DURABILITY DESIGN OF CONCRETE STRUCTURES

Phenomena, Modeling, and Practice

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Preface

Durability of Concrete Structures: State of the Art

Durability is a term related to both performance and time, reflecting the degree to which a structure/infrastructure meets its intended functions for a given duration of time. This description applies to all types of structure and infrastructures in civil engineering. Actually, during the service life a structure displays time-dependent behaviors by ageing of the structural materials. The ageing processes can be intrinsic to the structural materials or induced by the interactions between the service conditions and the structural materials. This picture holds for all structures and their constitutive materials. In fact, concrete structures have transient behaviors due to some well-known time-dependent properties of structural concrete, such as shrinkage and creep. Take creep, for example. Engineers had been challenged by this evolving property as early as the 1900s, the very beginning of concrete structures coming into use. During the following years the lack of consideration of creep, surely due to lack of knowledge, had caused some serious accidents in structural engineering; for example, the collapse of the Koror–Babelthuap Bridge, Palau, in 1996. The past century has witnessed considerable research efforts dedicated to this subject, and the colossal creep models and established databases. The awareness of the deterioration of concrete properties by environmental actions comes much later. In the early 1990s, field investigations from various sources showed that concrete structures, massively constructed during 1950s and 1960s, were in very poor condition. The cost of the maintenance works due to deterioration by environmental actions was reported to be reaching an alarming level and generated heavy financial burdens on the structure owners. This situation makes durability a worldwide concern for decision-makers, structural designers, and material suppliers. Accordingly, the past three decades witnessed enormous efforts dedicated to intensive research on deterioration processes of structural elements and concretes, and the durability specifications for concrete structures at the design level.

Today, the term "durability" is somewhat standardized in a technical sense. The standard ISO-13823 provided the definition as the "capability of a structure or any component to satisfy, with planned maintenance, the design performance requirements over a specified period of time under the influence of the environmental actions, or as a result of a self-ageing process"; the ACI Concrete Terminology gives the definition as the "ability of a material to resist weathering action, chemical attack, abrasion, or any other process of deterioration." Evidently, the former definition is more adapted to structural engineering, while the latter is more oriented to concrete materials. However, one can notice that both definitions exclude the most evident time-dependent properties of structural concrete: shrinkage and creep. This is doubtless due to the fact that the recent engineering concern, as well as the corresponding efforts, mainly focuses on the environmental actions, the reason why the term "environmental actions" is explicitly expressed in both definitions. In this book, this established terminology is also followed, though shrinkage and creep remain the most important transient properties of structural concretes. The awareness of structural durability leads to two important changes in structural design. First, the design changes from a "static" mode to an "evolving" mode and the evolution of certain structural and materials properties must be taken into account through appropriate approaches. The design service life, or design working life, becomes an independent design parameter and target for the design procedure. Hence, the design changes from a loading-based procedure to a service life-based one. Second, durability awareness enables the life-cycle concept in structural design and management. Modern civil engineering is a highly multidisciplinary domain, connected with more fundamental social stakes, such as sustainability and ecological impacts. The life-cycle concept introduces into the structural design procedure, besides the structural requirements, the requirements of structural demolition, reuse, material recycling, and other ecological considerations.

Durability Design: Multilevel Procedure and Challenge

Performing a design for durability is by no means a trivial task. First of all, durability design is by nature a multilevel problem: durability design has different meanings for the whole structure, structural elements, and structural materials. For a structure as a whole, the durability design aims, for a given service life, given environmental actions and given budgetary constraints, to ensure the most rational structural element assemblage and global layout so that the transient performance can always be maintained to an expected level. Furthermore, a rational partition of initial investment in the construction phase and subsequent investment on maintenance works is also expected. For structural elements, the durability design, following the design strategy at the whole structure level, is to fulfill the design service life through more specified requirements, such as bearing capacity, section details, concrete cover thickness, and material properties. On this level, the durability design focuses on the technical requirements, and less on the budgetary factors. Structural design transfers also on this level the technical requirements on durability onto the material level through specified material properties. Then comes the material design part. On this level, material engineers should design the concrete mixture appropriately, both in order to satisfy the specified material properties transferred from the structural design, and to ensure good workability of the concrete mixture for in-place operation. Good workmanship is crucial to achieving durability of concrete structures in construction, since concretes need in-place operation and curing to grow into a structural materials.

This multilevel design process necessitates good communication between the structural design part and the material design part. This procedure is a performance-based one and also an ideal one. Although easy to understand, this performance-based procedure relies heavily on the available knowledge of the deterioration processes. Thus far, the state-of-the-art of the knowledge on durability is unfortunately far from homogeneous. For the processes such as concrete carbonation and chloride ingress, the available knowledge can provide models and support quantitative requirements for design of given service life and environmental actions. This is by no means the case for other processes, like salt attack and pore crystallization. As a result, only empirical and qualitative requirements can be formulated for the material design against these processes. Actually, this empirical format of durability design existed long before the performance-based format was established, and is still used in design codes such as ACI-318 code and Eurocode2.

The second challenge comes from the concrete material itself. Modern concretes change…, and quite radically. Owing to the importance of CO_2 emission from cement clinker production, modern concretes incorporate more and more secondary cementitious materials into the binder, including fly ash, ground granulated blast-furnace slag, and lime powder. The alkali-activated binder even contains no Portland cement clinkers. Also, from ecological considerations, recycled and artificial aggregates are incorporated into concrete to replace natural aggregates. Concretes made from these composites can have quite different properties and behaviors compared with ordinary Portland cement (OPC) concretes. Historically, it is the OPC concretes that have undergone intensive research and own more return of experiences from existing structures. The technical requirements, quantitative or qualitative, are based heavily on the accumulation of such data. With the dearth of systematic data and experiences with these new concrete composites, extrapolation from the available knowledge to the appropriate specification of these new composites for durability design seems highly challenging. The knowledge on the deterioration process in time scale constitutes the last challenge. To establish a reliable deterioration law, one needs to have a reliable model formulated from correct mechanisms and validated by real-scale tests or in-place structural investigations. Here, the term "scale" refers to time. Normally, the deterioration process under natural environmental actions is extremely slow; for example, it takes normally 15–30 years to obtain meaningful chloride ingress results for specimens stored in marine exposure stations. However, most deterioration research is conducted in the laboratory under artificial environmental actions to accelerate the process to obtain measurable data within an acceptable time scale. Since the similarity between these accelerated tests and the natural deteriorations is rather low, how to extrapolate the laboratory observations to natural processes remains always a tricky problem.

Given all the realistic aspects related to the multilevel design process, we can find ourselves in a dilemma, between the need to formulate requirements and specification for a given service life and the constant lack of sufficient data and experiences to support them due to the use of new concrete composites, new exposure conditions, or new service conditions. So, one can imagine that the durability design following a mixed performance–empirical format will always be a design option, a rather realistic one.

Modeling of Durability Processes: Common Basis

The deterioration of concrete materials under environmental actions is fundamental knowledge for durability design. The very reason that concrete can deteriorate stems from the facts that concrete is a porous material and through the pore network the material can have mass and energy exchange with the external environment or within its internal components. The term "deterioration" encompasses actually all the intrinsic or action-induced exchange processes. Accordingly, deterioration has a multi-physical nature. Mastering such processes is normally difficult, if not impossible, due to the multi-nature of concrete.

First, concrete is a heterogeneous composite with hardened cement paste as matrix and aggregates and fillers as inclusions. The heterogeneity depends on the size distribution of aggregates and fillers, and also on the properties under investigation. In particular, many durability processes occur on the concrete surface, where the boundary effect of aggregates cannot be neglected. Second, concrete is a porous medium, with pore structure playing a primary role in the related transport processes. The pore size of concrete covers more than six orders of magnitude: the typical interlayer distance within calcium silicate hydrates (C-S-H) is about 2 nm, the intergranular gap among C-S-H bundles is about 5 nm, the size of capillary pores ranges between 10 nm and 1 μm, the thickness of the interfacial transition zone (ITZ) is on the order of 10 μm, the entrained air bubble is about 100 μm, and the residual air voids in concrete can reach 1–2 mm. Pores and voids with different sizes have very different contributions to the physical properties of concrete. To complicate the scenario further, concrete pores can be saturated partially with pore solution, normally a highly alkaline electrolytic solution in equilibrium with the surrounding hydrates and minerals, and partially with pore gas phases. Thus, all masses, ions or gas molecules, transport through the pore structure of this complexity.

Third, concretes have only partial multiscaling property. The hardened cement paste can be regarded as a multiscale assemblage: C-S-H with its inherent porosity as the basic scale (~1 nm), different packing patterns of C-S-H bundles as the second scale (~10 nm), then hydrates cells containing C-S-H bundles and other hydrates as the third scale (~10 μm). The hardened cement paste was reported to have good multiscale property for the elastic properties. However, this property breaks down from cement paste to mortar because the coarse pores and weak mechanical properties of the ITZ perturb this multiscaling property.

Given all these aspects, a correct description of deterioration of concrete materials is far from an easy task, even with the physical and chemical mechanisms clarified. Fortunately, we talk about modeling rather than reality here. Modeling is basically an approximation of what is really going on. The good news is that, for a specified purpose, the facts and the mechanisms can be simplified, but not too much to lose its capacity to predict. For engineering use, this point is crucial and the key to depicting sophisticated phenomena. The last several decades witnessed some powerful tools for concrete modeling, such as poromechanics, micromechanics, and multi-physical transport theory. In Part 1 of this book the deterioration mechanisms will be presented in the individual chapters treating different processes, and the relevant models are introduced for engineering use. For a book aiming at durability design, no attempt is taken to establish a general theoretical framework for all deterioration processes. Instead, regardless of the theoretical basis, the following three principles are used for modeling the durability-related processes.

Principle 1. Correct estimation of the length scale. Concrete is a heterogeneous material, but the material components distribute randomly in space, allowing for the definition of a representative elementary volume (REV). The size of the REV scales to such an extent that concrete can be regarded as a homogeneous medium. As a rule of thumb, the REV size of concrete is usually estimated to five times the maximum aggregate size for transport properties. If a process occurs on a length scale smaller than the REV size, it can only be described in a heterogeneous context. The mass transport across a concrete surface with a length scale smaller than the REV size belongs to this case.

Principle 2. Correct estimation of the time scale. Normally the time scale of deterioration processes in durability design is on the order of the service life. Thus, all transient phenomena with a characteristic time much shorter than this time scale can be simplified as instantaneous, a powerful tool to propose simplified models. Take the transport process, for example. As ions transport in the pores of concrete, the pore-wall hydrates adsorb the ions. The adsorption has its own characteristic time; for example, 2–3 days for chloride ions. Compared with the target time scale (>10 years), all adsorptions can be regarded as instantaneous events. Accordingly, transport models need not include a transient adsorption.

Principle 3. Correct estimation of modeling error. The principal role of a model is to predict, and the capacity of a model is judged by its prediction accuracy. The raw materials of concrete, except binder materials, are all natural materials. Their properties and compositions have quite significant variation, and so do the properties of concrete. If the model takes into account detailed physical/chemical mechanisms, then the dispersion of model prediction must be estimated considering the randomness of related properties. As the dispersion is important, the model had better include statistical characteristics of the properties. This aspect is quite important for structural-level specification to leave a sufficient safety margin for design.

Besides the above three principles, a physically meaningful model is always a better choice than otherwise (e.g., purely empirical models). Physically meaningful models have explicit mechanisms behind them, whereas empirical models provide merely a fit of experimental data. As the environmental conditions or the concrete composition change, empirical models are in a situation where they need to extrapolate their prediction to other cases not included in the model fitting data, and thus are less probable to remain predictive. On the last point, validation is crucial for the engineering use of models. Normally, laboratory research tends to build a model only on a few sets of experiments, which is far from sufficient for engineering use. In some cases the model is even validated by the same set of data from which the model is made. Indeed, a big contrast exists between the huge number of models proposed in the literature and the few reliable ones really used in durability design work. The underlying reason is that most literature models have not been validated by enough in-site data. Reliable model validation should best be performed on real structures with long-term monitoring data.

This Book: Structure and Audience

This book attempts to treat durability design, addressing simultaneously the material and structural disciplines in civil engineering. The book follows a basic logic line from concrete materials to structural design, and the content is accordingly divided into three parts. Part 1 is dedicated to the deterioration of concrete materials under different environmental actions, including carbonation, chloride ingress, freeze–thaw, leaching, and salt crystallization, treated respectively in Chapters 1 to 5. In each chapter, the deterioration process is presented following a phenomena–mechanism–modeling logic line. Part 2, consisting of a single chapter, Chapter 6, treats the subject of concrete deterioration in a structural context, including the effect of mechanical loading, the impact of cracks, the multi-field problems, and drying–wetting actions. Part 3 elaborates the topics of durability design for concrete structures in four chapters, Chapters 7–10, treating respectively the global method and approach, durability indicators, design applications, and the codes and standards.

The intended audience of this book includes structural design engineers and civil engineering students in their postgraduate programs or later part of their bachelor programs. This book can be used as a reference for durability design work or as a textbook for graduate courses on durability of concrete structures. Part of this book can be assigned to undergraduate students as extensive reading materials for standard courses on structural design and construction materials. Structural engineers can also benefit from this book by learning the deterioration processes and the related models for engineering use, and researchers of concrete materials can benefit from this book by discovering how knowledge on the material level is transferred to the structural level.

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When I bravely proposed to write this book, I had no idea how deep is the water I was stepping in. This book cannot see its day without the support of people behind. The content of this book comes from the work of my team on the durability of concrete materials and structures in the past 10 years in Tsinghua University, China. The contributions of my former PhD students and postdoc fellow, Chunqiu Li, Chunsheng Zhou, Qiang Zeng, Xiaoyun Pang, Le Li, and Linhu Yang, are deeply acknowledged. I am indebted to Professor Olivier Coussy for the spirit of modeling for engineering use: always keeping equilibrium between scientifically correct and practically usable, which I hope to have achieved in this book. Part of this book has been used as the teaching materials in the postgraduate course "Durability and Assessment of Engineering Structures" in Tsinghua University. This course has been taught for 10 years, and the feedback from each class has substantially enriched the related content. A part of Chapter 10 is extracted from the drafting works of the China design code GB/T 50476-2008 and its revision work in 2014–2015. Thus, I would like to thank the drafting team for the collective work and support for this book, especially Professor Zhaoyuan Chen and Professor Huizhen Lian, initiators of durability standards in China. Moreover, my colleagues are gratefully acknowledged for providing the photographs to enhance the illustration of this book, especially Dr Tingyu Hao. Finally, I express my deep gratitude to my wife and my son for their support during the writing of this book, and they may include me in the regular family events from now on.

Contents

Part One

Deterioration of Concrete Materials

1

Carbonation and Induced Steel Corrosion

This chapter treats the first important durability process of concrete materials and structures: the carbonation and the induced corrosion of steel bars in concrete. The carbonation of concrete originates from the reaction between the alkaline pore solution of concrete and the carbon dioxide (CO_2) gas migrating into the pores. The carbonation does not compromise the material properties but decreases the alkalinity of the pore solution, which has an adverse effect on the electrochemical stability of steel bars in concrete. The risk of steel corrosion can be substantially enhanced in a carbonated concrete. This chapter begins with the phenomena of concrete carbonation and its effect on the long-term durability of concrete materials and structures. Then the detailed mechanisms are presented, according to the state of the art of knowledge, for concrete carbonation and the induced steel corrosion, together with a comprehensive analysis on the main influential factors for these processes. On the basis of the available knowledge, the modeling aspect is brought forth through mechanism-based and empirical models for engineering use. Since the valid scope and the uncertainty are two fundamental aspects for model application, the critical analysis is given to the models presented and their application. Some basis for durability design against the carbonation and the induced corrosion is given at the end.

1.1 Phenomena and Observations

As concrete is exposed to the atmosphere, the CO_2 present in the atmosphere can migrate into the material through the pore structure and react with the cement hydrates such as portlandite ($Ca(OH)_2$ or CH) and the calcium silicate hydrates (C-S-H). These reactions are termed the "carbonation" of concrete materials. The direct consequence of carbonation is the consumption of CH, eventually C-S-H, and the decrease in pH value of the pore solution. Under a less alkaline environment, the electrochemical stability of the embedded steel bars in concrete can be destroyed, the steel can be depassivated and the electrochemical process of corrosion can

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