DURACRETE: SERVICE LIFE DESIGN FOR CONCRETE STRUCTURES
A basis for durability of other building materials and components?

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Durability of Building Materials and Components 8. (1999) *Edited by M.A. Lacasse and D.J. Vanier*. Institute for Research in Construction, Ottawa ON, K1A 0R6, Canada, pp. 1343-1356.

Abstract

In the past decades much effort has been put into the improvement of the durability of concrete structures. This has resulted in a reasonable understanding of the main degradation processes or in experience with measures to prevent degradation. The results of this effort can be found in the present concrete codes and in manuals on durability design. The design rules are in general presented as deem-to-satisfy rules. If the rules are followed it may be assumed that the structure is durable. The present approach does not give direct insight in the service life, the necessary maintenance or the probability of premature failure. Further it is clear that lack of durability can have an influence on the structural behaviour. The direct relationship between durability and safety and serviceability of concrete structures has however not been made in the concrete codes. In the Brite-EuRam project 'DuraCrete' the durability design has been developed into a service life design based on performances and on reliability for reinforced concrete structures. This offers the possibility to present the design on the same level as the structural design that has also been based on performances and reliability. The structural and service life design can even be integrated. The 'DuraCrete' approach offers good opportunities for the service life design of other structural materials and building materials.

Keywords: durability, probabilistic design, reinforced concrete

1 State-of-the-art durability design of concrete structures

The present design approach with respect to durability of concrete structures is based on a reasonable understanding of the main degradation processes for concrete, reinforcement and prestressing steel. The performance of the design is however not explicitly formulated as a service life. It is based on deem-to-satisfy rules (e.g. minimum cover, maximum water/binder ratio, and crack width limitation) and the assumption that if these rules are met, the structure will achieve an acceptable long but unspecified life. The information about the service life to be achieved is to a large extent empirical. Improving the durability increases building costs without any quantification of the reduction of maintenance costs or failure costs. Current design methods only permit to calculate the whole life cycle costs from assumptions with respect to maintenance and failure rates. There are thus no objective means for demonstrating that future maintenance and repair costs will be low.

This common design approach to durability has other disadvantages. The rules are inadequate in some aggressive environments, while they are too rigorous in other environments. In some cases, this results in a 'belts and braces' approach (many different types of measures on top of each other) which may contain unnecessary and even counteractive measures.

Lack of durability can cause serious safety and serviceability problems for structures. Despite this, usually designers have considerably more attention for load and resistance based structural design than for durability design. Recent history has however shown that due to a lack of durability, serious collapses and other types of damages may occur with large amounts of damage.

On 4 December 1984 at 7 o'clock in the morning the Ynys-y-Gwas bridge in the neighbourhood of Port Talbot in Wales (UK) collapsed (Woodward 1988). This concrete bridge was a single span segmental post-tensioned structure. Its span was about 18 meters. The bridge was constructed in 1953 and carried a minor road. When its deck collapsed there was no traffic on the bridge. The cause of the collapse was serious corrosion of the post-tensioned tendons. The corrosion took place at the transverse joints in which chloride-containing water could penetrate. This penetration was possible as a consequence of a number of factors, such as the lack of a slab over the beams, ineffective waterproofing, inadequate protection of the tendons, opening of the gap between the segments under live load, poor workmanship and the damp environment over the river.

In Berlin the southern outer roof of the Congress Hall collapsed on 21 May 1980 due to hydrogen-induced stress corrosion (Schaich 1980). One person died and another was badly injured. The outer roof was characterised by a reinforced concrete arch, which was hollow. Post tensioned steel tendons, which were installed in roof sheeting served as the anchorage of the arch against an inner ring beam. In a part of the roof the sheeting broke away from the ring beam. In another part the sheeting broke away at the outer arch. Corrosion could occur due to design faults leading to cracks in the joints in combination with a porous mortar in the prestressing ducts.

In 1990 a reinforced concrete gallery in Wormerveer (NL) collapsed. This was caused by chloride induced corrosion. Due to poor construction, the main reinforcement in the gallery was situated in the lower part (the actual compression zone) instead of the upper part of the slab (the actual tension zone). This resulted in a crack where de-icing salts could penetrate. In Melle (B) a prestressed concrete bridge collapsed during the passage of a tank-car filled with gas. The driver died. The cause was a crack that opened during the passage of high loads. Chloride could penetrate through this crack and reach the post-tensioned tendons.

The previous list of structures in which serious accidents occurred as a consequence of insufficient durability demonstrates that design for durability can be as important as common structural design. These failures are partly due to bad construction and workmanship in addition to bad joint design. These examples are presented here to demonstrate that lack of durability may lead to collapse. Lack of durability may also lead to other types of failures, leading to a reduced serviceability of the structure and to premature maintenance, repair or even demolition.

In the last decades much effort has been put into the development of models and methods for predicting deterioration of concrete structures. A number of methods have matured to a level where these can be used in a formalised approach for the assessment and design of concrete structures with respect to destructive mechanisms.

Controlling the durability of concrete structures will be a fundamental challenge for the engineer in the next millennium. Past decades have shown us that the classical procedures for design, construction and use of concrete structures have failed to provide reliable long-term performance. Deterioration processes, in particular corrosion of reinforcement, frost action, alkali aggregate reactions and sulphate attack have caused serious damage to concrete structures.

To improve this situation a new concept for durability design needs to be established. Similar to the current procedures for structural design, a design for durability should be performance based taking into account the probabilistic nature of the environmental aggressiveness, degradation processes and material properties involved.

In order to quantify the durability the concept of a service life design has been introduced. In this respect the performance requirements for a service life design as stated in the CEB-FIP Model Code (1990) has been adopted:

Concrete structures shall be designed, constructed and operated in such a way that, under the expected environmental influences, they maintain their safety, serviceability and acceptable appearance during an explicit or implicit period of time without requiring unforeseen high costs for maintenance and repair.

Such a rational design for durability, however, requires both an overall methodology and calculation models for the actual degradation processes of concrete structures. Similar to the structural design code for loads, safety requirements and limit states must be defined for the design service life.

2 DuraCrete project

The new durability design methodology should be able to document the efficiency of the materials to resist the aggressiveness of typical environments in Europe. The structural designer will, therefore, be able to document the fulfillment of a specific limit state. For the designer the deterioration models showing the degradation over time, or showing the service life as a function of appropriate design parameters, are valuable tools. With the aid of this methodology for durability design the designer can make decisions on the required dimensions and material specifications for structures with service life requirements.

One consequence of the requirements to design for durability is that structural engineers and designers need to be educated in the durability aspects of various materials as well as in the structural layout, the effect of execution on the in situ qualities, and the interaction between structure and environment. This is a prerequisite to enhance cost optimal durability designs incorporated into the overall 'life cycle' costs, and is thus a prerequisite to be able to satisfy the future requirements to the performance of concrete structures. An immediate spin-off will also have to be reflected in the structural engineering curriculum. The design engineer will need a design guide to assist him in making a proper service life design, not only for new structures but also for the redesign of existing concrete structures. A first edition of such a guide has been developed in the project 'DuraCrete'. The project has been subdivided in 8 separate tasks:

1. Establishing theoretical framework for Task 7 and providing a mini-project to show how all the tasks are interrelated.
2. Modelling of the deterioration mechanisms. A simple form of each of the models is provided for engineering design purposes.
3. Evaluation of compliance tests available for the key-point parameters of the models selected in Task 2. Furthermore, a number of test results for different concrete mixes are provided with regard to carbonation resistance, resistance against chloride penetration, corrosion resistance, frost de-icing salt resistance and finally fatigue.
4. Statistical quantification of the uncertain parameters regarding the deterioration models. The results are tables identifying statistical distributions, mean values and coefficients of variation (standard deviations). Furthermore the environmental parameters are classified and quantified and the mechanical behaviour of concrete structures is statistically quantified.
5. Provides Task 6 with a range of relevant structural elements designed using current code recommendations in Europe.
6. Limit state functions, sensitivity measures for the input parameters and finally target reliabilities corresponding to today's practice concerning durability (Task 5 structural elements).
7. Developing General Guidelines for Durability Design and Redesign (in short: A Durability Design Guide) based on the work carried out in the previous tasks of the DuraCrete project:
8. Dissemination.

3 Framework

3.1 Basis for design

In principle, the design strategy for durability is to select an optimal material composition and structural detailing to reliably resist, for a specified period of use, the degradation threatening the structure. In the case of redesign there is however less freedom available, as we have to accept (partly) the choices that have been made during the original design. As the redesign is based on the same principles as the design we will concentrate further just on the design.

Sometimes, it will be clear that a design is very reliable (the structure is protected from the aggressive environment by tanking, membranes, coatings etc.; non-reactive or inert, materials like stainless steel reinforcement has been used; the aggressive reactions are inhibited by cathodic protection). In that case a further prove of the reliability may be omitted.

The durability design strategy has different types of interventions. For example, corrosion protection could be achieved by selection of appropriate cover and concrete mix. In addition, the structure can be made more robust against aggressive environments of different sorts by appropriate detailing such as minimising the exposed surface, by rounded corners, or by adequate drainage.

The durability design will be based upon:

- realistic and sufficiently accurate definitions of environmental actions (different micro-environmental aggressiveness classes) depending on the resulting type of degradation
- material parameters for concrete and reinforcement
- mathematical models for degradation processes. In the present version of the guide the mechanisms which have been modelled have been limited to:

    - carbonation induced corrosion
    - chloride induced corrosion
    - cracking and spalling of concrete due to corrosion products.

3.2 Structural design

The durability design guide follows the same principles (reliability and performance) as a structural design code. As is the case of the structural design load, resistance variables also need to be defined. By definition a load variable is a variable where an increase of the numerical value leads to a reduction of the reliability of the structure, whereas an increase of the numerical value of a resistance variable leads to an increase of the reliability.

The basis of the conventional design procedure for the safety and serviceability of structures with a static loading can be expressed as the limit state function. This limit state defines the border between an adverse state (such as collapse, buckling, deflection, and vibration) and the desired state. The limit state can in principle be formulated as:

$$R - S = R(X_1, X_2, ..., X_n) - S(X_{n+1}, X_{n+2}, ..., X_m) = 0 \qquad \textbf{(1)}$$

in which:

R - a function that describes the load bearing capacity of the structure
S - a function that describes the influence of the load on the structure
X_i - a basic variable for the functions R or S.

The structural design procedure is worked out in such a way that the failure probability is restricted:

$$P\{failure\} = P_f = P\{R - S < 0\} < P_{target} = \Phi(-\beta) \qquad \textbf{(2)}$$

in which:

P{failure} or P_f - the probability of failure of the structure
1- P_f - the reliability of the structure
P_{target} - the accepted maximum value of the probability of failure
Φ - standard normal distribution function
β - reliability index (this parameter is normally used in codes in stead of the failure probability)

With the aid of probabilistic techniques this failure probability can be calculated. In practice the design has been simplified to a semi-probabilistic level with characteristic values and partial factors γ. These values are calibrated in such a way that the target reliability will be achieved:

$$R_c / \gamma_R - S_c \cdot \gamma_S = R_d - S_d > 0 \qquad \textbf{(3)}$$

in which:

R_c - load-bearing capacity of the structure based on characteristic values
γ_R - material factor
S_c - characteristic value of the influence of the loading
γ_S - load factor.
R_d - design value of the load bearing capacity
S_d - design value of the load.

3.3 Time dependent design

In the performance based structural design both the resistance R and the load S are considered to be time independent. In many loading situations this is not realistic. Relationship (1) should then be rewritten as a time dependent limit state function (Siemes and Rostam 1996):

$$R(t) - S(t) > 0 \qquad \textbf{(4)}$$

A special case for this limit state function occurs if either R or S is not time dependent. The working out of these relationships do in principle not differ from working out (2).

Relationship (4) applies for all t in the time interval (0,T) where T is the intended service period (i.e. reference period). Even if the loading or the capacity of a structure is time dependent, the limit state functions for the design of structures are never formulated in this way (with an exception for fatigue). They are always simplified to time independent quantities for which relationship (1) can be used. From a mathematical point of view it can be stated that relationship (4) is of the same type as the functions that will have to be solved for the durability design. The service life concept can be expressed in a design formula, equivalent to relationship (2):

$$P_{f,T} = P\{R - S < 0\}_T < P_{target} = \Phi(-\beta) \qquad \textbf{(5)}$$

in which:

$P_{f,T}$ - the probability of failure of the structure within T
T - intended service period.

It will probably be possible to simplify relationship (5) to a similar one as for the conventional design procedure (3), but at a later stage.

The mathematical model for describing the event "failure", i.e. passing a durability limit state, comprises a load variable S and a resistance variable R, (Figure 1). Failure occurs if the resistance is smaller than the load. The probability of failure within the period of time [0, T], $P_f(T)$ is defined as the probability of the load not exceeding the resistance within the given period. I.e.,:

$$P_f(T) = 1 - P\left\{R(t) > S(t) \quad \forall t \in [0;T]\right\} \qquad \textbf{(6)}$$

As either the resistance R or the load S or both can be time dependant quantities, the failure probability is a time dependant quantity.

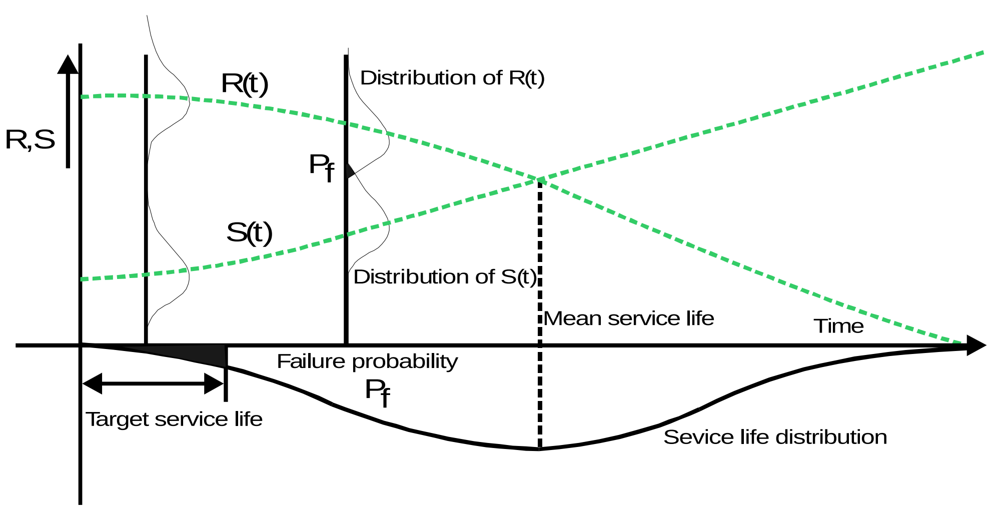

Fig. 1: Failure probability and target service life (illustrative presentation)

With equation (6) a target service life t = target can be determined for a certain allowable failure probability, thus satisfying a certain acceptance criterion. As in structural design, the failure probability, P_f, and thus the acceptance criterion, is usually being given in terms of a safety index or reliability index β, defined by

$$b = -\Phi^{-1}\left(P_f\right) \tag{7}$$

3.4 Limit states and design service life

The first step of this durability design will be the definition of the desired/required performance of the structure. The client or the owner of the structure is asked to define their requirements for quality and target service life. The definition of performance criteria will be related to a limit state criterion. Figure 2 shows in principle the performance (damage function) of a concrete structure with respect to reinforcement corrosion and related limit states. In general points 1 and 2 represent serviceability limit states related to durability and point 3 and 4 represent ultimate limit states where point 3 relates to both durability and safety.

In the DuraCrete project the following durability limit states have been identified with regard to service life:

1. Depassivation of reinforcement.
2. Cracking of concrete cover
3. Spalling of concrete cover
4. Collapse.

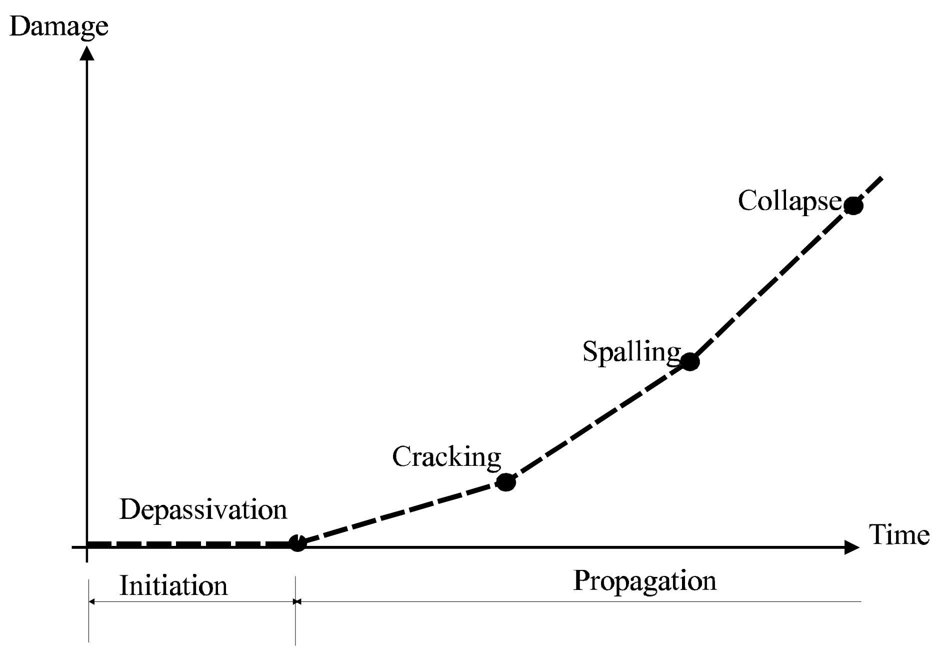

Fig. 2: Determination of service life and limit states with respect to reinforcement corrosion

3.5 Degradation models

The second step of the durability design is to analyse the environmental actions and to identify the relevant degradation mechanisms. Mathematical models describing the time dependant degradation processes and the material resistance against it are needed. The big step forward to performance related durability design is that these models enable the designer to evaluate the time-related changes in materials and structures depending on the specific material and environmental conditions.

The different models used for this durability design consist of design parameters such as structural dimensions, environmental parameters and material properties that correspond to the load and resistance variables of the structural design procedure. In the case of chloride induced corrosion the following model describing the initiation of corrosion has been identified:

$$x(t) = 2 \cdot k \cdot \sqrt{D_{cl,0} \cdot k_e \cdot k_c \cdot t \cdot \left(\frac{t_0}{t}\right)^n} \tag{8}$$

$$k = \operatorname{erf}^{-1}\left(1 - \frac{C_{cr}}{C_s}\right) \tag{9}$$

Table 1: Load and resistance variables in relationship

Load variable	Resistance variable
C_s **= chloride surface concentration**	$x(t)$ **= required concrete cover**
$D = D_{cl,0} k_e k_c \left(\frac{t_0}{t}\right)^n$ **= chloride diffusion coefficient**	C_{cr} **= critical chloride concentration**

The environmental factor k_e (accounting for the actual environmental class), the curing factor k_c (accounting for the actual curing period) and the age factor n (accounting for the desired service life t) are neutral factors, i.e. neither load nor resistance factors. These factors are used to determine the actual, effective chloride diffusion coefficient

Taking the example of onset of chloride induced corrosion the durability inputs are as follows:

The limit state is given by the requirement that the chloride concentration at the surface of the reinforcement may not reach the critical chloride concentration.
The resistance R is given by the critical chloride concentration and the quality and thickness of the concrete cover.
The load S is represented by the actual chloride concentration at the reinforcement level. This depends on material parameters (chloride diffusion coefficient) and environmental effects.

3.6 Level of reliability and quality control

The knowledge about the structural and material characteristics of a structure is uncertain due to the uncertainties associated with structural layout, material characteristics, execution and environmental input. Testing and quality control is therefore important at several stages during the life of a structure. To check the real performance of the structure the material properties, the geometrical and execution variables that influence the selected degradation models have to be affected by quality control. The aim is to define and to update the statistical quantities (type of distribution, mean value, standard deviation) of these affected stochastic variables.

If a high degree of quality control can be documented and quantified it serves as basis for documenting service lives. In this way the updating of the statistical quantities by reducing the coefficient of variation will result in the possibility to consider lower partial factors. The combined set of problems to be considered can be summarised as follows:

1. The factual information on the aggressiveness of the environment, the characteristics of the materials in the structure, and the structure-environment interaction, is uncertain.
2. The degree of uncertainty depends on the type and direct relevance of the available information on the above variables.
3. The reliability of the available information is different depending on the stage being considered, such as the design stage, the construction stage, the handing over stage, and the period of use.
4. From a durability design point of view this means that design input data with different levels of reliability must be used at the different stages.

Quality control (QC) in the sense of the durability design guide is mainly to control the variation of the material parameters and the geometrical variables at the different stages. For concrete the quality control can be based on cement or concrete properties on basis of compliance tests to measure the relevant quality of the cement or the concrete under standardised conditions. The test results may serve as input for the designer in the design situation. The cement producer can classify the potential material resistance against degradation, measuring the following quality controlled material parameters:

- Carbonation: carbonation penetration coefficient D_{eff}
- Chloride ingress: chloride diffusion coefficient, D_o
- Corrosion rate: electrical resistivity, ρ_o.

Compliance tests to measure the potential quality of the supplied concrete with the composition defined (binder content, water/cement ratio) in the design by the contractor/ready mix producer under standardised conditions. The same QC-measurements like for the cement are performed. By means of this the quality of the concrete supplied can be checked against the design requirements.

Similar to the classification system used in structural design (for example the concrete strength classes) the durability design can be based on durability classes of concrete which corresponds to specified values (characteristic values) with regard to the carbonation penetration rate, the chloride diffusion coefficient and the electric resistivity.

Verification tests are needed to determine the actual quality of the concrete in the structure in service. The actual resistance of the concrete to premature degradation is influenced by execution (compaction, curing) and micro-environment.

3.7 Further developments for DuraCrete

To demonstrate the use of the DuraCrete design method a practical example for the lining of a bored tunnel has been presented in (Breitenbücher *et al.* 1999). Although it has been possible to make the service life design for this lining and also for all the other parts of the tunnel, it is obvious that further developments have to be made. Some of them are:

- reliable mathematical models for degradations like frost, frost and de-icing salts, alkali aggregate reaction, sulphate attack have to be developed
- more information and data are needed for the effects of corrosion of the reinforcement (such as corrosion rate, cracking, spalling and collapse); until now most research has been directed to avoid corrosion and is therefore restricted to the initiation phase
- better understanding of the corrosion process under water and under the ground; due to lack of oxygen or to slow transport of aggressive substances the type and the rate of corrosion products may be different from atmospheric corrosion
- improved knowledge of environmental conditions
- determine the reliability of durability measures like repair materials and methods, coatings, cathodic protection etc
- knowledge must be disseminated; the method must be used in practice and in education.

The two main results of the DuraCrete projects are that all disciplines that are necessary for a durability design are brought together: material science, reliability engineering, structural engineering, and further a framework for the durability design has been presented. The objective has not been to develop new knowledge on degradation of concrete. The list of developments to be made in DuraCrete might suggest that the method is not yet applicable in practice. The example of the bored tunnel by Breintenbücher *et al.* (1999) proves the contrary.

4 Extension to other materials

4.1 Structural materials

Modern structural codes for steel, aluminium, timber, plastics and masonry are in principle based on performances. These performances are formulated as limit states with reliability indexes and reference periods. This is similar to the approach in modern concrete codes. In principle, it will therefore be possible to apply the

DuraCrete approach to these materials.

The use of reinforced and prestressed concrete has always been connected with research on degradations and durability. In this respect concrete differs from most of the other structural materials. Timber is an exception to this. This means that for most of the structural materials a lack of practical knowledge might be available. At the same time we must realise that a designer of concrete structures is always aware of the fact that he must take care of the durability of the structure.

The durability measures that are taken at the present state of knowledge are in general the application of coatings (organic and metallic), sacrificial layers (e.g. pile sheeting) or for steel cathodic protection. In severe conditions durable materials are applied such as stainless steel instead of low carbon steel.

With the aid of the DuraCrete approach it is possible to make an objective estimate about the service life costs, including the maintenance. It will be a challenge for the other materials to present a life cycle costing for structures made of other structural materials than concrete. Owners of large structures, like buildings and infrastructures will more and more demand such an objective cost comparison. Contractors working on the basis of a design and construct contract can make their profits by selecting the material with the lowest overall price.

4.2 Building materials and components in general

Besides structural materials the building industry uses a lot of other materials, such as plasters, copper and bitumen. The industry uses further structural materials in non-structural applications, like steel window frames or timber doors. This situation differs in some aspects from the structural materials:

- the design is in principle not explicitly based on performances and on reliability
- the design is based on experience and on deem to satisfy rules in codes
- for a part of the applications the service life is restricted
- in some of the applications there is a high degree of repetition.

Making a service life prediction on the bases of performances and on reliability, as in DuraCrete, will require considerable effort. On the other hand a great deal of work has already been done. CIB W80/RILEM 175-SLM, its preceding committees and other national and international committees on durability of building materials and components have through the past years obtained useful results. This applies in particular for the CIB W80/RILEM 71-PSL (1987), RILEM technical recommendation: “Prediction of service life of building materials and components”.

The main shortcoming of past work is the fact that in many cases the end of the service life has not been defined on basis of performance but rather on the basis of a lack of functionality or on other subjective judgements. Furthermore, aspects of reliability are not explicitly taken into account. However, these shortcomings can easily be overcome.

An essential part of the research and testing in the past has been based on routine testing where the testing conditions are not similar to the in-service environment in which the building material or component is to function. These tests are essentially robustness tests. An example of this type of testing is the salt spray test for metals and organic coatings. Passing this test with a good result does not necessarily mean that the service life in an industrial environment with high SO2 contents in the atmosphere will be adequate.

5 Concluding remarks

The DuraCrete approach that has been developed for the service life design of new and existing concrete structures is based on the same principles and framework as the performance based structural design. It is based on terms such as performances, limit states, reliability and reference period or design service life. It may be expected that this approach will be the basis for service life design of concrete structures in the future.

The DuraCrete approach can easily be developed towards a methodology that can be used for the service life design of structural materials, like steel, aluminium, timber, plastic and so on. Defining the limit states, degradations, environmental conditions and undertaking the relevant tests are future activities that must be completed if this new design approach is to be used in practice.

For non-structural building materials it is also possible to use the new service life design approach. In fact many steps towards the application of the new methodology have already been made. In general it can be stated that the notions of performance and reliability have to be firmly incorporated in the service life prediction methods. The fact that many applications have a highly repetitive character and that the service life is often restricted (in relation to structural applications where design service lives of 100 or 200 years are sometimes required) make it easier to complete the necessary developments.

6 Acknowledgement

The DuraCrete-project 'Probabilistic Performance based Durability Design of Concrete Structures' is being carried out in the framework of the Brite-EuRam Programme (project BE95-1347), with a financial contribution of the European Commission.

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