistance of the concrete against the considered environmental action), the following design options are presented:

- Option 1: Full probabilistic approach
- Option 2: Semi probabilistic approach (partial safety factor design)
- Option 3: Deemed to satisfy rules
- Option 4: Avoidance of deterioration.

The full probabilistic approach, which is intended to be used for exceptional structures only, should be based on probabilistic models that are sufficiently validated to give realistic and representative results of deterioration mechanisms and material resistance. The basis of this approach is formed by appropriate test methods and statistical evaluation models.

In the partial safety factor approach, the probabilistic nature of the problem (scatter of material resistance and load) is considered through partial safety factors. It is based on the same models as for the full probabilistic approach and intends to present a practical, yet statistically reliable design tool.

The deemed to satisfy approach is comparable to the durability specifications given in most current codes and standards, i.e. specifications based on a selection of certain design values (dimensioning, material and product selection, execution procedures) based on environmental classes. The difference between the deemed to satisfy approach envisaged by the fib Model Code and traditional service life design rules is that the latter are commonly not based on physically and chemically correct models but largely on practical experience, whereas the fib method is intended to be calibrated against the full probabilistic approach.

The fourth level of service life design (avoidance of deterioration) is based on the use of non-reactive materials such as stainless steel, or protection systems, such as coatings.

In the presentation of the above design options, fib has taken a major step towards designing concrete structures for durability. Fundamental principles and design options for concrete durability have been clearly laid out. For the successful application of the various design options, however, further work is necessary in the following fields:

- Defining rational limit state criteria,
- Testing actual material performance against relevant material deterioration models,
- Calibrating service life models against uncertainties in material properties and environmental influences (probabilistic methods),
- Identifying suitable test methods for the characterization of relevant concrete properties. For existing test methods, clear guidance needs to be provided on how to interpret test results and on how to incorporate them into service life models,
- Identifying efficiency and durability of protection systems, such as coatings.

Many international research efforts are and have been underway in resolving the above listed issues. However, most countries struggle with the implementation of durability design guidelines, due to the many questions yet to be answered.

In contrast, in South Africa, durability design guidelines have been implemented in the past decade and are nowadays frequently applied in concrete construction. The approach has been developed to a point where it can be used with some confidence; however the development of the approach is ongoing as remaining uncertainties still need to be addressed.

Based on the South African durability design approach, some of the most common shortcomings associated with durability design are discussed in the following.

3.3 *The South African approach for durability design*

The philosophy of the South African durability design approach involves the understanding that durability will be improved only when unambiguous measurements of appropriate cover concrete properties can be made. Such measurements must reflect the in situ properties of concrete, influenced by the dual aspects of material potential and construction quality. Key stages in formulating this approach were developing suitable test methods, characterizing a range of concretes using these tests, studying in-situ concrete performance, and applying the results to practical construction.

The approach links durability index parameters, service life prediction models, and performance specifications. Concrete quality is characterized in-situ and/or on laboratory specimens by use of durability index tests, covering oxygen permeation, water absorption, and chloride conduction (Alexander et al 2001, Beushausen et al 2003, Alexander and Stanish 2005). The service life models in turn are based on the relevant DI parameter, depending on whether the design accounts for carbonation-induced or chloride-induced corrosion. Designers and constructors can use the approach to optimize the balance between required concrete quality and cover thickness for a given environment and binder system.

A framework for the development and application of performance-based specification methods for concrete durability is illustrated schematically in Figure 2.

In view of the various options for service life design presented by fib (2006), the South African Durability Index approach principally adopted the strategy of providing deemed to satisfy rules, which limit

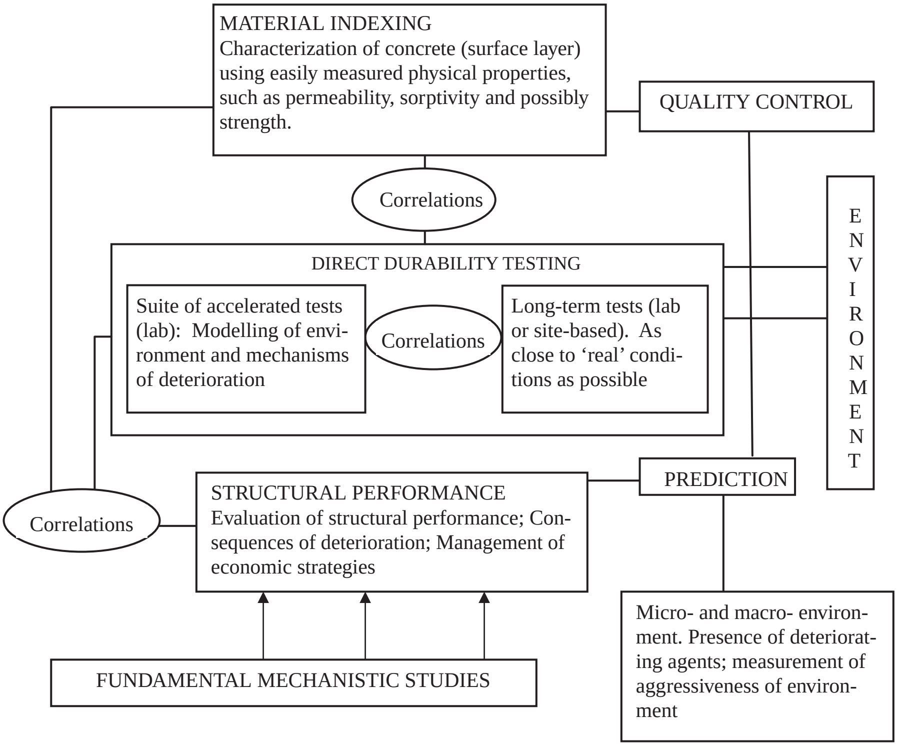

Figure 2. Framework for carrying out durability studies in South Africa.

durability index values and cover depths for given environmental classes and selected binder types.

Limiting durability index values are based on service life models, which in turn relate to partial factor design and partly to full probabilistic modelling of relevant parameters. The South African approach therefore aims at combining Options 1, 2, and 3, as presented by fib, to provide a practical tool for durability design and quality control.

The durability index approach is currently being applied in a number of large scale construction projects in South Africa. This is considered a large step towards improvement of concrete quality and structural durability. However, much work remains to be done, in particular generating correlations between indexes and actual structural performance. Future research needs in the field of durability index design and service life modelling are discussed in the following.

3.4 *Future needs in durability design and service life modelling*

3.4.1 *Calibration of service life models and test methods against field performance of concrete structures*

The design against chloride ingress, using chloride conductivity indexes, is based on service life models that were developed at the University of Cape Town (Mackechnie, 2001). The relationship between conductivity index values and the potential field performance of reinforced concrete structures was established from 2 different techniques:

- Correlation between 28-day conductivity index values and chloride ingress in structures in the Western Cape Province.
- Laboratory-based experimental correlations between 28-day conductivity index values and chloride diffusion coefficients.

Further work is necessary to test 28-day conductivity index values against chloride ingress in various marine environments in South Africa, taking into account that chloride ingress is dependent on environmental conditions such as water and air temperature and relative humidity. In a current study at the University of Cape Town, chloride ingress into various different types of concrete is being investigated, based on site exposure in the Cape Town and Durban harbours, which, from a temperature and relative humidity point of view, represent very different environmental conditions. Measurements taken on site-exposed samples are correlated to laboratory-based measurements of chloride conductivity index values and diffusion coefficients, in order to refine existing service life models for application in various regions in South Africa. This project is described in more detail in another paper presented at ICCRRR 2008 (Heiyantuduwa, 2008).

The design against carbonation using oxygen permeability indexes is based on empirical relationships between 28-day OPI values and carbonation depth measurements on actual structures and laboratory-cured samples (under accelerated carbonating conditions). Carbonation depth measurements, particularly on real structures, show large variations, making statistical evaluations of test results difficult. It is therefore important to collect more data to calibrate the service life models used for the prediction of carbonation. This needs to be done taking various climatic conditions into account and researching fundamental influences on carbonation of concrete.

3.4.2 *Definition of environmental classes*

The environmental classes used in durability design in South Africa are related to the EN 206 classes as modified for South African conditions (Table 1). As discussed in the previous section, it needs to be established whether the current environmental classes are sufficient in describing potential deterioration mechanisms, or whether a more refined approach needs to be developed that classifies environmental exposure based on the prevailing climate conditions.

Table 1. Environmental Classes adopted in South Africa (Natural environments only) (after EN206).

Carbonation-Induced Corrosion	
Designation	**Description**
XC1	Permanently dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity (60–80%) (Ext. concrete sheltered from rain)
XC4	Cyclic wet and dry
Corrosion Induced by Chlorides from Seawater	
Designation	**Description**
XS1	Exposed to airborne salt but not in direct contact with seawater
XS2a*	Permanently submerged
XS2b*	XS2a + exposed to abrasion
XS3a*	Tidal, splash and spray zones Buried elements in desert areas exposed to salt spray
XS3b*	XS3a + exposed to abrasion

* These sub clauses have been added for South African coastal conditions.

3.4.3 *Development of probabilistic models*

The natural variability in the concrete material makes it inevitable to use probability theory in formally including the uncertainties in the service life prediction model parameters.

A framework for the application of probabilistic models in durability design of reinforced concrete (RC) structures in South African marine conditions has been developed in a research project at the University of Cape Town. This involved incorporating the steady state diffusion coefficient derived theoretically from the chloride conductivity test results in a probabilistic model as discussed in Muigai et al (2008).

Statistical information for each parameter in the model was applied in providing improved estimates of the predicted service life. The research study also demonstrated the use of the probabilistic model in specifying limiting values for chloride conductivity based on initiation limit state target probability values given in fib Model Code for Service Life Design (fib, 2006).

However, additional data sets still need to be acquired for each of the quantified model parameters to improve on the accuracy of the model. Further research in this field also requires the application of the oxygen permeability test in the carbonation service life prediction model based on the same probabilistic framework.

3.4.4 *Definition of limit state criteria*

A number of service life models for reinforced concrete structures exist. Many of these adopt the two-stage service life model first proposed by Tuutti (1982), in which the deterioration is split into two distinct phases, namely the initiation period and the propagation period, as shown in Figure 3.

Most service life models assume that the end of the initiation period denotes the end of service life. However, since a concrete structure does not immediately lose its strength or functionality at the onset of the propagation period, a more sensible approach would make use of a detailed maintenance strategy for corrosion-damaged structures. The definition of a suitable maintenance strategy depends on knowledge of the following aspects:

- influence of steel reinforcement corrosion on the load-bearing capacity of structural members
- performance (and durability) of materials and systems for repair and protection of corrosion-damaged structures.

Both of the above aspects still need further research to be fully understood in the context of service-life modeling. Two research projects are currently being undertaken at the University of Cape Town, addressing the above 2 aspects. Aspects relating to the structural capacity of corrosion-damaged reinforced beams are discussed by Malumbela et al (2008).

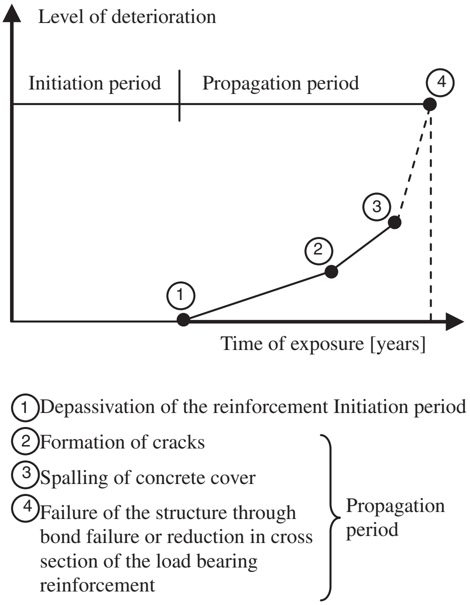

Figure 3. Deterioration process of reinforcement corrosion: 2-phase model for service life (Tuuti 1982, fib 2006).

3.4.5 *Investigating the effects of cracking on concrete durability*

Most service life prediction models cover the ingress of harmful substances into uncracked concrete only. As a result, transport mechanisms for chlorides and carbon dioxide are primarily assumed to relate to established diffusion models. However, cracks do frequently occur in concrete structures, especially under the influence of load-induced stresses. Transport mechanisms and corrosion cell development in cracked concrete may be very different, in comparison to uncracked concrete.

Further research needs to be done to establish the influence of cracks on the corrosion of steel reinforcement. It appears ineffective to model the ingress of harmful substances into uncracked concrete when existing cracks may accelerate the deterioration process. In particular, the influences of various crack widths on the ingress of harmful substances into concrete needs to be established and considered in the modeling of service life.

In another paper presented at ICCRRR 2008, Otieno et al (2008) discuss the influence of crack widths on reinforcement corrosion in more detail.

3.4.6 *Remedial measures for structures that do not meet durability specifications*

The South African Durability Index approach enables engineers to specify certain durability parameters (indexes) in relation to the anticipated service life, environmental conditions, binder types and cover depth requirements. Durability specifications commonly comprise limiting values for the thickness and penetrability of the concrete cover. When limiting values, obtained on the as-built structure, meet the specified requirements, the structure is considered to be inherently durable.

However, a clear design methodology for concrete structures that do not meet the specified requirements needs to be established. If limiting durability index values have not been achieved, the owner of the structure principally has the following options:

- Demolish and rebuild the structure
- Accept that the anticipated service life duration may not be reached
- Protect the structure against the ingress of harmful substances, such as carbon dioxide and chlorides
- Accept that harmful substances can reach the reinforcement, but protect the reinforcement against corrosion.

For most projects, the first of the above options will be undesirable, for obvious reasons. The second option involves a re-evaluation of the original design parameters and may in many cases also not be acceptable.

Probably in most cases, the third or fourth option will be aimed at, i.e. protecting the structure against deterioration to ensure that the design service life can be reached. Such methodology may for example include the application of protective surface coatings or corrosion inhibitors. Depending on the quality of the structure (by how much did it not reach the limiting durability design parameters?), a once-off application may be sufficient, whereas in other cases a detailed maintenance plan may need to be established, taking repeated application of protective measures into account.

The decision of appropriate repair and maintenance strategies needs to be based on an evaluation of the expected service life. For this, the measured durability index value needs to be used as an input parameter in the service life model, with which the original design parameter was established. This will allow an estimation of the actual service life duration that can be expected. This, in turn, will give the information of how many years of additional service life the protective measure needs to provide.

Based on this, it can for example be argued that a coating, which prevents the ingress of harmful substances over that required duration, presents a suitable protective measure, bringing the structure back to its original service life. However, a clear philosophy needs to be developed, based on which the design of appropriate protective measures can be carried out. The design engineer and the owner of the structure need to be given clear guidance on what steps to follow and on what options are available.

From a technical point of view, it needs to be established, which coatings can be used to either prevent or slow down the ingress of chlorides or carbon dioxide sufficiently. The performance of protective coatings commercially available can commonly be shown to be promising in short-term tests. However, there is a lack of data available on the durability of such coatings. Future research is needed to fill this gap of knowledge. A current project at the University of Cape Town is dealing with these issues.

Another promising protection method for reinforced concrete structures is the application of corrosion inhibitors. However, also for these materials the long-term efficiency still needs to be established.

4 CLOSURE AND OUTLOOK

In this paper, we have tried to undertake a particularly difficult task: to define what future users of concrete will need from the research that we are currently undertaking. Nevertheless, we feel that the issues we have raised are practical and draw directly from our experience of the knowledgebase of concrete deterioration and durability research.

It is important to acknowledge that the global concrete research community has made remarkable contributions to our understanding of concrete durability and deterioration. In the same breath, this paper has tried to emphasise that there is much understanding that has yet to be developed through research. The particular problem of deterioration due to reinforcement corrosion will continue to demand much research time and effort before we can say that international concerns in this area have largely been allayed.

This paper has also made a strong case for a more rigorous approach to service life modelling, durability design and specification. In this regard, the proposals presented in this paper are intended as a basis for the development of a framework towards addressing this concern.

Finally, the important challenge of technology transfer should not be neglected. Our success in these areas of research endeavour will be measured by the extent to which we positively influence the practice of concrete technology to produce more durable concrete structures.

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