D1.1 List of technical directives, surveys, standards and regulations for concrete materials in the target applications

WP 1, T 1.1, T1.2, T1.3

Lead Partner: RINA

Partner Contributors: ALL

Dissemination Level: PU

Deliverable due date: April 30. 2018 Actual submission date: September 03.2018

Deliverable Version: V0

Project Acronym	EnDurCrete
Project Title	New Environmental friendly and Durable conCrete, integrating industrial by-products and hybrid systems, for civil, industrial and offshore applications
Grant Agreement n°	760639
Funding Scheme	Research Innovation Action
Call	H2020-NMBP-2017
Topic	NMBP-06-2017 Improved material durability in buildings and infrastructures, including offshore
Starting Date	1st January 2018
Duration	42 Months

Executive Summary

The present document provides an overview of the main technical directives, guidelines and standards for concrete materials having a specific focus on its application for civil infrastructures. Focal topic is the study of concrete performance in severe environmental conditions, having a particular attention to continental, marine and offshore applications. The aim is to provide an overview of the main relevant technical requirements regarding design and maintenance of civil infrastructures built from reinforced concrete. A particular attention is devoted to European standards, but the document also accounted for numerous standards provided in non-European context as a function of their relevance or innovative contribution.

The judgement about concrete performance is developed by the point of view of durability, and this lead to assume the “serviceability limit state” (SLS) as reference operational state. The design process is then interpreted as aimed at enhancing the structures service life in the specific case of structures submitted to severe environmental conditions.

The state-of-art of technical practices and requirements currently applied provides a starting point for developing innovative concrete materials and constructive strategies.

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Abbreviations and Acronyms

[AASHTO] - American Association of State Highway and Transportation Officials
[AAR] - Alkali Aggregate Reaction
[ACI] - American Concrete Institute
[ASTM] - American Society for Testing and Materials
[API] - American Petroleum Institute
[CEN] - Comité Européen de Normalisation (French: European Committee for Standardization)
[CSA] - Canadian Standards Association
[DNV] - Det Norske Veritas
[EC0] - Eurocode 0 (NS-EN 1990:2002), Ref. [74]
[EC1] - Eurocode 1, part 2 (EN 1991-2), Ref. [35]
[EC2] - Eurocode 2, part 1 (EN 1992-1-1), Ref [59]
[EC2] - Eurocode 2, part 2 (EN 1992-2), Ref [36]
[EC8] - Eurocode 8, part 2 (EN 1998-2), Ref [37]
[JSCE] - Japanese Society of Civil Engineers
[NS] - Norwegian Standard
[NZS} - Standards New Zealand
[RILEM] - Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages (French: International Union of Laboratories and Experts in Construction Materials, Systems, and Structures)
[SAA] - Standard Association of Australia
[SLS] - Serviceability Limit State
[WSDOT] - Washington State Department of Transportation

Definitions

Design criteria / Performance criteria – Quantitative limits, associated to a measurable/testable parameter (that quantitatively describes a performance aspect), defining the border between desired and adverse behaviour [21].

Design of structures – Process of developing a suitable solution, taking due account of safety, functionality, and sustainability of a structure during its intended service life [21].

Design service life/Service life – The period in which the required performance of a structure or structural element is achieved, when it is used for its intended purpose and under the expected conditions of use [21].

Deterioration – Worsening of condition with time, or a progressive reduction in the ability of a structure or its components to perform according to their intended functional specifications [21].

Deterioration mechanism - Process of the cause and development of deterioration [21].

Durability – The capability of structures, products or materials to fulfil the requirements defined, determined after a specified period of time and usage [21].

Environment – Surrounding in which an organization operates, including air, water, land, natural resources, flora, fauna, humans and their interrelation [21].

Environmental influences – Physical, chemical and biological actions resulting from the atmospheric conditions or characteristics of the surrounding to the structure. Environmental influences need to be taken into account during planning of service life, design and construction of a particular structure or asset [21].

Limit state - State beyond which the structure no longer satisfies the relevant performance criteria [21].

Serviceability – Ability of a structure or structural element to perform adequately for normal use under all combinations of actions expected during service life [21].

Serviceability limit state (SLS) – State that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met [21].

Ultimate limit state (ULS) - states associated with collapse or with other similar forms of structural failure. Generally, the ultimate limit state (ULS) corresponds to the maximum load-carrying resistance of a structure or structural member [21]

1 Introduction

Concrete represents the most widely used construction material all around the world and its application involved almost all the typologies of civil structures and infrastructures. From this consideration results the focal importance to refine new design and construction tools aimed at enhancing concrete durability and, consequently, service life of reinforced concrete structures. In this line, the present document provides an overview of the main important technical requirements strictly related to the definition of appropriate measures for achieving a good compromise between the design of durable and sustainable concrete infrastructures and the reduction of their environmental and economic cost.

The document starts by providing the most relevant technical requirements regarding traditional concrete composition and underlining the relevant factors that influence concrete durability.

Once provided general technological references for concrete as structural material, the report focuses on different target applications of concrete, which correspond to civil infrastructures in continental, marine and offshore environments. For each application, the document deals with design processes, exposure conditions and technical requirements regarding the performance of reinforced concrete infrastructures to specific environmental conditions.

All the main deterioration phenomena are analysed by outlining concrete properties that can contribute to their prevention. In this description, the attention is focused on the main standards dealing with concrete deterioration phenomena and regulating concrete mechanical and structural properties for enhancing its durability. Design approaches and constructive procedures, but also experimental methodologies for testing concrete “resistance” to each deteriorating agent are here briefly reviewed by collecting the main standards regulating them. The aim is to provide all the necessary references for having a detailed state-of-art about concrete durability in civil infrastructures in the target applications mentioned above.

2 Reinforced concrete structures durability design concept

2.1 General

Concrete is traditionally thought to be durable building material requiring minimum maintenance or none at all. The situation is, however, different from what is believed, and enormous repair costs of structures deteriorated by reinforcement corrosion and other deterioration processes are the reason that those concerned have developed awareness of the importance of durability design.

The performance of a concrete structure or a structural component refers to its behaviour as a consequence of actions to which it is subjected or which it generates. Structures and structural members shall be designed, constructed and maintained in such a way that they perform adequately and in an economically reasonable way during construction, service life and dismantlement. [21]

The service life of a structure depends on:

(1) structure dimensioning;
(2) the choice of details;
(3) concrete composition, manufacture and placing;
(4) construction techniques, and
(5) maintenance.

Chemical and physical degradation of concrete with time, i.e. a reduction in concrete durability in general depends on the presence of different substances in concrete and their transport through it, and effects of loads acting on a structure.

Durability is an inherent aspect of serviceability and structural safety, and the performance verification shall be conducted with proper consideration of the change of performance in time. Accordingly, durability criteria are implicitly involved in the requirement that structures are designed for structural safety and serviceability for a predefined service life, where:

- serviceability implies the ability of a structure or structural members to perform, with appropriate levels of reliability, adequately for normal use under all (combinations of) actions expected during service life; and
- structural safety i.e. ability of a structure and its structural members to guarantee the overall stability, adequate deformability and ultimate bearing resistance, corresponding to the assumed actions (both extreme and/or frequently repeated actions and accidental and/or exceptional events) with appropriate levels of reliability for the specified reference periods. The structural safety shall be analyzed for all possible damage states and exposure events relevant for the design situation under consideration. [21]

Existing European standards (EN 1990, EN 1991, EN 1992) for design of concrete structures are based on limit states design concept, which defines two limit states:

- ultimate limit state (ULS) - state associated with collapse or with other similar forms of structural failure
- serviceability limit state (SLS) state that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met.

In order to quantify durability, the concept of performance based has been introduced. For the first time it was introduced in CEB-FIP Model Code 1990 (MC 90), and then further developed in Model Code 2010 [21]. Since 2015 fib started an initiative of developing new fib Model Code 2020 (MC2020), as a single merged general structural code for both new and existing concrete structures.

The basic approach of performance based design is presented in the schematic diagram shown in Figure 2-1. As it can be seen from the flowchart, the analytical prediction of the service life of the structure is based on material degradation processes, which are divided into several stages with respect to the level of damage, depending on the time.

Such a quantitative approach to durability design also requires development of numerical models and simulating degradation processes in concrete. Similarly to calculation of bearing capacity of a structure for external loads, design requirements and limit states must be defined for service life design.

At the moment there are several mathematical models based on the process of diffusion of aggressive substances (Cl, CO_2) into concrete which are proposed to be applied in the codes. [21, 25, 26, 30]

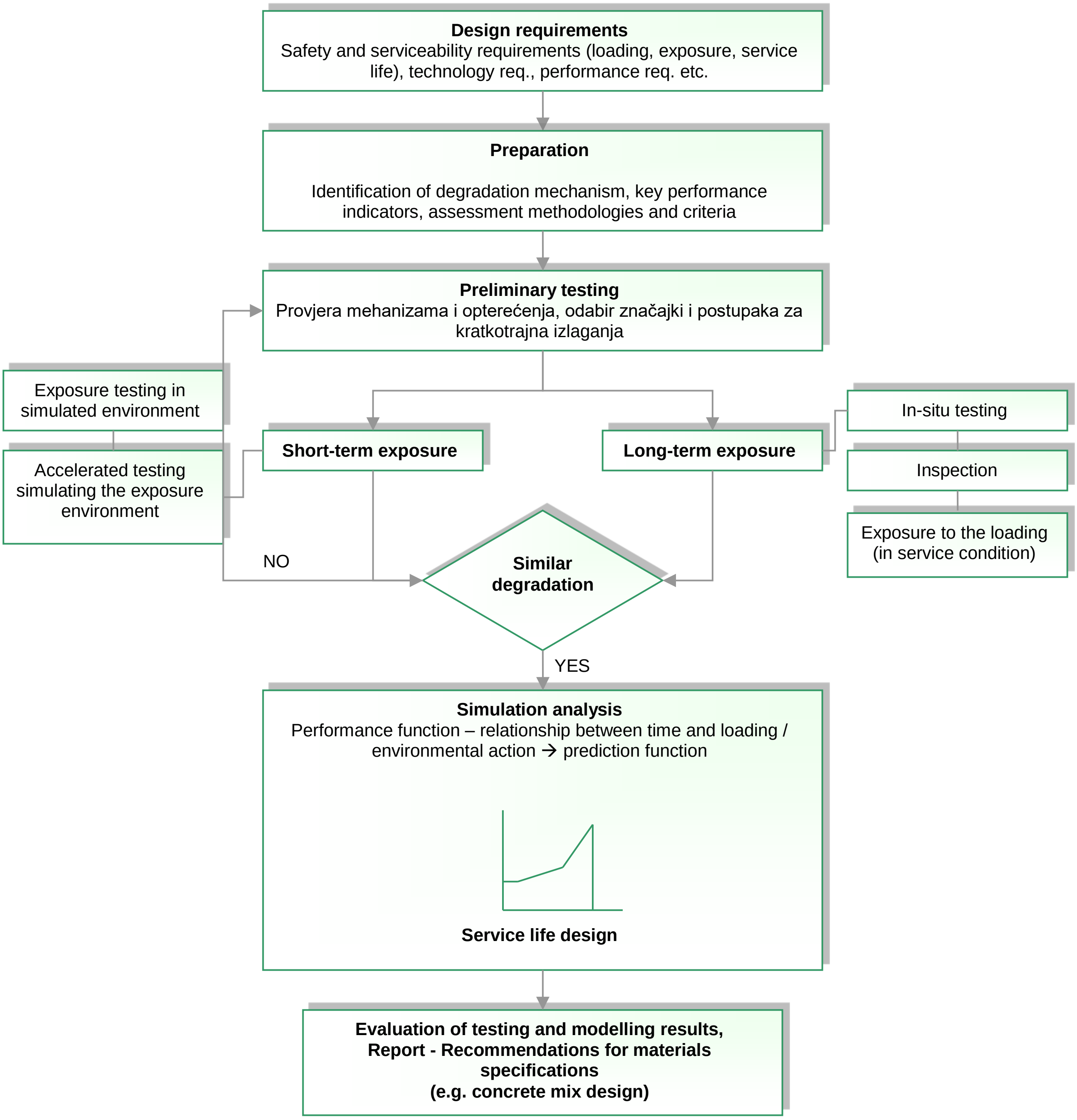


Figure 2-1. Concept of performance based design of concrete

2.2 Exposure classes

Reinforced concrete as a combination of steel (reinforcement) and concrete (a mixture of cement, water and aggregates) is one of the most widely used materials in construction. For a long time, reinforced concrete structures have been considered durable, requiring minimum maintenance or none. The situation is, however, different from what is believed, and enormous repair costs of structures deteriorated by reinforcement corrosion are the reason that those concerned have developed awareness of the importance of durability design.

Based on the experience and historical evidence of concrete structures damages, it was established that reinforced concrete structures are mostly damaged due to various environmental effects, which can be divided into four major categories:

1. Chemical and electrochemical processes
    a) corrosion of steel in concrete due to chlorides and / or carbonation
    b) alkali-aggregate reaction, seawater, sulphates
    c) mineral water, base acids, salt solutions, water with CO2
2. Physical processes
    a) volume changes due to temperature difference, salt crystallization pressure, corrosion of the reinforcement
    b) extreme temperatures due to freezing and thawing, fire
3. Biological effects
    a) shells
    b) bacteria
4. Mechanical actions
    a) abrasion, erosion, cavitation
    b) overload
    c) cyclic load
    d) sudden impact.

Those processes are the basis of design codes, when the exposure class is selected and dominant degradation process identified. In **EnDurCrete** project the main focus is on concrete structures exposed to marine, offshore and continental environment, where the pilot projects will be demonstrated. Although different classes, in many cases those structures will have similar degradation process, as presented in Table 2-1.

Table 2-1 Overview of deterioration phenomena relevant for EnDurCrete pilot projects

		Environment		
Deterioration phenomena		**Marine**	**Offshore**	**Continental**
Corrosion of steel	Marine chlorides	+	+	
	De-icing salts			+
	Carbonation	+	+	+
Alkali-aggregate reaction				+
Sulphate attack		+	+	
Freeze-thaw cycle with or without de-icing salts			+	+
(Ice) abrasion		+	+	
Deep sea pressure			+	

In Table 2-2 the exposure classes identified by EN-206 [1] are presented. The table reports for each class also the information regarding the definition of the corresponding environmental conditions.

Figure 2-2 presents the hierarchy of the standards and their relation of the EN 206-1 standard with other standards for design and construction of concrete structures.

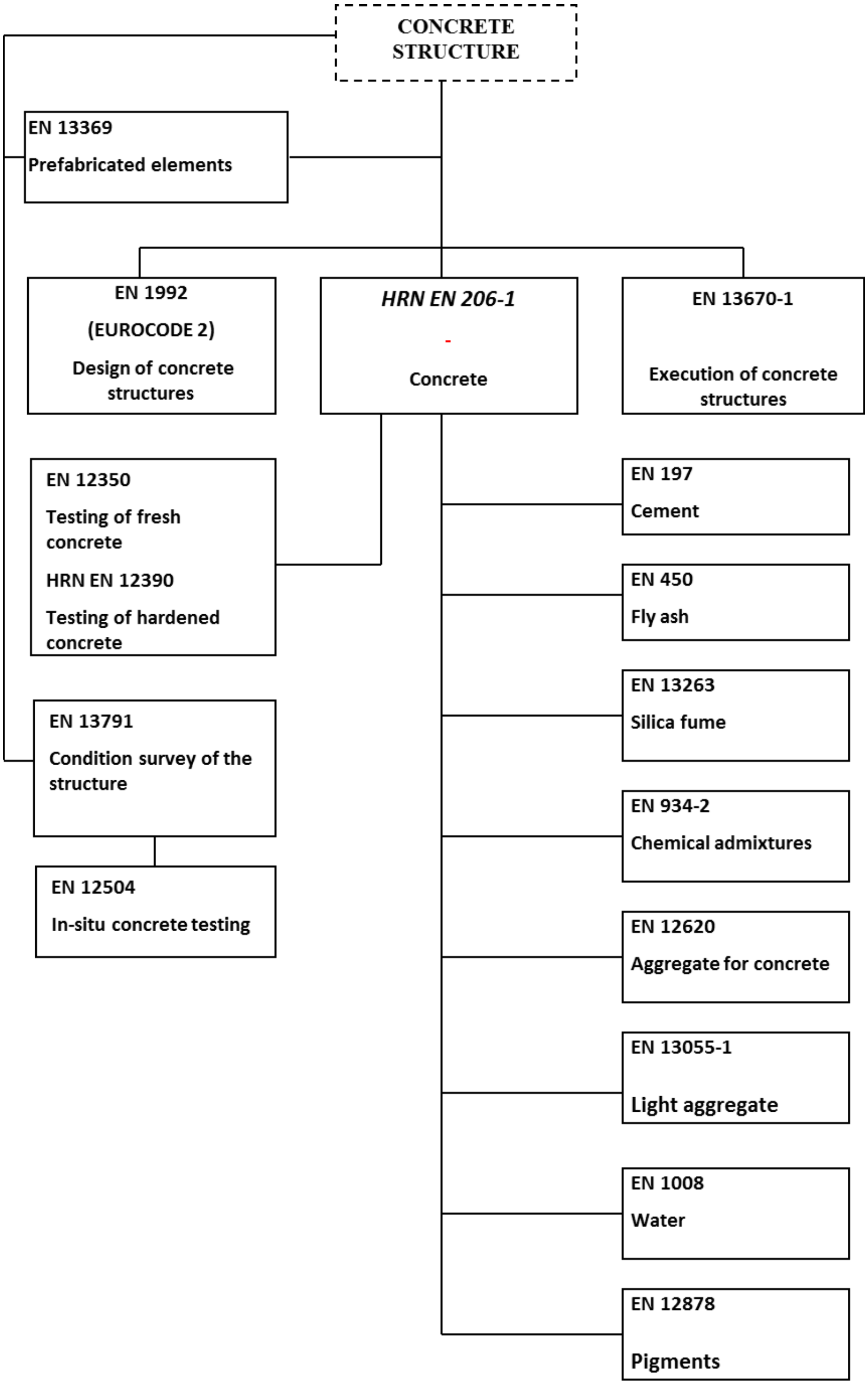


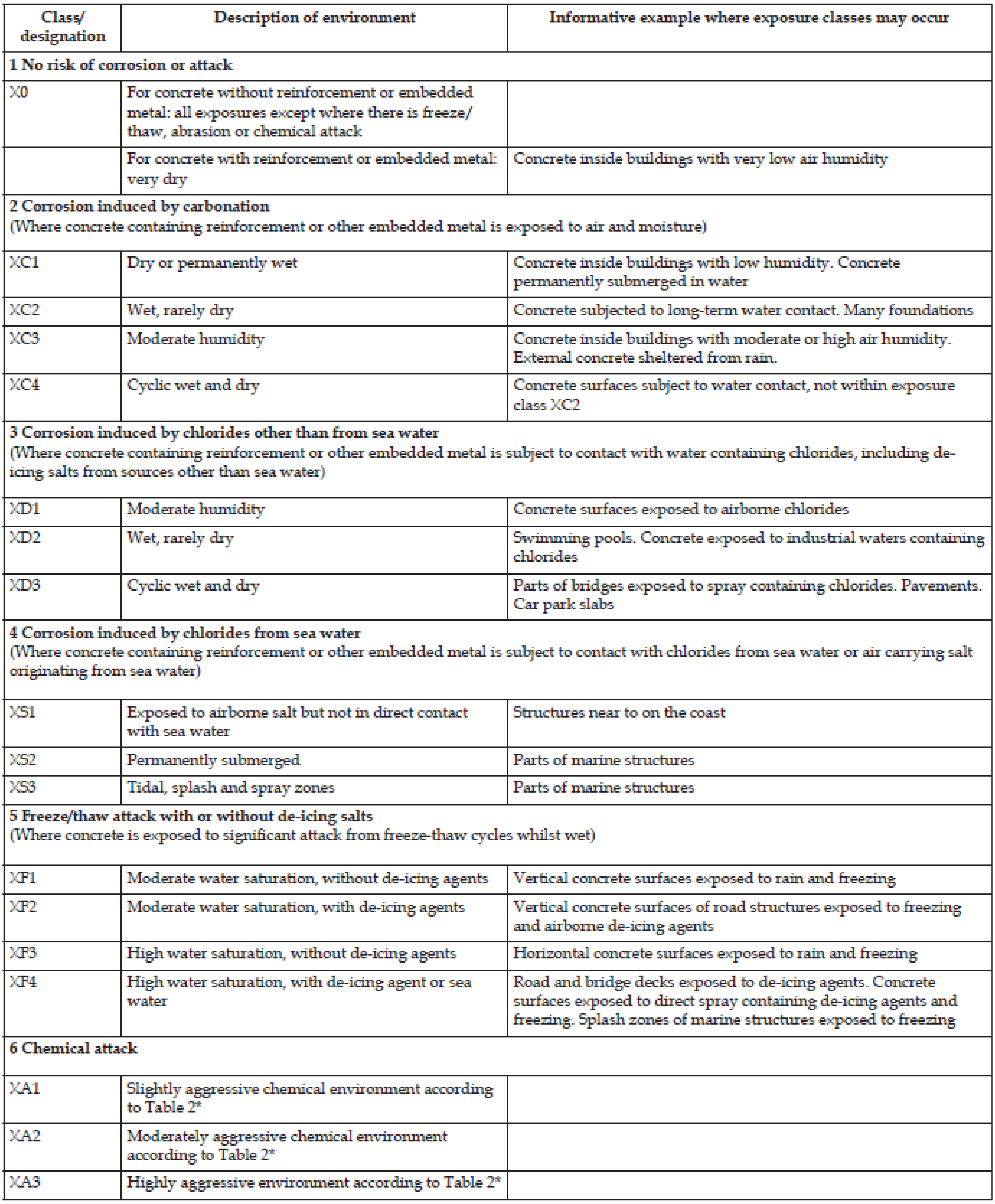
Figure 2-2 Relationships between the EN 206-1 and standards for design and construction, standards for constituent materials and standards for testing [1]

EN-206 [1] provides performance-related methods (PRMs) to apply in case of service life significantly higher of 50 years for the final product and/or particularly aggressive environmental conditions. This approach provides a quantitative evaluation of the effective service life of the structures by accounting or each relevant deterioration mechanisms based on data provided by experimental tests or reliable predictive models. More specifically, a PRM allows to establish the requirements associated to a specific exposure class by using and to specify them in terms of performance –related parameters; hence, a direct correlation between the single deterioration mechanism and the required performance, from one side, and the technical requirements to fulfil is established.

An overview of national annexes to EN 206-1, which provide PRMs, is given by documents CEN/TR 15868:2009 *Survey of national requirements used in conjunction with EN 206-1:2000.* [32].

In Slovenian addition to EN 206, the *SIST 1026:2016 Concrete - Specification, performance, production and conformity - Rules for the implementation of SIST EN 206* [33] performance related criteria including performance-related test methods for each exposure class were introduced.

Table 2-2: Classification of exposure classes for concrete according to European Standard EN 206-1 [1]



Class/ designation	Description of environment	Informative example where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/ thaw, abrasion or chemical attack	
	For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation (Where concrete containing reinforcement or other embedded metal is exposed to air and moisture)		
XC1	Dry or permanently wet	Concrete inside buildings with low humidity. Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete subjected to long-term water contact. Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain.
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides other than from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts from sources other than sea water)		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools. Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements. Car park slabs
4 Corrosion induced by chlorides from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water)		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing salts (Where concrete is exposed to significant attack from freeze-thaw cycles whilst wet)		
XF1	Moderate water saturation, without de-icing agents	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agents	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones of marine structures exposed to freezing
6 Chemical attack		
XA1	Slightly aggressive chemical environment according to Table 2*	
XA2	Moderately aggressive chemical environment according to Table 2*	
XA3	Highly aggressive environment according to Table 2*	

2.3 Requirements for Concrete Durability

Durability represents, after the required mechanical properties, a focal requisite for concrete, especially in the case of reinforced concrete structures were the environmental conditions can strongly affect the service performance. It is also important to highlight the strong correlation existing between concrete durability and the capacity of concrete structures to guarantee safety service conditions, but also the economic effects associated to a low durability of concrete.

With general reference to civil structural systems, durability is the capability to resist at specific environmental conditions by guaranteeing a minimum acceptable level of structural performance. The main factors influencing the concrete durability are:

- Concrete mix design, corresponding to the quality and quantity of concrete components;
- Structural design,
- Construction phase,
- Maintenance phases of the building process;
- Environmental conditions.

Given the focal importance of durability, many technical standards and guidelines are available all around the world that provide indications and technical requirements for durability design of concrete. Besides, in strict connection to durability design, many guidelines provide also new methodologies for predicting concrete effective service life. In the following, some examples of national technical standards approaching the topic of concrete durability are reported with reference to both European and non-European context:

- CEB Bulletin 238 (1997), “New Approach to Durability Design – An example for Carbonation Induced Corrosion”, CEB, Lausanne, pp.138 [13];
- CEB Bulletin N. 183 (1992), “Durable concrete structures. Design guide”, Thomas Telford Services Ltd, London [14];
- CIB W80/RILEM 71-PSL, “Recommendation: Prediction of service life of building materials and components”, Materials and Structures, Vol. 20, No. 115, 198 [15];
- RILEM (1994), “Durability Design of Concrete Structures”, Report of RILEM Technical Committee 130-CSL, E&FN: London, UK [16];
- ACI 201.2R (2001), “Guide to Durable Concrete,” American Concrete Institute [17];
- ACI Committee 365 (2001), “Service life prediction—state of-the-art report. Manual of Concrete Practice”, ACI 365.1R-00-44 [18];
- GB/T 50476-2008 (2008), Code for Durability Design of Concrete Structures. China [19];
- State of the Art Report RILEM TC 230 PSC. Performance Based Specifications and Control of Concrete Durability, 2016 [20];
- CEB-FIP, Model Code2010, International Federation for Structural Concrete (fib), 2012 [21];
- FIB Bulletin No. 76 Benchmarking of deemed-to-satisfy provisions in standards: Durability of reinforced concrete structures exposed to chlorides, 2015 [22].
- CUR (2009), Durability of structural concrete with regard to chloride induced reinforcement corrosion - Guideline for formulating performance requirements [23].

At the same time, many research projects focused in the last years on studying new design approaches for concrete durability. As results of the main relevant projects, the following technical manual and guidelines represent further references for managing the definition of concrete durability:

- BE-1347/TG7/ Report R14 (1999), "General Guidelines for Durability Design and Redesign", Brussels: Brite-EuRam, 1999, Project No. BE95-1347 [24];

- "DuraCrete - Final Technical Report" (2000), The European Union - Brite EuRam III Research Project: "Probabilistic performance based durability design of concrete structures", Document BE95-1347/R17, CUR, Gouda [25];
- "DuraCrete - General Guidelines for Durability Design and Redesign" (2000), The European Union – Brite EuRam III Research Project: "Probabilistic performance based durability design of concrete structures", Document BE95-1347/R15, CUR, Gouda [26];
- Critical Chloride Content – State of the art. SINTEF-report SBF BK A07037, Angst, U. (2007) [27];
- Effect of surface treatment on chloride ingress and carbonation in concrete. COIN- report 3. Plesser, T.S.W. (2008) [28]:
- Stainless steel reinforcement in concrete structures - State of the art. COIN-report 4. Markeset, G. (2008) [29];
- Modelling of reinforcement corrosion in concrete - State of the art. COIN-report 7. Markeset, G. (2008) [30];
- Corrosion Inhibitors – State of the art. COIN-report 22. Myrdal, R. (2010) [31];

Focusing on the European context, the main important standard regulating concrete composition and providing indication for approaching concrete durability is EN-206 [1]. Analogously, EN 197-1 [2] provides technical criteria for defining cement composition also with the aim to improve the durability of the final product. EN-206 [1] provided specific limits for cement and concrete composition aimed at improving concrete durability. More specifically, the mentioned standard indicates specific technical requirements as a function of the exposure class of the final product, hence as a function of the environmental conditions. These requirements are expressed in terms of permitted types and classes of constituent materials, maximum water-to-cement ratio, minimum cement content, minimum concrete compressive strength class and, in case of relevance, minimum air content of concrete.

2.4 Requirements for Concrete Composition Materials

Concrete is a structural material composed by mixing cement, aggregates and water, additional admixture can be eventually included in the base composition for achieving specific technical requirements. The main reference for the definition of concrete mix design in European context is EN-206 [1]. While the standards reported below represent European references for the definition of specific composition and properties of each concrete components:

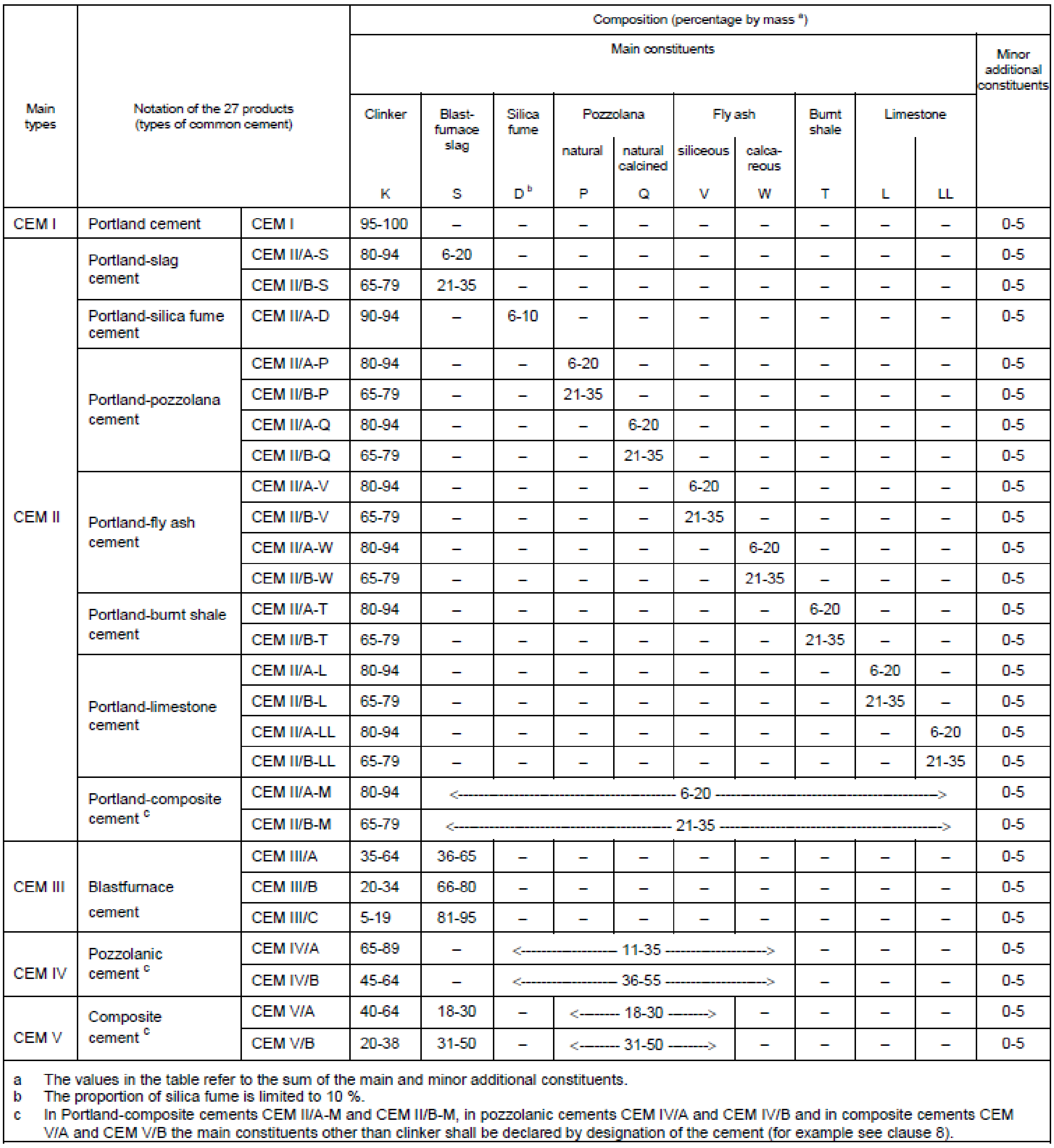
- EN 197-1 (2011), "Cement – Part 1: Composition, specifications and conformity criteria for common cements", European Committee for Standardization [2];
- EN 12620:2008 (2008), "Aggregates for concrete", European Committee for Standardization [3];
- EN 1008:2003 (2003), "Mixing water for Concrete – Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete, European Committee for Standardization [4];
- EN 934-2:2002 (2002), "Admixtures for concrete, mortar and grout – Concrete admixtures – Definitions, requirements, conformity, marking and labelling", European Committee for Standardization [5].
- Standards for mineral additions type II (e.g. EN 13263-1 [6], EN 450-1 [7], EN 15167-1 [8]) are also worth to be listed as they sometimes have significant influence on concrete properties

With reference to cement, EN 197-1 [2] provides a classification of cement typologies (CEM) suitable for composing concrete as a function of their capability of retaining workability for a sufficient time and attain specified strength levels after a defined hardened period. The composition of cement is regulated by EN 197-1 [2], in accordance to the criteria provided by EN 196-1 [9], by distinguishing between main constituents, minor additional constituents, calcium sulphate and additives. Table 2-3 resumes the specific composition requirements provided by EN 197-1 [2].

Aggregate compositions are also regulated by specific European Standards by distinguishing between normal, heavy-weight and light-weight aggregates. In the first case, the category of normal weight aggregate includes components with an oven-dry density included in the range 2000 – 3000 kg/m^3, while aggregate with oven-dry density greater than 3000 kg/m^3 belongs to the category of heavy-weight aggregates. Both the mentioned types are regulated by EN 1097-6 [10]. Finally, light-weight aggregates include aggregate of mineral origin characterized by an oven-dry density lower than 2000 kg/m^3 (according to EN 1097-6 [10]) and should conform to EN 13055-1 requirements [11]. All the mentioned standards provide indications for defining aggregates properties, such as frost resistance, flakiness and abrasion resistance, and consequently to select the most adequate concrete components as a function of the final use and environmental conditions.

As already mentioned above, EN 1008:2003 [3] is the main reference for establishing suitability condition for mixing water. The final effective water content is estimated as the difference between the total amount of water included in fresh concrete and the water absorbed by the aggregates.

Table 2-3: Classification of common cements according to European Standard EN 197-1 [2]



Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass [a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D [b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement [c]	CEM II/A-M	80-94	<------ 6-20 ------>									0-5
		CEM II/B-M	65-79	<------ 21-35 ------>									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement [c]	CEM IV/A	65-89	–	<------ 11-35 ------>					–	–	–	0-5
		CEM IV/B	45-64	–	<------ 36-55 ------>					–	–	–	0-5
CEM V	Composite cement [c]	CEM V/A	40-64	18-30	–	<---- 18-30 ---->			–	–	–	–	0-5
		CEM V/B	20-38	31-50	–	<---- 31-50 ---->			–	–	–	–	0-5

a The values in the table refer to the sum of the main and minor additional constituents.
b The proportion of silica fume is limited to 10 %.
c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for example see clause 8).

Regarding additions, EN-206 [1] distinguishes between two types of inorganic additions, which are nearly inert (type I) and pozzolanic or latent hydraulic (type II) additions. The use of additions in concrete mix design is aimed at improving specific technical properties of the final mixture. Specific standards regulates the technical requirements and the composition of both types of additions while a European Technical Approval is required in the eventuality of substances not specifically mentioned in the standards reported below:

- EN 12620:2008 (2008), "Aggregates for concrete", European Committee for Standardization [3];
- EN 12878:2005 (2005), "Pigments for the colouring of building materials based on cement and/or lime – Specifications and methods of test, European Committee for Standardization [12];
- EN 450 (2002), "Fly ash for concrete – Definitions, specifications and conformity criteria, European Committee for Standardization [7];
- EN 13263:2005 (2005), "Silica fume for concrete", European Committee for Standardization [6].

EN 934-2 [5] provides technical requirements for admixtures added during the mixing process of concrete in smaller quantities with respect to the mass of cement with the aim to modify the properties of fresh and hardened concrete.

3 Concrete structures in continental infrastructure applications

3.1 General design requirements

General provisions for the structural design of concrete continental infrastructures are included in many national technical standards among European and non-European countries. In order to have a general overview, in the following some examples of technical standards focused on the structural design of concrete infrastructures including road infrastructures, bridges and tunnels are reported. Dealing with the European Standards, specific provisions for design, maintenance and retrofitting of concrete continental infrastructures can be find in the following reference codes:

- EN 1991-2 (2005). Eurocode 1 (EC1) "Action on structures –Part 2: Traffic loads on bridges." Brussels, Belgium: European Committee for Standardization (CEN) [35];
- EN 1992-2 (2001). Eurocode 2 (EC2) "Design of Concrete structures – Part 2. Concrete Bridges", Belgium: European Committee for Standardization (CEN) [36];
- EN 1998-2 (1996). "Eurocode 8 (EC8) Design Provisions for earthquake resistance of structures – Part 2. Bridges", Belgium: European Committee for Standardization (CEN) [37];

In addition to the standards mentioned above, and having a general validity in all European Countries, the following national standards deal with technical requirements for land infrastructures:

- DM 14.01.2008 - "Norme tecniche per le Costruzioni" (NTC2008), cap. 5 (in Italian) [38];
- Istruzioni per l'applicazione delle Norme tecniche per le costruzioni di cui al DM 14/01/2008 – Circolare 2 Febbraio 2009 n°617 (in Italian) [39];
- DM 17.01.2018 – "Norme tecniche per le Costruzioni" (NTC2018), cap. 5 in substitution of DM 14.01.2008 (in Italian) [40];
- BTS (2004), "Tunnel lining design guide", The British tunneling society [41];
- Ministerio de Fomento (2010), "EHE-08 - Code on Structural Concrete [42].

Analogous specifications can be also found out of Europe in the national standards and technical guidelines reported below:

- ACI 343R-95 (1995), "Analysis and Design of Reinforced Concrete Bridge Structures", American Concrete Institute ACI [43];
- U.S. Department of Transportation Publication No. FHWA-NHI-10-034 Federal Highway Administration December 2009, "Technical Manual for Design and Construction of Road Tunnels — Civil Elements" [44];
- AASHTO LRFD (2012), "Bridge design specifications", American Association of State Highway and Transportation Officials [45];
- AASHTO LRFD (2010), "Technical Manual for Design and Construction of Road Tunnels-Civil Elements", American Association of State Highway and Transportation Officials [46];
- AASHTO (2011), NCHRP Project 20-68A – "Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations American Association of State Highway and Transportation Officials", American Association of State Highway and Transportation Officials [47];
- NZS3101 (1995), "Design of Concrete Structures" - Vols. 1 and 2, (Standards Association of New Zealand, Wellington) [48];
- NZS 3101:1995, "Concrete Structures Standard", Standards New Zealand, Wellington [49];
- Transit New Zealand Bridge Manual 2000 and Amendments 1 to 4 and Draft Amendment, December 2005 [50];
- CSA (1994), "CAN/CSA-A23.3-94: Design of concrete structures", Canadian Standards Association, Ottawa, Ontario, Canada [51];
- SAA (1990): Australian Standard for Concrete Structures (AS 3600), Standard Association of Australia [52].

3.2 Requirements for concrete in continental environment

Dealing with concrete structures in continental environment, the main phenomena that can affect concrete durability and induce long-term deterioration are:

- Carbonation;
- Freeze-thaw cycles;
- De-icing salts or chemicals agents;
- Alkali-aggregate reactions;
- Mechanical damage;
- Exposure to fire.

In the case of carbonation and chloride attack, the deterioration effect seems to be mainly related to the rebar corrosion, while the concrete composition itself seems not to be affected[1]. For this reason, the mentioned phenomena can be considered as mechanisms of "indirect" deterioration of concrete because their primary effect is the deterioration of steel reinforcement (reduction of the effective steel resisting section), but they indirectly affect also the concrete because it is usually associated also to a volume increase that can induce concrete cracking and spalling. In the most commonly corrosion products, the volume increase for iron ranges from 100% to 300%, the increase of internal pressure in the hardened concrete matrix is consequently significant.

Chloride ingress and carbonation can induce the breakdown of the oxide film protecting steel reinforcements and consequently activate the corrosion process.

Regarding the procedures for measuring the corrosion rate of reinforcing steel in concrete, many technical standards and guidelines are available in European and non-European references:

- ACI Committee 222. (1985). Corrosion of metals in concrete (Tech. Rep. No. ACI222R-85). American Concrete Institute. (30 pp.) [53];
- ACI Committee 365 (2001), "Service life prediction—state of-the-art report. Manual of Concrete Practice", ACI 365.1R-00-44 [18];

Several international research committees have been active on research related to reinforcement corrosion. Among the technical reports produced by the research committees, the references listed below provide detailed technical recommendations about the design, assessment and repair methodologies regarding reinforcement corrosion in concrete structures:

- COST-509 (1997), "Corrosion and protection of metals in contact with concrete. Final report", European Commission, Directorate General Science, Research and Development, Brussels, 1997:148 [54];
- COST 521 (2003), "Corrosion of steel in reinforced concrete structures," European Cooperation in the field of Scientific and Technical Research, Technical Report 521, Sep. 2003 [55];
- RILEM TC 130-CSL (2000), "Durability design of concrete structures -Committee report ," Technical Report, Feb. 2000 [56];
- RILEM TC154-EMC (2000), "Electrochemical techniques for measuring metallic corrosion", RILEM Technical Committees, [57].

Mechanisms of "direct" deterioration of concrete are, conversely, freeze-thaw cycling, de-icing salts or chemicals agents and alkali-aggregate reaction. These agents represent causes of deterioration mainly and directly affecting concrete integrity and resistance. The effects on concrete are generally cracking and strength reduction, but at the same time rebar corrosion is also induced by the breaking down of concrete's steel protection function [58].

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[1] Even if this conclusion is the most found in literature, it must be said that the influence of carbonation on concrete hasn't been adequately explained yet, especially in the case of mix cements or binders with high friction of SCMs.

3.2.1 Carbonation of concrete

Indications for determining all the parameters influencing carbonation are provided in EN-206 [1] as a function of the exposure classes on the reinforced concrete structure. Further indications for establishing the minimum concrete cover can be found in Eurocode 2 and American standards provided for regulating the design of bridges and road infrastructures:

- EN 1992-1-1:2004: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings [59].
- AASHTO LRFD (2012), "Bridge design specifications", American Association of State Highway and Transportation Officials [45].

The carbonation rate depends on humidity (see Figure 3-1), CO_2 concentration and porosity of the concrete and the type of binder and is proportion to the square root of time [61]. In EN 206-1 exposure classes XC1 to XC4 are defining carbonation induced corrosion depending on the humidity level, as presented in Table 2-2. In Eurocode 2 minimum cover depths and compressive strength classes for exposure classes XC1 to XC4 are given, as shown in Table 3-1. For the most severe wet-dry exposure class XC4 a minimum cover depth of 30 mm and concrete class C 30/37 is prescribed for 50 year design life-time of the concrete structure.

Table 3-1: Minimum cover depth for 50 year design life-time (S4 acc. Eurocode).

	XC1	XC2	XC3	XC4
Min. cover depth [mm]	15	25	25	30
compressive strength classes	C 25/30	C 25/30	C 30/37	C 30/37

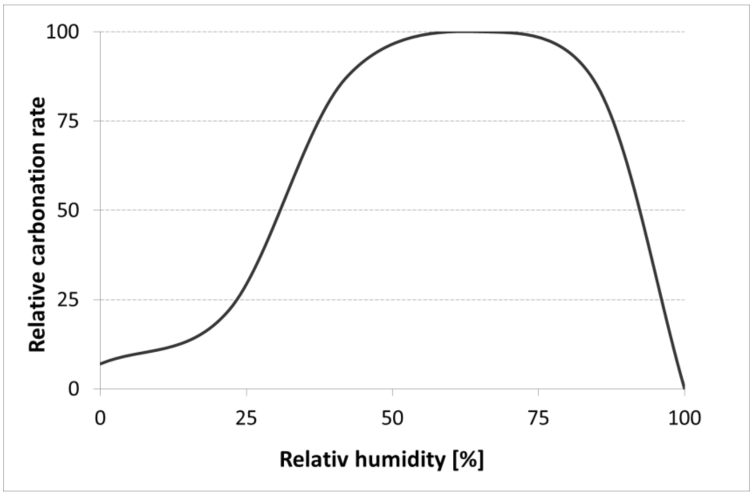

Figure 3-1 – Influence of humidity on carbonation rate. [113]

Requirements and recommendations for XC4 concrete mixtures are given in EN 206-1 and its national appendences of some European countries (CEN/TR 15868:2009 Survey of national requirements used in conjunction with EN 206-1:2000 [32]). Some of them are summarized in Table 3-2. In addition, in Slovenia the penetration of water under pressure measured according to EN 12390-8 [62] shall not exceed 30 mm for XC4 concrete.

Table 3-2: Requirements and recommendations for XC4 concrete mixes

reference	(w/c) max [/]	Min. cement content [kg/m3]	Min. compressive strength, cube [MPa]
EN 206-1	0.50	300	37
CEN/TR 15868, max	0.60	340	50
CEN/TR 15868, median	0.55	300	37
CEN/TR 15868, min	0.45	200	30
SIST 1026	0.50	340	/

In regards with cement types, recommendation of national CEN members can also be found in CEN/TR 15868. Cement CEM I is permitted by EN 206-1 and all CEN members for exposure class XC4 and for an intended working lifetime of at least 50 years. Cements CEM II/B-M are permitted in 7 countries and are not prohibited in any of them. Cements CEM IV/B and CEM V/A are permitted in 6 countries and not permitted in one.

3.2.2 Effects of de-icing salts

The impact of de-icing salts, and consequently the exposure to chlorides originated by these agents, represents one of the most common deteriorating factors for concrete structure (i.e. bridges) which are part of road infrastructures. The spread of de-icing salt is in fact one of the most common measure to prevent slippery road conditions produced by ice and snow all around the world. The exposure to the chloride agents deriving by de-icing salt is influenced by several environmental conditions, such as the exposure to rain, the temperature and the amount of de-icing spread on the road that is a consequence of the climatic conditions.

For structures exposed to chlorides other than sea water, which is the case for structures in continental environment, the European standard EN-206 [1] specifies exposure class XD. The exposure classification provided by EN-206 is then associated to specific requirements regarding concrete composition and properties defined with the aim to limit the impact of chloride and other environmental agents. In particular, EN-206 provides specific requirements regarding the maximum water to cement ratio, the minimum strength class of cement and minimum content of cement.

There are three sub-classes for each humidity level of the class XD: moderate humidity (XD1); wet, rarely dry (XD2); cyclic wet and dry (XD3). All these sub-classes (Table 3-3) refer to concrete structures exposed to chlorides other than from sea water, and including chlorides from de-icing salts but without freezing-thawing (for instance slabs of internal car park in winter time).

Table 3-3 Exposure class XD: Corrosion of the reinforcement induced by chlorides other than from sea water

Exposure class	Description	Examples where exposure class may occur	Max w/c	Minimum strength class	Min cement content (kg/m^3)
XD1	Moderate humidity	Structures exposed to direct spray containing chlorides	0.55	C 30/37	300
XD2	Wet, rarely dry	Swimming pools Structures exposed to industrial waters with Cl-	0.55	C 25/30	300
XD3	Cyclic wet and dry	• Parts of bridges • Pavements • Car park slabs	0.45	C 35/45	320

The activation of rusting can occurs in case of achieving a critical concentration of chloride in the concrete matrix. Consequently, the definition of critical chloride concentration under real environmental condition is a focal topic. Specific references regarding the definition of critical chloride concentration in concrete can be find in the Dutch technical standards listed below:

- CUR (1992), Kritisch Chloridegehalte in gewapend beton (rapport 92-7), Gouda, (in Dutch) [65];
- CUR (1997), Toelaatbaar chloridegehalte in gewapend beton (rapport 97-3), Gouda (in Dutch) [66];
- RILEM TC 235-CTC: Corrosion Initiating Chloride Threshold Concentrations in Concrete [67]

The study of the effects produced by de-icing salts received a remarkable interest in USA where many researchers have deepened the topic providing technical manual and guidelines. In this context, the documents reported below represent references of particular interest for investigating the effects of de-icing salts on reinforced concrete infrastructures in continental environment:

- WSDOT Research Report WA-RD 741.1 (2010), “Effect of chloride-based de-icers on reinforced concrete structures”, Washington State Department of Transportation [68];
- Adirondack Watershed Institute Report # AWI2010-01 (2010), “Review of effects and costs of road de-icing with recommendations for winter road managements in the Adirondack park” [69];
- Michigan Tech Transportation Institute (2008), “The deleterious chemical effects of concentrated de-icing solutions on Portland cement concrete” [70].

3.2.3 Freeze-thaw cycles

Freeze-thaw cycles represent a significant cause of deterioration for concrete in countries having sub-zero temperature conditions. Frost damage, a progressive deterioration which starts from the surface separation or scaling and ends up with complete delamination, is a major concern when concrete is used in colder regions. In particular, the volume expansion of water involved in the concrete pores, produced by wet concrete freezing, can induce cracking in case its pressure exceed the tensile strength of binding matrix. The iteration of this process can strongly affect the concrete integrity by causing concrete spalling and consequently weaken its resistance capacity. Moreover, the wet concrete frost can induce harsher damages during its early ages due to the higher capillary water content and lower strength that characterize unhardened concrete.

Regarding the concrete composition, the main factors influencing the concrete frost resistance are the porosity, water saturation and concrete strength. These factors are then influenced by the type of cement, the water to cement ration, the type of aggregates and additives characterizing concrete composition. Concrete mix design requirements are defined in EN 206-1, related to the XF exposure classes, as presented in Table 3-4.

Table 3-4: Concrete requirement for FX classes acc. to EN 206 [1]

Exposure class	Description	Examples where exposure class may occur	Max w/c	Minimum strength class	Min air volume content (%)
XF1	Moderate water saturation, without de-icing salts	Vertical surfaces exposed to rain and freezing	0.55	C 30/37	-
XF2	Moderate water saturation, with de-icing agent	Vertical surfaces of road structure exposed to freezing and airborne de-icing salts	0.55	C 25/30	4

XF3	High water saturation, without de-icing agent	Horizontal surfaces exposed to rain and freezing	0.50	C 30/37	4
XF4	High water saturation with de-icing agent or sea water	Horizontal surfaces of road structures and vertical surfaces exposed to direct spray of de-icing salts	0.45	C 30/37	4

As mitigation measure for concrete cracking induced by freeze-thaw cycles, especially to prevent spalling, air entrainment admixtures can provide extra air-filled voids. The air-filled voids provide extra space to be occupied by freezing water during its volume expansion reducing in this way concrete cracking. To this regard, ACI 211/1991 [64] provides specific requirements for air content as a function of the maximum aggregate size characterizing the concrete mixes.

3.2.4 Alkali-aggregate reactions

The presence of certain aggregates and alkali in the cement can lead to an expansive reaction that is called alkali aggregate reaction (AAR). This reaction is usually associated to a gel production characterized by a high tendency to absorb moisture. The volume expansion associated to the moisture absorption can lead finally to concrete cracking. Alkali-aggregate reaction can cause considerable volume expansion and cracking of concrete, changing the microstructure of concrete, and consequently leading to significant decrease of strength and stiffness. It also decreases concrete permeability and affects concrete durability and appearance.

The factors that mainly influence the activation of AAR are the alkali content in concrete, generally derived by Portland cement, additives and aggregates, the presence of reactive minerals in aggregates, temperature and the presence of moisture [71].

Common test methods to assess ASR are presented in Table 3-5:

Table 3-5 Overview of test methods to assess AAR

Test method	RILEM [115]	ASTM standard	Canadian standard	British standard
Petrographic examination	AAR-1	ASTM C295	--	BS 812: Part 104
Accelerated Mortar Bar Test (AMBT)	AAR-2	ASTM C1260	CSA A23 2-25A	DD 249:1999
Concrete Prism Test (CPT)	AAR-3	ASTM C1293	CSA A23 2-14A	BS 812: Part 123
Accelerated Concrete Prism Test (ACPT)	AAR-4	--		
Chemical Method		ASTM C289		

National Dutch standards provided indications about the environmental conditions that facilitate this phenomenon but also some technical requirements for prevent its formation:

- CUR (1998): Duurzaamheid en onderhoud van betonconstructies (CUR-172), Civieltechnisch Centrum Uitvoering Research en Onderzoek, Gouda (in Dutch) [72];
- CUR (2002): Maatregelen ter voorkoming van betonschade door alkalisilicareactie (CUR-Aanbeveling 89), Civieltechnisch Centrum Uitvoering Research en Regelgeving, Gouda (in Dutch) [73].

4 Concrete structures in offshore applications

4.1 General design requirements

Even if characterized by a relevant variability, the design approach to reinforced concrete offshore infrastructures usually bases on shell-theory and the iteration method, including assumptions of section-wise strain and load compatibility. Once fixed the acting loads and the structure geometry, a typical design procedure can be recognised by referring to some more relevant standards. Concerning European context, the structural design of offshore concrete structures usually refers to standards of general validity for concrete structures such as:

- EN 1990:2002. Eurocode 0 – Basis of structural design – CEN European Committee for Standardization, 2002+NA: 2008 [74];
- EN-1992-1-1. Eurocode 2: Design of Concrete Structures. Part 1-1: General Rules and Rules for Buildings. Brussels, CEN European Committee for Standardization, 2004 [59].

Detailed requirements can be also found in the Norwegian standards reported below:

- NS 3473 (2003), "Concrete Structures: Design and Detailing Rules", 6th edition, Standard Norway, Oslo, [75].
- DNV-OS-C502 (2010), "Offshore concrete structures", offshore standard DNV DET NORSKE VERITAS [76].

The standards implement the specific requirements provided by EC2 and represent a detailed guideline for the structural design of reinforced concrete offshore infrastructures. Focusing on "serviceability limit state" (SLS), both the standards focus the attention on limiting the surface crack width as primary prevention measure against the effects of harsh environmental conditions.

4.2 Requirements for concrete in offshore applications

In offshore applications, reinforced concrete structures can experience many harsh operation conditions such as:

- Corrosion induced by chlorides, deriving both by sea water and de-icing agents;
- Ice impact and abrasion;
- Wind and Ocean current;
- Freezing and thawing cycles;
- Extreme cold thermal gradients;
- Deep-sea conditions, where high hydrostatic pressure can occur.

The relevance of each environmental condition depends on the geographical location of the offshore infrastructures. The following sections provide specific technical requirements included in European and non-European standards with reference to each mentioned scenario.

4.2.1 Effects of de-icing salts and sea water

A description of the effects produced by de-icing salt and chloride attack is already provided in the previous section; here the attention is focused on the specific exposure conditions that characterize offshore structures. For these structures, the main source of chloride is seawater, even if the use of de-icing agents containing chloride can be also relevant.

The exposure scenario under consideration is regulated by EN 206-1, EC2 [59] and NS 3473 [75]. The mentioned standards provide a list of exposure classes accounting for the specific effects of chloride attack. Table 4-1 reports the classification of marine exposure classes provided by [1].

Table 4-1: Exposure classes in the case of chloride corrosion recommended in EN 206-1

Class	Environment description	Examples where exposure classes may occur	Max w/c	Minimum strength class	Minimum cement content (kg/m^3)
XS1	Exposed to airborne salt, but not in direct contact with sea water	Strictures near to or on the coast	0.50	30/37	300
XS2	Permanently submerged	Parts of marine structures	0.45	35/45	320
XS3	Tidal, splash and spray zone	Parts of marine structures	0.45	35/45	340

The chloride ion ingress can occur throughout surface cracks by means of diffusion phenomena. For this reason, the limitation of surface concrete cracking is considered one of the most efficient prevention measure for chloride ion attack. With the same aim, also the definition of a minimum concrete cover thickness represents a relevant prevention measure provided by technical standards. In addition to the standards mentioned above, specific indications regarding the limitation of concrete cover and surface cracking are provided by the following standards:

- CEB/FIP bulletin 65 (2010), “Model Code for Concrete Structures “, Recommendation of FIP and CEB [78];
- DNV-OS-C502 (2010), “Offshore concrete structures”, Offshore standard DNV DET NORSKE VERITAS [76].

As already mentioned in section 3.2**Error! Reference source not found.**, the activation of reinforcement corrosion induced by chloride ions depends on the attainment of a critical chloride concentration. To this regard, the European standard EN-206-1 [1] provides specific limitations for chlorides concentration in fresh concrete (as the percentage of chloride ions by mass of cement) depending on the concrete use (not containing steel, containing steel, containing prestressing steel), presented in Table 4-2.

Table 4-2: Maximum chloride content of concrete in EN 206 [1]

Concrete use	Chloride content class [a]	Maximum Cl- content by mass of cement [b] %
Not containing steel reinforcement or other embedded metal with the exception of corrosion-resisting lifting devices	Cl 1.00	1.00
Containing steel reinforcement or other embedded metal	Cl 0.20	0.20
	Cl 0.40 [c]	0.40
Containing prestressing steel reinforcement in direct contact with concrete	Cl 0.10	0.10
	Cl 0.20	0.20

a For a specific concrete use, the class to be applied depends upon the previsions valid in the place of use of concrete.

b Where additions are used and are taken into account for the cement content, the chloride content is expresses as the percentage chloride ion by mass of cement plus total mass of additions that are taken into account.

c Different chlorides content classes may be permitted for concrete containing CEM III-cements according to provisions valid in the place of use.

4.2.2 Freeze – thaw cycles

In case of offshore structures in cold regions, water freezing can affect concrete durability by producing concrete cracking and spalling. The freezing of water included in concrete pores generally induces a remarkable volume expansion and, hence, an increase of the internal pressures from which concrete cracking can result. In addition to the frosting effects, also the alternation of freezing and thawing cycles can induce concrete deterioration by causing cumulative damages both in terms of surface cracking and interior damage.

Concerning the effects produced by freezing – thawing cycles, the European standard EN 206-1 [1] provides the exposure classes listed in Table 2-2. The mentioned classes accounted for not only water saturation but also the presence of de-icing salts. This is because salt solutions causes an additional freezing point depression and provide available liquid to be transported to ice lenses in concrete during the freezing thus increasing the overall pore pressure exerted by the ice. The standard is recommending limiting values for composition and properties of concrete based on different exposure classes, namely maximum water-to-cement ratio, minimum strength class, minimum cement content and minimum air content.

The technical requirements and the reference standards mentioned in section 3.2.3, for the specific case of land structures, can be considered of general validity also in case of offshore structures.

4.2.3 Exposure to Ice abrasion /Ice impact

The exposure of offshore structures to ice-infested waters can affect remarkably concrete durability. In this case, the most dangerous phenomenon is the concrete abrasion caused by drifting ice. Concrete abrasion can initially produce a reduction of the concrete cover, then, as secondary deterioration effect, the reduction of concrete cover can potentially facilitate the chloride and water diffusion into the concrete leading to the well-known deterioration phenomena affecting steel reinforcement. Regarding concrete abrasion, there are very limited indications by standards currently available. The two most relevant standards for offshore installations in artic locations are:

- ISO 19906:2010, “Petroleum and Natural Gas Industries – Arctic Offshore Structures” [76];
- API RP 2N (2015), “Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Artic Conditions”, 3rd edition [77].

The API RP is in principle similar to the ISO 19906 with some modifications. Both the standards, promote a design approach in which careful attention is devoted to proper concrete detailing, such as the definition of adequate concrete cover or the application of smooth external surfaces in areas subjected to moving ice. The standards promote also the application of protective steel cover sheets as further prevention measure in case of extremely severe conditions.

4.2.4 Offshore structures in deep sea

Oil and gas installations and large dams built up in deep-sea environment are submitted to extensive hydrostatic pressures requiring usually the use of high-performance concrete material. The achievement of high strength requires the optimizations of several concrete components, such as in particular aggregate shape, high-strength cement, hydration and heat properties.

Technical requirements relevant to deep-sea concrete structures are mainly limited to the inclusion of water pressure in crack widths calculations, e.g. requirement given in the Norwegian concrete standard NS3473 [75]. Furthermore, the use and development of high strength concrete is usually covered in most standards. Model Code 2010 [78] for instance does cover concrete up to characteristic strength of 120MPa. In terms of concrete quality, the Model Code does also refer to the following ISO standards:

- ISO 22965-1 (2007), “Concrete – Part 1: Methods of specifying and guidance to the specifier” [79];
- ISO 22965-2 (2007), “Concrete – Part 2: Specification of constituent materials, production of concrete and conformity of concrete” [80].

5 Concrete structures in marine environment

5.1 General design requirements

General provisions for the structural design of concrete marine infrastructures are included in many national technical standards among European and non-European countries. In order to have a general overview, in the following are reported some examples of technical standards focused on the structural design of concrete structures including port and harbour facilities such as berths, piers, dry docks, etc. Dealing with the European Standards, specific provisions for design, maintenance and retrofitting of concrete land structures can be found in the following reference codes:

- EN 1991-2 (2005). Eurocode 1 (EC1) “Action on structures –Part 2: Traffic loads on bridges.” Brussels, Belgium: European Committee for Standardization (CEN) [35];
- EN 1992-2 (2001). Eurocode 2 (EC2) “Design of Concrete structures – Part 2. Concrete Bridges”, Belgium: European Committee for Standardization (CEN) [36];
- EN 1998-2 (1996). “Eurocode 8 (EC8) Design Provisions for earthquake resistance of structures – Part 2. Bridges”, Belgium: European Committee for Standardization (CEN) [37];

In addition to the standards mentioned above, the following national standards deal with technical requirements for marine structures:

- BS 6349-1-4 [81] provides guidance for the materials used in the design and construction of maritime environment structures, and includes specific provisions for use in a seawater environment.
- BS 6349-1-1 [82] provides guidance on general criteria relevant to the planning, design, construction and maintenance of structures and facilities set in the maritime environment. It also gives recommendations in respect of environmental and operational matters that need to be considered in the planning and design of maritime works.
- BS 6349-2 [83] gives recommendations and guidance on the design of quay walls, jetties and dolphins. It also includes references to Eurocodes and other European standards published since the previous edition of BS 6349-2.
- BS 6349-1-2 [84] gives recommendations for the assessment of actions for the planning and design of maritime works. It covers partial factors and load case combinations for maritime structures.
- BS 6349-3 [85] focuses on shipyard-specific design considerations and applies to the design of both commercial and naval base facilities. It also covers all the principal types of facility and how all the factors which impact the maritime structure design should be taken into account through the design process.
- BS 6349-1-3 [86] gives recommendations for geotechnical activities associated with the design and implementation of maritime works. It covers site investigation and gives additional guidance on testing procedures and typical ground properties.
- EAU 2012 [87] represents a completely updated edition of the Recommendations of the Committee for Waterfront Structures Harbours and Waterways . It provides those working in this field with a valuable work of reference for design, tendering, award of contract, engineering tasks, economically and environmentally compatible construction, site supervision and contractual procedures. The recommendations correspond to the latest international findings and form the foundation for building ports, harbours and waterways according to the state of the art and with consistent specifications. By incorporating the European standardisation concept, the 9th edition of the English version of the recommendations satisfies the requirements for notification by the European Commission.

Analogous specifications can be also find out of Europe in the national standards and technical guidelines reported below:

5. PHRI (2009). Technical Standards for Port and Harbor Facilities in Japan. The Overseas Coastal Area Development Institute of Japan, Bureau of Ports and Harbors, Ministry of Transport, Port and Harbor Research Institute, Tokyo [88]

- AASHTO LRFD (2012), "Bridge design specifications", American Association of State Highway and Transportation Officials [45];
- NZS3101 (1995), "Design of Concrete Structures" - Vols. 1 and 2, (Standards Association of New Zealand, Wellington) [48];
- NZS 3101:1995, "Concrete Structures Standard", Standards New Zealand, Wellington [49];
- Transit New Zealand Bridge Manual 2000 and Amendments 1 to 4 and Draft Amendment, December 2005 [50];
- CSA (1994), "CAN/CSA-A23.3-94: Design of concrete structures", Canadian Standards Association, Ottawa, Ontario, Canada [51];
- SAA (1990): Australian Standard for Concrete Structures (AS 3600), Standard Association of Australia [52].

5.2 Requirements for concrete in marine environment

Marine structures are subject to relatively rapid rates of deterioration due to environmental forces such as waves, currents, tides, extreme water levels, and ice, and mechanisms such as corrosion, physical/chemical attacks, general wear, abrasion, erosion, and fatigue, and damage caused by vessel impact and overloads. Structures also may become unserviceable because of the movement of bottom materials (i.e., through scour and siltation effects). Rapid deterioration rates also may be attributed to poor design, workmanship, and quality of materials.

The site-specific physical and chemical properties of seawater often play an important role in deterioration rates. A more thorough overview of the effects of the marine environment on structural design has been provided by Gaythwaite [90]. The general properties of various materials for marine use are described in references [91] and [92].

Principal modes of deterioration for concrete structures and examples of their primary effects are as follows:

- Corrosion of concrete-reinforcing steel (bars and wire strands) induced by chlorides;
- Physical-chemical processes such as freeze-thaw damage, alkali-silica reaction (ASR), delayed ettringite formation, and sulfate attack of concrete;
- Mechanical damage such as abrasion and wear of concrete, and over-loading.

Since marine structures can be considered at the edge between continental concrete structures and offshore applications, most of the chemical and physical deterioration processes listed above have been discussed in the previous sections. Therefore, general standards and regulations coming from both continental and offshore applications apply to marine structures design too.

Additional worth-mentioning guidelines which apply specifically to marine structures design are reported in the following sub-sections.

5.2.1 Effects of de-icing salts and sea water

All marine structures are exposed to seawater, while marine structures in Nordic countries, with sub-zero temperatures are also exposed to de-icing salts. A description of the effects produced by sea salt and chloride attack is already provided in the previous sections for continental and offshore applications and the same is applied in the case of marine environment.

Finally, considering protection against corrosion phenomenon, the standards below deal with cathodic protection of steel in concrete and harbour installations:

- ISO 12696:2016 - Cathodic protection of steel in concrete [103]
- ISO 13174:2012 - Cathodic protection of harbour installations [104]

5.2.2 Sulfate attack

Sulfate attack of seawater constituents on the calcium hydroxide [Ca(OH)2] and/or tri- calcium aluminate (C3A) of the hardened cement paste can result in softening and degradation of the concrete. If there is widespread softening of the surficial concrete and map pattern cracking [98], then the concrete may have ASR deterioration [99]. ASR deterioration is being identified in bridges and waterfront structures, though it is sometimes mistakenly identified as delayed ettringite formation (DEF), which has similar symptoms but is associated with precast concrete that has been heat cured [100]. Petrographic examination of the concrete is used to determine the cause of chemical deterioration. The uranyl acetate fluorescence method is an economical technique to test for ASR [101].

Table 5-1: Exposure classes XA :chemical attack in natural soils, ground water and sea water from EN 206-1

Class	Environment description							Max w/c	Max strength class	Min cement kg/m3
	SOIL		WATER							
	Acidity (Baumann Gully)**	SO_4^- (mg/kg)***	SO_4^- (mg/l)	PH	CO_2 (mg/l)	NH_4^+ (mg/l)	Mg^{++} (mg/l)			
XA1	<200	≥2000 ≤3000	≥200 ≤600	≥6.5 ≤5.5	≥15 ≤40	≥15 ≤30	≥300 ≤1000	0.55	30/37	300
XA2	-	≥3000 ≤12000	≥600 ≤3000	<5.0 ≤4.5	<10 ≤100	<30 ≤60	<1000 ≤3000	0.50	30/37	320
XA3	-	≥12000 ≤24000	≥3000 ≤6000	<4.5 ≤4.0	<100	<60 ≤100	<3000	0.45	35/45	360

* When two or more aggressive characteristics lead to the same class, the environment shall be classified into the next higher class.

** To be checked according to the German DIN 4030-2 test

*** Clay soils with a permeability below 10-5 m/s may be moved into a lower class

****Cylinder/Cube concrete strength class (N/mm2) based on cement strength class 32.5

5.2.3 Mechanical deterioration

Concrete is subject to physical (abrasion and freeze-thaw cycles) and chemical (chloride and sulfate attack, reactive aggregates, etc.) deterioration. In temperate and northern climates, concrete is especially vulnerable in the tidal zone where, with each tidal cycle, the concrete goes through a freeze-thaw cycle during the winter months. This effect may be exacerbated by the abrasive action of ice rising and falling with the tide or borne by currents.

Waterfront structures, in particular fender systems [102], are subject to mechanical damage due to accidental vessel impact and the cumulative effects of frequent normal berthings. Specific indications regarding the limitation of loads are provided by the following standards:

- BS 6349-1-2:2016 - Maritime works – General. Code of practice for assessment of actions [85];

6 Conclusions

In view of detailing the design requirements for concrete structures exposed to aggressive environments, a collection of standards, regulations and more general references to support designers has been provided, focusing on durability issues.

It is highlighted that, although European standards and regulations generally cover all aspects of design, some specific topics are only discussed in national and/or international references (e.g. BS 6349 series for Maritime works).

7 References

1. EN 206:2013 (2013), Concrete – Specification, performance, production and conformity, CEN European Committee for Standardization, 2016.
2. EN 197-1:2011 (2011), Cement – Part 1: Composition, specifications and conformity criteria for common cements. CEN European Committee for Standardization.
3. EN 12620:2008 (2008), “Aggregates for concrete”, CEN European Committee for Standardization.
4. EN 1008:2003 (2003), “Mixing water for Concrete – Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete, CEN European Committee for Standardization.
5. EN 934-2:2002 (2002), “Admixtures for concrete, mortar and grout – Concrete admixtures – Definitions, requirements, conformity, marking and labelling”, CEN European Committee for Standardization.
6. EN 13263-1:2005+A1:2009, "Silica fume for concrete - Part 1: Definitions, requirements and conformity criteria", CEN European Committee for Standardization.
7. EN 450-1:2012, "Fly ash for concrete - Part 1: Definition, specifications and conformity criteria", CEN European Committee for Standardization.
8. EN 15167-1:2006, "Ground granulated blast furnace slag for use in concrete, mortar and grout - Part 1: Definitions, specifications and conformity criteria", CEN European Committee for Standardization.
9. EN 196-1 (2005), “Methods of testing cement - Part 1: Determination of strength”, CEN European Committee for Standardization.
10. EN 1097-6:2008 (2008), “Tests for mechanical and physical properties of aggregates – Part 6: Determination of particles density and water absorption”, CEN European Committee for Standardization.
11. EN 13055-1:2003 (2003), “Lightweight aggregates – Part 1: Lightweight aggregates for concrete, mortar and grout”, CEN European Committee for Standardization.
12. EN 12878:2005 (2005), “Pigments for the colouring of building materials based on cement and/or lime – Specifications and methods of test, CEN European Committee for Standardization.
13. CEB Bulletin 238 (1997), “New Approach to Durability Design – An example for Carbonation Induced Corrosion”, CEB, Lausanne, pp.138.
14. CEB Bulletin N. 183 (1992), “Durable concrete structures. Design guide”, Thomas Telford Services Ltd, London.
15. CIB W80/RILEM 71-PSL, “Recommendation: Prediction of service life of building materials and components”, Materials and Structures, Vol. 20, No. 115, 198.
16. RILEM (1994), “Durability Design of Concrete Structures”, Report of RILEM Technical Committee 130-CSL, E&FN: London, UK.
17. ACI 201.2R (2001), “Guide to Durable Concrete,” American Concrete Institute.
18. ACI Committee 365 (2001), “Service life prediction—state of-the-art report. Manual of Concrete Practice”, ACI 365.1R-00-44.
19. GB/T 50476-2008 (2008), Code for Durability Design of Concrete Structures. China.
20. State of the Art Report RILEM TC 230 PSC. Performance Based Specifications and Control of Concrete Durability, 2016.
21. CEB-FIP, Model Code2010, International Federation for Structural Concrete (fib), 2012.
22. FIB Bulletin No. 76 Benchmarking of deemed-to-satisfy provisions in standards: Durability of reinforced concrete structures exposed to chlorides, 2015.
23. CUR, 'Durability of structural concrete with regard to chloride induced reinforcement corrosion - Guideline for formulating performance requirements', (2009).
24. BE-1347/TG7/ Report R14 (1999), "General Guidelines for Durability Design and Redesign", Brussels: Brite-EuRam, 1999, Project No. BE95-1347.

25. "DuraCrete - Final Technical Report" (2000), The European Union - Brite EuRam III Research Project: "Probabilistic performance based durability design of concrete structures", Document BE95-1347/R17, CUR, Gouda.
26. "DuraCrete - General Guidelines for Durability Design and Redesign" (2000), The European Union – Brite EuRam III Research Project: "Probabilistic performance based durability design of concrete structures", Document BE95-1347/R15, CUR, Gouda.
27. Critical Chloride Content – State of the art. SINTEF-report SBF BK A07037, Angst, U. 2007.
28. Effect of surface treatment on chloride ingress and carbonation in concrete. COIN- report 3. Plesser, T.S.W. 2008.
29. Stainless steel reinforcement in concrete structures - State of the art. COIN-report 4. Markeset, G. 2008.
30. Modelling of reinforcement corrosion in concrete - State of the art. COIN-report 7. Markeset, G. 2008.
31. Corrosion Inhibitors – State of the art. COIN-report 22. Myrdal, R. 2010.
32. CEN/TR 15868:2009 Survey of national requirements used in conjunction with EN 206-1:2000.
33. SIST 1026:2016 Concrete - Specification, performance, production and conformity - Rules for the implementation of SIST EN 206.
34. JSCE Guidelines for Concrete n° 16 (2007), "Standard specifications for concrete structures – Materials and Construction", Japanese Society of Civil Engineers.
35. EN 1991-2 (2005). Eurocode 1 (EC1) "Action on structures –Part 2: Traffic loads on bridges." Brussels, Belgium: European Committee for Standardization (CEN).
36. EN 1992-2 (2001). Eurocode 2 (EC2) "Design of Concrete structures – Part 2. Concrete Bridges", Belgium: European Committee for Standardization (CEN).
37. EN 1998-2 (1996). "Eurocode 8 (EC8) Design Provisions for earthquake resistance of structures – Part 2. Bridges", Belgium: European Committee for Standardization (CEN).
38. DM 14.01.2008 - "Norme tecniche per le Costruzioni" (NTC2008), cap. 5 (in Italian).
39. Istruzioni per l'applicazione delle Norme tecniche per le costruzioni di cui al DM 14/01/2008 – Circolare 2 Febbraio 2009 n°617 (in Italian).
40. DM 17.01.2018 – "Norme tecniche per le Costruzioni" (NTC2018), cap. 5 (in Italian).
41. BTS (2004), "Tunnel lining design guide", The British tunneling society.
42. Ministerio de Fomento (2010), "EHE-08 - Code on Structural Concrete.
43. ACI 343R-95 (1995), "Analysis and Design of Reinforced Concrete Bridge Structures", American Concrete Institute ACI.
44. U.S. Department of Transportation Publication No. FHWA-NHI-10-034 Federal Highway Administration December 2009, "Technical Manual for Design and Construction of Road Tunnels — Civil Elements".
45. AASHTO LRFD (2012), "Bridge design specifications", American Association of State Highway and Transportation Officials.
46. AASHTO LRFD (2010), "Technical Manual for Design and Construction of Road Tunnels-Civil Elements", American Association of State Highway and Transportation Officials.
47. AASHTO (2011), NCHRP Project 20-68A – "Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations American Association of State Highway and Transportation Officials", American Association of State Highway and Transportation Officials.
48. NZS3101 (1995), "Design of Concrete Structures" - Vols. 1 and 2, (Standards Association of New Zealand, Wellington).
49. NZS 3101:1995, "Concrete Structures Standard", Standards New Zealand, Wellington.
50. Transit New Zealand Bridge Manual 2000 and Amendments 1 to 4 and Draft Amendment, December 2005.
51. CSA (1994), "CAN/CSA-A23.3-94: Design of concrete structures", Canadian Standards Association, Ottawa, Ontario, Canada.
52. SAA (1990), Australian Standard for Concrete Structures (AS 3600), Standard Association of Australia.

53. ACI Committee 222. (1985). Corrosion of metals in concrete (Tech. Rep. No. ACI222R-85). American Concrete Institute. (30 pp.).
54. COST-509 (1997), "Corrosion and protection of metals in contact with concrete. Final report", European Commission, Directorate General Science, Research and Development, Brussels, 1997:148.
55. COST 521 (2003), "Corrosion of steel in reinforced concrete structures," European Cooperation in the field of Scientific and Technical Research, Technical Report 521, Sep. 2003.
56. RILEM TC 130-CSL (2000), "Durability design of concrete structures -Committee report ," Technical Report, Feb. 2000.
57. RILEM TC154-EMC (2000), "Electrochemical techniques for measuring metallic corrosion", RILEM Technical Committees.
58. Masanori Hamada (2014), Critical Urban Infrastructure Handbook, Japan Society of Civil Engineers.
59. EN-1992-1-1. Eurocode 2: Design of Concrete Structures. Part 1-1: General Rules and Rules for Buildings. Brussels, CEN European Committee for Standardization, 2004.
60. Marcel Pourbaix, Atlas of Electrochemical Equilibria in Aqueous Solutions, NACE, Houston, USA 1974.
61. Šajna, A., Bras, V., Završnik, L. Influence of blended cement type on concrete carbonation, capillary uptake and chloride penetration. Zagreb. 2014.
62. EN 12390-8:2009. "Testing hardened concrete - Part 8: Depth of penetration of water under pressure", CEN European Committee for Standardization.
63. Neville A. M. (2002), "Properties of concrete." John Wiley & Sons, Inc., New York, New York, U.S.A.
64. ACI Committee 211. (1991). 211.1-91, "Standard Practice for Selecting Proportions for Normal, Height weight and Mass Concrete". ACI Manual of Concrete Practice, Part 1. Detroit, Michigan: American Concrete Institute.
65. CUR (1992), Kritisch Chloridegehalte in gewapend beton (rapport 92-7), Gouda, (in Dutch).
66. CUR (1997), Toelaatbaar chloridegehalte in gewapend beton (rapport 97-3), Gouda (in Dutch).
67. RILEM TC 235-CTC: Corrosion Initiating Chloride Threshold Concentrations in Concrete. 2014.
68. WSDOT Research Report WA-RD 741.1 (2010), "Effect of chloride-based deicers on reinforced concrete structures", Washington State Department of Transportation.
69. Adirondack Watershed Institute Report # AWI2010-01 (2010), "Review of effects and costs of road de-icing with recommendations for winter road managements in the Adirondack park".
70. Michigan Tech Transportation Institute (2008), "The deleterious chemical effects of concentrated deicing solutions on Portland cement concrete".
71. Mehta P. K. (1986). Concrete: Structures Properties, and Materials, Prentice-Hall, Englewood Cliffs, NJ 07632
72. CUR (1998): Duurzaamheid en onderhoud van betonconstructies (CUR-172), Civieltechnisch Centrum Uitvoering Research en Onderzoek, Gouda (in Dutch).
73. CUR (2002): Maatregelen ter voorkoming van betonschade door alkalisilicareactie (CUR-Aanbeveling 89), Civieltechnisch Centrum Uitvoering Research en Regelgeving, Gouda (in Dutch).
74. EN 1990:2002. Eurocode 0 – Basis of structural design – CEN European Committee for Standardization, 2002+NA: 2008.
75. NS 3473 (2003), "Concrete Structures: Design and Detailing Rules", 6th edition, Standard Norway, Oslo.
76. DNV-OS-C502 (2010), "Offshore concrete structures", Offshore standard DNV DET NORSKE VERITAS
77. ISO 19906:2010, "Petroleum and Natural Gas Industries – Arctic Offshore Structures".
78. API RP 2N (2015), "Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Artic Conditions", 3rd edition.
79. CEB/FIP bulletin 65 (2010), "Model Code for Concrete Structures ", Recommendation of FIP and CEB.
80. ISO 22965-1 (2007), "Concrete – Part 1: Methods of specifying and guidance to the specifier".
81. ISO 22965-2 (2007), "Concrete – Part 2: Specification of constituent materials, production of concrete and conformity of concrete".
82. BS 6349-1-4:2013 - Maritime works – General. Code of practice for materials.

83. BS 6349-1-1:2013 - Maritime works – General. Code of practice for planning and designs for operations.
84. BS 6349-2:2010 - Maritime works. Code of practice for the design of quay walls, jetties and dolphins.
85. BS 6349-1-2:2016 - Maritime works – General. Code of practice for assessment of actions.
86. BS 6349-3:2013 - Maritime works. Code of practice for the design of shipyards and sea locks.
87. BS 6349-1-3:2012 - Maritime works – General. Code of practice for geotechnical design.
88. EAU (2012). Recommendations of the Committee for Waterfront Structures. EAU 1996, Commission for Waterfront Structures, Society for Harbor Engineering and The German Society for Soil Mechanics and Foundation Engineering. 4th English trans. Wilhelm Emst und Sohn, Berlin-Munich.
89. PHRI (2009). Technical Standards for Port and Harbor Facilities in Japan. The Overseas Coastal Area Development Institute of Japan, Bureau of Ports and Harbors, Ministry of Transport, Port and Harbor Research Institute, Tokyo.
90. Gaythwaite, J. W. (1981). The Marine Environment and Structural Design. Van Nostrand Reinhold, New York.
91. Whiteneck, L. L. and Hockney, L. A. (1989). Structural Materials for Harbor and Coastal Construction. McGraw-Hill, New York.
92. US ACE (1983, Feb.). Construction Materials for Coastal Structures, SR-010. CERC, Ft. Bel voir, Va.
93. ACI (1980). Performance of Concrete in the Marine Environment. SP-I09, American Concrete Institute, Detroit, Mich.
94. ACI (1988). Concrete in the Marine Environment, Proceedings of the 2nd International Conference. SP-I09, American Concrete Institute, Detroit, Mich.
95. ACI (1982, March). "Concrete in a Marine Environment." Special Issue, Concrete International, 4, 3.
96. Buslov, V. (1979). "Durability of Various Types of Wharves." Coastal Structures '79, Proceedings of the Special Conference.
97. Bazant, Z. P. (1979, June). "Physical Model for Steel Corrosion in Concrete Sea Structures— Theory and Application." Proc. ASCE, 105, ST-6.
98. ACI (1992). Guide for Making a Condition Survey of Concrete in Service. ACI 201.1R-92, American Concrete Institute, Detroit, Mich. (Reapproved 1997.)
99. Farny, J. A. and Kosmatka, S. H. (1997). Diagnosis and Control of Alkali-Aggregate Reactions in Concrete. PC A IS 413, Portland Cement Association, Skokie, 111.
100. Erlin, B. (ed.) (1999). Ettringite—The Sometimes Host of Destruction. ACI SP-177, American Concrete Institute, Farmington Hills, Mich.
101. Emmons, H. P. (1993). Concrete Repairs and Maintenance Illustrated. R. S. Means Company, Inc., Kingston, Mass.
102. Padron, D. and Han, H. Y. (1983, Aug.). "Fender System Problems in U.S. Ports." Proc. ASCE, JWPCOE, 109, 3.
103. ISO 12696:2016 - Cathodic protection of steel in concrete.
104. ISO 13174:2012 - Cathodic protection of harbour installations.
105. Melchers R. E., (2011). Observations about the Corrosion of Reinforcement in Marine Environments. International Conference on Durability of Building Materials and Components.
106. Melchers R.E. (2006). Modelling immersion corrosion of structural steels in natural fresh and brackish waters, Corrosion Science 48(12) 4174-4201.
107. Melchers, R.E. & Li, C.Q. (2006). Phenomenological modelling of corrosion loss of steel reinforcement in marine environments, ACI Materials Journal, 103(1) 25-32.
108. Schilling M. (2006). Soluble salt frenzy - junk science, Corrosion & Materials, 31(5) 10-15
109. Melchers R.E. & Pape T. (2010). Aspects of long-term durability of reinforced concrete structures in marine environments, Medachs2010, La Rochelle, 28-30 April 2010.
110. Waseda Y. & Suzuki S. (Eds) (2006). Characterization of Corrosion Products on Steel Surfaces,
111. Springer, Berlin.

112. Davies, D.H. & Burstein, G.T. 1980. The effects of bicarbonate on the corrosion and passivation of iron, Corrosion 36(8) 416-422.

113. Bertolini, L., Elsener, B., Pedeferri, P., Polder, R.: Corrosion of steel in concrete - Prevention, Diagnosis, Repair, Wiley-VCH, Weinheim, 2004.

114. Kropp, J., Hilsdorf, K.H., Grube, H., Andrade, C., Nilsson, L.-O.: Transport mechanisms and definitions, RILEM Report 12 Performance Criteria for Concrete Durability, 1995

115. RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures, State-of-the-Art Report of the RILEM Technical Committee 219-ACS