CONCRETE PERMEABILITY AND DURABILITY PERFORMANCE

FROM THEORY TO FIELD APPLICATIONS

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RUI D. NEVES
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Concrete Permeability and Durability Performance

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Foreword

Concrete as such is a very durable material. There are magnificent examples of concrete structures which have survived 2,000 years without substantial repair measures, and they will survive hundreds of years to come. The Pantheon in Rome and numerous bridges built during the Roman Empire in Italy and Spain that served up to 2,000 years are well-known examples.

Since the large-scale application of reinforced concrete, the construction industry has experienced enormous challenges with respect to achieving the designed service life of concrete structures. According to most standards, reinforced concrete structures are expected to have a service life of at least 100 years. In reality, however, expensive repair and renovation are frequently necessary after not more than 30 years. In recent years, a number of bridges collapsed after less than 50 years. It is estimated that repair of a damaged bridge costs approximately six to eight times more than that of the construction of a new bridge. During repair operation or reconstruction process, the necessary deviation of traffic alone causes additional financial and environmental burdens. Therefore, one major subject in concrete technology research has been to increase repair-free service life of reinforced concrete structures.

Concrete is a porous material with a wide-range distribution of the size of pores, running from a few millimetres down to nanometres. The surface of concrete structures is usually in contact with changing climatic conditions. During a wet period, rain water will be absorbed by capillary action and in humid environment by capillary condensation. The micropores remain water-filled even during dry periods. The humidity in the pore system will initiate corrosion of the steel reinforcement as soon as the carbonation depth exceeds the cover thickness. Another disadvantage of reinforced concrete elements exposed to natural environment is the crack formation due to bending or temperature and humidity gradients. These cracks are preferential pathways for locally deep carbonation and hence early beginning of corrosion of reinforcement.

Service life of reinforced concrete structures depends essentially on the cover thickness and on the permeability of the concrete cover. It is comparatively easy to determine the thickness of the concrete cover. Permeability of the cover, however, is a more complex property. Based on the research findings and experience from practice, the present volume presents various topics related to permeability of concrete. A method to determine permeability of concrete is described in detail, and many possible applications in practice are discussed here. It can be expected that this volume will contribute to our knowledge on how to increase service life of reinforced concrete structures, and the discussions on durability and service life will certainly bring broader awareness of the implications of permeability of concrete.

Durability and service life of reinforced concrete structures, however, do not depend on one dominating parameter. This was shown in a convincing way in a recent publication of RILEM Technical Committee (RILEM TC 246-TDC). Results of this Technical Committee have clearly demonstrated that durability depends on the combination of environmental actions and mechanical load. This volume is an excellent basis for a better understanding of dominating processes which may substantially reduce service life of concrete structures and of steel reinforced concrete structures.

Prof. Dr. Dr. h.c. Folker H. Wittmann

Preface

The genesis of this book originated on August 29, 2016, with a proposal of Prof. Neves to Dr. Torrent on the possibility of writing jointly a book about the permeability of concrete. After some consideration, the proposal was accepted, ending in a first draft of its possible content. Then, finding a suitable interested publisher was required. Believe it or not, on June 1, 2017, an invitation by Tony Moore (Senior Editor of CRC) arrived, asking Dr. Torrent about his willingness to write a book on permeability testing, on advice of Profs. S. Mindess and A. Bentur. This was a fortunate coincidence or superb intelligence services of CRC Press in act… The offer was accepted and, immediately, Prof. Imamoto was invited to join the authors' team, invitation he accepted on July 29, 2017, during an unforgettable exquisite dinner in a small, special sushi restaurant near Tokyo's Narita Airport, agreement possibly helped by a considerable dose of excellent cold sake…

Regarding the subject of this book, it is good to recall that until the early 1980s, the main research efforts on hardened concrete properties were predominantly focused on its mechanical and viscoelastic properties, required for the structural design of reinforced concrete constructions. Since then, a considerable interest arose on durability issues, both in understanding the deterioration mechanisms and in developing suitable test methods and, more recently, in modelling the durability performance of concrete structures.

A quantum leap was made by the work of RILEM TC 116-PCD "Permeability of concrete as a criterion for its durability", chaired by Profs. H.K. Hilsdorf and J. Kropp, that stressed the importance of transport mechanisms, chiefly permeation, on the durability of concrete structures. The results of this work were condensed in a State-of-the-Art Report (RILEM Report 12), published in 1999.

During the ensuing 20 years, several test methods for measuring the permeability of concrete to gases and liquids have been developed and a formidable amount of information has been produced through their application in the laboratory and on site. Part of it was included in RILEM Report 40 (2007) and RILEM State-of-the-Art Report v18 (2016), condensing the work of RILEM TCs 189-NEC and 230-PSC, respectively.

It is the purpose of this book to present the existing knowledge on the permeability of concrete in a consolidated form, describing the available test methods and the effect key technological parameters of concrete have on the measured permeability. It presents a large amount of experimental data from investigations performed on laboratory specimens and full-scale elements and also from real cases of site permeability testing, conducted to solve complex and challenging concrete construction issues (durability, water-tightness, defects, spalling under fire, condition assessment, etc.).

The three authors combine a formidable experience, covering over 30 years of research and testing the permeability of concrete in the lab and on site (they have conducted, with their own hands, permeability tests applying 13 different methods). Thanks to their geographical diversity, they have been active in relevant technical activities in Europe, the Americas, Africa and Asia, thus gaining a good insight into the global situation regarding permeability and durability testing and service life assessment of concrete structures.

This book places a special emphasis on one test method (called *kT*), developed by Dr. Torrent around 1990, that was included in the Swiss Standards in 2003 under the title 'Air-Permeability on Site', with successive updates in 2013 and, recently, in 2019. The credit for this inclusion lies mainly on the initiatives and research work of Prof. E. Brühwiler and Dr. E. Denarié (EPFL, Lausanne), of Dr. F. Jacobs (TFB, Wildegg) and Dr. T. Teruzzi (SUPSI, Lugano). Over 430 documents on the *kT* test method have been recorded to date, out of which some 90 were authored by at least one of this book's authors.

Following Chapter 1, summarizing the fundamentals of durability, the relevance of permeability as a key performance property of concrete is discussed in Chapter 2, already opening the field to the possible applications of its measurement. An understanding of concrete microstructure and of the laws that govern the flow of matter through concrete is considered as essential, aspects that are dealt with in detail in Chapter 3. This is followed by Chapter 4 in which 25 test methods to measure concrete permeability (including capillary suction) are described. Chapter 5 describes in detail the *kT* test method, its fundamentals and the effect of external influences on its results.

Chapter 6 is concerned with the effect of key technological factors on the permeability of concrete to gases and water, tested by various methods.

Chapter 7 reflects the strong conviction of the authors on the relevance of site permeability testing of the end-product to get a realistic assessment of the concrete quality, in particular of its surface layers (the *Covercrete*), of vital importance for the durability of reinforced concrete structures. Having been designed to that end, i.e. to measure the permeability of the *Covercrete* on site, Chapter 8 provides evidence on the suitability of the *kT* test as Durability Indicator, relating its results with other relevant transport properties (sorptivity, diffusion, migration) and with simulation tests (carbonation, freezing/thawing). The same as for any other test, especially when applied on site, the application of *kT* test has not been up to the expectations in a few cases, which are also presented in Chapter 8.

Today, test results are often not enough for designers and owners, who want an assessment of the potential service life of new and existing structures. Chapter 9 presents different service life prediction models with the site permeability of the *Covercrete* as input, often accompanied by a non-destructive evaluation of its thickness.

Chapter 10 presents the relatively new field linking the gas-permeability of concrete to the explosive spalling of the concrete cover during fires. Here, contrary to durability, a not too low permeability is desirable.

Chapter 11 presents a comprehensive series of investigations conducted on site, on full-scale elements and real structures, new and old. Some applications not related to concrete structures are also included.

At the end, in Chapter 12, we draw some conclusions on the present and future of permeability testing of concrete structures, needed developments and unexplored research fields. The book is complemented with Annexes that describe transport tests other than permeation, and a Model Standard on how to conduct *kT* tests in the field and in the laboratory.

The reader is invited to accompany us along this fascinating voyage from the theory of mass transport in concrete to field applications of permeability testing…, fasten your seat belts!!

The Authors

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All: To so many researchers worldwide that contributed their experiences to the body of knowledge compiled in this book. A thorough literature research has been conducted which, by no means can be considered complete; we apologize to those researchers, the valuable work of whom might have been overlooked when writing this book.

Authors

Dr. Roberto J. Torrent is a researcher, consultant and partner of Materials Advanced Services Ltd. He held positions at the National Institute of Industrial Technology and Portland Cement Institute (Argentina), as well as at Holcim Technology Ltd. (Switzerland). For 30 years, he has been directly involved in durability testing of a large variety of concretes, both in the lab and on site. In the 1990s, he invented the Torrent NDT Method for measuring air-permeability. He is a RILEM Honorary Member.

Dr. Rui Neves was formerly a researcher at the National Laboratory for Civil Engineering (LNEC-Portugal). Currently he is Professor in the Structures and Geotechnics Division at Barreiro School of Technology, Polytechnic Institute of Setúbal, Portugal. His research efforts are mainly devoted to service life of reinforced concrete structures, with special emphasis on investigating and testing the permeability of concrete and rocks. He has carried out relevant consulting activity within the frame of concrete quality control, as well as inspection and appraisal of reinforced concrete structures.

Dr. Kei-ichi Imamoto is a graduate of Tokyo University of Science, Japan. He performed research at Tokyu Construction Co. Ltd. for 9 years and is now Professor at Tokyo University of Science. He received the Young Researcher's award from AIJ (Architectural Institute of Japan) in 2008, and prizes from Japan Society for Finishing Technology, Japan Concrete Institute and Suga Weathering Foundation. He is very active in durability testing and service life assessment of concrete structures.

Chapter 1

Durability performance of concrete structures

1.1 WHAT IS DURABILITY?

Since the title of the book intimately associates permeability with concrete durability, it is worth discussing the latter in this initial chapter.

A good definition of durability has been coined in Section 3.1 of Neville (2003), to which some addenda have been made, resulting in the following tentative definition:

> Durability of a given concrete structure, in its specific exposure environment, is its ability to perform its intended functions, i.e. to maintain its required strength and serviceability, during the specified or traditionally expected service life, without unplanned, extraordinary maintenance or repair efforts.

1.2 DETERIORATION MECHANISMS OF CONCRETE STRUCTURES

Discussing in detail the deterioration mechanisms of concrete structures is beyond the scope of this book; yet, the main ones can be briefly enumerated: steel corrosion induced by carbonation or chlorides, chemical attack (typically by sulphates in the soil and ground water and by acids in sewage systems), Alkali-Silica Reaction (ASR) and frost in cold climates.

All these deterioration mechanisms have two aspects in common:

a. they involve the transfer of mass into or within the concrete member
b. they require the presence of water to take place

The transfer of mass takes place by three physical actions: permeation, diffusion and, to a lesser extent, also by migration (all three thoroughly discussed in Chapter 3) and happens through the interconnected network of pores within the microstructure of concrete (also discussed in Chapter 3).

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A succinct analysis will be made in the following sections. For a deeper insight into the problem, the reader can refer to Mehta et al. (1992), Richardson (2002), Dyer (2014), Li (2016), Alexander et al. (2017) and, more specifically for the case of steel corrosion in concrete, to Bertolini et al. (2004), Böhni (2005), Gjørv (2014) and Alexander (2016).

1.2.1 Carbonation-Induced Steel Corrosion

This case of deterioration is due to the penetration (by gas diffusion) of CO_2 from the environment which, in the presence of moisture, reacts preferentially with the reaction product of cement hydration $Ca(OH)_2$ to form $CaCO_3$. From the durability point of view, the main consequence of this reaction is a sharp drop of the pH of the pore solution, displacing the thermodynamic equilibrium of the steel bar, from "passive" to "corrosion". The subsequent corrosion rate is highly dependent on the moisture conditions (as is also the carbonation rate).

According to Mehta et al. (1992), "only porous and permeable concrete products, made with low cement contents, high water/cement ratio (*w/c*), and inadequately moist-cured tend to suffer from serious carbonation".

A tight pore system and a sufficiently thick cover are the main defense strategies against this mechanism, although the cement type (especially the amount of carbonatable material) also plays a role (see Section 9.2.1).

1.2.2 Chloride-Induced Steel Corrosion

This case of deterioration is due to the penetration (by mix modes) of chloride ions from salty solutions in permanent or sporadic contact with the structure. The situation is much more complex than carbonation, due to the overlapping of several physical phenomena taking place, as illustrated in Figure 1.1 for a concrete element in a marine environment (adapted from Hunkeler (2000)).

Chlorides may penetrate by permeation, carried by the saline water solution either under a pressure head for deep parts of the structure or/and due to capillary suction in the critical areas subjected to wetting-drying cycles and, alternatively or complementary, by ion diffusion. Rain washout and evaporation, affecting predominantly the surface layers, add complication to the phenomenon.

When the penetration of the front of a certain elusive critical Cl^- concentration reaches the position of the steel, this is depassivated and metal corrosion may start. The same structure, placed by the sea, will deteriorate much earlier than if exposed to carbonation.

According to Mehta et al. (1992), "The ingress of chlorides into hardened concrete is decisively dependent on and influenced by water transport mechanisms. Substantially greater amounts of chlorides may ingress into the hardened concrete via water transport mechanisms than via pure chloride ion diffusion".

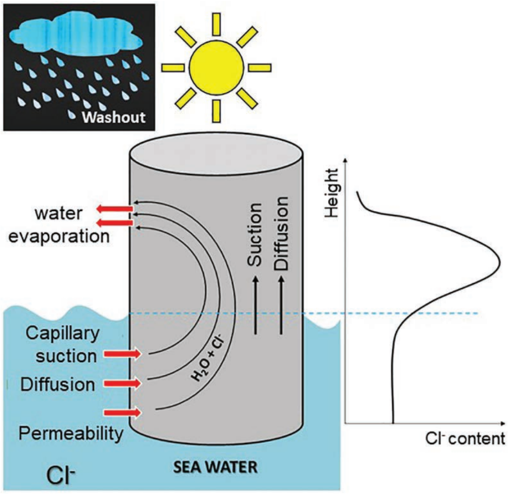

Figure 1.1 Complex combination of physical phenomena in the movement of Cl^- in marine concrete, based on Hunkeler (2000).

1.2.3 External Sulphate Attack

This case of deterioration takes place when sulphate ions from the environment, typically from the soil or ground water, penetrate into concrete, developing deleterious physical–chemical interactions with some minerals in the hydrated cement paste. The main penetration mechanism is permeation of the SO_4^{2-}-rich solution in the form of capillary suction, accompanied by internal redistribution by diffusion.

Salt crystallization, combined with expansive reaction products (e.g. ettringite, gypsum and thaumasite), leads to cracking, loss of mass and/or disintegration of the concrete. There are cements that, due to their composition or performance, are considered as "Sulphate Resistant Cement", although it would be more appropriate to talk of "Sulphate Resistant Concrete", since not just the use of such cements is sufficient to guarantee the immunity of the concrete against sulphate attack.

According to Mehta et al. (1992), "…it can be concluded that, for improved resistance to sulfate attack, a reduction in the porosity and consequently the coefficient of permeability, is more important than modifications in the chemistry of Portland cements".

1.2.4 Alkali-Silica Reaction

This case of deterioration takes place when aggregates containing certain reactive minerals (typically some forms of SiO_2) in sufficient or *pessimum* quantities react, in the presence of moisture, with the alkali (Na^+, K^+) ions in the pore solution, developing expansive reactions. The reaction products,

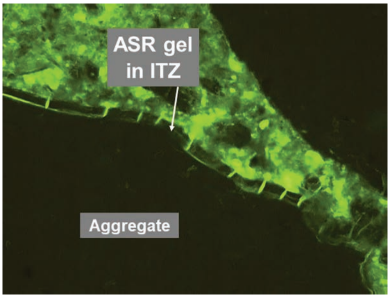

Figure 1.2 ASR gel accommodated along ITZ.

again in the presence of moisture, take the form of an expansive gel which, depending on the circumstances may be innocuous or create enormous deformations of the structure (e.g. dams), cracks, loss of mass and even total disintegration of the concrete.

The expansive gel is sometimes accommodated in microcracks, air voids or along the more porous Interfacial Transition Zone (ITZ), see Section 3.2.3, as shown by the UV light observation of a thin section in Figure 1.2 (Fernández Luco & Torrent, 2003).

The main mechanism of transport of the gel within concrete is permeation, due to expansive pressure, across the system of existing pores and of cracks generated by the expansive action.

The water required to feed the expansive reaction and to swell the ASR gel penetrates the concrete predominantly by permeation (capillary suction) and moves internally by diffusion.

The main defense line against ASR is to avoid the usage of reactive aggregates but, when this is unavoidable, to keep the quantity of alkalis in the concrete sufficiently low (e.g. by using low-alkali cements) or by using adequate types and contents of pozzolanic materials (that compete with advantage in neutralizing the alkalis).

In the case of ASR, the pore structure and permeability of the concrete play a secondary role.

1.2.5 Freezing and Thawing

This case of deterioration takes place when concrete, with a high degree of water-saturation, is exposed to sub-zero temperatures; the saturating water penetrates typically by permeation (capillary suction). The water in the pores freezes, augmenting its volume by 8%, pushing the still unfrozen water along the capillaries, creating damaging pressure on their walls. Successive freeze–thaw cycles continue to accumulate this type of damage, causing scaling and spalling of the surface layers due to internal cracks, typically oriented parallel to the element's surface. The water in the larger pores freezes at higher below-zero temperatures than that in smaller pores. The problem is aggravated if the liquid in the pores contains salts, as typically happens with de-icing compounds, sprayed in winter on roads.

The best-known prevention measure to avoid the freeze–thaw damage is to entrain air bubbles, in quantities and sizes sufficient to relieve the expansion pressures. As discussed in Section 8.3.8, this should be accompanied by a sufficiently tight pore structure (hence the maximum *w/c* ratio typically specified for this case). There is some debate on whether high-strength concrete (HSC), with its reduced porosity and permeability, is resistant to freeze–thaw damage without air-entrainment.

1.3 DETERIORATION PROCESS OF CONCRETE STRUCTURES

When the designer, with the help of codes and standards, defines/specifies the architectural details, the shape and dimensions of the structural elements, the amount, quality and position of the steel bars (including cover thickness) and the quality of the concrete (typically strength and resistance to certain aggressive media), he/she is defining an initial design quality (IDQ), see Figure 1.3 adapted from Beushausen (2014). It is being assumed that, starting with this IDQ, the inevitable degradation process the structure will undergo through the years will follow a certain expected performance such that, when the "traditionally expected" or Design Service Life (DSL) is reached, the structure will still perform at a level above a not very well defined Unacceptable Level of Deterioration (ULD). This is indicated by the full line in Figure 1.3.

Regrettably, in too many cases the True Initial Quality (TIQ) achieved during construction is below that assumed during the design, due to lack of care and/or application of inadequate concrete practices by the Contractor, or to concrete mixes of insufficient quality, or due to lack of zeal of the Inspection or, usually, a combination thereof. Hence, the true decay process (dotted curved line) is faster and the True Service Life (TSL) is reached much earlier than specified or expected (DSL). This requires some Interventions (I1, I2) to restore the condition of the structure to an acceptable level, so as to finally reach the DSL.

This is an expensive solution not only due to the usually high cost of the interventions themselves but also for the lost revenue if the operation of the facility has to be partially or totally interrupted (roads, bridges, tunnels, power stations, cement plants, etc.), not to mention the serious consequences for human lives caused by the deterioration itself (e.g. debris falling from a tall building) or by increased accidents rates caused by traffic restrictions.

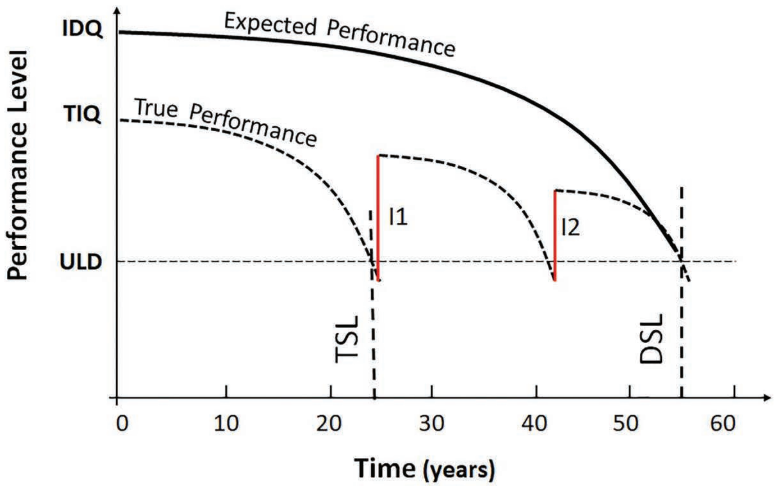

Figure 1.3 Expected and true durability performance of concrete structures (Beushausen, 2014).

Most deterioration processes (steel corrosion, sulphate or chemical attack, frost damage, ASR, etc.) follow a similar pattern, illustrated in Figure 1.4, based on the model proposed by Tuutti (1982), later extended by Nilsson (2012) for steel corrosion.

Initially, there is a period in which no visual damage of the structure is observable. Yet, in this period, some phenomena are taking place internally, such as penetration of the carbonation front or accumulation of enough chloride at the surface of the steel bars (or generation of enough ASR expansive gel), so as to initiate the visible deterioration process. This period

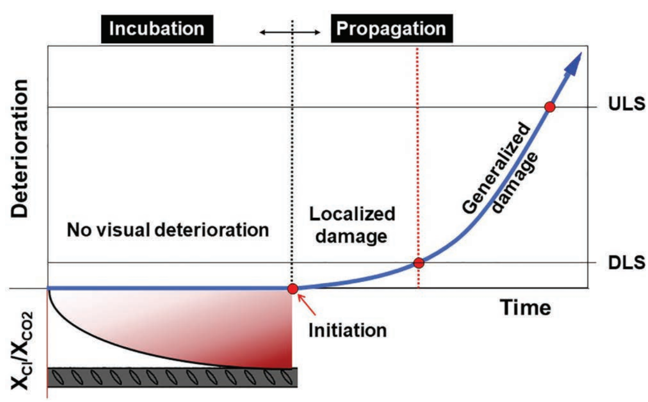

Figure 1.4 Tuutti's model for steel corrosion (Tuutti, 1982), extended by Nilsson (2012).

is defined here as "Incubation" period and the time at which the true damage process starts is called "Initiation" time.

At a certain "Initiation" time, the carbonation front (X_{CO2}) or the penetration of the critical chloride content front (X_{Cl}) has reached the surface of the rebars (see bottom left corner of Figure 1.4), depassivating the steel which under unfavourable conditions will start to corrode. The expansive nature of the corrosion products will produce isolated rust stains and microcracks (which can be considered as localized damage in Figure 1.4), to be followed by spalling of the concrete cover and reduction of the cross section of the steel (generalized damage, see Figure 1.4). This process, if not checked, will lead to a loss of bearing capacity of the element that eventually will reach its Ultimate Limit State (ULS), requiring major retrofitting or simply demolition. Although it is difficult to imagine that a structure would be left deteriorating to such extent, one of the authors was involved in a case in which an important industrial asset had to be stopped and evacuated, due to the risk of collapse caused by extensive steel corrosion damage.

1.4 THE COSTS OF LACK OF DURABILITY

Figure 1.5 shows the deterioration process, after Tuutti's model, as a dotted line referred to the right-hand-side vertical axis. The full line (referred to the left axis) shows the incremental costs of remedial interventions along the service life of the structure.

The full line represents what is called the "Law of Fives" (de Sitter, 1984), by which the cost of intervention grows with time by a factor of 5, law that was confirmed in practice (Wolfseher, 1998); below some further explanations.

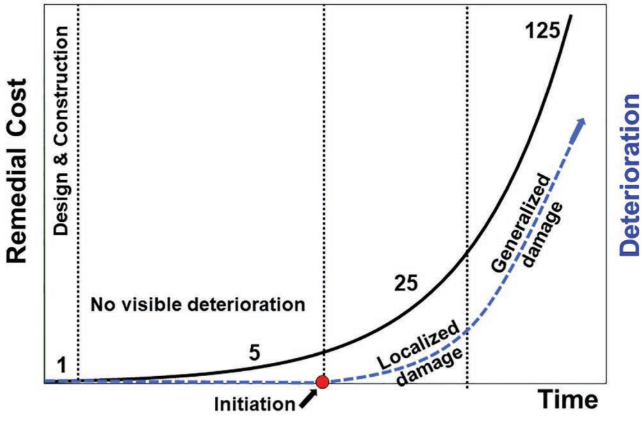

Figure 1.5 Increasing costs of remedial interventions with time, or "Law of Fives" (de Sitter, 1984).

Design and Construction Phase: Here the germs of an unsatisfactory performance are seeded, as a result of a poor design and materials specification or of bad execution. Relative Corrective Cost=1.

Incubation Phase: There is no visible damage yet. If the problem is detected at this stage (NDTs, covermeters, carbonation, chloride profiles, etc.) it is still possible to act preventively, for example, by applying appropriate surface treatments. Relative Corrective Cost=5.

Localized Damage Phase: Deterioration has started in some areas, as revealed by stains, cracks and/or localized spalling. Repair and maintenance work is required. Relative Corrective Cost=25.

Generalized Damage Phase: If repair and maintenance work has not been carried out, the structure will reach a stage in which delicate and complex repair and retrofitting work is required or even the complete replacement of the elements. Relative Corrective Cost=125.

The importance of having things done correctly from the very beginning can be realized from Figure 1.5; it is in the interest of the owners that a good design and construction is achieved. In general, but especially regarding public works, it is in the interest of the whole society and taxpayers that the constructions are durable.

1.5 ECONOMICAL, ECOLOGICAL AND SOCIAL IMPACTS OF DURABILITY

Today it is clear that civil engineers, builders and architects have succeeded in establishing and applying sound criteria to ensure the stability and strength of concrete structures. Fortunately, cases of partial or total collapse of such structures are extremely rare or due to exceptional events.

On the contrary, regarding durability, the situation is not so satisfactory. Indeed, all over the world huge amounts of money are spent in the repair or restoration of concrete structures affected by one or a combination of different degradation mechanisms.

R. Torrent, M. Alexander and J. Kropp have addressed the problem in Chapter 1 of RILEM Report 40 (2007), citing several papers that provide quantitative evidence of the onerous macroeconomic consequences of the problem (Peacock, 1985; Browne, 1989; Mehta, 1997; Neville, 1997; Hoff, 1999; Vanier, 1999; Coppola, 2000).

As the amount of money available for construction in any society is limited, this means that a steady shift of activity from new constructions onto repair and maintenance is taking place. For emerging countries, with a pressing need to improve their infrastructure, this constitutes a serious barrier against development. This has also strong repercussions for the concrete construction industry and all its players (owners, contractors, materials suppliers, engineers, specialized workers, insurance companies, etc.). An example is the recent partial collapse, at an age of 51 years, of an important concrete bridge in Genoa, Italy (Seitz, 2019), in which apparently durability weaknesses might have played a role (Virlogeux, 2019). It is interesting to remark that these weaknesses had already been revealed when the bridge was just 15 years old (Collepardi et al., 2018). Being an essential element in the Italian highways network, it was rebuilt very fast, but as a hybrid steel-concrete structure. Indeed, the deck is a 5 m deep, 30 m wide, hollow hybrid steel concrete structure, with a steel shell and a reinforced concrete slab forming the road surface, supported by 18 reinforced concrete elliptical-shaped piers. The steel shell has been divided into sections which have been prefabricated off-site (Horgan, 2020).

Moreover, ongoing research activities go on to develop solutions aimed at replacing concrete bridge decks by reinforced polymer solutions (Scott, 2010; Rodriguez-Vera et al., 2011; Mara et al., 2014). Construction companies can adapt to building with other materials, but the negative impact on the cement and concrete industry is direct and can be considerable. Repair work involves high costs in diagnosis and design (consulting companies) and uses relatively low volumes of special (usually high-cost) materials that contain little amount of cement/concrete. Hence, the more the activities are shifted from new construction towards repair activities, the higher the negative impact on the cement and concrete industries.

Furthermore, durability and ecology or sustainability go hand by hand. As illustrated in Figure 1.3, a non-durable structure will require one or more interventions during its service life (unnecessary if it had been properly designed, constructed and used). These interventions require partial demolitions and replacement with new materials, with the energy and emissions involved in their production and processing and, in the case of road transport facilities, the extra emissions due to traffic jams caused by the repair work. Quoting de Schutter (2014), it can be stated that “No concrete construction can be sustainable without being durable”.

1.6 DURABILITY DESIGN: THE CLASSICAL PRESCRIPTIVE APPROACH

This approach is also known as “deemed-to-satisfy” approach.

The three pillars supposedly supporting the achievement of durable concrete, according to the classical approach adopted by most codes and standards for structural concrete worldwide, are depicted in Figure 1.6 (de Schutter, 2009). The approach is based on specifying maximum limits for the *w/c* or *w/b* (water/binder) ratio and minimum limits for the compressive strength and the cement or binder content (the latter is not always included in codes). The title of the chart is “Parameters for durable concrete?” (de

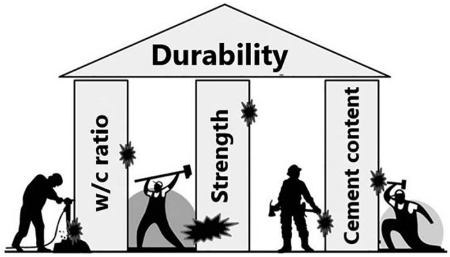

Figure 1.6 Parameters for durable concrete? After EN 206 (de Schutter, 2009).

Table 1.1 Durability requirements for reinforced concrete in Eurocode 2 and EN 206

		Corrosion induced by:									
		Carbonation				*Deicing chlorides*			*Marine chlorides*		
	Exposure class	*XC1*	*XC2*	*XC3*	*XC4*	*XD1*	*XD2*	*XD3*	*XS1*	*XS2*	*XS3*
Row	**Durability indicator**	**Requirements established in Eurocode 2**									
1	$f'c_{min}$ (MPa)[a]	25	30	37	37	37	37	45	37	45	45
2	$c_{min,dur}$ 50 year[b]	15	25	25	30	35	40	45	35	40	45
	Durability indicator	**Requirements established in EN 206**									
3	$f'c_{min}$ (MPa)[a,c]	25	30	37	37	37	37	45	37	45	45
4	w/c_{max}	0.65	0.60	0.55	0.50	0.55	0.55	0.45	0.50	0.45	0.45
5	$Cement_{min}$ (kg/m^3)	260	280	280	300	300	300	320	300	320	340

[a] Compressive strength measured at 28 days on moist-cured concrete cubes.
[b] Minimum cover thickness (mm) for service life of 50 years, structural classes S4.
[c] Optional requirement.

Schutter, 2009), intended to show the weaknesses of each of the three pillars. Regarding steel corrosion, a fourth pillar exists, representing the thickness of the concrete cover.

Table 1.1 shows the three pillars in practice, for the case of steel corrosion induced by carbonation and chlorides, according to Eurocode 2 (EN 1992-1-1, 2004; EN 206, 2013).

In what follows, a brief consideration on the suitability of the four durability indicators in Table 1.1 is provided; for a more detailed discussion of the subject, the reader can refer to Torrent (2018).

1.6.1 Compressive Strength as Durability Indicator

Regarding the suitability of compressive strength as durability indicator, the following comment in CEB-FIP Model Code 1990 (CEB/FIP, 1991), Section d.5.3 "Classification by Durability", is very relevant:

"Though concrete of a high strength class is in most instances more durable than concrete of a lower strength class, compressive strength per se is not a complete measure of concrete durability, because durability primarily depends on the properties of the surface layers of a concrete member which have only a limited effect on concrete compressive strength."

Similar considerations can be found in p. 156 of Model Code 2010 (*fib*, 2010).

The example in Figure 1.7 illustrates the lack of direct association between strength and durability. Represented in the chart are 18 concretes made with widely different cement types and *w/c* ratios of 0.40 and 0.65 (see Table 5.4); more details on the characteristics of the mixes in Moro and Torrent (2016). In ordinates, the Coefficient of Chloride Migration M_{Cl} (Tang-Nilsson method, described in Section A.2.1.2); in abscissae the compressive strength measured on 150 mm cubes. The samples were moist cured for 28 days, age at which the tests were initiated. Two extreme sets of data are explicitly shown in the chart: those of two different OPCs (triangles) and those of a cement containing 68% of GGBFS (squares). On the right-hand edge of the chart, a classification of resistance to chloride ingress based on 28-day chloride migration results, proposed by Nilsson et al. (1998), is shown with abbreviations: L=Low; M=Moderate; H=High; VH=Very High and EH=Extremely High. A general trend of increasing resistance to chloride ingress with compressive strength can be observed in Figure 1.7. However, for the same strength, the OPC concretes show higher migration coefficients than the rest and, even for strengths above

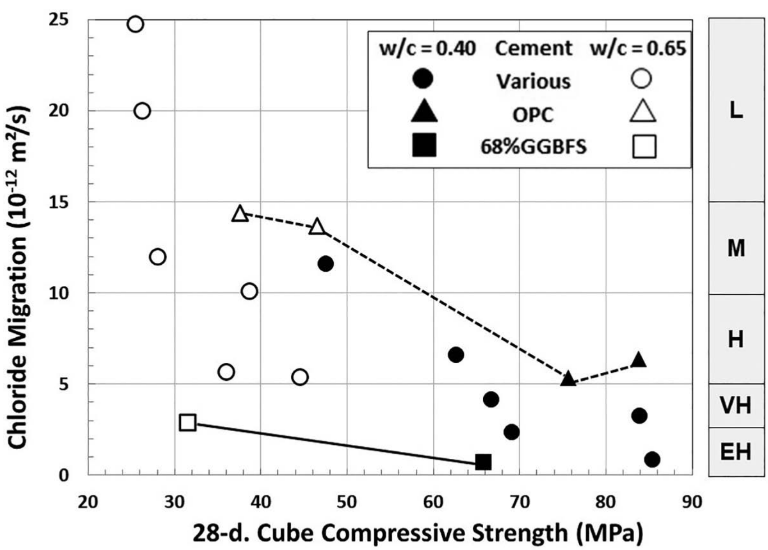

Figure 1.7 Relationship between chloride migration and cube strength at 28 days.

75 MPa, cannot reach a level of VH resistance to chlorides ingress. On the other extreme, the concretes made with a cement containing 68% GGBFS (incidentally made with the same clinker as one of the OPCs) present lower migration coefficients than the rest, for the same compressive strength.

Establishing minimum strength classes as durability requirement is a way to keep *w/c* ratio at low levels, due to the impossibility of measuring the latter. Section R4.1.1 of ACI 318 (2011) openly confesses:

> "Because it is difficult to accurately determine the w/cm of concrete, the f′c specified should be reasonably consistent with the w/cm required for durability. Selection of an f′c that is consistent with the maximum permitted w/cm for durability will help ensure that the maximum w/cm is not exceeded in the field."

1.6.2 Water/Cement Ratio as Durability Indicator

Concrete durability depends, to a large extent, on the resistance of the material to the penetration of aggressive species by a combination of different mechanisms (chiefly permeability and diffusion). This resistance is governed, primarily, by the pore structure of the concrete system, especially that of the cement paste and of the interfacial transition zone around the aggregates (see Chapter 3).

Establishing limits to the composition of the concrete (especially to its *w/c* ratio) constitutes an attempt to regulate the pore structure of the concrete system. However, it implies assuming that all materials (especially cements) perform identically; that is, all concretes of the same *w/c* ratio will perform identically, irrespective of the characteristics of the cement (and other constituents) involved. For the same constituents, it is true that a higher *w/c* ratio means higher "penetrability" of the concrete (Section 3.2.2). However, for the same *w/c* ratio, the "penetrability" of a concrete varies significantly with the type and characteristics of the cement used. Figure 1.8 shows the large range of values of the Coefficient of Chloride Migration M_{Cl} (Jacobs & Leemann, 2007), Tang-Nilsson method (Section A.2.1.2), that can be found for a given *w/c*, when concretes are made with different cements. A similar pattern is shown in Figure 6.5 regarding air-permeability.

These examples show that, technically speaking, *w/c* is not a good durability indicator. This fact is greatly aggravated by the difficulties for the user of the concrete to check compliance with the maximum limits specified.

Two options are offered in EN 206 (2013) for checking compliance with the prescriptive limits for *w/c* ratio:

a. In order to compute the *w/c* ratio of each concrete batch, the contents of cement and added water shall be taken as stated on the print-out of the batch record.

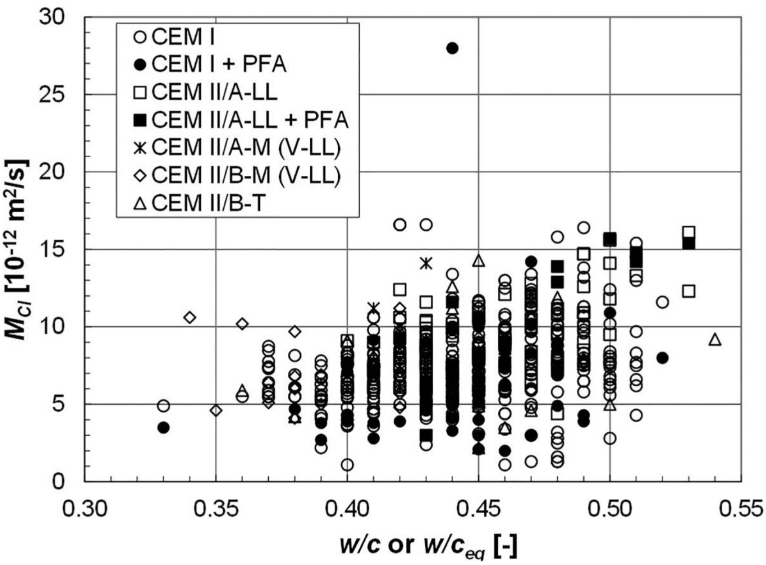

Figure 1.8 Relation of chloride migration with *w/c* ratio.

b. Where the *w/c* ratio of concrete is to be determined experimentally, it shall be calculated on the basis of the determined cement content and the effective water content. The test method and tolerances shall be agreed between the specifier and the producer.

Option (a) is almost exclusively used, despite its grave deficiencies. Indeed, an accidental or deliberate error in the stated sand moisture will end up in a wrong *w/c* ratio reported in the batching print-out. An example is presented in Torrent (2018), where an error in the sand moisture used for the calculation brought the declared *w/c*=0.44 for reported moisture of 0.4% to a true *w/c*=0.59 for the true measured 6.0% of sand moisture.

To this we should add that, sometimes, washing water is left inside the drum when the ready-mixed concrete (r-mc) truck is loaded with a new batch. In addition, "slumping" is a very common practice in the r-mc industry whereas the driver, while washing the loaded truck still in the plant, watches the consistency of the concrete and, if judged too stiff, adds uncontrolled amounts of water into the drum. On arrival to the jobsite, water is sometimes added to *retemper* the mix (in a Western European country, the addition of 30 L/m³ into a truck, was witnessed by one of the authors). All the extra water, discussed in this paragraph, which may be added to the truck, is usually not recorded in the batching protocol which, therefore, underestimates the *w/c* ratio of the concrete delivered, with negative effects on the resulting durability.

Regarding option (b), despite several attempts, no standardized or widely accepted test method to experimentally measure the *w/c* ratio of the freshly delivered concrete has been developed. An overview of such attempts can be found in CR 13902 (2000) that states: "It follows […] that the problem of measuring water/cement ratio on a sample of fresh concrete about which nothing is known is very difficult and probably impossible".

The fact remains that one of the critical weaknesses of the use of *w/c* ratio as durability indicator is the impossibility of checking compliance by the user. Specifying a characteristic that cannot be measured is clearly meaningless and opens roads to unfair competition by fraudulent practices undetected by the user.

1.6.3 Cement Content as Durability Indicator

The main argument behind the specification of a minimum cement content in the mix is the chemical binding effect that hydrated cement offers to free chlorides and CO_2 that can penetrate the concrete (Wassermann et al., 2009). Along this line of thinking, a higher cement content would imply a higher reservoir of alkalis that need more CO_2 to be carbonated (same for more Cl^- binding), thus delaying the advance of the critical front. But, for the same *w/c* ratio (which is specified in parallel), a higher cement content means also a proportionally higher volume of porous paste that allows more CO_2 (or Cl^-) to penetrate, with a null net result; this has been proved experimentally (Wassermann et al., 2009). Moreover, more paste and more cement mean more susceptibility of the concrete to shrinkage and thermal cracking.

The use of mineral additions batched separately into the concrete mixer adds further complications to establishing the cement content (and also the *w/c* ratio), due to the application of the controversial "k-value concept" of EN 206 (2013) to assess the "cementitious contribution" of the addition used.

1.6.4 Cover Thickness as Durability Indicator

The thickness of the concrete cover is a very important durability indicator for the deterioration of structures due to steel corrosion. A lack of sufficient cover thickness is a recurrent cause of premature corrosion of reinforcing steel (Wallbank, 1989; Neville, 1998; Torrent, 2018).

In theory, both second Fick's diffusion law (through the argument of the error function solution, Section 3.4.1) and capillary suction theory (see Section 3.7) predict a progress of the penetration front of carbonation, chlorides and water with the square root of time. This means that a 10% reduction in cover thickness implies a reduction in service life of 20%, so great is the importance of observing the specified cover thickness. Yet, despite the progress made on electromagnetic instruments capable of assessing non-destructively the cover thickness quite accurately (Fernández Luco, 2005), now largely enhanced by the development of ground penetrating radar (GPR) instruments, their use is not forcibly specified in the standards.

1.7 DURABILITY DESIGN: THE PERFORMANCE APPROACH

In Sections 1.6.1–1.6.3, the inherent weaknesses of the three pillars of the classical durability approach have been revealed. With more or less degree of boldness, codes and standards have been moving, rather timidly, along the P2P (Prescriptive to Performance) road, as discussed in this section and also in Section 12.1.

1.7.1 The "Durability Test" Question

The P2P transit brings to the forefront the question of suitable durability tests, that was discussed in Torrent (2018) and that, given the scope of this book, deserves a revisit.

The durability of concrete is, almost by definition, hardly measurable by testing, as each structure is performing its own durability test, live under its own specific conditions. The prediction of the evolution of the structure condition is uncertain, particularly when based on testing specimens and not the real structure.

Durability involves deterioration processes lasting several years; therefore, it is clear that tests lasting months or even years, although in some cases possibly closer to reality, are not practical for specification and quality control purposes.

Performance specifications need short-term tests, lasting not more than, say, 1 week, including preconditioning of the specimens; otherwise, the approach would not be practical nor acceptable for conformity control purposes, given the current pace of concrete construction.

The durability of concrete structures against deteriorating actions originated from the surrounding environment is strongly related to the resistance of the concrete cover to the penetration, by different transport mechanisms, of external deleterious substances. As a result of 30–40 years of durability research, several test methods have been developed to measure mass transport properties of concrete (RILEM Report 40, 2007; RILEM STAR 18, 2016). They consist typically of tests that measure the resistance of concrete to the transport of matter (gaseous or liquid) by appropriate driving forces (see Chapters 3 and 4 and Annex A). Some of these tests have been standardized in different European countries and in the USA.

All these durability tests have merits and demerits. If we wait until the perfect "durability" test is developed, we will never leave the unsatisfactory and ineffective current prescriptive approach. Indeed, any reasonable durability test will be better than the *w/c* ratio, used today as the durability "panacea".

Drawing a parallel, concrete structural design relies heavily on the compressive strength (measured with a standard test), adopted as the universal, used-for-all property (in codes almost all properties of concrete are derived from its value). And yet, this test can be questioned from different angles: the true stress field is far from uniaxial compression (hence the 20%–25% difference when testing cylinders and cubes); the size is much smaller than that of the structural elements (size effect); the load is statically applied in less than 5 minutes (in bridges, static loads are applied for decades with ≈ 15% strength reduction effect and even cyclically, bringing in also the deleterious effect of fatigue); the specimens are tested saturated (a condition seldom found in reality, which influences the strength by ≈ 20%), and so on and so forth. Yet, despite all these limitations, the standard compressive strength is accepted by civil engineers as a suitable indicator of the bearing capacity of concrete and is used, without objections, in the structural design of concrete structures.

A similar, pragmatic approach is required for durability, that is, the adoption of well proved standard tests to measure relevant "Durability Performance Indicators", focusing on the merits and positive contribution of the tests and less on their demerits.

1.7.2 Canadian Standards

Canadian Standards specify limiting values of the result (electrical charge passed *Q* in Coulombs) in a migration test (ASTM C1202, 2019) (see description in Section A.2.1.1).

Canadian Standard (CSA, 2004) specifies a maximum limit of $Q = 1{,}500$ Coulombs for exposure classes C-1 (structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions) and A-1 (structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas may be generated). That limit is reduced to $Q = 1{,}000$ Coulombs for exposure class C-XL (structurally reinforced concrete exposed to chlorides or other severe environments with or without freezing and thawing conditions, with higher durability performance expectations). The testing age should not exceed 56 days.

1.7.3 Argentine and Spanish Codes

The Codes for Structural Concrete of Argentina (CIRSOC 201, 2005) and Spain (EHE-08, 2008) rely on a water-permeability test for durability specifications. The test is known as Water Penetration under Pressure (EN 12390-8, 2009), described in Section 4.1.1.2, and the result is the maximum (sometimes also the mean) depth of penetration of water W_p reached under pressure onto the surface of a concrete specimen. Table 1.2 summarizes the requirements of the Argentine and Spanish Codes referred to this test.

The Argentine Code also specifies, for all aggressive environments, a maximum water sorptivity of 4.0 $g/m^2/s^{½}$ (see Section 4.2.1) which looks quite demanding, especially if applied to all exposure classes.

1.7.4 Japanese Architectural Code

The Japanese Architectural Code "Recommendations for Durability Design and Construction Practice of Reinforced Concrete Buildings" (Noguchi et al., 2005) includes, in its Chapter 2, the principles of durability design.

Regarding performance-based design of carbonation-induced steel corrosion, a probabilistic approach is adopted, based on Eq. (1.1) of carbonation progress.

$$C_t = k \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \beta_1 \cdot \beta_2 \cdot \beta_3 \cdot \sqrt{t} \tag{1.1}$$

Table 1.2 Performance laboratory tests and limiting values specified in some national standards

Country	*Standard*	*Indicator*	*Test method*	*Exposure*	*Limit*
Canada	CSA A23.1/ A23.2	Electric charge passed (Coulomb)	ASTM C1202	Chlorides, manure gases	≤1,500
				Extended service life	≤1,000
Argentina and Spain	CIRSOC 201, EHE 08	Maximum water penetration under pressure (mm)	EN 12390-8	Moderate	≤50
				Severe	≤30
Switzerland	SIA 262/1	Water sorptivity ($g/m^2/h$)	SIA 262/1: Annex A	Mild chlorides	≤10
		Chloride migration coefficient (10^{-12} m^2/s)	SIA 262/1: Annex B	Chlorides	≤10
		Carbonation rate ($mm/y^{½}$)	SIA 262/1: Annex I	Carbonation	≤5.0
		Frost-thaw-salts, mass loss (g/m^2)	SIA 262/1: Annex C	Mild frost	≤200
				Severe frost	≤1,200
		Sulphate resistance expansion (‰)	SIA 262/1: Annex D	Sulphates	≤1.2

where

C_t=carbonation depth at time t
k=coefficient (1.72 after Kishitani or 1.41 after Shirayama)
α_1=coefficient function of concrete and aggregate type
α_2=coefficient function of cement type
α_3=coefficient function of mix proportions (w/c ratio)
β_1=coefficient function of air temperature
β_2=coefficient function of relative humidity of air
β_3=coefficient function of CO_2 concentration

In Chapter 7 of AIJ (2016), "Practice and quality management", the coefficient of air-permeability *kT* (Torrent method, described in Chapter 5) is used to predict concrete carbonation with consideration of moisture effect. Sampling method follows Annex E of Swiss Standard (SIA 262/1, 2019).

The main purpose of this code is not to establish durability specifications but to predict the carbonation progress in concrete structures.

1.7.5 Portuguese Standards

In Portugal, the performance-based durability design is possible through the application of LNEC E 465 (2007). This standard addresses the deterioration by reinforcement corrosion, induced by carbonation and sea chlorides. Its major features are summarized as follows:

- applies a semi-probabilistic approach, where the reliability analysis is carried out in the service life format
- the end of service life is defined as the occurrence of corrosion-induced cracking
- the service life is broken down in two periods (initiation and propagation) following Tuutti's model (Figure 1.4)
- comprises one analytical model for the propagation period, based on Faraday's law and on the empirical expression proposed by Rodriguez et al. (1996)
- comprises three analytical models for the initiation period, one for chloride penetration and two for concrete carbonation
- the analytical model for chloride penetration is based on the model proposed by Mejlbro (1996) and uses chloride migration coefficient from NT Build 492 test (see A.2.1.2), as durability indicator
- one of the analytical models for concrete carbonation is also based on "CEB Task Group V, 1+2 model" (DuraCrete, 1998) and uses concrete resistance to accelerated carbonation (LNEC E 391, 1993) as durability indicator
- the other model for concrete carbonation uses the oxygen-permeability coefficient from CEMBUREAU test (see 4.3.1.2) as durability indicator, adapting Parrott's model (Parrott, 1984), see Section 9.3.1.

Further, the input parameters for the analytical models vary according to the exposure conditions and these are grouped in exposure classes according to EN 206 (2013). Three safety factors for service life are defined, one for each of the reliability classes identified in Eurocode 0 (EN 1990, 2002).

This methodology allows the user to define a combination of nominal cover thickness and performance requirement (chloride migration coefficient. oxygen-permeability coefficient or carbonation resistance), to ensure the intended service life.

1.7.6 South African Standards

For many years, thanks to the continuous and persistent work of several distinguished researchers such as Alexander et al. (1999), Alexander (2004) and Beushausen and Alexander (2009), an original performance concept was introduced and consolidated in South Africa, crowned with its acceptance in South African Standards (CO3-2, 2015; CO3-3, 2015). It consists in measuring "Durability Indices" (oxygen-permeability and chloride conductivity) in the laboratory, on cores drilled from the finished structure. These indices, coupled with the assumed or measured cover thickness allow, via modelling, the assessment of the service life of reinforced concrete structures exposed to carbonation or chlorides. This approach and its test methods are described in more detail in Sections 4.3.1.3, 9.3.2 and A.2.2.3.

1.7.7 Swiss Standards

The Swiss Codes and Standards for Concrete Construction have taken decisively the road to performance specifications, based primarily on three separate standards, namely:

- SIA 262 (2013) based on Eurocode 2 is the Swiss Concrete Construction Code, defining exposure classes and corresponding cover thicknesses
- SIA 262/1 (2019) describes special, non-EN Standard tests and sets performance requirements associated with the exposure classes, to be fulfilled for laboratory and site tests (NDT or drilled cores)
- SN EN 206 (2013), prescriptive, is the Swiss version of EN 206
- Table 1.3 shows the evolution of Swiss Standards' requirements for exposures that promote steel corrosion, moving from purely Prescriptive to Performance-based; more details can be found in Torrent and Jacobs (2014). In Switzerland, the following has been achieved:
- for each exposure class, a suitable "Durability Performance Indicator" test has been adopted, for example:
  - accelerated carbonation for XC3 and XC4
  - water capillary suction for XD1 and XD2a
  - chloride migration for XD2b and XD3

- a standard for conducting each of these tests has been issued (SIA 262/1, 2019)
- limiting values and conformity rules have been established for the test results (average of different samples) in each exposure class (see Table 1.2 and Table 1.3, rows 5–7)

The concrete producer, supplying concrete for structures under a given exposure classes, shall design the mixes complying with the prescriptive requirements of rows 1 and 2 in Table 1.3. In addition, the concrete producer shall cast specimens ("*Labcrete*", see Section 7.1.2) from samples taken during the regular production with a frequency that is function of the volume produced, but at least four times per year. The averages of the test results on these samples must comply with the maximum requirements of Table 1.3, rows 5–7. More important, perhaps, now the user can take samples during delivery and check compliance of the received concrete with the specifications. It is envisaged that, once enough experience has been accumulated with the performance requirements, the prescriptive requirements will be removed from the standard or kept as recommended values.

One of the most innovative aspects of the Swiss Standards is the recognition that tests made on cast samples are not truly representative of that of the cover concrete *Covercrete*, see Section 7.1.4) of the real structure.

SIA 262 Code (SIA 262, 2013) describes the measures to be adopted in order to ensure durability and, acknowledging the importance of the role of the *Covercrete*, specifically states (free translation from German into English):

- "with regard to durability, the quality of the cover concrete is of particular importance", Section 5.2.2.7 of SIA 262 (2013)
- "the tightness of the cover concrete shall be checked, by means of permeability tests (e.g. air-permeability measurements), on the structure or on cores taken from the structure", Section 6.4.2.2 of SIA 262 (2013)

Therefore, since 2013, the air-permeability kT of the *Covercrete* of structural elements exposed to the most severe environments shall be checked on site, with the "Air-Permeability on the Structure" test, according to Annex E of SIA 262/1 (2019).

The requirements for site air-permeability are indicated in Row 8 of Table 1.3, the specified kT_s values being "characteristic" upper limits, having their own conformity rules (SIA 262/1, 2019; Torrent et al., 2012), see Section 8.5.1.

Table 1.3 Evolution of Swiss Standards requirements (for corrosion exposure classes)

Year	Row	Exposure class	*Carbonation-induced corrosion*				*Chloride-induced corrosion*			
			XC1	*XC2*	*XC3*	*XC4*	*XD1*	*XD2a*	*XD2b*	*XD3*
2003		**Durability indicator**	*PRESCRIPTIVE*							
	1	w/c_{max}	0.65	0.65	0.60	0.50	0.50	0.50	0.45	0.45
	2	C_{min} (kg/m³)	280	280	280	300	300	300	320	320
	3	$f'c_{min}$ (MPa)	25	25	30	37	30	30	37	37
	4	d_{nom} (mm)	20	35	35	40	40	40	55	55
2008		**Durability indicator**	*LABCRETE*							
	5	$q_{w\ max}$ (g/m²/h)	-	-	-	-	10	10	-	-
	6	$D_{Cl\ max}$ (10^{-12} m²/s)	-	-	-	-	-	-	10	10
	7	$K_{N\ max}$ (mm/y$^{1/2}$)	-	-	5.0/4.0	5.0/4.5	-	-	-	-
2013		**Durability indicator**	*REALCRETE*							
	8	kT_s (10^{-16} m²)	-	-	-	2.0	2.0	2.0	0.5	0.5

Note: EN 206 Class XD2 was subdivided in 2008 into XD2a and XD2b, for chloride contents of the solution in contact with the concrete of up to or over 0.5 g/L, respectively.

w/c, water/cement ratio by mass; *C*, cement content, including SCM with corresponding factors *k*; *f'c*, strength class (cube); q_w, water conductivity coefficient, Annex A of SIA 262/1 (2019). Rather complex indicator, closely related to water absorbed in 24 hours w_{24} (g/m²): $w_{24}=217+326\times q_w$; D_{Cl} = chloride migration coefficient, measured after Tang-Nilsson method (Section A.2.1.2); K_N = carbonation resistance = 0.136 K_S, with K_S measured in an accelerated test after 7, 28 and 63 days exposure to CO_2 concentration of 4%-vol. (Annex I of SIA 262/1 (2019)). The values indicated correspond to expected service lives of 50/100 years; *kT*, coefficient of air-permeability, measured after Torrent method (Annex E of SIA 262/1 (2019)); value not be exceeded by more than 1 test out of 6; d_{nom}, nominal cover depth, values indicated are for reinforced concrete (values for prestressed concrete are 10 mm higher); typical tolerance ± 10 mm.

1.8 CONCRETE PERMEABILITY AS "DURABILITY INDICATOR"

In Section 1.2, we could see that most relevant mechanisms of deterioration of concrete structures have a close relation to the permeability of concrete.

It is not surprising, then, that several performance-based standards and codes (see Sections 1.7.3–1.7.7) select water-permeability (in the form of penetration under pressure or of capillary suction) or gas-permeability as durability indicator. In the particular case of the South African and Swiss

Standards, based on core testing and non-destructive measurements conducted on site, respectively, the end-product is tested, which is more representative than laboratory tests performed on cast specimens, as discussed in Chapter 7.

Being the main topic of this book, the suitability of concrete permeability as a durability indicator is broadly and deeply dealt with.

1.9 BEYOND 50 YEARS: MODELLING

Most requirements described in Sections 1.5 and 1.6 correspond to an expected service life of 50 years. Nowadays, important infrastructure constructions are intended for service lives that largely exceed the 50 years expected by the application of the prescriptive EN standards or the performance Swiss standards. Examples are the Alp Transit Tunnel in Switzerland (100 years) (Alp Transit, 2012), the new Panama Canal (100 years) (Cho, 2012), the Chacao Bridge in Chile (100 years) (Valenzuela & Márquez, 2014), the Hong Kong-Zhuhai-Macao link in China (120 years) (Li et al., 2015), the Port of Miami Tunnel in USA (150 years) (Torrent et al., 2013) and the second Brisbane Gateway Bridge in Australia (300 years) (Gateway, 2009), all of them exposed to very aggressive environments.

Due to the lack of experience with such longevous structures (reinforced concrete is a rather "recent" building system) from which to draw learnings, the solution lies on the judicious use of predictive models.

The most widespread model used today in Europe is Duracrete (DuraCrete, 2000), later partially adopted by *fib* (2006), dealing with steel corrosion induced by carbonation or chlorides, whilst in North America (Life-365, 2012) model (only for chloride-induced corrosion) is the preferred one. These models are based on the assumption that the penetration of chlorides (and carbonation) is a purely diffusive process governed by Fick's second law (see Chapter 3), with the main input durability indicators being the cover thickness and the coefficient of chloride-diffusion (or migration) of the concrete. In Chapter 9, several service life design models, based on the use of concrete permeability as input, are presented.

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Chapter 2

Permeability as key concrete property

2.1 FOUNDATIONS OF PERMEATION LAWS

The foundations of today's knowledge on the permeation of fluids through porous media were laid down by the work of Jean Léonard Marie Poiseuille (1799–1869), a French physician and physiologist, who was interested in the conditions of the flow of liquids through narrow tubes, basically associated with the arterial system of blood circulation. He conducted a series of experiments, from which he established that the flow rate of a fluid through a tube of radius r is proportional to r^4. Independently, the German civil engineer Gotthilf Heindrich Ludwig Hagen (1797–1884) arrived at the same result by conducting experiments in brass tubes of different diameters, concluding in what is now known as Hagen-Poiseuille law (see Section 3.5.1).

More or less simultaneously, the French engineer Henry Darcy (1803–1858) was studying the laminar flow of water through sand beds, finding that the flow rate was proportional to the energy loss (water head loss), inversely proportional to the length of the flow path and proportional to a coefficient K that depended on the type of sand and also on the type of fluid.

The combination of these discoveries led to the general law of permeation of liquids through porous media (viscous laminar flow of Newtonian liquids):

$$Q = K \cdot \frac{A}{\mu} \cdot \frac{\Delta P}{\Delta L} \tag{2.1}$$

where

Q = flow rate (m^3/s)
K = (intrinsic) coefficient of permeability (m^2)
A = cross-sectional area traversed by the fluid (m^2)
μ = viscosity of the fluid (Pa.s)
$\Delta P/\Delta L$ = gradient of pressure across the element (Pa/m)

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In the case of an ideal impermeable solid body traversed by parallel capillary tubes of radius *r*, the coefficient of permeability is (see derivation of formulae in Section 3.5.1):

$$K = \frac{\varepsilon \cdot r^2}{8} \tag{2.2}$$

where ε is the porosity of the body (area of tubes/total cross-sectional area of the body).

2.2 RELATION BETWEEN PERMEABILITY AND PORE STRUCTURE OF CONCRETE

Equation (2.2) indicates that the coefficient of permeability of concrete, recognized as a porous medium, must be closely related to the pore structure of the material.

One of the main investigations on the permeability of cementitious material was due to the researcher who, possibly, did more to establish studies on concrete as a scientific, rather than an empirical discipline: Treval C. Powers (1900–1997).

During his fundamental research on the microstructure of hardened cement paste (h.c.p.), still valid today, and its effect on key properties, he could establish a relationship between the coefficient of water-permeability of h.c.p. and its capillary porosity, quite independent of the cement types investigated at the time (Powers, 1958). He also found that, due to the extremely low size of the gel pores, flow through h.c.p. takes place primarily through its capillary pores.

He also established the approximate hydration time required for the capillary pores of h.c.p. of different *w/c* ratios to become segmented, i.e. connected between them through the gel pores, resulting in very low permeability (Powers et al., 1959). They found that for *w/c* ratios above 0.70 that segmentation is impossible, as shown in Table 1.6 of Neville (1995).

Since that pioneer work, the permeability of concrete received growing attention by researchers worldwide, which resulted in a consolidated knowledge on that property, on how it is influenced by different factors and on how it can be measured, both in the laboratory and on site. These aspects are dealt with in detail in the rest of this book.

2.3 PERMEABILITY AS KEY CONCRETE PROPERTY

Water-permeability of concrete is relevant to structures that contain or transport water (or other liquids), in particular dams, tanks containing water or other liquids, retaining walls, canals, culverts, pipes, etc.

Similarly, gas-permeability of concrete is relevant to structures that contain or transport gases, in particular tanks and pipes, underground gas reservoirs to store/release energy, evacuated tunnels for high speed trains, etc.

Gas-permeability plays an important role in the release of water vapour under fire, thus decreasing the risk of explosive spalling in the event of fire, topic that is discussed in detail in Chapter 10.

In this section, some engineering applications in which concrete permeability plays a key role, not specifically associated with durability, are presented.

2.3.1 Permeability for Liquids' Containment

2.3.1.1 ACI Low Permeability Concrete

Section 4.3 of ACI 318 (2019) includes exposure class P1 "Low Permeability Requirement", assigned on the basis of the need for concrete to have a low permeability to water, when the permeation of water into concrete might reduce durability or affect the intended function of the structural member. An example is an interior water tank. Requirements: $w/b \leq 0.50$ and cylinder compressive strength class ≥ 28 MPa.

2.3.1.2 Dams

Conventional concrete for dams is usually sufficiently water-tight to avoid leakage across the thick body of the dam. For conventional concrete dams, built in lifts, construction joints as well as expansion joints are the weak points regarding water-tightness. An interesting research was reported by Görtz et al. (2021), in which the water-tightness of the joints was measured experimentally and modelled numerically. The coefficient of permeability was measured on Ø64.5 mm cores, drilled from a 90-year-old dam in Germany, so as to obtain specimens without joints and with horizontal and vertical joints. The measured water-permeability of the specimens without joints was in the range $0.5-3.0\times10^{-9}$ m/s, whilst for those containing horizontal and vertical joints it climbed to the ranges $5-100\times10^{-9}$ m/s and $1-30\times10^{-6}$ m/s, respectively (i.e. one and three orders of magnitude higher, respectively). Two numerical models were applied, that successfully fit to the experimental results, especially the 'dual-permeability model'.

In the case of two concrete-face rockfill dams (Barrancosa and Condor Cliff) on the River Santa Cruz, Patagonia, Argentina, a maximum value for the water-permeability of 2×10^{-9} cm/s was specified for the upstream concrete slab (Di Pace, 2021). Due to difficulties in measuring that property, an equivalent value of the coefficient of air-permeability (Torrent method) of 0.2×10^{-16} m² was proposed, applying the relation:

$$K_w = 6.24 \cdot kT^{0.68} \tag{2.1}$$