Influence of Material Properties on the Durability of Structures

Influence des caractéristiques des matériaux sur la durabilité des structures

Einfluss von Materialeigenschaften auf die Dauerhaftigkeit von Bauwerken

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SUMMARY

The influence of material properties on the durability of structures is an integrated part of the interaction between environmental aggressivity and the resistance of the structure. Durability is treated in a Service Life concept depending on level of modelling of deterioration mechanisms. The Service Life achieved depends on initial decisions, codes and standards and on Management and Maintenance Systems employed. CEB-FIP Model Code 1990 is the first Service Life Code and helps bridge the communication gap between material scientists and structural engineers.

RÉSUMÉ

L'influence des caractéristiques des matériaux sur la durabilité des constructions est une partie intégrante de l'interaction entre l'aggressivité du milieu ambiant et la résistance de la structure. La durabilité est traitée dans le concept Durée de vie dépendant du niveau de détail de la modélisation des mécanismes de détérioration. La Durée de vie dépend des décisions initiales, des codes et des normes et des systèmes de gestion et de maintenance utilisés. Le Code Modèle CEB-FIP 1990 est le premier code de Durée de vie, et permet de rétablir le dialogue entre les spécialistes de la science des matériaux et les ingénieurs civils.

ZUSAMMENFASSUNG

Der Einfluss von Materialeigenschaften auf die Dauerhaftigkeit von Bauwerken ist Bestandteil der Wechselwirkung zwischen der Aggressivität der Umwelt und der Widerstandsfähigkeif des Bauwerks. Die Dauerhaftigkeit wird in einem Nutzungsdauer-Konzept behandelt, welches vom Niveau des Modells für den Alterungsprozess abhängt. Die erreichte Nutzungsdauer ihrerseits hängt ab von anfangs getroffenen Entscheidungen, von Vorschriften und Normen und von den angewandten Verwaltungs- und Unterhaltungssystemen. Der CEB-FIP Model Code 1990 (Mustervorschrift) ist die erste Vorschrift zur Nutzungsdauer, und hilft die Verständigungslücke zwischen Materialforschern und Bauingenieuren zu überbrücken.

0. INTRODUCTION

The influence of material properties on the durability of structures is an integrated part of the overall interaction between the

- aggressivity of the environment, and the
- resistance against premature degradation as provided by the structure.

The environmental aggressivity is determined by the

- moisture availability
- temperature level
- type and amount of aggressive substance in gaseous or dissolved form,

and the concentrations, variations and gradiants of these parametres on a micro-environmental scale determined very locally by the interaction between the environment and the stucture.

The resistance of a structure against premature degradation, when exposed to an aggressive environment, is determined by the combined effect of the

- structural design and layout as fixed by the architect and the engineer,
- building material, or combination of the chosen materials,
- quality of execution, determining if the in-situ material properties are obtained including their variability,
- development of material properties with time, as determined by the physico-chemical micro-environment and type, level and frequency of maintenance performed.

0.1 Building Materials

The most widely used building materials are concrete, steel, wood and masonry, and the aggressivity of an environment differs considerably, depending on which building material that is being employed in the structure.

Our traditional approach in constructing and maintaining buildings differs surprisingly, depending on the chosen building material. In crude form this means that

- **Masonry** is chosen for wall-type structures in compression and is in general considered to be a robust low-maintenance material mainly because of its inorganic nature resembling stone. Its sensitivity to salt bursting caused by crystal growth in a polluted environment, sensitivity to moisture accumulation and freeze-thaw action often comes as a surprise, though these mechanisms are well-known to material scientists.
- **Wood** is a very versatile material, but its organic nature has led to the acceptance, that exposed structures very early need a regular maintenance and supplementary protection in the form of paint and impregnation.
- **Steel** is a high performance refined material threatened only by rusting, so regular re-painting will ensure a long term durability.
- **Concrete** is a unique material due to its as believed very simple production out of domestic materials, and due to its formability. The development of reinforced and prestressed concrete has created an ideal interaction between steel and concrete judged from a load carrying and a

durability point of view. The inorganic nature and the strength levels of concrete, make users believe that this material in all respects is superior to natural stone, and to constitute maintenance-free structures.

The errors in these simplistic characteristics are painfully evident, looking at the durability problems arising in many areas all over the world.

The structural engineer and the user have forgotten the thermodynamic instability inherently associated with these highly energy containing, worked materials. However, the physicists and chemists (material scientists) have had a clear mind on these durability problems for more than a century. This raises the questions:

- Why does this serious knowledge gap prevail today?
- How do we overcome the problems?
- Will theses problems last into the next century?
- Who should lead the way - those who mainly know the answers (material scientists) or those who have realized their own ignorance and ask the questions (structural engineers)?

1. SERVICE LIFE OF STRUCTURES

The natural ageing of building materials renders the concept of "Durable Structures" non-operational in practice because it leaves the questions "How durable?" and "Durable for how long?" unanswered. By considering the associated time scale, a "Service Life Concept" evolves which is directly applicable by the structural engineer when handling design of new structures and when assessing the residual service life of existing structures (1).

These considerations have led to the definition of the Service Life of a structure, as being the time for which the structure satisfies the imposed functional requirements, without needing unforeseen or excessive costs for maintenance and repair.

In this way durability is not merely a technical problem of relevance mainly to the engineer and the scientist, but becomes a combined technical and economic problem, which directly reflects the interest of the user and the owner (2).

1.1 Technical, Economic and Functional Service Life

The Technical Service Life depends on the performance of the materials and the structure in time, when exposed to a given environment.

The Economic and Functional Service Life depends on the economic demands in time, to ensure safe and satisfactory use of the structure.

The Economic and Functional Service Life of structures is a political instrument in the overall economic optimization of costs for creating a structure and keeping it in operation. The required minimum quality of a structure may reflect:

- the condition of structural and non-structural elements,
- the load carrying capacity, or safety, of the structure,

- the geometric restraints such as clearances, construction depths, etc.,
- the aesthetical qualities of the ageing structure.

Political decisions may influence the imposed requirements with respect to

- the safety level required
- the design loads and required clearances (room heights, bridge clearance, etc.)
- the acceptable appearance.

Changes in such requirements will simultaneously change the corresponding residual Economic and Functional Service Life, although the Technical Service Life is kept unaltered. In practice it would be optimal, if the Technical Service Life is longer than or equal to the Economic and Functional Service Life.

The Service Life Concept allows individual design policies to be pursued for each structure, based on an economic sub-optimization of the economy of each individual owner. From society's point of view this will soon become an unacceptable situation, why some uniformity must be ensured. This is mainly achieved through Codes and Regulations which may be tailored such as to ensure a reasonable uniformity in the safety and the serviceability of similar structures over the years, i.e. ensure an acceptable service life of the structures viewed from the point of view of society.

2. CONCRETE STRUCTURES - A LONG TERM CHALLENGE

Out of the previously mentioned four main building materials, concrete and concrete structures, including reinforced and prestressed structures, present probably the most complicated set of problems with respect to the durability and service life of structures.

Concrete is a conglomerate of many different inorganic materials bound together by several types of cementiteous and pozzolanic materials. The size of each particle is several orders of magnitude larger than the individual particles in other materials such as steel, and each particle (aggregate) is in itself a complicated component.

The production of concrete, and the execution of concrete structures, follows very simple procedures compared to the procedures in other structural technologies such as in the airplane, nuclear and electronic industry. Therefore, the influence of workmanship and the conditions of execution has a very pronounced influence on the quality of the outcome of the process.

2.1 "Lab-crete" and "real-crete"

The hardened concrete achieved on site very often differs substantially from the specified concrete, and when quality is to be verified, specially cast and cured cylinders or cubes are produced, and tested for strength. The sometimes humorous differentiation between "lab-crete", representing performance test specimens and specimens for research, and "real-crete", representing the in-situ concrete, is a serious matter when evaluating the durability of structures. A service life design having a reasonable degree of reliability will have to be based on in-situ measurements of the decisive parametres for durability as determined from the deterioration mechanisms which threaten the structures.

The variability of in-situ concrete quality is even more pronounced, when the hardening and curing conditions are taken into account. If the curing does not control the moisture exchange between hardening concrete and the environment, the surface layer - or skin - of concrete will exhibit early micro-cracking and even plastic shrinkage cracking, due to drying out, or may be harmfully porous due to excessive water uptake during the curing process. Similarly, the temperature levels and temperature differences between the newly cast concrete and the surrounding air, or between new and old concrete across a construction joint must be kept below specified values to avoid the early age cracking which will once and for all open up the concrete for penetrating aggressive agents including water.

2.2 Strength versus durability

The traditional 28 day strength requirement for concrete has been a simple and operational means of verifying the strength requirements. With the growing concern for durability, this parameter is not sufficient to reveal the durability characteristics of concrete. Much more involved testing is required in order to clarify if a concrete will be durable in a structure exposed to certain aggressive environments.

2.2.1 Testing for durability

Nearly all deterioration mechanisms depend on some type of aggressive media entering from the surrounding environment through the surface of the concrete and penetrating into the concrete. The one most important substance promoting deterioration is water. In fact only mechanical damage and temperature differences may cause damage without the governing influence of water.

The important rate-determining parameter then becomes the rate of penetration of aggressive substance including water. The permeability and the diffusivity of the concrete becomes decisive, and especially the conditions of the outer concrete layer, i.e. the skin of the concrete, or possibly the concrete cover will be a main controlling factor in the rate of deterioration.

There is no tradition for designing concrete with low permeability nor any well established test methods to verify the permeability of structural concrete. The permeability also differs for the same concrete, depending on the penetrating medium such as gaseous substance (CO_2), water, and chlorides dissolved in water. New concrete mix designs are currently being developed to cope with the service life requirements.

The one well established parameter controlling the permeability and diffusivity of concrete is the W/C-ratio. A very low W/C-ratio, usually achieved by introducing plasticising or superplasticising admixtures, will enhance the durability. Penetration of chlorides is a main governing risk with respect to corrosion of reinforcement. However, pozzolanic admixtures develop their properties at very different rates. Microsilica usually reacts very quickly, and the effect is obtained after just a few days. Contrary to this flyash reacts very slowly, and the effect is usually not traceable at the classical 28 days testing age. After 3 months a considerable improvement in permeability and diffusivity e.g. in connection with chloride penetration, is observed, but the effect may still improve after 1-2 years. Consequently the age at which veryfying tests shall be performed is very difficult to fix, and the 28 days testing age with respect to concrete strength cannot uncritically be maintained when the effects on durability are considered. This has further implications when performing pre-production trials and production controls, as the test results are not available until long after production has started or corrective interventions have become very difficult.

2.3 Hazards

Due to the usual progression of deterioration from the surface inwards and due to the composite nature of concrete structures, where concrete is combined with reinforcement, deterioration may have different consequences.

The corresponding hazards may be graded as follows (3):

- local hazards, where the surface of the structure slowly disintegrates and spalls due to cracking of the concrete (freeze/thaw action, Alkali-Silica Reactions etc.) or due to corrosion of the reinforcement. This creates serious hazards for users and bypassers risking being hit by falling debries. In the initial stage of development this does not cause noticeable reductions in overall load carrying capacity, stability and safety of the structure.
- global hazards,where damage has developed to such an extend that the structural integrity, stability and safety is reduced, and parts of or the whole structure may collapse or otherwise become unfit for use.

In this respect the warning associated with initial cracking, miscolouring and spalls are valuable signals of distress which should not be left unattended.

2.4 Concrete is expected to crack

It should be recalled, that concrete structures by virtue of their designed load uptaking mechanics are expected to develop load induced cracks with limited crack widths. For this reason cracking in concrete structures shall not à priori be considered signs of deterioration or malfunction.

3. DETERIORATION MODELLING

In order to understand the mechanisms of deterioration it is essential that physico-chemical models are available explaining how degradation occurs and clarifies which parametres are governing the process. This knowledge is a prerequisite in order to:

- perform a rational assessment into the damage type and the rate of development,
- select correct interventions and remedial measures and avoid aggravating the ongoing degradation, - the latter point unfortunately often being the case when incorrect remedial measures are being employed,
- avoid premature deterioration to develop in future structures,
- perform relevant maintenance during the operation of structures.

Decisions on these aspects are usually taken by structural engineers whereas the deteriorating processes are occurring within the micro-structure of the materials. The problem thus contains an inherent conflict between the level of modelling being directly or indirectly employed.

3.1 Micro, mesa or macro level of modelling

The deep insight into materials behaviour is represented by the materials scientist who naturally bases his models on micro-level materials science models whereas the structural engineer takes decisions based on his understanding of the problem which incorporates macro-level modelling or structural engineering models.

If these two basically different levels of modelling are not fully clarified in the information transfer between the structural engineer and the materials scientist, misunderstandings will occur. They will not speak the same language, and the so called communication gaps develops. The intermediate, or mesa-level modelling, performed by the materials engineer is an attempt to help bridging the main communication gap between micro-level and macro-level approaches.

However, it should be clear, that models on each level have the same degree of validity and are all indispensable. I.e. micro-level models are not necessarily more correct, or better than macro-level models.

3.2 Modelling, credibility and education

The tasks of the scientists and the engineers are to ensure compatibility between models on different levels treating the same phenomena. This is maybe the area most neglected in modern materials science and materials engineering; a communication problem that may well continue to create the most serious conflicts in the building and construction sector, including repair and rehabilitation.

The situation may well remain so well into the next century, if our engineering educational system is not changed. This represents the most serious dilemma of our profession in our relations to society and is contributing to our growing credibility problem. The lack of interdisciplinary understanding (and mutual respect) among engineers makes it especially difficult to cope with the durability problems of our structures, because these problems encompass all the disciplines of the engineer such as

- structural design, statics and mathematics,
- materials and their degradation,
- heat and moisture insulation,
- climatic conditions,
- execution and maintenance,
- repair and strengthening.

Information must be received and transferred between the different levels of detailing. This highlights the true need for a professional and rational interdisciplinary scientifically based engineering curriculum, - a true poly-technical education (4).

4. EXISTING STRUCTURES

4.1 Operation and maintenance strategies

Recent years growing durability problems with part of the existing buildings and structures have emphasized the need to follow a rational operation and maintenance strategy in the upkeep of structures.

These problems have grown to levels where the traditional approach of repairing damaged structures and attempting to bring them back near to initial quality will be exorbitantly expensive. Completely new ways of handling these problems on both structural level, and safety and reliability level have been sought. In the intermediate say 10 years with unclear maintenance and repair strategies the size of the problems have been close to getting out of hand, especially what concerns problems associated to concrete structures, because major parts of concrete problems are rather new and the total number of concrete structures is very large.

Today we have realized the following needs

- Repairs do not necessarily have to re-install initial or near initial quality and performance, a sufficient target quality of the repaired structure must be determined.
- From a service life concept point of view the economic optimization will often lead to the conclusion that repair and upgrading is not optimal, and a decision of non-repair together with an intensified inspection and maintenance routine, e.g. including monitoring, may well be the optimal solution. I.e. degenerate under control.
- The traditional visual inspections of structures may tend to maximize maintenance costs instead of the minimizing effect sought. The reason being that interventions are not made until an active or rapidly propagating deterioration mechanism is in progress. Preventive maintenance is thus not applicable or is of very little value.
- Deterioration mechanisms threatening our building materials in the structures must be clarified, and the main governing - and influenceable parameters must be identified in order to allow for a repair procedure which can slow down or stop an ongoing deterioration.
- Inspection procedures - also so-called superficial inspections - should include on-site testing to determine the degree of break-down of inherent protective effects in the structure. For concrete structures this means determining the current state with regard to e.g. carbonation depth, chloride penetration, electro-chemical potentials, depth of deleterious reactions, residual bar diameter etc.
- Preventive maintenance performed before the onset of rapid propagation of deterioration will be a very cost-effective way of prolonging the service life of structures. This leads to a need to make users and owners of structures much more conscious of the long term economic benefits of such interventions. This task is difficult from a political and psychological point of view, because maintenance activities must be performed on an otherwise intact structure showing no visual signs of distress.
- In order to keep track of the condition of structures and their time-dependent developments, rational management systems should be employed.

Thus the management of structures becomes a major task in the overall optimization of costs and technical efforts in the upkeep of structures (5).

4.2 Structures Management and Maintenance Systems

Structures Management and Maintenance Systems thus performs a rational and systematic administration of structures aiming at:

- maintaining an acceptable performance of each structure
- ensuring an optimum economic service-life of each individual structure.

In doing this, the following factors shall be considered:

- safety, local as well as global,
- current construction and repair technology,
- economic constraints,
- aesthetics,
- social and political aspects.

It shall be noted, that the road and bridge sector has been the forerunners with respect to combined Bridge Management and Maintenance Systems. Much value can be gained by profiting from experience from this field (6).

5. DESIGN OF NEW STRUCTURES

5.1 Codes and standards

Codes and standards constitute the legal technical basis for structural design and execution. They represent the requirements of society towards safety and serviceability in the complex task of creating structures. Thereby codes and standards constitute the most important structural design pre-requisites, and will remain to do so in a foreseeable future. Codes often incorporate centuries of invaluable national or regional experience. As such they may, however, at times be regarded as obstacles towards introducing new technologies.

Recent years' rapid technological development coinciding with the growing awareness to consider the long term durability of structures present a challenge to code writers. Future generations of codes shall focus on formulating basic principles of long term validity and allow freedom and openness in specifying means of fulfilling these principles. Only so can they be sufficiently flexible to profit from new technological achievements and accomodate new techniques without loosing the valuable parts of accumulated experience.

Concrete is - and will continue to be - our most important building material and ongoing international concrete code-writing activities will strongly influence the civil and structural engineering profession and may well set milestones for the code developments for other materials.

5.2 CEB-FIP Model Code 1990

CEB is, in cooperation with FIP, currently preparing a new Model Code for Concrete Structures for the 90'ies, MC 90. The Model Code attempts to incorporate service life design concepts in an operational code-like format penetrating all relevant aspects of safety and serviceability. By avoiding that service life aspects constitute a separate limit state, but are integrated into sections of Ultimate Limit State and Serviceability Limit States, a harmonic evolution of the Model Code is ensured. The Model Code is further supported by a separate Design Guide: "CEB -Guide to Durable Concrete Structures" (7).

MC 90 thus leads towards a new generation of structural Codes of Practice being prepared for concrete structures, but being conceptually adaptable to codes for other building materials. This represents the internationalization of design concepts which is leading to ongoing harmonization of codes and standards, e.g. as represented by the Eurocodes and Euronorms of the European Community and by the Comecon Codes of the CMEA countries in Eastern Europe.

This valuable achievement can be attributed mainly to the year-long international professional cooperation within private organizations like IABSE, FIP, RILEM and CEB.

5.2.1 Service Life Requirements in CEB-FIP Model Code 1990

The basic requirements in the Draft CEB-FIP Model Code 1990 currently under discussion are (8):

"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".

In order to fulfil these requirements the Draft - Model Code focus on the whole building process. It is assumed that durability problems only can be avoided if adequate and coordinated efforts are imposed upon all persons involved and upon all phases in the process of defining, planning, building and using the structure until the end of its expected lifetime.

The whole process of creating structures and keeping them in satisfactory use and service requires cooperation between the following four parties:

- The owner, by defining his present and foreseen future demands and wishes.
- The designers (engineers and architects) by preparing design specifications (including quality control schemes) and conditions.
- The contractor who will try to follow these intentions in his construction works. Most commonly also subcontractors are involved.
- The user, who will normally be responsible for the maintenance of the structure during the period of use.

Any of these four parties may - by their actions or lack of actions -contribute to any unsatisfactory state of durability of the structure and thus cause a reduction of the service life. Also interactions between two parties may cause faults which can have an adverse effect on durability and service life.

5.2.2 Decisions on design life and exposure class

The selection of design life and of exposure class constitute the two most important decisions with respect to the resulting long term durability and appearance of the structure.

The required service life should be obtained without relying on special protections needing frequent maintenance or redoing. However, in cases of especially aggressive environments special protective measures may be foreseen.

5.2.3 Service Life Design Strategy

The design strategy should consider possible measures protecting the structure against premature deterioration. A set of appropriate measures (one or more) shall be combined to ensure that the required service life is obtained with a sufficiently high probability.

Protective measures may be established by, i.a.:

- the selected structural form,
- the concrete composition, including special additions or admixtures,
- the reinforcement detailing including cover,
- a special skin concrete quality, including skin reinforcement,
- limiting or avoiding crack development and crack widths by prestressing,
- additional protective measures such as tanking, membranes or coatings, including coating of reinforcement,
- specified inspection and maintenance procedures during in-service operation of the structure, including monitoring procedures,
- special active protective measures such as cathodic protection or warning systems.

A service life design may profit from a multitude of protective measures cooperating simultaneously to ensure the required service life with an acceptable level of reliability.

This design strategy is considered a Multistage Protection Strategy which leaves the selection of individual protective measures to the designer.

6. RESEARCH, DEVELOPMENT AND EDUCATION

The durability problems facing the structural engineer has lead to a dilemma in the research community.

It is a well established procedure in research, that complicated problems are split into more easily defined part-problems. These part-problems are then solved one by one, and the results combined to constitute the answers to the initial and more complicated problems.

However, the durability problems - especially in the field of concrete structures - have proven to be so interdependent that splitting may result in misleading conclusions. The interdisciplinary problems relate partly to macro-level and partly to micro-level problems including physical, chemical, electro-chemical and even biological processes, which complicate the problem solving process even further.

In this connection it should be recalled, that the durability problems in so-called more advanced technologies like the aircraft, space and nuclear industries are faced with only one major problem of durability, being the development and growth of cracks (3). In this way the assessment and maintenance activities are reduces to - crudely speaking - a simple analysis, track recording, and management of crack propagation.

The complexity of the durability problems are in reality shaking the established scientific schooling, and a new multidisciplinary approach must evolve from the turmoil.

Part of the problems may also be related back to our basic education in which two simplifications distort part of our spontaneous understanding of the problems:

- we think in linear scales, both in geometric terms and in time,
- we think in deterministic events.

For reasons above, we are faced with a communication gap between engineers and everyday people not trained in a technical approach to problems.

The technical community should therefore concentrate more effort in presenting and explaining the problems of durability and service life considerations - and the uncertainties associated with our answers - to the users and owners of the structures, including lawyers, politicians and other decision makers. Education is needed on all levels!

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