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Ocean Power Innovation Network Collaborative Innovation Group (CIG) Report

Corrosion in reinforced concrete structures used for offshore renewables

Deliverable: WP T2 D3.1
Version: v1 – Public
Date: 02.03.2022

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Abbreviations

AFGC	Association Française de Génie Civil (French)
ANR	Agence Nationale de la Recherche (French)
ASR	Alkali-Silica Reaction
BFS	Blast Furnace Slag
CASH	Calcium Alumina Silicate Hydrate
CIG	Collaborative Innovation Group
FOS	Fiber Optic Sensors
FRP	Fiber Reinforced Polymer
GBFS	Granulated Blast Furnace Slag
LC3	Limestone Calcined Clay Cement
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
MCI	Migrating Corrosion Inhibitors
MK	Metakaolin
NASH	Sodium Alumina Silicate Hydrate
NDT	Non-Destructive Testing
OPIN	Ocean Power Innovation Network
OWF	Offshore Wind Farm
PC	Portland Cement
RC	Reinforced Concrete
SHC	Self-Healing Concrete
SHM	Structural Health Monitoring

1 Introduction

An increasing number of offshore renewable energy devices using concrete material are currently being developed and installed, for instance substructures for floating offshore wind turbines (XCF by MAREAL, Hywind Tampen by Equinor, SATH by SAITEC, Damping Pool by BW IDEOL, etc.). Concrete structures present the advantages of competitive manufacturing, operation and maintenance costs, high durability and a strong local content. They are particularly suitable for serial production.

However, concrete structures are usually reinforced with steel rebars that are prone to corrosion, in particular in offshore environment. The reinforced concrete structures can be protected against corrosion by cathodic protection (sacrificial anodes, impressed current), increased concrete cover, specific coatings, etc. These protective measures lead to additional costs, increased material quantities and potential environmental impacts.

Within the Ocean Power Innovation Network (OPIN)[1], a Collaborative Innovation Group (CIG) has been set up to explore opportunities (alternative rebar materials, specific concrete formulations, etc.) to **reduce the cost of corrosion and increase the lifetime of reinforced concrete structures in offshore renewables applications.**

The main objective of this CIG was to identify **one or several future R&D collaboration opportunities** within the CIG members (all or a subset) and start preparing the basis for associated grant applications. A state-of-the-art report has been prepared to support this final goal, collecting inputs from all CIG members on the activities identified in Table 1.

The present report is not a comprehensive, international state-of-the-art study. The aim was to share knowledge, information and ideas amongst the CIG members. This information was collected by means of written contributions, online workshops, surveys, etc. All CIG members were invited to provide content for all activities relevant to their competencies**.**

Table 1: CIG activities

#	Activity	Co-chair
1	**Chloride propagation and corrosion mechanisms** within the concrete material in sea environment	**UN (SB)**
2	State-of-the-art on corrosion protection **current practices in more mature sectors** (O&G, ports, bottom fixed offshore wind, etc.) and associated challenges for reinforced concrete structures	**Elsyca**
3	Identification of **biofouling impact** on corrosion resistance of reinforced concrete	**UN (FS)**
4	Overview of existing **inspection and monitoring** methods (in particular Non-Destructive Testing and Structural Health Monitoring) that could be suitable to monitor concrete degradation; with benefits, drawbacks and remaining challenges	**ENGIE Laborelec**

[1] Ocean Power Innovation Network (OPIN), www.nweurope.eu/opin

5	Identification of **alternative materials for concrete reinforcement** (FRP, stainless steel, etc.). Identify the state of the art, maturity level, ongoing R&D projects, and remaining challenges	**UGE**
6	Identification of **alternative concrete formulations** (aggregate, slag, additive, etc.). Identify the state of the art, maturity level, ongoing R&D projects, and remaining challenges	**UN (SB)**
7	Overview of **rules and standards** (DNVGL, LR, BV, Eurocode, etc.) applicable for the corrosion management of concrete rebars, with comparison of their requirements and developments required	**Bureau Veritas**
8	Building a framework for a future **research and demonstration project**. Identify available public funding opportunities (European, national, regional). Identify required competencies and build a preliminary consortium. Build a Work Package structure and start tasks definition. Define a macro planning (Gantt chart) for the project	**WEAMEC**

2 CIG organisation

Table 2: CIG organisation

CIG name	**Corrosion in reinforced concrete structures used for offshore renewables**
Duration	5 months, from October 2021 to February 2022
Lead	Laura-Mae Macadré, WEAMEC / Centrale Nantes
Members	• Arnaud Gerthoffert, Bureau Veritas (France) • Marwa Darraz, Bureau Veritas (France) • Kim Nielsen, Development v. Kim Nielsen (Denmark) • Christophe Baeté, Elsyca (Belgium) • Jan Wielant, ENGIE Laborelec (Belgium) • Sokratis Iliopoulos, ENGIE Laborelec (Belgium) • Francisco J. Presuel-Moreno, Florida Atlantic University (USA) • Jean-Philippe Touzanne, MAREAL (France) • Paolo Biagini, MAREAL (France) • Pascal Heisel, Phiconseil (France) • Jeroen Tacq, Sirris (Belgium) • Laurent Gaillet, Université Gustave Eiffel (France) • Sylvain Chataigner, Université Gustave Eiffel (France) • Géraldine Villain, Université Gustave Eiffel (France) • Stéphanie Bonnet, Nantes Université (France) • Yann Lecieux, Nantes Université (France) • Franck Schoefs, Nantes Université (France) • Magda Torres Luque, Capacités SAS (France) • Erik Friis-Madsen, Wave Dragon (Denmark)

Online meetings	**15/07/21 – Preparatory meeting** • draft Action Plan **27/09/21 – Meeting #1** • Kick off meeting **21/10/21 – Meeting #2** • CIG update • Presentation from S. Bonnet (Univ. Nantes) on the DEMCOM project **01/12/21 – Meeting #3** • CIG update **24/01/22 – Meeting #4** • CIG update • Presentation from F. Presuel-Moreno (Florida Atlantic University) on Durability and Corrosion Propagation of Carbon Steel Rebars Embedded in Concrete **22/02/22 – Meeting #5** • CIG report presentation • Future opportunities • Wrap up

3 Needs and expectations

3.1 Motivation and context

Only few publications are available regarding the specific application of concrete structures for offshore renewables, in particular floating ones, and even less addressing corrosion issues. A non-exhaustive list is available in section 3.6, covering both publications and deliverables, in particular from European collaborative projects such as FLOATGEN, LIFES50+, FLAGSHIP, COREWIND, etc. for floating offshore wind turbines.

The CIG group members have therefore decided to conduct a survey on corrosion protection current practices and improvement paths for offshore reinforced concrete structures. The aggregated results of this study are analysed below to identify future R&D paths to reduce corrosion costs for offshore renewables.

The CIG group jointly built the survey, compiling questions suggested by the CIG members on various topics such as corrosion protection current practices, inspection, monitoring, rules and standards, etc.

For most of the questions, a list of pre-defined answer was prepared by the CIG group to facilitate the survey completion. These pre-defined answers are directly included in the charts presented in the next section. Respondents also had the opportunity to enter customized answers through dedicated open fields. These inputs are also listed in the next section.

Most of the questions were not mandatory, therefore the number of answers varies from one question to another. For most of the questions, participants could select multiple answers, therefore the total number of answers to a question can exceed the number of respondents.

The survey was then disseminated to the offshore renewables community in December 2021 through various networks and channels: OPIN, WEAMEC, ETIP Ocean, Offshore-Energy.biz, ORE Catapult, etc.

Twenty answers were received during the period of December 2021 - January 2022. Care should be taken with the interpretation of the results in the next section, considering the limited sample size.

3.2 Respondents profile

Twenty answers were received during the period of December 2021 - January 2022, from a mix of industry and academics representatives. Respondents come from Europe and beyond, as illustrated on Figure 1 and Figure 2.

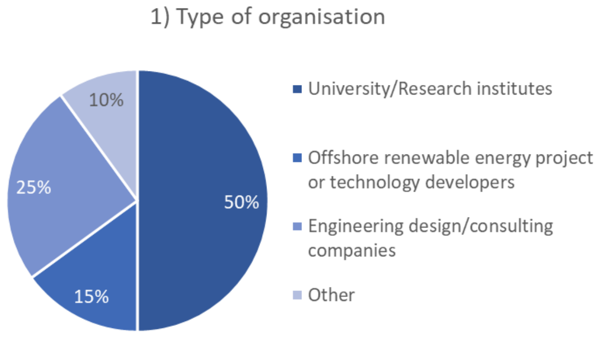

Figure 1

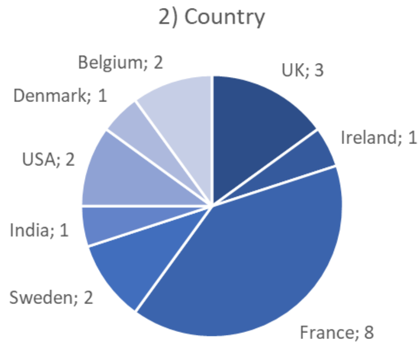

Figure 2

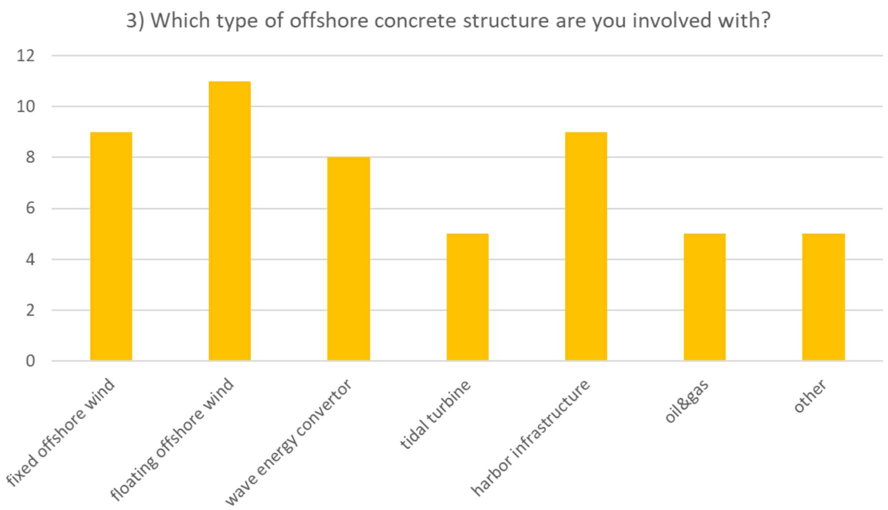

Figure 3

As illustrated in Figure 3, most of the 20 respondents are involved with fixed and floating offshore wind structures, but also harbor infrastructures and wave energy convertors. As part of the "other" option (i.e. free text typed an open field), respondents are also involved with the following offshore concrete structures:

1. *aquaculture farms*
2. *combined wind and wave floating offshore platform*
3. *ocean current energy converter*
4. *all concrete structures in marine environment: wharf, bridge, dykes etc....*
5. *bridge foundations and columns*
6. *reinforced concrete floating structure*

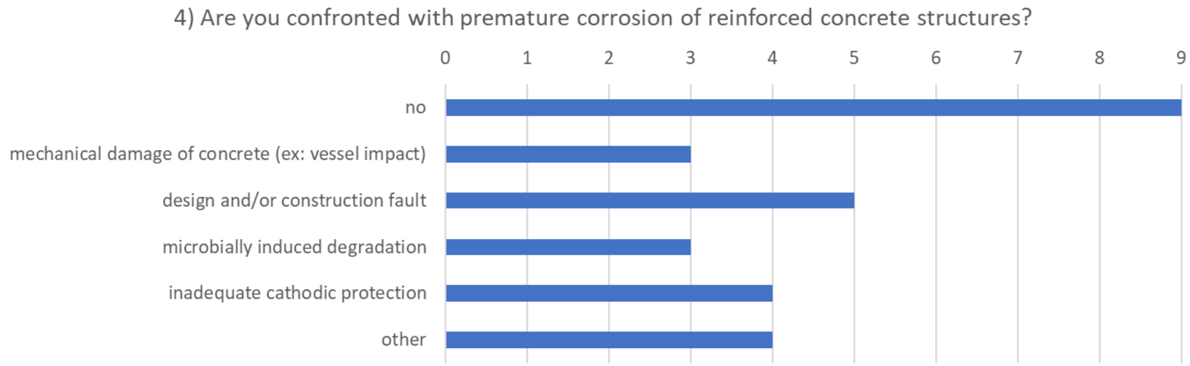

Figure 4

10 respondents out of 19 indicated the identified causes of premature corrosion of reinforced concrete structures, with an even distribution between the pre-defined options listed in Figure 4 and some additional input below:

- *In-service decay of concrete*
- *inadequate cover thickness, carbonisation, use of chlorides in the concrete*
- *Chloride ingress leading to rebar corrosion*

9 respondents out of 19 indicated that they are not confronted with premature corrosion of reinforced concrete structures.

3.3 Corrosion protection current practices

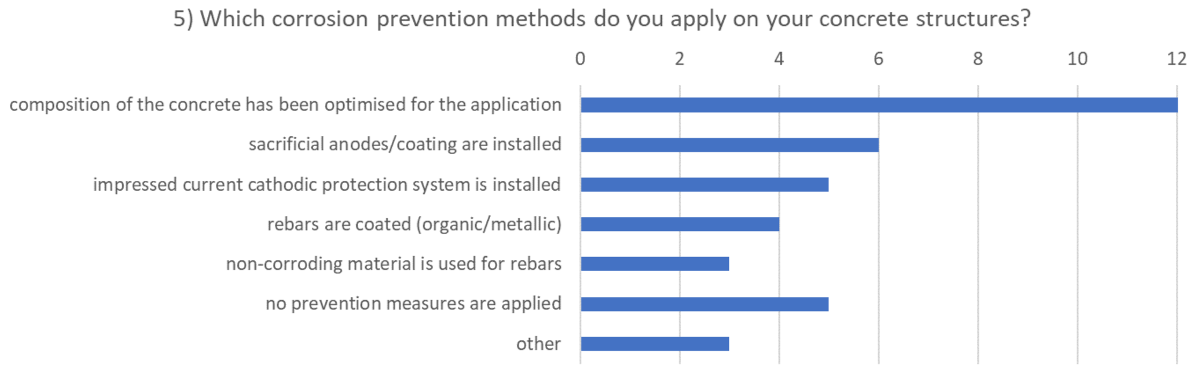

Figure 5

Out of 19 answers to question 5 (Figure 5), 13 respondents indicated that the concrete composition has been optimised for the application as a corrosion prevention method. As part of the "other" option, respondents also suggested:

- *Cathodic protection seems to lose some amount of popularity over time*
- *Sufficient concrete cover*

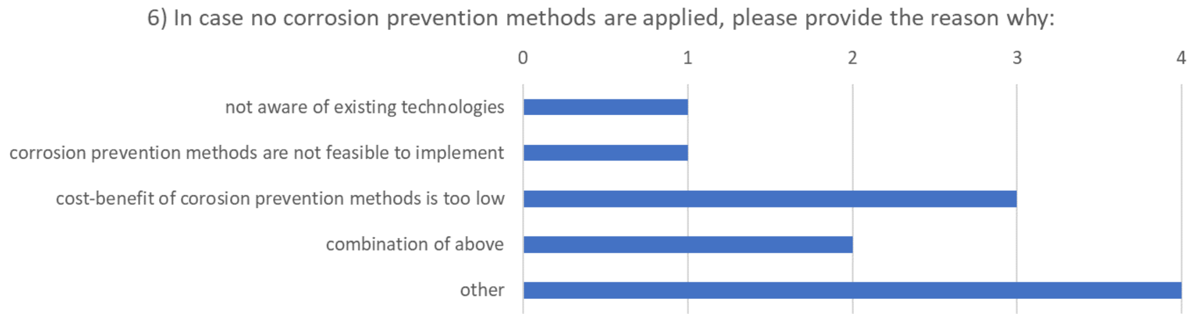

Figure 6

Out of 8 answers, the main reason identified in Figure 6 for not applying corrosion prevention methods is the perception that cost-benefit is too low. Other reasons identified by the respondents are:

- *Early in design but aiming for only fiber reinforcement, possibly with steel fibers. Only fibers as reinforcement and should be protected / corrosion resistant.*
- *rebars are deeply embedded in concrete structure*
- *the concept is under development*
- *study of old harbour RC structure*

3.4 Inspection and monitoring

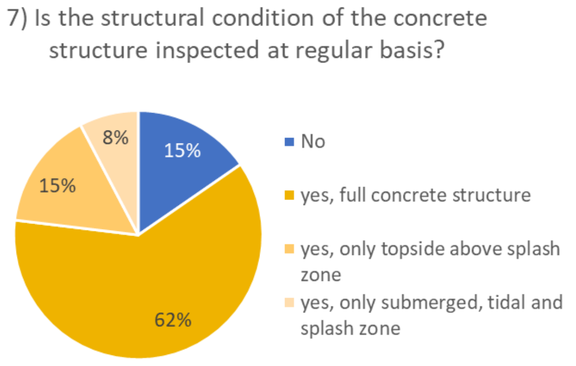

Figure 7

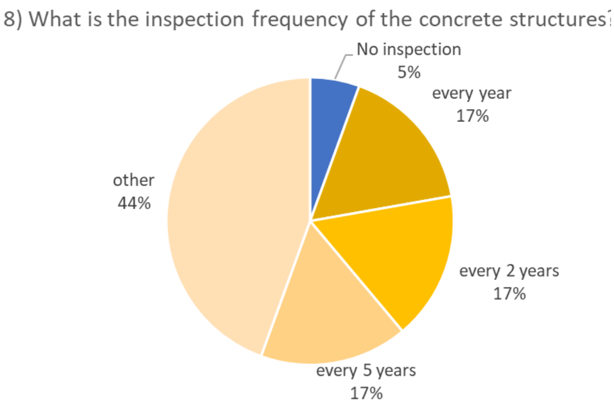

Figure 8

Out of 12, 8 respondents indicated that the full concrete structure was inspected on a regular basis (Figure 7). Regarding the frequency (Figure 8), the 16 answers collected range from 6 months to 10 years. Respondents from the industry seems to inspect the structure every one or two years in general. For a couple of them still at the design stage, the inspection frequency is not defined yet. As part of the "other" option, respondents suggested:

- *for research topic each 6 months*
- *10 years*
- *The top side more regularly than the bottom side. But overall, there is a lack of guidelines. Note - this is not true for bridges, where guidelines exist.*
- *at the moment experimental device (prototype) immersed for few months*

- *this will be decided once the design is further developed*
- *not built yet = not inspected*
- *I don't know the frequency, it is for research purposes*
- *don't know*

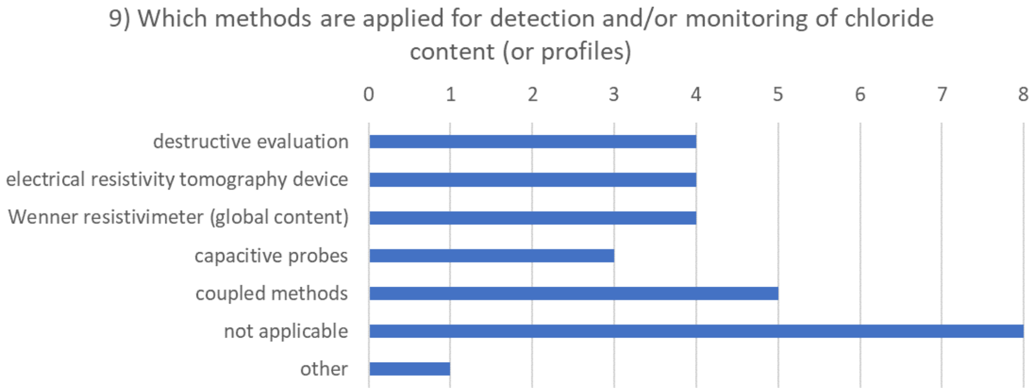

Figure 9

Regarding chloride content detection and monitoring, 8 respondents out of 14, mainly from the industry, indicated that it is not applicable. Others respondents, mainly academics, identified several methods illustrated in Figure 9, with Wenner resistivimeter and coupled methods having the highest ranking. As part of the "other" and "coupled methods" options, respondents suggested:

- *New sensors (Smartcore and 2RProbe[2]) developed in University of Nantes*
- *ERT+capacitive method+US*

If "destructive evaluation" was selected, respondents were asked to specify:

1. how the concrete powder is obtained (directly grinded on the structures or from a core in a lab)
2. what is the depth investigated
3. which kind of chloride content (or profiles) is determined (Water soluble or total chloride content)
4. do you use the RILEM protocol?

- *Directly grinded and from core. Depth leave out first 5 mm, then every 15mm or so (e.g. 12.5, ..., 37.5...) - we take 3 points to fit Fick's law. Both contents are found as they are sent for labs. Overall RILEM has created the guidance anyway. In Ireland the Special Inspection manual for bridges is the closest to such a guidance that we can get.*
- *Core - 8 cm - total chloride – Yes*
- *1) from cores in lab, 2) depending on expectation, 3) both water soluble and total Cl content , 4) yes*

[2] see SIMAR project

Figure 10

As illustrated in Figure 10, most of the respondents indicated a preference for visual inspection (11 out of 17). Other methods such as half-cell, ultrasonic testing and galvanostatic pulse were selected but to a more limited extent. The respondents to this survey did not select pulsed eddy current at all. As part of the "other" option, a respondent suggested:

- *experiments of accelerated aging on test blocks of armed concrete, post mortem studies at the end of the immersion period of the experimental device (destructive);*

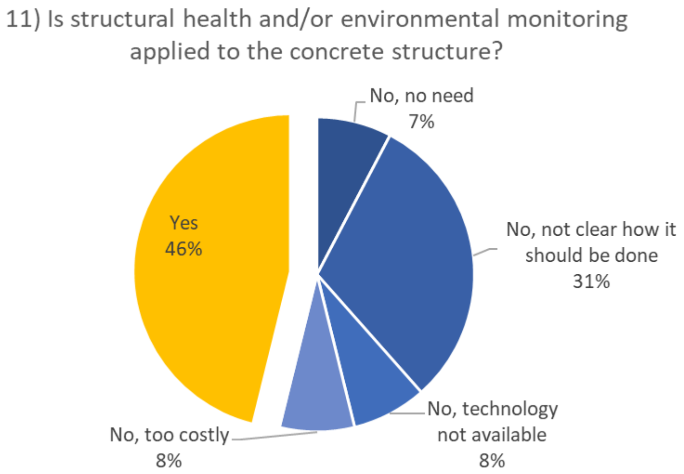

Figure 11

Regarding structural health and/or environmental monitoring (Figure 11), almost half of the respondents (6 out of 13) indicated a positive answer, with more details on the monitoring approach:

- *Resistivity + Humidity and Temperature or Capacity.*
- *Temperature, Chloride content, pH close to the rebar, Sensor network*
- *It is in progress (new research programs) and it should be developed further. Concrete properties: degree of saturation and porosity, chloride content…*

- *Mooring and applied loads monitored in real time. Hydrostatic and hydrodynamic loads assessed via numerical modelling referenced to measured loads.*
- *Was part of the annual Inspection reported to Integrity team*
- *Not built yet = but plan is to have a minimum need for monitoring.*

The other 60% expressed some concerns mainly about the monitoring implementation, but also about technology availability and cost, with the following comments:

- *There is inadequate evidence base an example for this to be more popular. And this is the right time.*

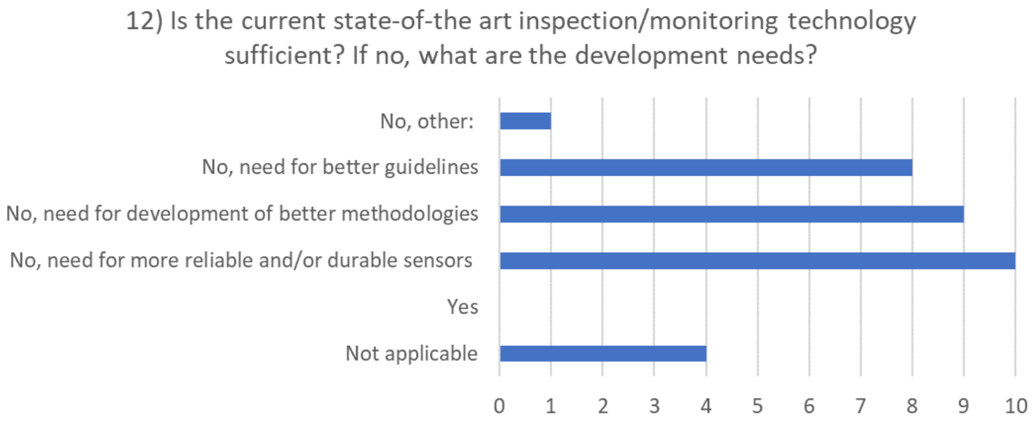

Figure 12

Figure 12 clearly highlights the need for better inspection/monitoring guidelines, methodologies and more reliable/durable sensors; identified by the 17 respondents to this question. As part of the "other" option, respondents suggested:

- *Need for more demonstration and examples*
- *New developments should be validated by different cases, concrete mixes, env. conditions...*

Regarding the use of calibration blocks (Figure 13), a quarter of the 16 respondents use unreinforced or reinforced concrete blocks, a quarter do not use them and half do not think it is applicable to their project.

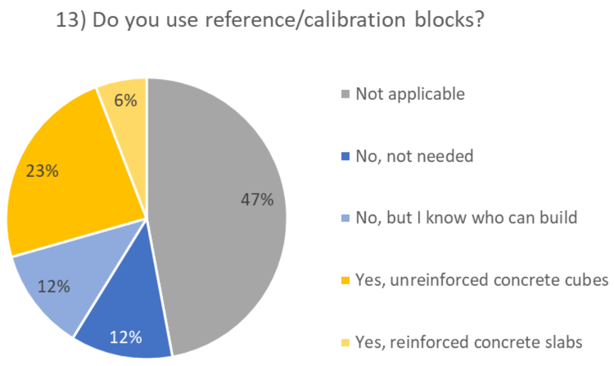

Figure 13

3.5 Rules and standards

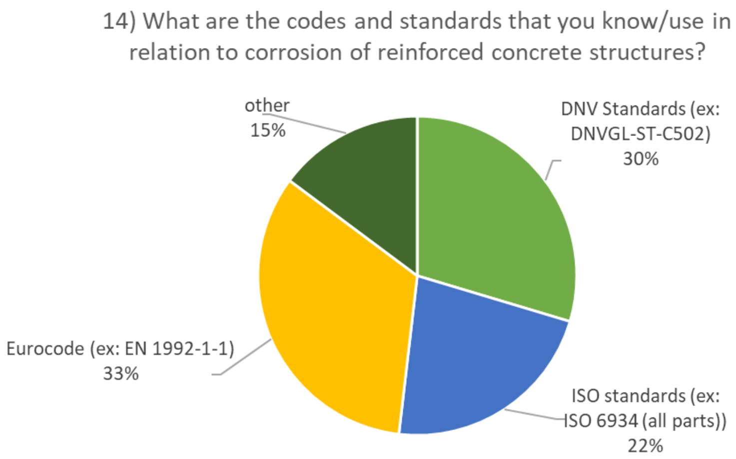

Figure 14

The respondents indicated using mainly Eurocode and DNV standards, followed closely by ISO standards (Figure 14). Other inputs were collected:

- *EN 206-1, Rilem Recommandations.*
- *Norsok; Bureau Veritas*
- *Company documentation*

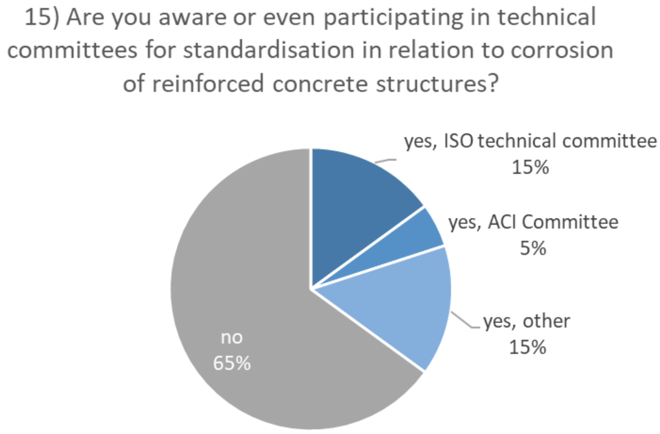

Figure 15

As illustrated in (Figure 15), 6 respondents out of 19 are participating in technical committees such as ISO, ACI or:

- *BS EN1992 (via BSI)*
- *AMPP (NACE)*

- *Eurostruct in EU engages with guidelines and recommendations and can be interesting especially around SHM*

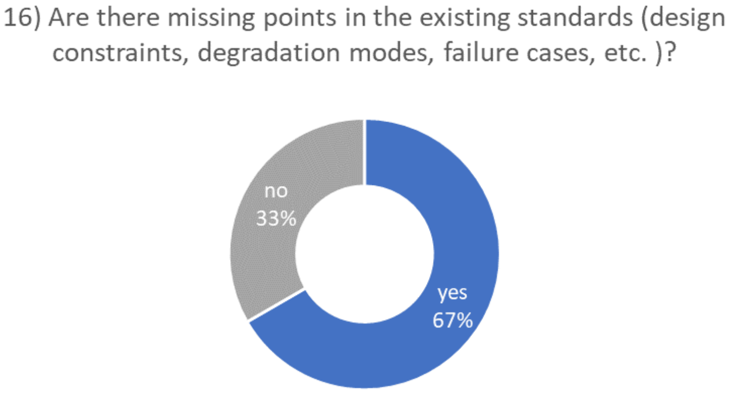

Figure 16

Most of the respondents identified missing points in the existing standards (Figure 16), with the following explanations:

- *SHM - choice, use, implementation and interpretation*
- *The standards do not explicit how to use on site inspections with the data collected.*
- *Degradation modes and failure cases, design constraints*
- *Ultra high cycle fatigue on WECs hard to implement.*
- *Effect of biocolonisation of corrosion processes*
- *Relationship between structural conditions, corrosion potential and current demand are not sufficient specified*
- *Take into account the tension resistance of the concrete. Like it is done in French Regulations for water retaining tanks for example. This is related to the economical point of view.*
- *Flexure in tubular sections where the inside of the tube must be watertight. Watertightness is related to corrosion as corrosion of reinforcement means cracks that means watertightness problem. Regulations consider slabs or walls, that means that the rectangular section is partly in compression and partly in tension. In case of a tube, the wall or the slab is fully in compression or in tension and different regulations must apply.*

Finally, the last question was “17) What recognized publications could be used in order to draw a future technical database for standardisation/best practices?”

- *Tacq, J., Coolegem, G., Schoefs, F., Gonzalez, V., Gonzales, S., Gaillet, L., Chataigner, S., Pakrashi, V., O'Boyle, L., Baeté, C., Wielant, J. and Devaney, T., 2021. Corrosion Monitoring CIG Report.*
- *M, Ghosh B, Schoefs F and Pakrashi V. (2018). Image-based Damage Assessment for Underwater Inspections: A Primer – From Theory to Implementation. Taylor and Francis, ISBN 9781138031869 - CAT# K30666*
- *ULTIR repository: https://ultir.github.io/*

- *Quirk L, Matos J, Murphy J and Pakrashi V. (2018). Visual Inspection and Bridge Management. Journal of Structure and Infrastructure Engineering, 14(3), 320-332. [adaptation of this here could be interesting]*
- *New standard are under construction about cementitious materials with low carbon impact. This new standard will replace the EN 206-1 by adding new binders.*
- *French Water Tank Regulations. Recommandations for Fiber Reinforced Concrete.*

3.6 Publications

(2021) Charles Adrien LOUIS, Simon GAUTHIER (BLévolution), Analyse bibliographique des bilans carbones de l'éolien flottant, www.eos.debatpublic.fr

(2020) Baita, Eugenio & Cordal, David & Filgueira, Almudena & Morato Casademunt, Alexandre & Lamas, M.I. & Alvarez, J. & Carral, Luis & Castro-Santos, Laura. An Economic Analysis of An Innovative Floating Offshore Wind Platform Built with Concrete: The SATH® Platform. Applied Sciences. 10. 3678. 10.3390/app10113678.

(2019) Hans Chr. Sørensen, Kim Nielsen, Erik Friis-Madsen, Bendt Aarup, Jens Peter Kofoed, Christian Munk Jensen, Concrete for Wave Power, EUDP 2018 - 64018-0600

FLOATGEN, floatgen.eu/en/deliverables

LIFES50+, lifes50plus.eu/results/

FLAGSHIP, www.flagshiproject.eu/documentation/

COREWIND, corewind.eu/publications/

4 Chloride propagation and corrosion mechanisms within the concrete material in sea environment

4.1 State-of-the-art

Corrosion of steel reinforcement due to chloride ingress is one of the major causes of degradation of Reinforced Concrete (RC) structures. According to Tuutti diagram in Figure 17 [Tuutti 1982], the corrosion can be divided into two stages: corrosion initiation and corrosion propagation. The corrosion initiation corresponds to the process of chloride ingress into concrete until the chloride concentration has reached the steel rebar and exceeds a threshold value. Then steel is de-passivated and the corrosion propagates into the reinforcement.

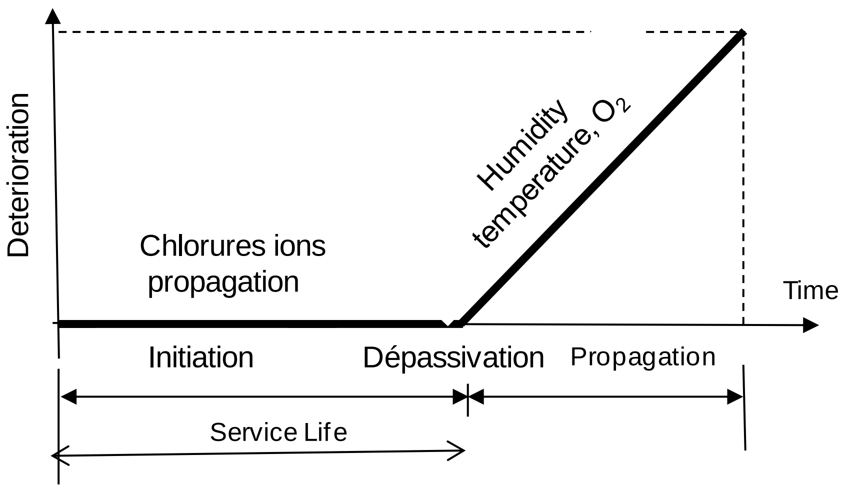

Figure 17: Diagram inspired from Tuutti diagram [Tuutti 1982]

The service life is defined as the period of penetration of chloride into the concrete cover until the chloride content exceeds a threshold value at the position of the reinforced steel bar. Indeed, at the end of that period, maintenance operations are required: most current maintenance operations consist in removing the chloride contaminated concrete and replacing it by a new one [BSEN1504-9 2008], thus inducing additional costs mainly caused by concrete production and offshore operations in the case of Marine Renewable Energy. There is thus a balance to ensure both long service life and minimum costs. In a broader perspective, we can also consider that there should also be a balance for environmental impacts because cement concrete is an important contributor to climate change [WBCSD IEA 2009]. Consequently, it is important to improve service life predictions, but also to determine influent parameters and to evaluate levels of potential risk in order to provide recommendations for longer service life to engineering designers when designing concrete structure exposed to chloride.

Before modelling the transport of seawater in concrete, a thorough identification should be conducted, covering all the phenomena that can occur when this water containing different ionic and organic species is in contact with the embedding concrete.

4.1.1 Physical and chemical Interactions between sea water and concrete

A significant part of this section comes from the following reference: [Touil 2021]

The exposure of concrete to the marine environment influences concrete material through various physical, chemical, mechanical and biological processes, which lead to modification of the concrete microstructure.

Indeed, the attack of cement matrices by seawater combines different types of chemical aggression such as dissolved salts, oxygen, carbon dioxide and sulphates, etc… [Mehta 2006, Cheng 2020]. It is well documented that chloride ion is the largest chemical composition of seawater and it is the main aggressiveness ions that cause concrete deterioration particularly by corrosion in case of reinforcement concrete structure [Mehta 2006]. However, the main physical effect of chloride ions is a reduction in porosity [Al Kailani 2015, Cherif 2020] and transport properties due to the pore filling effect of newly formed calcium chloro-aluminate, or Friedel Salt, when chloride ions react with the aluminate phase [Tang 2015]. Additionally, these changes in microstructure will in turn modify the multispecies diffusivity through cement-based materials [Cherif 2020].

Other ions present in the seawater can influence the chlorides penetration either by changing the chemistry and/or porosity or even by causing scaling [De Weerdt 2015]. In this context, the sulphates ions contributed by magnesium sulphate (MgSO4) react with the cement matrix by the formation of gypsum and additional ettringite [De Weerdt 2015], which produces high volume expansion and lead to cracking [Zhang 2020, Yeon Ting 2021]. So initially, the microstructure is densified with increasing compressive strength, but subsequently the accumulation of expansion products cause strength reduction due to calcium silicate hydrate gel (C-S-H) deprivation [Yeon Ting 2021, Cohen 1991, Li 2020].

Despite its weak concentration in the seawater, the magnesium ion can react with the calcium hydroxide (Ca(OH)2) in concrete, and lowers the alkalinity of pore solution and eventually destabilizes C-S-H gel [Bernard 2017 – Yi 2020]. In a marine environment, concrete is also exposed to carbonation which can originate from carbon dioxide (CO2) present in the sea water or from the air [De Weerdt 2014]. in this case, carbonation of concrete leads to the consumption of portlandite (Ca(OH)2) and transformation of C-S-H to calcite and amorphous silica [Sadati 2016], accompanied by the drop of alkalinity causing local dissolution of material and surface disintegration of concrete [Sadati 2016, Al-Rabiah 1990].

The synergistic effects of ions in seawater have been studied by some researchers [Cheng 2020, Yi 2020]. It has been reported that the level of the deterioration mechanism may worsen with composite ions, resulting in an increase in porosity due to the formation of more micro-cracks in the pore structure, and resulting in the dissolution of the portlandite and decalcification of the C-S-H [Cheng 2020, Yi 2020]. More details on the conceptual illustration of phase changes in concrete induced by seawater are reported by [Jakobsen 2016]. An illustration of the main physical and chemical attacks of the concrete in the marine environment is presented in Figure 18 [Yi 2020].

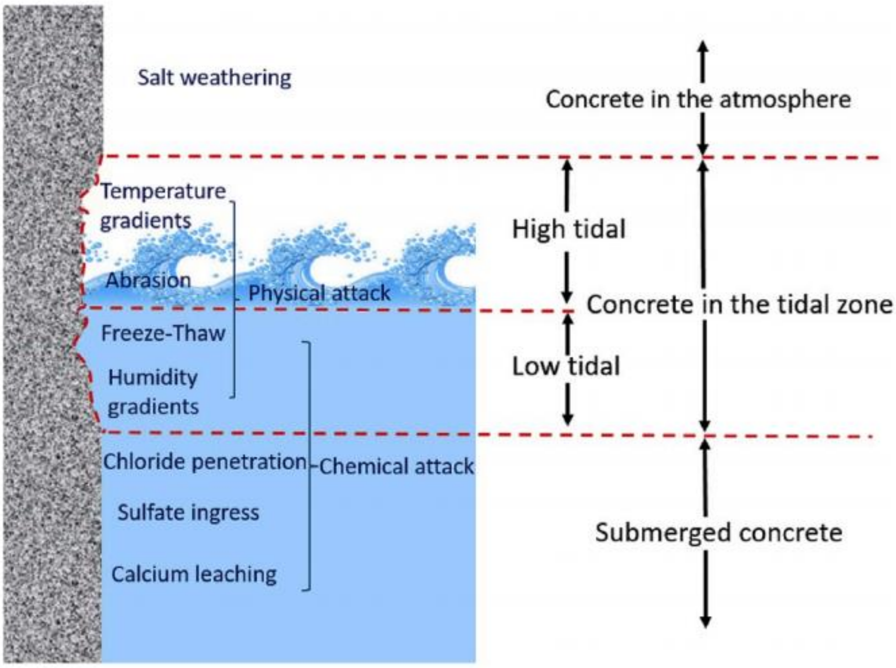

Figure 18: Main physical and chemical attacks of concrete exposed to marine environment [Yi 2020]

Further, depending on the exposure of the concrete structures, the deterioration mechanism severity is conventionally categorised into exposure zones [EN-206 2013] such as atmospheric, tidal and submerged zones (Figure 18). In the case of the atmospheric zone, the structure is exposed to salt weathering [Yi 2020], which the transport within the concrete is affected by other factors such as relative humidity and temperatures [Santhanam 2016]. Hence, such a mechanism leading to wetting and drying cycles results in physical degradation of the structure due to the salt crystallisation [Mehta 2006]. Concrete exposed to the tidal and/or splash zone is usually regarded as being in the worst deterioration condition of all the exposure categories [Yeon Ting 2021, Santhanam 2016]. The mechanical action of waves can lead to physical deterioration such as abrasion, cavitation and erosion with progressive loss of mass, and humidification-drying cycles can lead to salt crystallisation. Also, it's reported that high relative humidity coupled with increased temperatures can accelerate damage due to various deterioration processes and also aggravate ongoing ones [Santhanam 2016]. In addition, physical degradation of the structure due to freeze/thaw cycles can occur but in cold regions [Gjøry 2009, Mehta 2006]. Regarding concrete fully immersed in the sea, there is no effect of physical attack but concrete deterioration is commonly related to chemical deterioration processes such as sulphate attack or leaching and due to chloride-induced corrosion [Mehta 2006, Santhanam 2016].

Furthermore, concrete structures are prone to biodeterioration mainly by marine biological activity such as barnacles, molluscs, and different types of algae [Bjegović 2015, Chlayon 2020]. Thus far, the literature with regard to the effect of marine organisms on concrete is experimentally indicated that porous concrete creates a favourable environment for aquatic organisms. Thus, it is reported that usually microorganisms presence and growth cover the concrete surface by known a biofilm formation [Chlayon 2018]. Biofilm may change surface with condition exposure such as humidity, and temperature. These changes may increase the rate of deterioration, or reduce it [Coombes 2013]. Moreover, it is proposed that algal presence and growth within the matrix under immersed and tidal conditions must weaken the cement matrix with small cavities initiating cracks [Javaherdashti 2009], accelerating material loss and concrete surface degradation [Hughes 2013]. Otherwise, barnacle and oyster crusts that inhabit the concrete surface, have been found to act as natural protective surface coatings (bioprotection) especially for chloride attack and seemed not to cause surface micro-cracking. [Yi 2020, Chlayon 2020].

Considering the complexity of the deterioration mechanism in marine environments, the interdependence and synergy between individual deterioration mechanisms should be taken into account. Obviously, the characterisation of a marine exposure structure for investigative purposes is an important step for durability toward understanding the deterioration of concrete structures exposed to such environments.

4.1.2 Modelling chloride propagation into concrete

A significant part of this section comes from the following references: [Senga-Kiesse 2020] and [Bonnet 2022]

Various approaches were developed to model the chloride ingress through cement based materials. The main difference between models concern the fact that they considered concrete exposed in saturated and/or unsaturated conditions. For saturated conditions, the diffusion process obeying the Fick's second law is generally sufficient to model the chloride ingress [Samson 1999]. Likewise, the time-dependence of the apparent diffusion coefficient is considered as well as the chloride concentration of the exposed surface [Maage 1996, Audenaert 2010] by using empirical laws to establish time dependency functions.

For models accounting for unsaturated conditions, some studies have modeled chloride transport by taking into account both diffusion and convection [Ababneh 2003, Anna 1993, Baroghel-Bouny 2011, Meijers 2005, O'Neill Iqbal 2009, Samson 2005]. These models used semi-empirical laws found by fitting experimental data to get the moisture diffusivity and the chloride diffusion coefficient. These models can be mono-species (only chloride is considered) or multi-species (ions contained in the pore solution are also considered). They are considered as sophisticated models because they take into account some physical or chemical phenomena occurring into concrete such as chemical binding, electrical double layer, activity of pore solution. However, models suitable for unsaturated conditions require many input parameters that are not currently measured for concrete design because they are expensive or time-demanding to collect and they are not required by the standards [EN206-1 2004, EN1992-1-1 2005]. Moreover, reinforced concrete material in marine environment can generally be considered as saturated. Indeed, when casted on site, concrete is initially saturated and persistently exposed to high Relative Humidity (RH) that, for instance, stands superior to 80% on the French Atlantic coast [Othmen 2018].

In the case of maritime structures it is thus obvious to consider the chloride displacement into concrete by a diffusion equation as it was done by some studies to analyze chloride profiles obtained from reinforced concrete structures in unsaturated conditions [Othmen 2018, Chalee 2009, Tadayon 2016, Valipour 2013, Real 2018, Pradelle 2016]. From an engineer point of view, the Fick's second law is simple and the orders of magnitude of diffusion coefficient (or chloride profile), which we can obtain with this law, are correct and acceptable. In addition, numerical implementation of this law is not time consuming in order to conduct statistical investigation.

4.1.2.1 Solution of the Fick's second law

The diffusion of chloride in concrete can be regarded as a diffusion process which some of the chloride ions becomes immobilized as diffusion proceeds: diffusion may take place within the pores of concrete solid material which can absorb (physically or chemically) some of the diffusing substance: the rate of reaction depends on the rate of supply of chloride by diffusion inducing a problem of chemical kinetics. When diffusion is accompanied by physic-chemical absorption, the usual equation for diffusion in one dimension is described by equation 2 which takes into account the bound chloride content by adding a sink term (Crank 1975).

$$\frac{\partial c_f}{\partial t} = -\frac{\partial J}{\partial x} - \frac{\partial c_b}{\partial t} \qquad (2)$$

where J is the flow of chloride ions free to diffuse (kg of free chloride /area of concrete*time unit°, x the space coordinate measured normal to the section.

By introducing the bound chloride concentration per unit of mass concrete and the effective diffusion coefficient, D_{ediff} (m²/s), the equation 2 becomes equation 3.

$$\frac{\partial c_f}{\partial t} = -\frac{\partial J}{\partial x} - \frac{\partial c_b}{\partial t} = D_{ediff}\frac{\partial^2 c_f}{\partial x^2} - \frac{\partial c_b}{\partial t} = D_{ediff}\frac{\partial^2 c_f}{\partial x^2} - \frac{\rho_s}{p}\frac{\partial c_b^{'}}{\partial t} \qquad (3)$$

By introducing the chloride binding capacity $\partial C_b^{'}/\partial C_f$ in equation 3 and an apparent diffusion coefficient D_{adiff} (m²/s) which is a material property, the equation 4 is obtained for describing the conservation of free chloride ions into concrete.

$$\frac{\partial c_f}{\partial t} = \left(\frac{D_{ediff}}{1 + \frac{\partial c_b^{'}}{\partial c_f}\frac{\rho_s}{p}} \right) * \frac{\partial^2 c_f}{\partial x^2} = D_{adiff}\frac{\partial^2 c_f}{\partial x^2} \qquad (4)$$

This equation could be solved with some important hypothesis to get the equation 5:

hypothesis 1: the material is homogeneous and isotropic with an apparent diffusion coefficient non spatial dependant within its thickness, as it is supposed in concrete. Moreover the diffusion coefficient does not depend on the concentration of diffusing substance (dilute solutions). It is the case for chloride content in sea water.

hypothesis 2: the apparent diffusion coefficient and surface chloride content are not time dependant.

hypothesis 3: the media is one dimensional semi-infinite and remains saturated.

hypothesis 4: the concentration of immobilized chloride is directly proportional to the concentration of free chloride with a linear isotherm to get a chloride binding capacity constant ($\partial c_b^{'} / \partial c_f = k$). This allows getting an apparent diffusion coefficient non dependant from free chloride content as obtained with Freundlich or Langmuir isotherms.

This model is resumed in Figure 19:

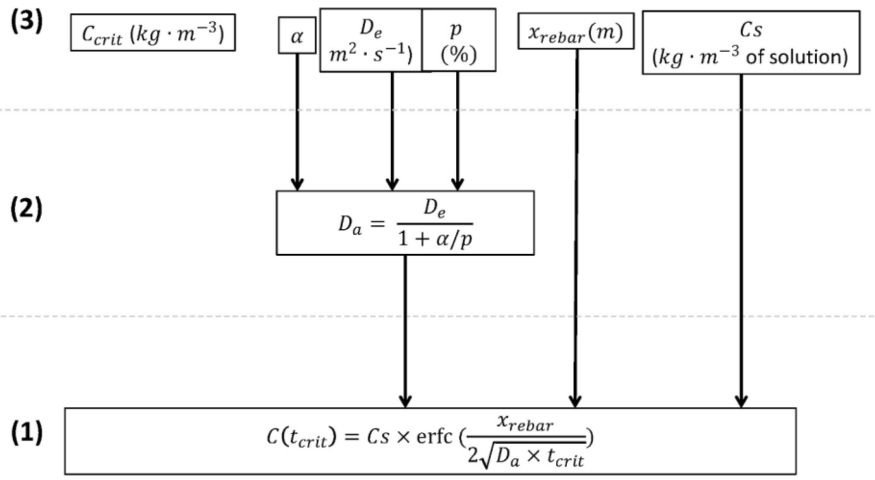

Figure 19: Representation of chloride diffusion model: (1) model output, (2) intermediary model, (3) input parameters [Senga_Kiesse 2021].

4.1.2.2 FIB modelling

References: Fib Model Code (2015 – bulletins 34 and 76)

It takes into account the depth of the water unsaturated zone Δx:

$$C(x,t) = C_0 + \left(C_{s,\Delta x} - C_0\right)\left[1 - \text{erf}\left(\frac{x - \Delta x}{2\sqrt{D_m(t) \cdot t}}\right)\right]$$

with:

C_0 : initial Cl content in the concrete (kg/kg of cement or binder)

Δx : depth of the water unsaturated zone or "convection zone" (m)

$C_{s,\Delta x}$: Cl content at the depth Δx (kg/kg of cement or binder)

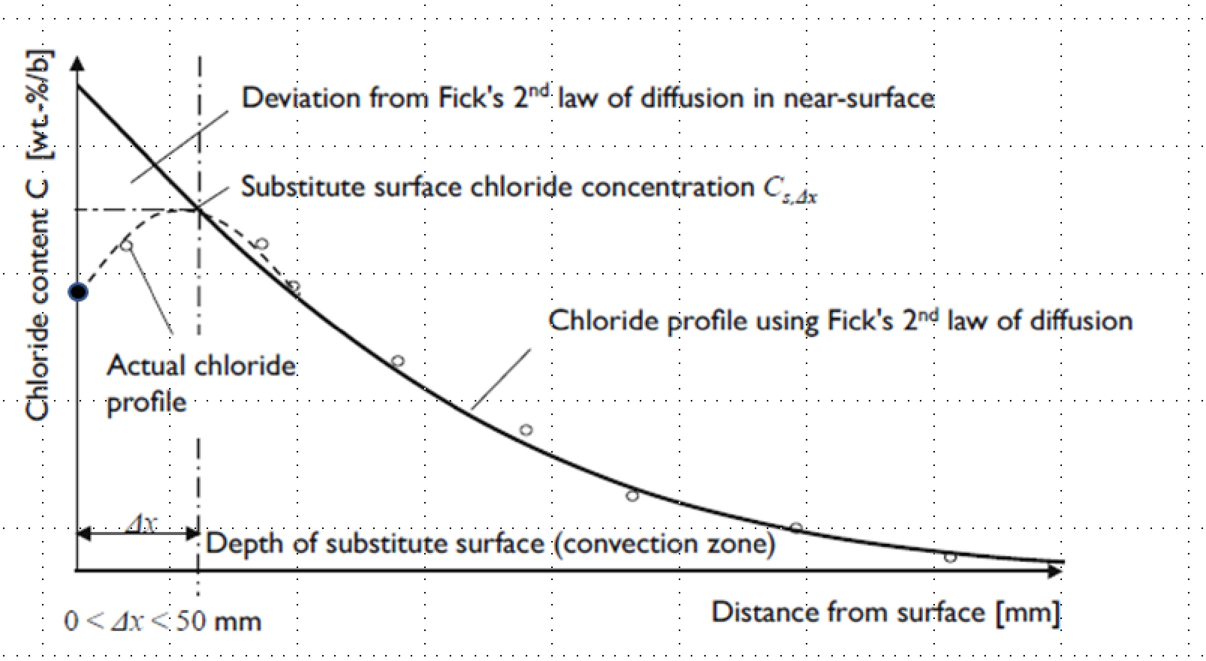

Figure 20: Near-surface deviation of chloride profiles from Fick's law of diffusion in the convection zone

D_{app} depends on time, as expressed below:

$$D_{app}(t) = k_e D_{app}(t_0)\left(\frac{t_0}{t}\right)^{\alpha}$$

$D_{app}(t_0)$: diffusion coefficient measured at t_0 (m^2/s)

t_0 : reference time, 28 days

α : ageing factor (-)

k_e: factor of temperature dependance (-) from Arrhenius law

$$k_e = \exp\left[\frac{E_a}{R}\left(\frac{1}{293} - \frac{1}{T_{real}}\right)\right]$$

T_{real} : Ambient temperature (K)

A value of 4800 K is generally considered for E_a/R

Two approaches are commonly used:

- Approach A: $D_{app}(t_0)$ and α are determined from inverse analysis from measured Cl profiles from existing structure and/or laboratory diffusion tests,

- Approach B: $D_{app}(t_0)$ is determined by a rapid chloride migration test (RCM). However, field data from real structures are needed to determine *α at least for one time t.*

→ Unfortunately, approaches A and B can lead to somewhat different for α!

Values of the ageing factor α and Δx, $C_{s,\Delta x}$ and their statistical distributions are given in the FIB bulletin n° 76 for new reinforced concrete structures.

4.1.3 Steel depassivation

A significant part of this section comes from the following references: [Soive 2021] and [Bonnet 2018]

4.1.3.1 Protective layer composition

Understanding the chemical deterioration mechanisms of the protective layer requires knowledge of its nature and its geometry. An electro-chemical balance between the interstitial solution and the reinforcement is set up, the reinforcement being "protected" by a protective layer and the alkalinity of the pore solution inside the concrete. In fact, this balance is an instable equilibrium since "healthy" steel is not present in natural conditions. Thus, corrosion of steel rebar is a slow process that cause the iron to oxidize and steel to have a protective layer of oxides and hydroxides on its external part. However, this process can be accelerated dramatically leading to protective layer breakdown.

Multiple studies [Sanchez 2007, Poursaee 2010, Ghods 2013] have addressed the nature of the passive layer for a steel immersed in a solution. The simplified Pourbaix diagram [Pourbaix 1963] at 25°C shows that two iron oxides in the passive layer are more stable when iron is in contact with water: hematite and magnetite (α-Fe_2O_3 and Fe_3O_4, respectively). Other iron oxides can be observed, including hydrated oxides such as goethite, lepidocrocite and maghemite (α-FeOOH, FeOOH and Fe_2O_3, respectively) [Poursaee 2010]. These tests were carried out by Raman spectrometer and X-ray diffraction (XRD) [Poursaee 2010] [Ghods 2013]. The different oxides/hydroxides present in the passive layer and observed experimentally are given in Table 3.

Table 3: Passive layer products observed experimentally by different techniques

Oxydes / hydroxides	Références
Magnétite Fe_3O_4, hématite α - Fe_2O_3, Lépidocrocite γ - FeOOH, goethite α - FeOOH	[Pan 2011, Ghods 2013]
Magnétite Fe_3O_4, maghémite γ - Fe_2O_3, hématite α - Fe_2O_3	[Poursaee 2007, 2010]
Magnétite Fe_3O_4, maghémite γ - Fe_2O_3, goethite α - FeOOH	[Sanchez 2007]

From a geometrical point of view, the protective layer is considered as a two-layered structure: an inner layer mainly composed of iron(II) oxides and an external layer mainly composed of iron(III) oxides [Ghods 2011, 2012 Sanchez 2006, 2007, Sanchez-Moreno 2009, Joiret 2002, Gunay 2013] (see Figure 21).

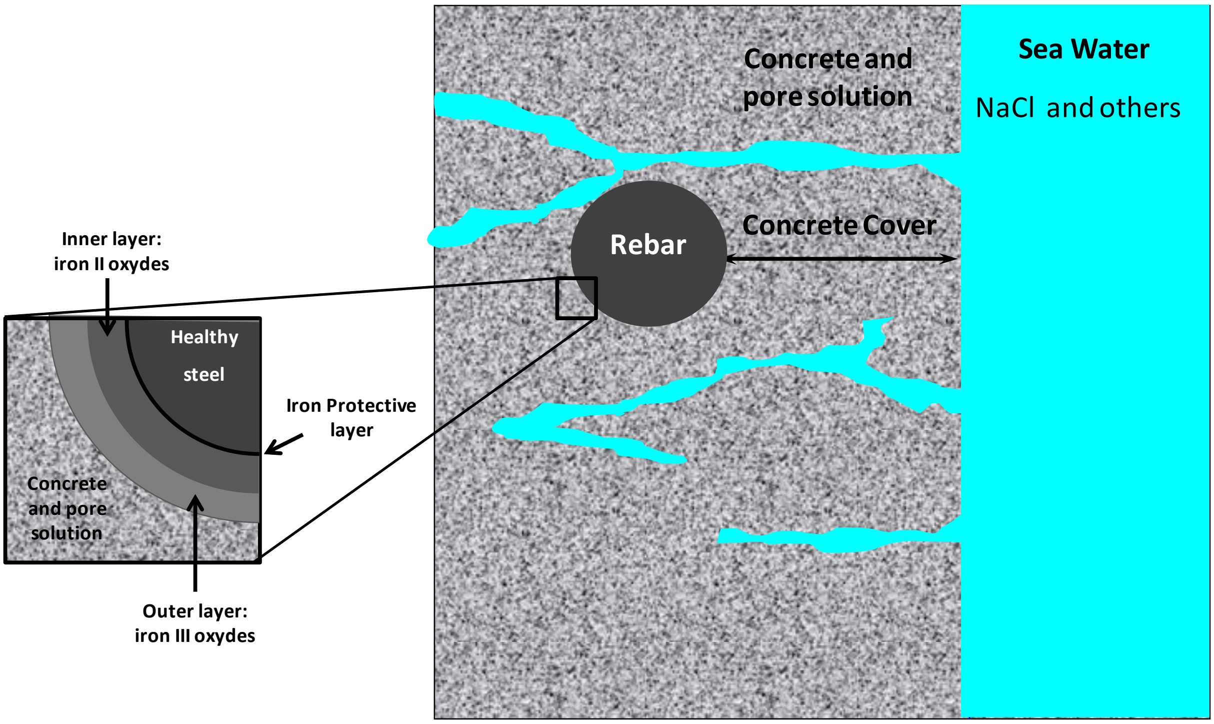

Figure 21: Reinforced concrete exposed to seawater and schematic protective layer on steel reinforcement as a two-layered structure [Soive 2021].

Suda et al [Suda 1993], Noda et al [Noda 1990] and Pan et al [Pan 2011] identify experimentally that the outer layer of the passive layer in contact with the interstitial solution is porous and consists of lepidocrocite and goethite or maghemite. The inner layer in contact with the Fe substrate layer is denser than the outer layer and consists of magnetite and hematite.

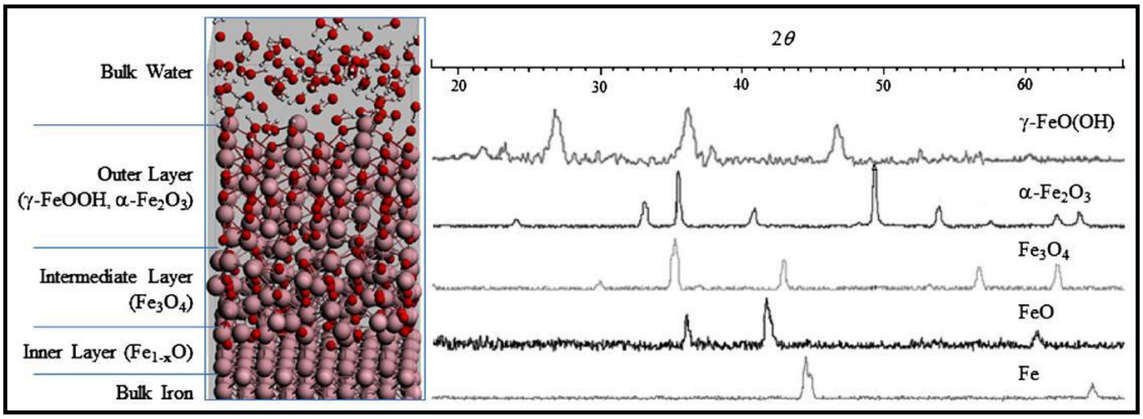

Figure 22: Passive layer components (Pan et al 2011)

In the literature the thicknesses of the protective layer is reported to be about 5 [Ghods 2013] to 10 nm [Zakroczymski 1985, Haupt 1987, Miserque 2006] in an alkaline electrolyte solution.

4.1.3.2 Breakdown of the protective layer

According to the literature, the protective layer breakdown in concrete corresponds to a critical concentration of chloride, this latter term being expressed as" critical chloride threshold" today. Generally, this threshold level at the depth of the reinforcement can be expressed in four ways: the concentration of total chlorides [ASTM C-1152, Andrade 2002], the concentration of free chlorides [Alonso 2000], the ratio [Cl^-] / [OH^-] [Haussmann 1967, Gouda 1970] and the ratio [Cl^-] / [ANC] [Glass 1997]. In the last case, ANC is the neutralization capacity of an acid (or alkalinity).

Angst et al. have listed the most influential parameters on breakdown among which steel-concrete interface, pH value of the pore solution and electrochemical potential of steel can be found. Cao et al. confirm that there is a wide scatter in critical chloride concentration (over 2 orders of magnitude) on a compilation of a significant number of data reported in Chinese publications.

The threshold level also depends on rebar surface conditions [Mammoliti 1996, Li 2001, Pillai 2005], properties of the rebar concrete interface [Ghods 2011] and chemistry of the concrete pore solution [Glass 1997, Veleva 2002, Ghods 2009, Gunay 2015, Alhozaimy 2016]. Furthermore, the expression to be used for these thresholds is the subject of much debate. Ann et al. [Ann 2007] and Glass et al. [Glass 1997] show that the concentration of total chlorides is more relevant than the concentration of free chlorides or than the ratio [Cl^-] / [OH^-]. Hausmann [Hausmann 1967] and Wedding [Wedding 1986] consider that the threshold level when expressed by the ratio [Cl^-] / [OH^-] is constant regardless of the cement composition and concrete mix-design. Gouda [Gouda 1970] proposed the expression [Cl^-]$^{0.83}$ / [OH^-].

However, other studies indicate that the threshold vary depending on the physicochemical parameters close to the protective layer. For example, Li et al. [Li 2001] and Moreno et al. [Moreno 2004] show that the threshold level expressed as the ratio [Cl^-] / [OH^-] increases when the pH increases. Yu et al. show also that corrosion depends on load-induced damage or casting-induced damage [Yu 2015].

In the literature several theories have been proposed to explain the steel protective layer breakdown in an aggressive electrolyte solution. It was first considered, in 1964 by Kolotyrkin, as a physical adsorption mechanism [Kolotyrkin 1963]. Kolotyrkin reasoned that the adsorption of aggressive anions on the external surface of the protective layer increases the transfer of cations Fe2+, Fe3+ to the surrounding electrolyte solution.

Later, Dabosi et al. [Dabosi 1994] corrected this Kolotrin's opinion by measuring only the Fe2+ ions when bare steel is in contact with the electrolyte at a point where the protective layer has fractured. Dabosi et al. further proposed that the protective layer becomes thinner over the time due to gradual dissolution of its constituents until possibly complete dissolution occurs during intense local dissolution. The penetration mechanism proposed by Hoar et al. in 1965 [Hoar 1965] is very different from the theory of Kolotyrkin since they consider only the transport of aggressive agents through the protective layer to reach the "iron/protective layer" interface, a zone in which these agents are most active. The iron is then in direct contact with the aggressive agents. Iron dissolves as iron(II) ions which, themselves react with the hydroxide ions OH^-. The combination of these ions produces iron hydroxide $Fe(OH)_2$, which can then further react with other ions to form other oxides/hydroxides. These products finally precipitate at the "iron/protective layer" interface. As the molar volumes of the substances formed are larger than the original volume, this results into pressure creating stresses in the protective layer that may cause it to crack.

In 1970, Vetter et al. [Vetter 1970] proposed a mechanism fairly similar to the one described previously. Nevertheless, Vetter et al. made the assumption that the protective layer has been previously damaged and already demonstrates micro-cracks. Propagation of aggressive agents through these cracks is then easier. Corrosion products resulting from the reactions of the aggressive agents with the" healthy" iron also lead to mechanical deterioration of the protective layer.

In 1976 Strehblow [Strehblow 1976] did not see these different mechanisms as being as contradicting. Quite the reverse: for Strehblow depassivation is characterized by three main mechanisms: (1) adsorption mechanism (physical and chemical), (2) mechanism involving penetration of aggressive agents through the protective layer, (3) mechanism involving failure of the layer due to formation of corrosion products formation in the iron/protective layer interface. All three of these mechanisms can occur simultaneously during the deterioration process. In addition, the phenomena associated with any of these mechanisms may influence the others.

In the scenarios previously described, only one scenario considers a dissolution of the protective layer by aggressive agents. The other scenarios involve a transport mechanism either through the protective layer or through micro-cracks. For all scenarios, the time to corrosion is then dependent on the steel-concrete interface and in particular the thickness of the protective layer [Kenny 2020] or to the mechanical history of the rebar (e.g. stress during rebar transport or casting, stress during service life of reinforced concrete). In the case of reinforced concrete, except at considering that for each reinforcement bar the protective layer thickness is similar or that micro-cracks always occurs at the same time, the scenarios other than dissolution should lead to a scatter of the critical chloride threshold value for the same cementitious material when exposed to the same environment but with different reinforcing bar. Although this scatter should then also be observed with the same reinforced concrete if the protective layer thickness varies along the reinforcing bar.

Whereas all scenarios except one are dependent on depth or mechanical protective layer history, the concept of a critical chloride threshold suggests that the degradation of the protective layer is only driven by dissolution. Of course, ingress through the protective layer depends on a concentration gradient of the agressive agents but, once again, the time to reach the steel depends on the protective layer geometry (thickness) or mechanical history.

Faced with these different scenarios, there is a need to find out whether thermochemical reactions (dissolution) at the steel/concrete interface are sufficient on their own to explain the degradation phenomenon.

4.1.4 Corrosion propagation

When the ions contained in seawater enter the concrete, the electrochemical equilibrium is disturbed leading to precipitation of Friedel's salt, ettringite or dissolution of portlandite (to cite a few). Upon arrival of chloride ions, the equilibrium of the protective layer is also disturbed. The protective layer begins to deteriorate and reaction products may develop, such as akaganeite Fe(OH)2.7Cl0.3 [Sagoe-Crentsil 1993, Cornell 2003, Asami 2003, Morcillo 2015] and different forms of green rust [Abdelmoula 1996, Refait 1998, Hansen 1989, Abdelmoula 1998].

Models on propagation of corrosion-induced cracks are available in the litterature (Richard, 2016) but are not addressed in details in this report.

4.2 Remaining challenges in the context of offshore renewable energy applications

A significant scientific challenge to be noted is the coupling between the different phenomena: chloride, sulphate and biocolonisation interactions. Another challenge is the early penetration of ions into the cementitious matrix in the case of parts cast in place and brought into contact with seawater at a young age. This phenomenon leads to a competition between hydration and ionic propagation, certainly modifying the nature of the hydrates formed, particularly for low carbon binders with pozolanic reactions (see §9)

4.3 Publications

(2022) Stephanie BONNET, Ines OTHMEN, Mohamad OUEIDAT & Franck SCHOEFS, On the use of free or total chloride profiles to investigate the diagnosis of reinforced concrete structure in marine environment, under review in Marine Structures.

(2021) Anthony Soive, Stéphanie Bonnet, Abdelhafid Khelidj & Véronique Baroghel-Bouny: Thermodynamic difficulties to determine a critical chloride threshold for breakdown of the protective layer of steel reinforcement in a maritime concrete structure, Journal of Sustainable Cement-Based Materials, DOI: 10.1080/21650373.2021.1961325

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5 Corrosion protection current practices in more mature sectors

5.1 State-of-the-art

Corrosion protection methods have been used for decades to effectively control the corrosion activity and stop further deterioration of the reinforcing steel in marine structures (bridges, docks, dams, piers, etc.).

Existing corrosion protection methods include cathodic protection systems, inhibitors, coatings, realcalisation, etc. Selection of the method is made on a case-by-case basis considering factors such as required service life, number of structural components to protect, economic factors, etc.

5.1.1 Cathodic protection

Cathodic protection is a technique that reduces the corrosion of a metal surface by making the surface the cathode of the corrosion cell. The transformation is accomplished by applying controlled amounts of current to the metal, polarizing the metal to a point where the current cannot be discharged from the previously anodic areas (Kessler 2006).

The cathodic protection current can be applied either by:

- a direct connection to an anode having a more negative electrode potential (less noble metal, for instance zinc, aluminium or magnesium) according to galvanic reaction chart, than the protected metal (galvanic cathodic protection, or sacrificial anodes) or,
- by using an external power supply that provides a flow of current from an inert anode to the metal to protect, through the environment (impressed current cathodic protection).

5.1.2 Corrosion inhibitors

A corrosion inhibitor is a chemical compound that, when added to a liquid or gas, decreases the corrosion rate of a material, typically a metal or an alloy, that comes into contact with the fluid.

Main protection mechanisms for inhibiting corrosion involve are the formation of a passivation layer (anodic inhibitors) or the increase of the corrosion potential (cathodic inhibitors) or the formation of a zinc phosphate coating (ELSHAMI 2017). Some inhibitors involve the two mechanisms.

These inhibitors can be used directly on the rebar, added to the mixing water or applied to the surface of the reinforced concrete with the inhibiting solution penetrating the concrete by capillarity as Migrating Corrosion Inhibitors (MCI) (ELSHAMI 2021). Main corrosion inhibitors used in reinforced concrete structures are sodium nitrite calcium nitrite and sodium monofluorophosphate (ELSHAMI 2018). It should be noted, however, that their effectiveness and relevance do not yet have feedback for large offshore structures.

5.1.3 Coatings

Sealers can be applied on top of concrete surface to prevent chloride ingress (Broomfield 2003). Different types of sealers are available (acrylic, silicone, silane, siloxane, (epoxy) resin). The chemistry of the process is that silanes, siloxysilanes and similar chemicals will penetrate the pores of the concrete and react with the water in the pores to from a hydrophobic (water repelling) layer that stops water getting in as a liquid (that may carry salt with it), but allows water vapour in and out of the concrete so that it will 'breath'.

There are anticarbonation coatings which should be applied after carbonation repairs to stop further carbon dioxide ingress. The principle of anticarbonation coatings are that they are porous enough to let water vapour move in and out of the concrete but the pores are too small for the large carbon dioxide molecule to pass through. Anticarbonation coatings are generally high build coatings, with the carbonation resistance increasing with thickness.

5.2 Remaining challenges in the context of offshore renewable energy applications

Corrosion protection of concrete rebar structures in offshore application is rather challenging. First it is difficult to assess the condition of the rebars before corrosion becomes visible. To the authors best knowledge, the number of inspection methods that can be applied under submerged conditions is very limited or existing inspection techniques are difficult to apply and can be dangerous in offshore conditions. Insufficient corrosion protection of the rebars can be detected by potential measurements by divers or ROV. ROV camera images may identify corrosion issues but rather in a late stage when concrete starts spalling. Taking core sample of the concrete to analyze the w/c ratio, material composition and degree of contamination by chlorides can be done in the splash zone but is not feasible or very challenging for the submerged parts.

In case cathodic protection is applied, the current demand of the structure may give a first impression on the condition of the concrete and rebars. However, this analysis becomes challenging when secondary steel structure is electrically continuous with the concrete (foundation structure) and consumes cathodic protection current as well. Numeric modeling may contribute to a better assessment upon condition that the CP current is measured directly on the anodes or via a dedicated coupon.

5.3 Publications

(2021) G. Sergi, G. Seneviratne, D. Simpson, Monitoring results of galvanic anodes in steel reinforced concrete over 20 years, Construction and Building Materials, Volume 269

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6 Biofouling impact on corrosion resistance of reinforced concrete

6.1 State-of-the-art

Biofouling (Marine Growth) is well known to cover every type of materials starting from a biofilm after several weeks to become a macro-fouling after several months. Until now, no antifouling system prevent this effect after 2-3 years. A brief state-of-the art on biofouling is provided below, although the specific effect of biofouling and especially macro-fouling on steel rebar corrosion issues has not been investigated until now.

6.1.1 Biofouling and biodegradation

If two conditions are respected - the fouling leads to an anaerobic area near the surface and there are suspended nutrients in the water- bacterial attacks can occur. This section does not focus on this aspect but it could affect the anchoring systems (lower oxygen in the environment + nutrients on the seabed). More information can be found in (Bastidas et al. 2008).

6.1.2 Biofouling process for its effect on added mass/change in hydrodynamical effect

6.1.2.1 Key factors and feed-back from oil & gas and wind energy

Marine Growth is known more for its effect on added mass and change of hydrodynamical behavior of structures (Ameryoun et al., 2019, Schoefs et al., 2022). Structures hosts usually more than 10 species and some global geometrical parameters allow to compute the loading (thickness, roughness) (Figure 23).

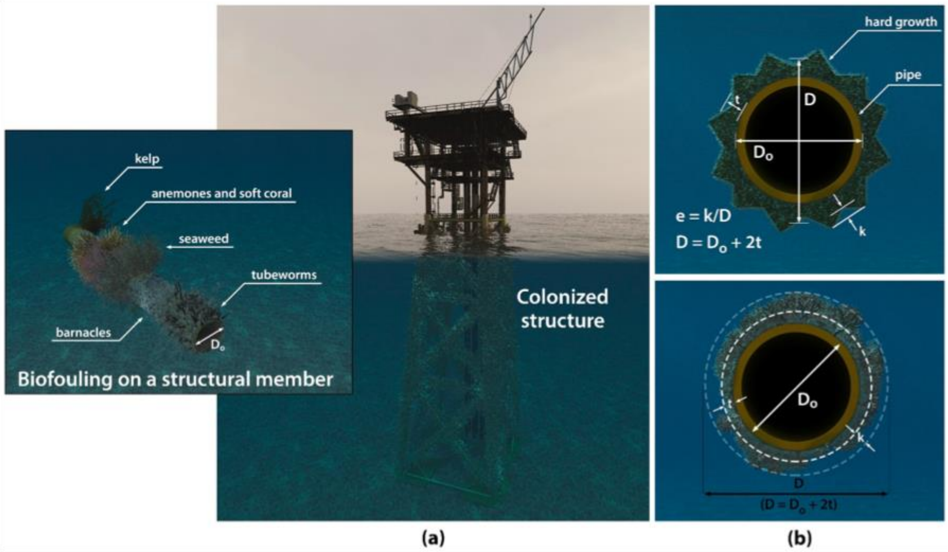


Figure 23: Marine growth on offshore structures (from Schoefs et al. 2021)

The fixation and growth depend on two main factors:

- The surface (shape, roughness, chemical make-up)

- The resistance of the species and their fixation to predators and storms.

Pomerat & Weiss (1946) studied the effect of surface texture and composition on the attachment of sessile marine organisms. Their study showed very early in this field of biofouling that larvae preferred to settle on rough, fibrous or porous surfaces rather than on smooth surfaces. Indeed, roughness creates heterogeneity on a very small scale and therefore offers a great diversity of microhabitats where each of these microhabitats have its particularity and specificity. These results have been found and validated many times after this pioneering study by other authors (e.g. Bortone & Kimmel, 1991; Harlin & Lindbergh, 1977; Harmelin-Vivien et al., 1985; Luckhurst & Luckhurst, 1977; Walters & Wethey, 1996). Following this work, Anderson & Underwood (1994) compared 4 materials (concrete, plywood, aluminum, polyvinyl chloride) that are among the most used to study and to measure biocolonization. Thus, they have shown once again that concrete tends to stand out from other materials concerning biocolonization.

Concrete was experienced to offer a welcoming habitat for species in the case of oil and gas offshore structures (Schoefs and Fianco, 1997) but only few studies report this effect on concrete structures when a lot report it on steel structures, especially Jackets. Coverage by organisms also depends on the organisms themselves. Indeed, Andersson et al. (2009) showed a difference in the communities covering concrete and those covering steel (the species differed, and their proportions too). This study underlined the fact that concrete was colonized more quickly than steel. Finally, some species may have an advantage by multiplying on smooth surfaces, such as barnacles (Semibalanus balanoides). However, their presence induces an increase of the heterogeneity of the habitat and promote the establishment of other species (Chabot & Bourget, 1988). With the expansion of marine renewable energies such as fixed offshore wind farms (OWF), authors have focused on the effect of adding hard substrate in the environment. The two materials mainly composing these fixed OWF being concrete (scour protection) and steel (monopile), studies focused on the biofouling on these two materials. This is particularly the case with the studies of Andersson et al. (2009) and Andersson & Öhman (2010). These studies have highlighted the difference in the communities between concrete and steel structures of different ages but also with respect to different structural complexities.

6.1.2.2 Feedback from artificial reefs

Interesting feedback concerns the colonization of artificial reefs because a lot of them were built in concrete. Recently, Hayek et al. (2021) looked at the impact of the cement and concrete compositions to create artificial reefs. Their study highlighted the importance of the material roughness on the creation of a biofilm and therefore on the installation of biofouling. The authors conclude their study by stating that roughness appears to be the main driver of the installation of biofouling. A review by Strain et al. (2017) established a description of the parameters of an artificial reef mainly done by authors in their studies that influence the most each of the ecological groups. The authors showed that the roughness (texture) of the substrate and the presence of small elevations (pits) or crevices are the main parameters having a beneficial effect on sessile organisms such as corals, algae or oysters.

6.2 Remaining challenges in the context of offshore renewable energy applications

Only few knowledge is transferable from one concrete structure to another and from one site to another but it is known that trends can be captured and modeled and reduce the uncertainty (Schoefs et al., 2022). A lot of work was developed during the recent years for measuring and detecting the marine growth with image processing (low-cost inspection) (O Byrne et al., 2017, 2018a, 2018b). In parallel a number of test sites includes already floaters or anchors that are inspected and that allow to collect information about existing species and install samples. Among them UN@SEA (Schoefs et al., 2021) is fully devoted to marine growth.

Effect of biofouling and especially macro-fouling on corrosion issues has not been investigated until now. By focusing only on steel rebar corrosion issue, two effects should be investigated: the mechanical degradation or protection of concrete surface (depending on the species barnacles/ mussels) and the effect on surface chloride content and thermal transferts that changes transfer mechanism (diffusion / convection).

We thus suggest to install coupons on several sites with the most probable composition of concrete that will be used for the anchor and for the floater of future offshore renewables projects and to study:

– The colonization processes
– Its effect on the concrete abrasion at the surface
– Its main characteristics for engineering (mass, roughness, thickness)
– Its effect on chloride diffusion, and therefore its impact on corrosion resistance of concrete structures

The main drawback is that this process cannot be accelerated. That is why, in parallel, models should integrate this factor and predict the effect on the whole life time and artificial reefs or other offshore installation in concrete should be inspected especially oil & gas barges, bottom fixed offshore platforms, wharves and artificial reefs.

6.3 Related projects

Name	Funding	Comment	CIG Member involved
I2FLOW	Regional WEAMEC (Pays de la Loire, France)	Improve the environmental Integration of Floating Offshore Wind Turbines 2020-2023	Nantes Université MAREAL
SIMAR	Regional, Pays de la Loire	Test new on site sensors for analysing the effect of marine growth on chloride penetration	Capacités SAS Nantes Université Charier

6.4 Publications

Anderson, M. J., & Underwood, A. J. (1994). Effects of substratum on the recruitment and development of an intertidal estuarine fouling assemblage. Journal of Experimental Marine Biology and Ecology, 184(2), 217- 236. https://doi.org/10.1016/0022-0981(94)90006-X

Andersson, M. H., Berggren, M., Wilhelmsson, D., & Öhman, M. C. (2009). Epibenthic colonization of concrete and steel pilings in a cold-temperate embayment : A field experiment. Helgoland Marine Research, 63(3), 249- 260. https://doi.org/10.1007/s10152-009-0156-9
Andersson, M. H., & Öhman, M. C. (2010). Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea. Marine and Freshwater Research, 61(6), 642. https://doi.org/10.1071/MF09117
Ameryoun, H.; Schoefs, F.; Barillé, L.; Thomas, Y. (2019). Stochastic Modeling of Forces on Jacket-Type Offshore Structures Colo-nized by Marine Growth. J. Mar. Sci. Eng. 7, 158. https://doi.org/10.3390/jmse7050158.
Bastidas-Arteaga, E., Sánchez-Silva, M., Chateauneuf, A., Ribas Silva, M. (2008). Coupled reliability model of biodeterioration, chloride ingress and cracking for reinforced concrete structures, Structural Safety, Volume 30, Issue 2, Pages 110-129, ISSN 0167-4730, https://doi.org/10.1016/j.strusafe.2006.09.001.
Bortone, S. A., & Kimmel, J. J. (1991). Environmental Assessment and Monitoring of Artificial Habitats. In Artificial Habitats for Marine and Freshwater Fisheries (p. 177- 236). Elsevier. https://doi.org/10.1016/B978-0-08-057117-1.50012-3
Chabot, R., & Bourget, E. (1988). Influence of substratum heterogeneity and settled barnacle density on the settlement of cypris larvae. Marine Biology, 97(1), 45- 56. https://doi.org/10.1007/BF00391244
Harlin, M. M., & Lindbergh, J. M. (1977). Selection of substrata by seaweeds : Optimal surface relief. Marine Biology, 40, 33- 40.
Harmelin-Vivien, M. L., Harmelin, J.-G., Chauvet, C., Duval, C., Galzin, R., Lejeune, P., Barnabé, G., Blanc, F., Chevalier, R., Duclerc, J., & Lasserre, G. (1985). Évaluation visuelle des peuplements et populations de poissons : Méthodes et problèmes. Rev. Ecol. (Terre Vie), 40, 467- 538.
Hayek, M., Salgues, M., Souche, J.-C., Cunge, E., Giraudel, C., & Paireau, O. (2021). Influence of the Intrinsic Characteristics of Cementitious Materials on Biofouling in the Marine Environment. Sustainability, 13(5), 2625. https://doi.org/10.3390/su13052625
Luckhurst, B. E., & Luckhurst, K. (1977). Recruitment patterns of coral reef fishes on the fringing reef of Curaçao, Netherlands Antilles. Canadian Journal of Zoology, 55(4), 681- 689. https://doi.org/10.1139/z77-089
O'Byrne, M., Schoefs, F., Pakrashi, V., Ghosh, B. (2017) An underwater lighting and turbidity image repository for analysing the performance of image-based non-destructive techniques. Struct. Infrastruct. Eng. 2017, 14, 104–123. https://doi.org/10.1080/15732479.2017.1330890.
O'Byrne, M., Pakrashi, V., Schoefs, F., Ghosh, B. (2018a) A Stereo-Matching Technique for Recovering 3D Information from Underwater Inspection Imagery. Comput. Civ. Infrastruct. Eng. 33, 193–208. https://doi.org/10.1111/mice.12307.
O'Byrne, M., Pakrashi, V., Schoefs, F., Ghosh, B. (2018b) Semantic Segmentation of Underwater Imagery Using Deep Networks Trained on Synthetic Imagery. J. Mar. Sci. Eng, 6, 93.
Pomerat, C. M., & Weiss, C. M. (1946). The Influence Of Texture And Composition Of Surface On The Attachment Of Sedentary Marine Organisms. The Biological Bulletin, 91(1), 57- 65. https://doi.org/10.2307/1538033
and Mauro, F. (1997). Influence des bio-salissures marines sur le comportement mécanique des plates-formes pétrolières en béton. Internal report in french. European project SOCRATES.

Schoefs, F., O'Byrne, M., Pakrashi, V., Ghosh, B., Oumouni, M., Soulard, T., Reynaud, M. (2021). Fractal Dimension as an Effective Feature for Characterizing Hard Marine Growth Roughness from Underwater Image Processing in Controlled and Uncontrolled Image Environments. J. Mar. Sci. Eng. 2021, 9, 1344. https://doi.org/10.3390/jmse9121344

Schoefs F., Tran B. (2022). Reliability updating of offshore structures subjected to marine growth, Energies, section: B2: Wind, Wave and Tidal Energy, Special Issue: Reliability of Marine Energy Converters.

Strain, E. M. A., Olabarria, C., Mayer-Pinto, M., Cumbo, V., Morris, R. L., Bugnot, A. B., Dafforn, K. A., Heery, E., Firth, L. B., Brooks, P. R., & Bishop, M. J. (2017). Eco-engineering urban infrastructure for marine and coastal biodiversity : Which interventions have the greatest ecological benefit? Journal of Applied Ecology, 55(1), 426‑ 441. https://doi.org/10.1111/1365-2664.12961

Walters, L., & Wethey, D. (1996). Settlement and early post-settlement survival of sessile marine invertebrates on topographically complex surfaces:the importance of refuge dimensions and adult morphology. Marine Ecology Progress Series, 137, 161‑ 171. https://doi.org/10.3354/meps137161

7 Inspection and monitoring methods (in particular Non-Destructive and Structural Health Monitoring)

7.1 State-of-the-art

Corrosion of steel reinforcements is the main cause of damage and early failure of reinforced concrete structures in civil engineering, leading to enormous costs for inspection, maintenance, restoration and replacement of the infrastructure worldwide. Preventive maintenance of RC structures subjected to chloride ingress focuses, among others, on diminishing corrosion initiation risks. Measuring the evolution in time of chloride content is useful for predicting, assessing, maintaining, and controlling lifetime, reliability, health and durability of RC structures. This information can be used, among others, to improve the understanding and modelling of the chloride ingress process, to determine a reliable chloride threshold for corrosion initiation, to characterize the uncertainties involved in the deterioration process, and to update deterioration models (Torres-Luque et al., 2014).

The measurement of chloride content at the concrete cover can be used to estimate the risk of corrosion initiation, and therefore, to optimize inspection and repair costs. There are many lab techniques and field measurements for measuring chloride content in RC. The most popular techniques are potentiometric and Volhard methods. They measure free and total chlorides in concrete cores extracted from in service structures. However, these techniques are mostly semi-destructive, time-consuming and costly.

Conventional methods for detecting corrosion are based on electrochemical techniques such as half-cell potential and linear polarization. IFSTTAR and CEREMA detail the methodology for a corrosion diagnostic of reinforced concrete. The methodology is presented in the open-source website https://www.ifsttar.fr/collections/CahiersInteractifs/CII1/index.html in the specific sheet D1-1 and the associated flowchart. Destructive and non-destructive testing methods are included in the document. The destructive, conventional methods can be affected by a number of factors and require direct contact with the concrete. To overcome difficulties with conventional inspection techniques non-destructive methods have been introduced (Arndt, 2009).

Below is a list of relevant and less relevant Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) techniques. The techniques are not necessarily monitoring techniques and their functioning underwater is not tested or completely known. The techniques mentioned below are based on the experience/knowledge gained by ENGIE Laborelec on several projects related to chemical degradation, quality assurance/quality control, material characterization and ageing and do not necessarily constitute the list of NDTs/SHM techniques for corrosion in reinforced concrete structures.. In addition, from Nantes University and Capacités' experiences, in following sections some techniques for chloride monitoring are described and analyzed from a practical and scientific point of view. The techniques below frame a general framework for the CIG working group.

From a preventive maintenance point of view, it is also important to develop NDT and SHM techniques for a quantitative evaluation of concrete properties and concrete conditions. Moreover, a better concrete cover characterization can help to predict chloride ingress. The results of 10-year research projects are synthetized in the book [Balayssac & Garnier 2017], giving recommendations by survey methodological guidelines [Balayssac 2018]. The principle of complementary NDT methods, the testing methods and material, the analysis of representative results are given for Ultrasonic Methods [Payan 2018], Electrical Methods [Lataste 2018], Electromagnetic Methods [Dérobert 2018]. It also underlines the need to master the measurement quality, to evaluate the uncertainties [Chaix 2018], to establish conversion models and calibration on the studied structure materials [Breysse 2018] and combination processes [Sbartaï 2018] for a pertinent evaluation of concrete indicators. The methodology is finally illustrated by cases studies on a roadway bridge [Villain 2018, 2018b] and also on a beam situated in the tidal zone in the harbor of Nantes-Saint-Nazaire [Villain 2012].

Concerning the SHM of concrete durability indicators and state conditions (in terms of water content or chloride contents) several embedded sensors have recently been developed [Torres-Luque 2017, Niederleithinger 2015, Samson 2018, Badr 2018]. New developments are in progress, for example, in the research projects ANR-SCaNING [Villain 2021] and ANR-DEMCOM [Bonnet 2022], the last being devoted to RC structures in marine environment. Meanwhile, embedded sensors for cover concrete evaluation and rebar corrosion monitoring are tested for validation in large RC concrete slabs (90x70x15 cm) submitted to salted water imbibition and outside atmospheric exposure [Boureau 2016, Bouteiller 2021]. In the future, it should be completed by the qualification of very recent interesting sensors and devices in marine environment and tidal simulation pools for several concrete mixes and types of reinforcements.

Below the techniques are divided in two categories. The first category concerns the indirect corrosion NDT and SHM techniques and the second category the direct corrosion inspection NDT and SHM techniques. The indirect techniques are related to the detection and monitoring of concrete degradation due to corrosion and not directly to the corrosion process itself. On the other hand, the direct techniques directly measure the corrosion likelihood, the corrosion rate and are directly linked with the chemical process.

7.1.1 Indirect NDT and SHM techniques for corrosion detection

7.1.1.1 Acoustic Emission

- Suitable for Alkali-silica reaction (ASR) detection, detection and follow-up of (minor) crack incidences, localization of the sources, identification of the severity of the phenomena. Also suitable for the detection of carbonation induced corrosion leading to cracking and spalling of the concrete cover (Van Steen, 2018)
- Novel technique based on passive monitoring rather than interval testing
- Advantage: relatively easy installation and operation
- Drawback: the interpretation can be complicated, real scale application can be cumbersome

References:

- *(2010) Recommendation of RILEM TC 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete. Mater Struct 43, 1177–1181*
- *(2010) Recommendation of RILEM TC 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete. Mater Struct 43, 1183–1186*

- *(2010) Recommendation of RILEM TC 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete. Mater Struct 43, 1187–1189*
- *(2018) Charlotte Van Steen, et al. On-site inspection of a reinforced concrete structure deteriorated due to corrosion by means of acoustic emission and other techniques.*

7.1.1.2 Infrared Thermography

- Suitable for the detection of ASR in concrete, .
- According to literature, a promising technique for corrosion detection is time-resolved thermography with induction heating combined with 3-D microwave imaging (Arndt, 2009).
- Advantage: Visual representation of the concrete structure, remote application, full-field view
- Drawback: Limited to the surface or a few mm below the surface, in some cases external excitation is needed

7.1.1.3 Microwave method

- Has been used for the detection of chemical degradation in concrete (ASR). The technique can identify differences in dielectric properties .

References:

- *(2013) K.M. Donnell, R. Zoughi, K.E. Kurtis, Demonstration of microwave method for detection of alkali–silica reaction (ASR) gel in cement-based materials, Cement and Concrete Research, Volume 44, Pages 1-7*
- *(2009) Arndt, Ralf & Jalinoos, Frank.. NDE for corrosion detection in reinforced concrete structures - a benchmark approach.*

7.1.1.4 Ultrasonic Pulse Velocity

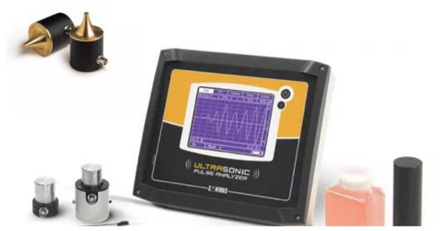
- Suitable for material properties testing (identification of Young's modulus E and poisson ratio v)
- Useful for quality control and quality assurance
- Suitable for crack detection and localization
- Indirectly linked to concrete compressive strength

References:

- *(2019) EN 13791 Assessment of in-situ compressive strength in structures and precast concrete components*
- *(2019) Recommendation of RILEM TC249-ISC on non destructive in situ strength assessment of concrete. Materials and Structures, Springer Verlag, 52 (4)*

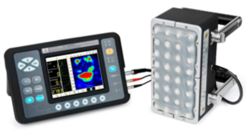
- Examples of UPV devices provided by ENGIE Laborelec:

TYPE: UPV system	NAME: A1410 PULSAR	SUPPLIER: ACS
APPLICABLE FOR	**PICTURES**	**ADVANTAGES**
• Quality assessment of concrete • Comparisons of corroded/non corroded areas • Point measurements following a grid		+ No need for couplant + Point contact rather than surface contact + Springs compensate concrete roughness + Compliant with EN 12504-4, BS 1881, ASTM C597, IS516 + Compact, ergonomic, handheld
ENVIRONMENT		**DOWNSIDES**
• Temp: -10° to +50° • Waterproof ?		- Based on transmission rather than reflection - Indirect transmission impairing accurate localization - Both emitter and receiver should be inside the pipe - Reading of values is done at the receiver inside the pipe - Characterization is not possible
TECHNICAL SPECIFICATIONS	**SENSITIVITY** (Theoretical Illustration)	**SCANNING GRID** (100% coverage)
• 2x7 Undamped Dry Point Contact Transducers • Operating frequency: 50 kHz • Emitter-Receiver Distance: 50 – 2500 mm • Velocity range:1000-15000 m/s • Dimensions: 230 x 125 x 65 mm • Weight: 420 gr	• The detection of corossion using UPV is based on the comparison of pulse velocity values between a corroded and a non-corroded area. • A difference higher than 150 m/s (assuming inherent variation of the order of 50 m/s) could be a sign of corrosion. The extent of corrosion is, however, difficult to be quantified. • Velocity resolution of the device: 10 m/s	• Minimum emitter-receiver distance : 50 mm (center to center) • For each emitter position the receiver should be placed at 100 mm/200 mm and 300 mm away from the emitter for acquiring a good average pulse velocity. • Minimum displacement of the emitter: 25 mm (50 % overlap) → too small • Representative values can be achieved if the emitter follows a 300 mm x 300 mm grid → fast and pragmatic approach
CONCLUSIONS	• **Suitable for detection (no quantification) using a pragmatic measuring approach**	

TYPE: UPV system	NAME: PULSONIC Pulse Analyzer	SUPPLIER: CONTROLS
APPLICABLE FOR	**PICTURES**	**ADVANTAGES**
• Quality assessment of concrete • Comparisons of corroded/non corroded areas • Point measurements following a grid		+ Advanced signal processing (transit time, wave shape, FFT) + Transmitter pulse 2500 V + Compliant with EN 12504-4, ASTM C597 + Exponential profile sensors, low frequency and higher frequency sensors can be attached
ENVIRONMENT		**DOWNSIDES**
• Temp: ? • Waterproof ?		- Based on transmission rather than reflection - Indirect transmission impairing accurate localization - Both emitter and receiver should be inside the pipe - Reading of values is done at the receiver inside the pipe - Characterization is not possible
TECHNICAL SPECIFICATIONS	**SENSITIVITY** (Theoretical Illustration)	**SCANNING GRID** (100% coverage)
• 2 Transducers (Emitter & Receiver) • Operating frequency: 50 kHz & 24 kHz & 150 kHz • Emitter-Receiver Distance: up to 3 m • 2 MHz sampling rate, 7 preamplifier gains • Selectable pulse rate: 1,2 5 per second • Dimensions: 264 x 233 x 83 mm • Weight: 2.6 kg	• The detection of corossion using UPV is based on the comparison of pulse velocity values between a corroded and a non-corroded area. • A difference higher than 150 m/s (assuming inherent variation of the order of 50 m/s) could be a sign of corrosion. The extent of corrosion is, however, difficult to be quantified. • Time resolution: 0.1 µs	• Minimum emitter-receiver distance : 50 mm (center to center) • For each emitter position the receiver should be placed at 100 mm/200 mm and 300 mm away from the emitter for acquiring a good average pulse velocity. • Minimum displacement of the emitter: 25 mm (50 % overlap) → too small • Representative values can be achieved if the emitter follows a 300 mm x 300 mm grid → fast and pragmatic approach
CONCLUSIONS	• **Suitable for detection (no quantification) using a pragmatic measuring approach**	

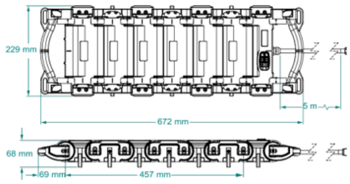
7.1.1.5 Ultrasonic Tomography

- Suitable for the detection and visualization of voids and delaminations
- Suitable for rebar detection and localization
- Advantage: visualization of the internal structure based on ultrasonic waves
- Examples of Ultrasonic Tomography Devices provided by ENGIE Laborelec

TYPE: UT system	NAME: A1020 MIRA Lite	SUPPLIER: ACS
APPLICABLE FOR	**PICTURES**	**ADVANTAGES**
• Quality assessment of concrete • 2D and 3D Visualization of concrete • Array measurements covering larger areas		+ No need for couplant + Point contact rather than surface contact + Springs compensate concrete roughness + Compact, ergonomic, handheld + Based on reflection thus allowing localization and characterization
ENVIRONMENT		**DOWNSIDES**
• Temp: -10° to +50° • Waterproof ?		- Both antenna and display screen should be inside the pipe - Triggering is done from the antenna or the display screen - 30 kg pressure is needed to ensure good contact with concrete - The resolution is low (of the order of the concrete wall thickness) - Time consuming (point by point measurement)
TECHNICAL SPECIFICATIONS	**SENSITIVITY** (Theoretical Illustration)	**SCANNING GRID** (100% coverage)
• Matrix antenna array : 4 x 8 DPC transducers • Operating frequency: 50 kHz • Transversal waves • Penetration depth up to 1 m • Dimensions: 220 x 110 x 90 mm • Weight: 5 kg	• The detection of corossion using UT is based on reflected images • It is expected that a corroded area will give different reflections (stronger/weaker) with respect to a non corroded one. • It is however difficult to identify small differences • Minimum detectable would be a sphere of 40 mm at depths higher than 25 mm	• 100x100 mm measuring grid is needed for good coverage
CONCLUSIONS	• **Suitable for larger areas**	

7.1.1.6 Pulsed Eddy Current

- Suitable for the detection of corrosion under insulation, corrosion of steel elements embedded in concrete (https://www.eddyfi.com/fr/industrie/extracotiere-et-sousmarine)
- Example of Pulsed Eddy Current Device provided by ENGIE Laborelec

TYPE: PEC system	NAME: Lyft 2.2 - PECA 6CH-MED	SUPPLIER: Eddyfi
APPLICABLE FOR	**PICTURES**	**ADVANTAGES**
• Non-contact assessment of WT ferromagnetic steel • Scanning of pipes	 PEC 6CH-MED probe (Array) 	+ Moderate sensitivity for small defects/moderate resolution + Encoder can be fitted to perform line scans
ENVIRONMENT		**DOWNSIDES**
• Temp: 0-40°		- Waterproof? - Applicable for scanning inside? (possibility to bend more than 180°?) - Min thickness range = 3mm
TECHNICAL SPECIFICATIONS	**SENSITIVITY** (Theoretical Illustration)	**SCANNING GRID** (100% coverage)
• 6 channels • Footprint (at zero Lo): 46mm • Wallthickness range: 3-25mm • Lift off range: 0-102 mm • Cable length till 100m • Weight probe: approx. 2kg	• Detectability threshold of a PEC system – minimum loss of 15% volume underneath the footprint area • SCCP configuration defect detection ○ 50mm dia. → min WT loss of 1mm ○ 25mm dia. → not detectable	• 457mm of coverage
CONCLUSIONS	• **Suitable for scanning large curved areas, with medium resolution (screening for suspectable areas)**	

ENGIE Laborelec participates in an EU Horizon 2020 project on corrosion assessment of embedded liners in concrete: https://aces-h2020.eu/

7.1.1.7 Ground Penetrating Radar

- Suitable for rebar detection and localization [Dérobert 2018].. A recent paper discusses the use of GPR for corrosion assessment (Tesic, 2021).

Reference:

- *(2021) Tesic, Ksenija & Baricevic, Ana & Serdar, Marijana. Non-Destructive Corrosion Inspection of Reinforced Concrete Using Ground-Penetrating Radar: A Review. Materials. 14. 975. 10.3390/ma14040975.*

Useful links:

- https://georeva.eu/en/produit/c-thrue-gpr/https://georeva.eu/en/produit/c-thrue-gpr/
- https://www.screeningeagle.com/en/products/category/concrete/ground-penetrating-radars-gprhttps://www.screeningeagle.com/en/products/category/concrete/ground-penetrating-radars-gpr

7.1.1.8 Non-linear acoustics

Reference:

- *(2020) Eiras, Jesús & Payan, Cédric & Rakotonarivo, Sandrine & Garnier, Vincent. Damage detection and localization from linear and nonlinear global vibration features in concrete slabs subjected to localized thermal damage. Structural Health Monitoring. 20.*

7.1.1.9 Modal analysis

Reference:

- *(2018) Eiras, Jesús & Payan, Cédric & Rakotonarivo, Sandrine & Garnier, Vincent. Experimental modal analysis and finite element model updating for structural health monitoring of reinforced concrete radioactive waste packages. Construction and Building Materials*

7.1.1.10 Hyperspectral Imaging

- Visual, full-field, remote monitoring technique
- Provides info on the chemical footprint of the investigated elements
- Would be useful to be evaluated for concrete corrosion

7.1.1.11 Fiber optics sensors (FOS)

The monitoring of concrete corrosion by optical fibers has been the subject of research since the 1990's. The monitoring methods developed can be classified in several categories among which:

- the measurement of environmental parameters related to corrosion such as moisture, temperature, or chloride rate (Mendoza 1995, Fuhr 1996);
- the measurement of corrosion products such as rust (Luo 2018) or the reduction measurement of a fiber metal coating (Leung 2008);
- the measurement of reinforcement deformation to estimate the change in volume of the reinforcement due to corrosion (Zheng 2008).

In the past 15 years, fiber optic sensors (FOS) have been developed for free chloride content assessment. This method involves detecting the refractive index shift due to the chloride presence that changes the light behavior that increases for larger chloride content. To make the measurement the incident light can be ultraviolet or laser (James 2003, Li 2004).

Monitoring the change of the color of the steel surface is a way to deduce the corrosion of rebars. Double optical fiber technology is used to detect rust in the end of a fiber through different reagents. Spectral analysis is used to detect the change of the reflected spectrum signals in the corrosion and non-corrosive cases, so as to infer whether the steel bar is corroded (Luo 2018).

A way to deduce corrosion rate from strain measurement is to fix a fiber bragg grating on the surface of round steel. Due to steel corrosion, the diameter of the rebar increases. The tensile strain of fiber grating changes, so as the wavelength of fiber grating shift. The reinforced corrosion degree can be deduced from the wavelength shift measurement (Zheng 2008) .

FOS presents several advantages over other methods: it is energy saving, very sensitive to small chloride concentrations, and measures are not affected by electromagnetic fields. In addition, because of its geometry (large and thin) and its interaction capacity with the surrounding, the distribution of sensors is more convenient for large structural applications. This means, that since each segment of the fiber can act as a sensor, little perturbations anywhere in the structure can be detected (Torres-Luque, 2014).

However, FOS have some drawbacks that are important for a reliable and accurate measurement. For instance, optical fiber needs adequate protection to prevent its break during casting or service life. This protection must allow light transmission without obstructing or bending the optical fiber because the data can be missed. Furthermore, FOS needs additional protection to isolate the fiber from corrosive environment and high temperatures regarding that temperature changes can affect the measurement (Torres-Luque, 2014).

7.1.2 Direct NDT and SHM techniques for corrosion detection

7.1.2.1 Electrochemical techniques (half-cell and galvanostatic pulse)

Electrochemical techniques have been used for determining the corrosion type of rebar in situ, the chloride presence in RC structures, electrical impedance of the material, behavior of the interfaces, microstructure changes due to degradation processes, and, in laboratory, chloride diffusion coefficient estimation in mortars samples (Torres-Luque, 2014).

At late 90s several studies started to use electrochemical techniques as sensor and biosensor for determining corrosion, degradation processes and inorganic ions in polymeric materials. In concrete structures, in 2008 and 2009 Vedalakshmi et al. estimated the diffusion coefficient of free chloride using electrochemical impedance spectroscopy by analyzing capacitive behavior of the system.

Other electrochemical techniques for assessing corrosion in new and existing reinforced concrete structures are (Figueira, 2017):

- Open circuit potential
- Surface potential
- Concrete resistivity
- Polarization resistance
- Noise analysis
- Galvanic current

Electrochemical techniques are widely known, and they are capable of distinguishing chloride ions from other ions present in the environment. However, geometric position, alkalinity, and temperature can affect measurements made with these techniques. In addition, the durability of the reference electrode is important for estimating the lifetime of these techniques. Besides, this technique requires a previous calibration of the reference electrode (Torres Luque, 2014).

References: [Laurens 2018]

Useful links:

http://www.proceq.be/files/proceq_profometer_operating_instructions_en.pdf
https://www.pcte.com.au/images/pdf/CaninHCP/CANIN+Manual.pdf
http://germann.org/products-by-application/half-cell-potential/galvapulse

7.1.2.2 Electrical resistivity

Electrical resistivity has been related to RC corrosion, to the moisture and heat transfer in concrete, and to the presence of chloride ions. This technique is related to chloride ingress because chloride presence can increase electrical current and reduce the resistivity of concrete. This method applies a voltage, measures the current flow and then computes electrical resistances through Ohm's law. The electrical resistivity is a unique characteristic and inherent for each material, and it depends on experimental conditions (Torres-Luque, 2014). Lately, Lecieux et al. in 2019, has tested a SHM system based on electrical resistivity method and calibrated regarding water content and temperature of the medium. Chloride sensors were designed to detect the front of chloride ion whet it first reaches the reinforcement.

Even if some sensors based on electrical resistivity do not need to be embedded in the concrete and therefore do not require high durability. Humidity, the presence of reinforcing bars, carbonation processes, the presence of electromagnetic fields, among others, can disturb the measurements made with this technique. In addition, for the optimal measurement it may be necessary to characterize the concrete in its initial state, that is, a previous calibration of the new material (Torres Luque, 2014, Lecieux, 2015).

7.2 Remaining challenges in the context of offshore renewable energy applications

As stated in (Tacq, 2021), sensors embedded in concrete can be used to monitor evolution of the environment (ingress of e.g. chlorides) or the corrosion itself. Main challenges are choosing the right location to put the sensors and the durability of the sensors.

- Embedded sensors typically do not last for the full lifetime of a structure (e.g. >20 years). Therefore, a combined approach could be envisaged, with embedded sensors for validation on the short term and external sensors for long term monitoring.
- At Nantes Université and Université Gustave Eiffel, technology is being developed to monitor the permeation of Cl^- through the concrete cover [Torres-Luque 2017, Badr 2018, Bonnet 2022]. At the time of writing of this report, development is at the stage of laboratory testing and almost ready for field trials.

Another challenge in the context of offshore renewable energy applications is the choice of the right number of sensors. This is linked to the area/volume of the structure to be inspected and the level of coverage/spatial resolution to be anticipated. A large number of sensors may require reasonable amounts of investment, even if the cost of operation and maintenance is significantly reduced.

In addition, most of the non-destructive testing techniques are used out of water. Their functioning underwater is not tested or completely known. Underwater implementation of NDTs has the risk of impairing the resolution and decreasing the sensitivity.

Visual inspection is often selected as the tool for corrosion inspection. This is, however, a late stage of corrosion assessment and is dangerous for the divers performing the inspections.

Moreover, as the reinforcement of RC structure can have an effect on the evaluation of concrete material conditions (water content or chloride content profiles) it is important to take them into account in electrical measurements (Lataste 2018, Alhajj 2019). Meanwhile, cover concrete conditions can induce perturbations in electrochemical measurements related to rebar corrosion (Laurens 2018, Bouteiller 2021). For these reason, collaborative studies have to be undertaken by specialists of concrete durability and steel corrosion.

7.3 Related projects

Name	Funding	Comment	CIG Member involved
ACES	EU Horizon 2020	Safety-critical concrete infrastructure of nuclear power plants. Corrosion assessment of embedded liners in concrete	ENGIE Laborelec
SIMAR	Regional, Pays de la Loire, France	Assessment in a non destructive way of different parameters (temperature, humidity and chloride intrusion) inside concrete structures exposed to marine environment in the North Atlantic. Tracing over the time of changes in-situ and their relationship with accelerated exposition in laboratory using embedded sensors, accelerated methods of chloride penetration and degradation models.	Capacités SAS Nantes Université Charier TP
SCaNING (Villain 2021)	National, France ANR PRCE2020	Suivi des infrastructures neuves et existantes par Capteurs Noyés pour évaluer les Indicateurs Nécessaires à leur Gestion durable Monitoring of new and existing infrastructures by means of embedded sensors to assess the indicators required for their sustainable management	Université Gustave Eiffel
DEMCOM (Bonnet 2022)	National, France ANR PRCE2020	Durable and Environmental design of Monitored COncrete structures in Marine environment	Nantes Université Université Gustave Eiffel
CSR-Dur&Cor	Univ Gustave Eiffel – CEREMA	Durabilité du béton d'enrobage & Corrosion des armatures – Monitoring et modélisations (Follow-up of the research project IFSTTAR-CEREMA APOS)	Université Gustave Eiffel

7.4 Publications

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8 Alternative materials for concrete reinforcement

8.1 Stainless steel reinforcements

8.1.1 State-of-the-art

Stainless steels exhibit a much higher corrosion resistance than carbon or galvanised steel. This improvement in the corrosion resistance of stainless steels is due to a film of chromium oxide (Cr_2O_3) which is formed on the surface of the steel. Stainless steels are therefore distinguished from carbon steel by their chromium content which is greater than 10.5% (Standard EN 10088-1) with a low carbon content (<1.2%). The classification of these steels is generally based on their microstructures. While four types of stainless steel can be distinguished (austenitic, ferritic, duplex, martensitic), only few grades are used in practice in the field of reinforced concrete:

Concerning mechanical properties, austenitic and duplex stainless steels exhibit high mechanical properties while ferritics have a lower ultimate strength and a smaller plasticity range. In practice austenitic and duplex stainless steels are almost exclusively used for the reinforcements in order to obtain high mechanical properties. It must be pointed out that cold hardening of theses steels slightly reduces the resistance to corrosion and in certain cases can generate the presence of small amount of residual martensite in the microstructure.

Stainless steel reinforcements can be used in association with carbon steel reinforcements. The galvanic corrosion risk has been shown to be negligible in most real situations as stainless steel is a less efficient cathode than passive carbon steel (Bertolini et al., 1998; Qian et al., 2005). Stainless steels are weldable, although the weld design, practice and steps must be carefully executed with adequate control to minimize the effects on microstructure, mechanical properties, and corrosion resistance.

As stainless steel is increasingly used for onshore reinforced concrete structures, there are practical recommendations for its implementation concerning the design, the grade selection, the welding processes, etc… (Concrete Society, 1998; Highways Agency, 2001).

The high corrosion resistance of stainless steel can also allow some gains in the design of structures compared to carbon steel, mainly concerning the concrete cover (can be limited to 30mm) or concrete quality [18E]. With a correct implantation, a high durability is expected without major maintenance even when used in very aggressive environments. (Bertolini et al., 2004; COST 521, 2003). The most obvious disadvantage of stainless steel is its initial cost, but over the years, the additional cost is compensated by considering a full cost of the life cycle of the structure (Concrete Society, 1998). Also, special care is needed during the production, welding and processing of stainless steel (COST 521, 2003; Bertolini et Pedeferri, 2004).

The most important aspect for the use of stainless steel is the choice of the grade for a given application which depends mainly on the aggressiveness of the environment and the expected service life. Other determining factors include mechanical properties as well as cost. For harsh environments, main stainless steel suitable are austenics and duplex with a high amount of Ni and Mo. This can be 1.4462 (318) or 1.4362 grades for duplex or 1.4571 (316Ti), 1.4401 (316), 1.4429 for austenics. The selection can also be done using the PREN (Pitting Resistance Equivalent Number index)

8.1.2 Remaining challenges in the context of offshore renewable energy applications

Mainly due to its cost, stainless steel is not intended to fully replace carbon steels, but used in critical areas of the structure subjected to severe environments, like offshore renewables sites. Each construction project must be analyzed on a case-by-case basis by identifying the specific risks incurred by each part of the structure. The simultaneous use in the same structure of carbon and stainless steels considerably reduces the cost of the structure by using stainless steel reinforcements in the most sensitive areas.

As remaining challenges, it is necessary to take into account that these steels must be prepared, implemented with specific precautions (in particular during welding) to avoid degrading the protective layer against corrosion. This is already recommended in the technical literature.

The other significant point is the selection of the right grade according to the environment and the expected durability. An inappropriate choice based only on budget criteria can lead to premature corrosion of stainless steel reinforcements. A detailed guide to selecting the stainless steel grade according to different marine exposures would be interesting to produce.

8.1.3 Publications

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8.2 Composite reinforcements

8.2.1 State-of-the-art

Composite reinforcements (or FRP, Fibre Reinforced Polymers) can have certain advantages over more traditional solutions (carbon steel or stainless steel): they can be non-conductive and non-magnetic, lighter, have interesting mechanical capacities, and are not subject to corrosion issues which is a momentous issue in the case of offshore applications for classical carbon steel rebars (AFGC, 2022). They are generally made of long fibres (carbon, glass, aramid or basalt) and an organic matrix (epoxy, vinylester or polyester) and have therefore anisotropic properties. Most of these reinforcements also show brittle elastic behaviour (Rolland et al., 2015). The design rules must therefore be adapted to these specificities.

The first applications of this type of reinforcement were carried out at the end of the 1990s in Japan and the United States, and there is now more than 20 years of experience for this type of technology. This feedback tends to demonstrate that natural aging conditions are much less aggressive than accelerated laboratory aging (Rolland et al., 2021) (AFGC, 2022), and highlights the conservative nature of existing standards. Furthermore, since the quality of the reinforcements has changed significantly since these first applications in North America, it might be possible to revise the environmental safety coefficients when new investigations relating to longer aging times have been carried out.

Several guides cover the design of reinforced concrete structures with internal composite reinforcement at European level (Fib, 2007; CNR-DT, 2006) and at international level (ACI, 2014; CAN/CSA, 2012). Eurocode is also working on integrating these reinforcements in a future additional annex. In France, a guide is being finalised by the AFGC (Association Française de Génie Civil) (AFGC, 2022). Certification of these products is currently under investigation, to support their wider use in Europe.

8.2.2 Remaining challenges in the context of offshore renewable energy applications

If additional works are still under progress regarding their durability, some research and development studies are also underway to better optimize fiber/matrix couples and surface treatments, to include thermoplastic matrices in order to ease fabrication processes, or to substitute those materials by more easily recyclable or even bio-sourced ones. Many authors are also working at the reinforced concrete structure scale by associating these reinforcements with concrete formulations having a lower environmental impact in line with the decarbonization needs (AFGC, 2022).

8.2.3 Publications

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9 Alternative concrete formulations

9.1 State-of-the-art

Data included in this section comes mainly from: (Ventura, 2020)

In 2016, about 4,200 million metric tons of cement were produced worldwide (Wang, 2017). Most of the cement is used to produce cement concrete for construction. Worldwide, CO2 emissions issued from cement production ranged between 0.6 and 1.45 giga metric tons CO2 in 2016 (Andrew, 2018; Le Quéré et al., 2016), out of 9.88 giga metric tons in total (Le Quéré et al., 2016), that is around 6% of anthropogenic global CO2. Moreover when a reinforced concrete structures is damaged by corrosion, most current maintenance operations consist in removing the contaminated concrete and replacing it by a new one (CEN, 2009), thus inducing new greenhouse gas emissions.

Today, European standards are based on the definition of an exposure class and subsequent prescriptions including (a) concrete composition (a maximum water-to-cement ratio W⁄C, a minimum cement content C); (b) a minimum 28-day compressive strength of the concrete; and (c) a minimum concrete cover depth d for service life design (CEN, 2005). The requirements for concrete mix design and concrete cover depth for XS exposure class (i.e., chloride induced corrosion), and corresponding to a 100-years-service-life design, are calculated by combining standard EN 206-1 and Eurocode 2. The standard-based approach is a regulatory approach: the 100-years service life are a minimum lifetime that is certified if conditions required by the standards are respected. This means that the 100-years service life are not calculated, they are guaranteed, which implies that different cement concrete mix design in the same exposure class can have different actual durations of service lives. In summary, basing the duration of the service lifetime on an identical exposure class as defined in the European standards does not reflect actual service life. For buildings, actual service life is generally estimated at 50 years independently from concrete alteration, but mainly resulting from other aspects such as standard evolution, changes in real estate market, urban planning policies (Augiseau, 2017), etc. For offshore renewable energy structures, actual service life is generally estimated at 25years, thus, using standards will lead to production of oversized structures that exceed the guaranteed service life, generating unnecessary environmental impacts.

This over-estimation of the quantity of cover concrete for a given lifetime is also effective with low-carbon concretes such as concretes based on mineral or natural additives or from industrial waste. These additives such as blast furnace slags allows the production of concrete with very good durability indicators. The new standard on cements will encourage the introduction of more calcined clays (MetaKaolin) and filler in the binder of concretes in order to reduce their environmental impact by more than half. However, these formulations with high percentages of additives other than clinker have yet to be tested in a maritime environment. Another solution is the production of geopolymer concretes that do not contain clinker. These concretes are currently used for specific applications in France but are developing more rapidly in Australia.

9.1.1 Low-carbon concrete with little clinker percentage

As the production of Portland Cement (PC) generates large amount of CO2 emissions, promoting alternative binders, in which mineral admixtures replace clinker, offers a promising solution.

9.1.1.1 Concrete with slag

Data included in this section comes mainly from: (Ben Fraj, 2012; Be Fraj, 2019; Fabien, 2021; El Achrafi, under review)

Blast Furnace Slag (BFS), considered as byproducts, is used as alternative binder as it may contribute to improve the long-term performance of concrete with higher resistance to aggressive agents.

Indeed blast furnace slag is extensively used in marine environments. Due to their fineness, BFS particles further refine the porous network, increase its tortuosity and enhance the concrete with higher compressive strength and resistance to aggressive agents.

The findings of Baroghel-Bouny et al. (2011), Divsholi et al. (2014), Duan et al. (2013) and Fabien et al. (2021) affirm the positive effect of BFS incorporation on the porous microstructure of concrete by showing the decrease of the critical pore size diameter 'd_c' with partial substitution of PC by BFS. The decrease in the pore size diameter was explained by the refinement of the pores thanks to the formation of new C-S-H gels during the pozzolanic reaction and the small average particle size of BFS compared to those of PC. A considerable amount of research have shown the slag effect on concrete-chloride resistance by assessing the apparent diffusion coefficient $D_{a,mig}$ (Baroghel-Bouny et al. 2011 ; Duan et al., 2013 ; Teng et al. 2013). **The studies showed an important reducing in the chloride's diffusivity of concrete when BFS was incorporated in the concrete mix** with different percentage as shown in Figure 24 with the BFSC60 concrete which contains only 30% of slag. As shown the substitution of 30% of cement by slag decreases chloride diffusion by 1.3, 1.2 and 4 times for RH of 50%, 75% and 90%, respectively. In agreement with these results, Michael et al. seawater exposure time, that the chloride diffusivity could be reduced by approximately 6 and 14 times, when the cement is replaced by 25% and 45% of slag, respectively.

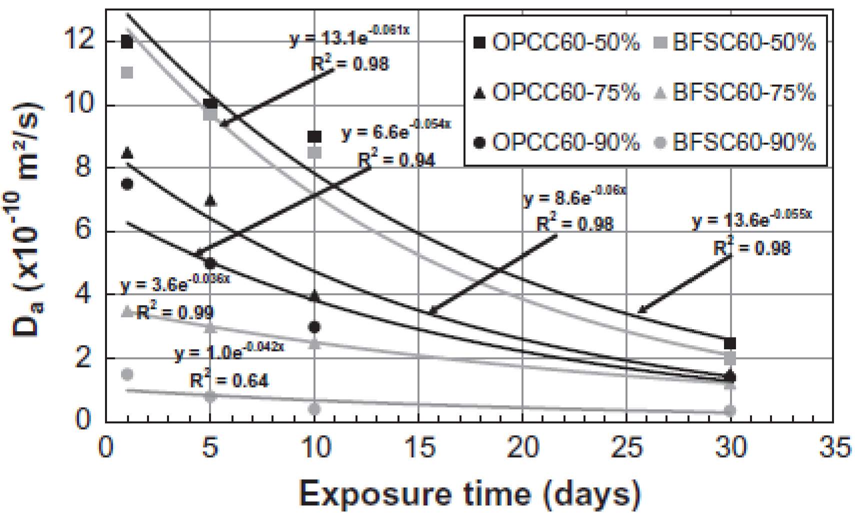

Figure 24: Evolution with time of the apparent diffusion coefficient calculated with chloride ions profiles

Nevertheless, their incorporation, notably in high volumes, greatly decreases the early-age performance of concrete. By virtue of their slow reaction, BFS particles decelerate the hydration reaction in a blended matrix and delay its rise in compressive strength; moreover, the chemical shrinkage is decreased. In the presence of this mineral admixture, the binder exhibits high porosity at an early age, which in turn raises the risk of aggressive agent ingress, as reported in [4]. **This point is a key point to study** for promoting alternative binders with pozzolanic reactions, in which clinker is replaced by mineral admixtures, as byproducts (blast furnace slag, fly ash, silica fume, pozzolane).

9.1.1.2 Limestone Calcined Clay Cement (LC^3)

Limestone Calcined Clay Cement (LC^3) is an innovative blended Portland cement that includes addition of metakaolin (calcined kaolinite clay) and limestone (Figure 25). The choice of calcined clay comes from the scarcity of conventional cement additives (slag, silica fumes, etc.). Their availability in other countries cannot match the massive production of cement, for example slag represents only 5 to 10% of the quantities of cement produced. On the contrary, clay is an abundant material around the world. In addition, the chemical composition of calcined clay is quite stable. With a high content of kaolinite, calcined clay has good pozzolanic properties after calcination between 700 and 850°C.

Kaolin is made up of a mixture of kaolinite (phyllosilicate) and other crystals such as quartz, oxides (iron oxide, etc.). Kaolinite is a phyllosilicate dioctahedral consisting of a regular stack of sheets composed of a siliceous tetrahedral layer (Si2O5)2- alternating with an aluminous octahedral layer (Al2(OH)4)2+. Kaolinite is extremely stable. When subjected to heat treatment (700 and 850°C), kaolinite loses its water by dehydroxylation to become **MetaKaolin (MK)**.

The use of limestone in LC^3 is due to the interactions between calcium aluminates and calcium carbonate (limestone) which participate in hydration reactions to form hydrated calcium carboaluminates.

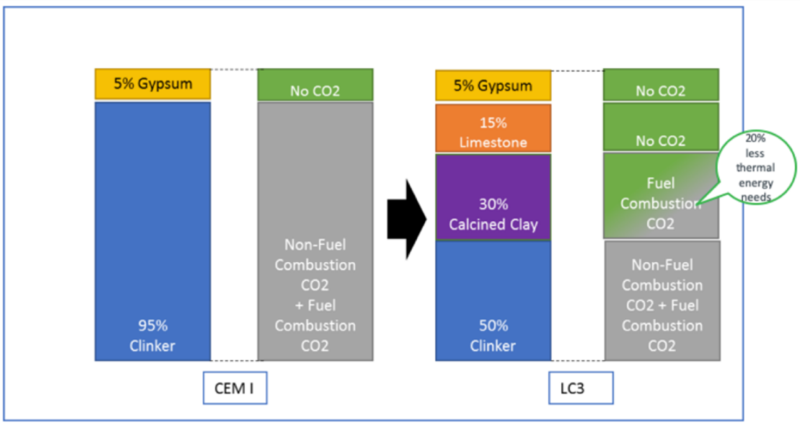

Figure 25: Composition and CO2 savings between an ordinary Portland cement and a LC^3 (source: https://lc3.ch/why-lc3)

The combination of physical and chemical effects of LC^3, with clinker contents of 50%, allow LC^3-based concretes to achieve compressive strengths and durability indices similar to those based on ordinary Portland cement.

LC^3-based concretes present indeed a finer porosity compared to concretes based on Portland cements. This finer structure decreases gas permeability and results in more durable concretes for severe exposure conditions. **Reduction of porosity also implies a reduction in capillarity and therefore LC^3-based concretes should present good performances when they are in a maritime environment.** The pH of LC^3 interstitial solution is slightly lower than other cements. Therefore, a higher resistivity of these concretes and probably a lower ionic mobility can be expected. However, the pore solution composition should be analysed in more details. Both steel depassivation and corrosion propagation should be influenced by the presence of metakaolin.

9.1.2 Geopolymer concrete

Data included in this section comes mainly from: (El Moustapha, 2022)

The reflection of a strategy to reduce the environmental impacts related to CO2 emissions and the improvement of the durability of concrete, encouraged the researcher Davidovits (Davidovits, 2013) to invent a new ecological cement (with less environmental impacts) called the Geopolymer. This material is the result of the activation of aluminosilicate materials by alkaline solutions (Davidovits, 2013). Aluminosilicate materials are industrial wastes, by-products, or types of clays such as Granulated Blast Furnace Slag (GBFS), metakaolin, fly ash, and red mud, etc. The use of these materials to replace Portland cement will reduce CO2 emissions and waste caused by the industries, thus helping to reduce the impact on the environment. Wang et al (Wang, 2004) shows that the CO2 emissions caused by the production of geopolymer are reduced by about 70 to 80% compared to the production of clinker. Furthermore, geopolymer has several advantages over traditional cement-based materials, such as higher initial mechanical strength, low drying shrinkage, high fire resistance, shorter curing time, higher resistance to acid attack (Carreño-Gallardo, 2018; Hasnaoui, 2019; Albitar, 2017; Valencia Saavedra, 2013). **Moreover geopolymer concrete is more resistant to chloride penetration because of its reduced overall permeability compared to Portland concrete** (Bernal, 2014).

Concerning the use of geopolymer, we note that the main gel produced in the geopolymerization process is in the form of a gel called sodium alumina silicate hydrate (NASH), resulting from the activation of alumina and silica found in metakaolin or fly ash (Mijarsh, 2015). This gel is the result of the chemical reaction between Na2O-AL2O3-SiO2-H2O. In recent years, several researchers have shown that it is possible to have in a single geopolymer matrix another hydration gel in addition to the geopolymer gel itself. This gel can be obtained in a matrix that is rich in calcium, silica and alumina to produce Calcium Alumina Silicate Hydrate (CASH), and it is obtained from the chemical reaction between Na2O-CaO-Al2O3-SiO2-H2O (Phoo-ngernkham, 2014; Yip, 2005; Bernal, 2011; Bernal, 2012). The CASH gel results from the activation of blast furnace slag (Kamath, 2021). The use of calcium-rich blast furnace slag with the inclusion of a small amount of silica (SiO2) and alumina (Al2O3) rich metakaolin (MK) contributes to a better workability and a structure mainly composed of the coexisting gels mentioned above. This coexistence of gels, once obtained, improves the mechanical performance and durability of the geopolymer (Bernal, 2012).

However, most of the research that has been carried out on the geopolymer is focused on a geopolymer based on a unique base material such as GBFS, fly ash, MK, etc. In addition, there are few studies on combining two primary materials rich in calcium, alumina, and silica at the same time, for studying their durability in marine environment..

The coexistence of CASH and NASH gels could be obtained by using an inclusion of a small amount of metakaolin in a geopolymer matrix based on blast furnace slag; this results in a geopolymer with high mechanical strength. Several tests were performed to characterize different mixtures (with and without MK) such as workability and microstructural properties, water porosity, mechanical properties (compressive strength, dynamic Young modulus). The results obtained showed that the coexistence of NASH and CASH gel brought improvements in terms of mechanical properties compared to GBFS-based geopolymer-MPCM only. Indeed, the addition of 10 and 20% of metakaolin was sufficient to obtain this coexistence. These improvements are explained by the high reactivity of the MK under the activation conditions used. This favored the good dissolution of silica and aluminum in the MK, which participated well with the calcium in the GBFS to create the NASH and CASH gels. In fact, it was felt that these two gels filled the small pores.

These results are promised and was completed with a durability study which will be submitted soon in Cement and Concrete Composites or an equivalent journal.

9.1.3 Self-healing concrete (SHC)

Alternative concrete formulations making use of healing concepts also present promising ways to reduce and/or mitigate unavoidable cracks issues. The formation of these cracks does not necessarily mean a loss of structural properties, but it is the onset of potential degradation and rebar corrosion. This will eventually reduce the service life of the material and its sustainability. Notwithstanding the development in concrete technology and the design of concrete with a low porosity grade did not alter the risk of damage by crack formation. Currently these cracks are restored by passive treatments but this approach only seals surface cracks in a rather superficial way.

As documented in (Laborelec, 2020), concrete has the remarkable property to inherently heal cracks to a certain extent. This is called autogenous healing. This process leads to partial or complete self-closure of cracks and results in a partial recovery of the initial mechanical properties. This intrinsic property can be stimulated using mineral additives, crystalline admixtures or superabsorbent polymers. Another approach is the development of autonomous self-healing mechanisms based on the use of micro, macro or vascular encapsulation, minerals or even bacteria.

9.2 Remaining challenges in the context of offshore renewable energy applications

The challenge to be met is the use of materials with low environmental impacts while increasing their durability in the offshore maritime environment. The objective is to avoid corrosion of the reinforcements while minimizing the environmental impact, during the lifetime of the offshore concrete structure.

A first option is to use alternative binders, for example formulations based on slag (9.1.1.1), Metakaolin (9.1.1.2) or geopolymers (9.1.2). More detailed investigations are needed on the evolution of the binder porosity, steel depassivation and corrosion propagation with these binders in offshore environment. In particular, formulations with high percentages of additives other than clinker have yet to be tested in a maritime environment.

Another option is to minimize the quantity of binder or even the quantity of concrete cover. As current standards maximize these thicknesses, alternative approaches could be investigated, in association with standardization committees.

Finally, the amount of steel in the offshore concrete structure could be minimized by using fiber-reinforced concretes[3] (AFGC, 2013). Investigating this option both from a material and from structural points of view is recommended.

Although promising, self-healing concrete (SHC) solutions need further investigations for offshore renewables applications. First, SHC solutions present a variable effectiveness depending on the crack size and the long-term healing efficiency of certain SHC solutions is a point of concern. Furthermore, the practical implementation of SHC in large offshore concrete structures is still challenging, in particular when remote activation is needed. SHC can be rather expensive compared to more traditional concretes, therefore conducting a Life Cycle Cost Analysis (LCCA) and a Life Cycle Analysis (LCA) of various self-healing mechanisms on a case by case basis is required to investigate if these types of concrete are more sustainable and economically interesting than conventional concrete that needs more inspection and repair interventions.

9.3 Related projects

Name	Funding	Comment	CIG Member involved
DEMCOM	National ANR, France	Durable and Environmental design of Monitored COncrete structures in Marine environment 2021-2025	Nantes Université Université Gustave Eiffel
Innovative Materials for OFWT	Regional Région Pays de La Loire	Innovative Materials for OFWT 2020-2024	Nantes Université CEA Tech

9.4 Publications

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9.1.1.1 Concrete with slag

BEN FRAJ A., BONNET S., KHELIDJ A., 2012, “New approach for coupled chloride/moisture transport in non-saturated concrete with and without slag”, Construction and Building Materials Volume 35, p. 761-771. http://dx.doi.org/10.1016/j.conbuildmat.2012.04.106.

A BEN FRAJ, S BONNET, N LEKLOU, A KHELIDJ, 2019, Investigating the early-age diffusion of chloride ions in hardening slag-blended mortars on the light of their hydration progress, Construction and Building Materials, 225, pp. 485-495, https://doi.org/10.1016/j.conbuildmat.2019.07.185.

[3] See for instance KRAMPE HAREX, ROCLAND, etc.

A. FABIEN, M. CHOINSKA, S. BONNET, A. PERTUE & A. KHELIDJ, 2021, Aggregate size effects on the mechanical behaviour and on the gas permeability at damaged state of cement-based materials with and without slag, Journal of Environmental and Civil Engineering, doi: 10.1080/19648189.2021.1915881.

Mohamad Khodor EL ACHRAFI, Géraldine VILLAIN, Stéphanie BONNET, Investigation of the chloride content evolution in Portland and Blast Furnace Slag concrete during a diffusion campaign after 6 years of curing with electrical resistivity tomography, Under Review in Cement and Concrete Composites.

V.G. Papadakis, Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress, Cement and Concrete Research, 30 (2000)291–299.

Michael DAT, Allan S, Ted B, Alain B, Donna D. Performance of slag concrete in marine environment. Mater J 2008;105(6):628–34.

9.1.1.2 Limestone Calcined Clay Cement (LC^3)

Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies Yudiesky Cancio Díaza,b, Sofia Sánchez Berriela, Urs Heierlic, Aurélie R. Favierd, Inocencio, R. Sánchez Machadoa, Karen L. Scrivenerd, José Fernando Martirena Hernándeza,Guillaume Habertb Development Engineering 2 (2017) 82–91

A study on fresh properties of limestone calcined clay blended cementitious systems Nithya Nair, K. Mohammed Haneefa, Manu Santhanam ⇑, Ravindra Gettu Department of Civil Engineering, IIT Madras, India Construction and Building Materials 254 (2020) 119326

Calcined clay – Limestone cements: Hydration processes with high and low-grade kaolinite clays Guillemette Cardinaud a,b, Emmanuel Rozière , Olivier Martinage , Ahmed Loukili , Laury Barnes-Davin b, Michael Paris , Dimitri Deneele Construction and Building Materials 277 (2021) 122271

Calcined clay limestone cements (LC3) Karen Scrivenera, Fernando Martirenab, Shashank Bishnoic, Soumen Maityd Cement and Concrete Research 114 (2018) 49–56

Engineered Cementitious Composites (ECC) with limestone calcined clay cement (LC3) Duo Zhang a, Beata Jaworska, He Zhu, Kensey Dahlquist a, Victor C. Li , Cement and Concrete Composites 114 (2020) 103766

Influence of pH on the chloride binding capacity of Limestone Calcined Clay Cements (LC3) François Avet, Karen Scrivener Cement and Concrete Research 131 (2020) 106031

Investigation of C-A-S-H composition, morphology and density in Limestone Calcined Clay Cement (LC3) François Avet∗, Emmanuelle Boehm-Courjault, Karen Scrivener Cement and Concrete Research 115 (2019) 70–79

Investigation of the calcined kaolinite content on the hydration of Limestone Calcined Clay Cement (LC3) François Avet∗, Karen Scrivener Cement and Concrete Research 107 (2018) 124–135

Limestone calcined clay cement and concrete: A state-of-the-art review Meenakshi Sharma, Shashank Bishnoia, Fernando Martirena, Karen Scrivener Cement and Concrete Research Volume 149, November 2021, 106564

Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cement (LC3)Yuvaraj Dhandapani, T. Sakthivel, Manu Santhanam, Ravindra Gettu, Radhakrishna G. Pillai, Cement and Concrete Research 107 (2018) 136–151

9.1.2 Geopolymer concrete

Bouha EL MOUSTAPHA, Stéphanie BONNET, Abdelhafid KHELIDJ, Nordine LEKLOU, Daniel FROELICH , Isselmou AHMEDOU BABAH, Carole CHARBUILLET, Abderahmane KHALIFA, 2022, Compensation of the negative effects of micro-encapsulated phase change materials by incorporating metakaolin in geopolymers based on blast furnace slag, Construction and Building Materials 314, 125556, https://doi.org/10.1016/j.conbuildmat.2021.125556.

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K. Wang et Iowa State University, Éd., Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China, May 20-21, 2004. Ames: Center for Transportation Research and Education, Iowa State University, 2004.

C. Carreño-Gallardo et al., « In the CO2 emission remediation by means of alternative geopolymers as substitutes for cements », Journal of Environmental Chemical Engineering, vol. 6, no 4, p. 4878‑4884, août 2018, doi: 10.1016/j.jece.2018.07.033.

A. Hasnaoui, E. Ghorbel, et G. Wardeh, « Optimization approach of granulated blast furnace slag and metakaolin based geopolymer mortars », Construction and Building Materials, vol. 198, p. 10‑26, févr. 2019, doi: 10.1016/j.conbuildmat.2018.11.251.

M. Albitar, M. S. Mohamed Ali, P. Visintin, et M. Drechsler, « Durability evaluation of geopolymer and conventional concretes », Construction and Building Materials, vol. 136, p. 374‑385, avr. 2017, doi: 10.1016/j.conbuildmat.2017.01.056.

W. G. Valencia Saavedra et R. Mejía de Gutiérrez, « Performance of geopolymer concrete composed of fly ash after exposure to elevated temperatures », Construction and Building Materials, vol. 154, p. 229‑235, nov. 2017, doi: 10.1016/j.conbuildmat.2017.07.208.

S. A. Bernal et J. L. Provis, « Durability of Alkali-Activated Materials: Progress and Perspectives », Journal of the American Ceramic Society, vol. 97, no 4, p. 997‑1008, 2014, doi: 10.1111/jace.12831.

M. J. A. Mijarsh, M. A. Megat Johari, et Z. A. Ahmad, « Effect of delay time and Na2SiO3 concentrations on compressive strength development of geopolymer mortar synthesized from TPOFA », Construction and Building Materials, vol. 86, p. 64-74, juill. 2015, doi: 10.1016/j.conbuildmat.2015.03.078.

T. Phoo-ngernkham, P. Chindaprasirt, V. Sata, S. Hanjitsuwan, et S. Hatanaka, « The effect of adding nano-SiO2 and nano-Al2O3 on properties of high calcium fly ash geopolymer cured at ambient temperature », Materials & Design, vol. 55, p. 58-65, mars 2014, doi: 10.1016/j.matdes.2013.09.049.

C. K. Yip, G. C. Lukey, et J. S. J. van Deventer, « The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation », Cement and Concrete Research, vol. 35, no 9, p. 1688-1697, sept. 2005, doi: 10.1016/j.cemconres.2004.10.042.

S. A. Bernal, E. D. Rodríguez, R. Mejía de Gutiérrez, M. Gordillo, et J. L. Provis, « Mechanical and thermal characterisation of geopolymers based on silicate-activated metakaolin/slag blends », J Mater Sci, vol. 46, no 16, p. 5477-5486, août 2011, doi: 10.1007/s10853-011-5490-z.

S. A. Bernal, R. Mejía de Gutiérrez, et J. L. Provis, « Engineering and durability properties of concretes based on alkali-activated granulated blast furnace slag/metakaolin blends », Construction and Building Materials, vol. 33, p. 99-108, août 2012, doi: 10.1016/j.conbuildmat.2012.01.017.

M. Kamath, S. Prashant, et M. Kumar, « Micro-characterisation of alkali activated paste with fly ash-GGBS-metakaolin binder system with ambient setting characteristics », Construction and Building Materials, vol. 277, p. 122323, mars 2021, doi: 10.1016/j.conbuildmat.2021.122323.

9.1.3 Self-healing concrete

Internal Laborelec report LBE3-1957048923-429, Literature survey on self-healing materials for energy applications (2020)

9.2 Fiber-reinforced concrete

AFGC, Ultra High Performance Fibre-Reinforced Concretes, June 2013

10 Rules and standards

10.1 State-of-the-art

This chapter reflects the state of the art of existing rules and standards dealing with corrosion of reinforcing steel in concrete.

Some standards includes paragraphs about the corrosion of reinforcing steel in concrete, however there is no dedicated standard or a practical guide focussed on this topic.

Table 4 contains standards that deal directly or indirectly with this subject:

Table 4: Rules and standards related to corrosion of reinforced concrete

Type	Reference	Date	Titre
DNV	DNVGL-ST-C502	2018	Offshore concrete structures
ISO	ISO 19903	2019	Petroleum and natural gas industries — Concrete offshore structures
	ISO 16020	2005	Steel for the reinforcement and prestressing of concrete – Vocabulary
EN	EN 1992-1-1 *(Eurocode 2)*	2011	Design of concrete structures - Part 1-1: General rules and rules for buildings
	EN 10138-3	2001	Prestressing steels
	EN 206	2014	Concrete - All Parts
ACI	ACI 222R	2010	Corrosion of metals in concrete
	ACI 318	2014	Building Code Requirements for Structural Concrete
Document	RILEM report (1988)		Corrosion of steel in concrete P. SCHIESSL

A broader list of standards addressing concrete structures, but not necessarily corrosion of the reinforcements, is available in:

- Appendix 1 – Rules and standards on concrete
- Appendix 2 - Rules and standards on concrete – focus on ISO 1920 Testing of concrete

10.2 Remaining challenges in the context of offshore renewable energy applications

Only few standards are available regarding the specific application of concrete structures for offshore renewables.

In the above list of standards, the subject of corrosion and the use of concrete is dealt with in a broad context and not specific to offshore renewables, which make the choice, use and implementation of those standards more complicated.

Moreover, there are still some missing points in the existing standards, for example:

- Some degradation modes
- Some design constraint specific to offshore renewable
- Some failures cases
- Explicit standards about on-site inspections and use of collected data

Therefore, a new guideline or an improvement of the existing standards is necessary to deal with subjects more specifically linked to offshore renewables, and to improve the consideration of regulations and standards.

10.3 Publications

See table of standards in section 10.1, Appendix 1 and Appendix 2.

11 Future research and demonstration project

The main objective of this CIG is to identify one or several future R&D collaboration opportunities within the CIG members (all or a subset) and start preparing the basis for associated grant applications. The objective of this section is therefore to provide a high level framework for a future research and demonstration project aiming at reducing corrosion costs for offshore renewables.

11.1 Motivation and objective

While there is an increasing number of offshore renewables devices using concrete material, challenges related to corrosion of steel rebars need to be tackled to avoid early failure of offshore reinforced concrete structures. Corrosion is particularly critical in the harsh environment where offshore renewable devices are usually deployed for more than 25 years.

The reinforced concrete structures can be protected against corrosion by cathodic protection (sacrificial anodes, impressed current), increased concrete cover, specific coatings, etc. These protective measures lead to additional costs, increased material quantities and potential environmental impacts.

Alternative reinforced concrete solutions (alternative rebar materials, specific concrete formulations, etc.) might be suitable to reduce the cost of corrosion and increase the lifetime of reinforced concrete structures in offshore renewables applications. A **proposal of R&D project** is presented below to tackle associated **challenges** (11.2), together with a suggestion of Work Packages breakdown and potential partners identified in the **workplan** (11.3). **Public funding opportunities** at the European, national and regional levels are identified in section 11.4.

Sections 11.2, 11.3 and 11.4 are only available to the CIG members. If you are interested to join a future collaborative project, please contact opin@seai.ie and/or contact@weamec.fr

12 Appendix 1 – Rules and standards on concrete

Reference	Date	Title	Comment
DNVGL-ST-C502	2018	Offshore concrete structures	This standard (ST) provides principles, technical requirements and guidelines for the design, construction and in-service inspection of offshore concrete structures. Concrete structures can be floating or ground-based structures.
ISO 19903	2019	Petroleum and natural gas industries — Concrete offshore structures	This document specifies requirements and makes recommendations for fixed, floating and stranded concrete offshore structures for the petroleum and natural gas industries. It also applies to national-scale structures supporting energy production, transmission or distribution facilities. This document covers more specifically: - the design, construction, transport and installation of new structures, as well as the requirements for in-service inspection and the possibility of removal of structures; - evaluation of structures in service; - evaluation of structures intended to be reused on other sites. This document is intended to cover the engineering processes required by major engineering disciplines in order to establish a facility intended for use at sea.

Reference	Date	Title	Comment
ISO 22965-1	2007	Concrete — Part 1: Methods of specifying and guidance for the specifier	ISO 22965-1: 2007 applies to concrete for cast-in-place structures, prefabricated structures and prefabricated structural products for buildings and civil engineering works. Concrete can be mixed in place, ready mixed concrete or produced in a precast concrete products plant. ISO 22965-1: 2007 applies to concrete compacted so as not to retain any appreciable amount of trapped air other than entrained air and to normal weight, heavy and light weight concrete. ISO 22965-1: 2007 contains requirements for the specification of concrete and guidelines for the exchange of information between the specifier and the supplier. An informative annex provides general guidance on the specification. More specific guidance on specifications related to local conditions can be given in a national annex. ISO 22965-1: 2007 does not apply to concretes with a maximum aggregate size equal to or less than 4 mm or 5 mm (mortar), aerated concrete, aerated concrete, open-structure concrete (concrete without fine aggregates), concrete with a density of less than 800 kg / m3 and refractory concrete. ISO 22965-1: 2007 does not cover health and safety requirements for the protection of workers during the production and delivery of concrete

Reference	Date	Title	Comment
ISO 22965-2	2007	Concrete — Part 2: Specification of constituent materials, production of concrete and compliance of concrete	ISO 22965-2: 2007 applies to concrete for cast-in-place structures, prefabricated structures and prefabricated structural products for buildings and civil engineering works. Concrete can be mixed in place, ready-mixed concrete or produced in a precast concrete products plant. ISO 22965-2: 2007 applies to concrete compacted so as not to retain any appreciable amount of trapped air other than entrained air and to normal weight, heavy and light weight concrete. ISO 22965-2: 2007 specifies the properties of the constituent materials, the construction of concrete and the concrete compliance system. ISO 22965-2: 2007 does not apply to concretes with a maximum aggregate size equal to or less than 4 mm or 5 mm (mortar), cellular concrete, cellular concrete, open-structure concrete (concrete without fine aggregates), concrete with a density of less than 800 kg / m3 or refractory concrete. ISO 22965-2: 2007 does not cover health and safety requirements for the protection of workers during the production and delivery of concrete.
ISO 15630-1	2019	Steel for the reinforcement and prestressing of concrete — Test methods — Part 1: Reinforcing bars, rods and wire	This document specifies chemical and mechanical test methods and methods for measuring geometric characteristics applicable to bars, rods and wires for reinforced concrete.
ISO 15630-2	2019	Steel for the reinforcement and prestressing of concrete — Test methods — Part 2: Welded fabric and lattice girders	This document specifies chemical and mechanical test methods and geometric characteristics measurement methods applicable to welded mesh and stiffening mesh for concrete reinforcement. NOTE In some countries the term "welded wire reinforcement" is used instead of "welded (wire) fabric". For tests not specified in this document (eg bend test, lock / recess geometry, linear density) ISO 15630-1 applies. This document does not cover the sampling conditions which are specified in the product standards.

Reference	Date	Title	Comment
ISO 15630-3	2019	Steel for the reinforcement and prestressing of concrete — Test methods — Part 3: Prestressing steel	This document specifies the test methods applicable to prestressing steels (bars, wires or strands) for concrete. This document does not cover the sampling conditions which are specified in the product standards.
ISO 6934 (all parts)	1991	Steel for the prestressing of concrete	
ISO 6935-1	2007	Steel for the reinforcement of concrete — Part 1: Plain bars	ISO 6935-1: 2007 specifies the technical requirements for smooth bars to be used for reinforcing concrete. ISO 6935-1: 2007 covers nine grades of steel, not intended for welding, namely B240A-P, B240B-P, B240C-P, B240D-P, B300A-P, B300B-P, B300C-P, B300D-P and B420D-P, and a steel grade intended for welding which is B420DWP. The manufacturing process is at the discretion of the producer. It also applies to smooth bars delivered in the form of crowns. The requirements of ISO 6935-1: 2007 apply to the straightened product. Steel grades are designated with symbolic steel designations assigned in accordance with ISO / TS 4949: 2003. This part of ISO 6935 covers products supplied in straight lengths. Smooth bars produced from finished products such as railway plates and rails are excluded.
ISO 6935-2	2019	Steel for the reinforcement of concrete — Part 2: Ribbed bars	This document specifies the technical requirements for ribbed bars to be used as reinforcement in concrete. It applies to steels delivered in the form of bars, coils and unwound products. This document covers both weldable and non-weldable steels. It does not apply to ribbed bars made from finished products, such as sheet metal and railroad tracks. The production process is at the discretion of the manufacturer.

Reference	Date	Title	Comment
ISO 6935-3	1992	Steel for the reinforcement of concrete — Part 3: Welded fabric	Specifies the technical requirements and test methods (shape and dimensions, chemical composition, mechanical properties, designation, marking, certification and control, verification of conformity) for sheets or rolls of welded fabric manufactured in the factory from wire or steel bars with a diameter of 4 mm to 16 mm.
ISO 11082	1992	Certification scheme for welded fabric for the reinforcement of concrete structures	Specifies the rules for a certification system. Such a continuous production scheme comprises the following stages: proficiency test, internal control by the manufacturer, control and control by an external body.
ISO 14654	1999	Epoxy coated steel for the reinforcement of concrete	This International Standard specifies the requirements for steel bars, wire and welded mesh for concrete reinforcement, with fusion crosslinked epoxy coating, pre or post-formed. This standard allows the application of either flexible (type A) or non-flexible (type B) coatings. Steel bars, wires and welded mesh for reinforced concrete with a non-flexible coating (type B) must not be shaped after coating.
ISO 14655	1999	Epoxy coated strand for the prestressing of concrete	This International Standard specifies requirements for fusion-bonded, epoxy-coated, or epoxy-coated and filled, seven-wire prestressing steel strand for the prestressing of concrete. NOTE Use of epoxy-coated strand in pre-tensioned applications such as fire-rated construction should be approached with caution.
ISO 14656	1999	Epoxy powder and sealing material for the coating of steel for the reinforcement of concrete	This International Standard specifies requirements for epoxy powders for use in preparing fusion-bonded epoxy coated steel reinforcing bar, wire and welded fabric. This International Standard also includes requirements for sealing material used to repair damaged areas and cut ends on reinforcing steel. This International Standard defines a flexible (type A) coating and a nonflexible (type B) coating. The adhesion and moisture resistance of fusion-bonded epoxy powder coatings can be enhanced by certain formulation designs. These coating enhancements typically result in a reduction of the coating's flexibility.

Reference	**Date**	**Title**	**Comment**
ISO 16020	2005	Steel for the reinforcement and prestressing of concrete – Vocabulary	ISO 16020: 2005 defines terms and symbols to be used in the field of steels for the reinforcement and prestressing of concrete
ISO 19338	2014	Performance and assessment requirements for design standards on structural concrete	ISO 19338: 2014 provides performance and evaluation requirements for structural concrete design standards. It can be used for international harmonization of design and construction requirements. ISO 19338: 2014 includes requirements that define the structural performance of concrete required; criteria, which provide the means to express requirements; and evaluation clauses, which provide acceptable methods of verifying specific criteria.
ISO 10144	2018	Certification scheme for steel bars and wires for the reinforcement	This document specifies the rules for a certification system for the continuous production of steel bars, rods and wires for the reinforcement of concrete structures in order to verify compliance with the requirements specified in product standards, such as 'ISO 6935-1 and ISO 6935-2. It includes requirements for the assessment activities of the production process and the management system. A product certification system for continuous production consists of the following steps: - initial assessment; - examination of the proofs of conformity; - certification decision and attestation; - surveillance activities.
ISO 11082	1992	Certification scheme for welded fabric for the reinforcement of concrete structures	Specifies rules for a certification scheme. Such a scheme for continuous production consists of the following stages: suitability testing, internal inspection by the manufacturer, inspection and supervision by an external body.

Reference	Date	Title	Comment
EN 1992-1-1	2011	Design of concrete structures - Part 1-1: General rules and rules for buildings	This part of Eurocode 2 gives the design and calculation rules to be used for concrete buildings and civil engineering works in order to meet the requirements of safety, serviceability and durability. The specific rules for fire resistance are discussed in section 1-2. This document does not include a national application document but must be supplemented by a national annex which defines the modalities of its application.
NF EN 10138-3	2001	Prestressing steels	
EN 206 (All Parts)	2014	Concrete - All Parts	
NF EN 10080	2005	Steel for the reinforcement of concrete	This document specifies the general requirements and definitions relating to the performance characteristics of weldable reinforced concrete steels used for the reinforcement of concrete structures, delivered as finished products in the form of bars, rings (wire rod, wire) and products. unrolled, machine-welded, factory-made mesh panels and stiffening mesh.
ACI 222R	2010	Corrosion of metals in concrete	This report reports on the state of the art of corrosion of metals, and in particular reinforcing steel, in concrete. Separate chapters are devoted to mechanisms of metal corrosion in concrete, protective measures for new concrete construction, procedures for identifying corrosive environments and active corrosion in concrete, and corrective actions.
ACI 318	2014	Building Code Requirements for Structural Concrete	
RILEM report	1988	Corrosion of steel in concrete P. SCHIESSL	
FIB 2007	2007	Guide for the design and construction of Fiber-	

Reference	Date	Title	Comment
		reinforced concrete strutures	
AFGC	2022 Under review	Utilisation d'armatures composites (à fibres longues et à matrice organique) pour le béton armé	
CSA S806-12	2012	Design and construction of building structures with fibre-reinforced polymers	

13 Appendix 2 - Rules and standards on concrete – focus on ISO 1920 Testing of concrete

ISO 1920 Testing of concrete			
Part	**Date**	**Title**	**Comment**
1	2004	Testing of concrete — Part 1: Sampling of fresh concrete	ISO 1920-1: 2004 specifies procedures for sampling fresh concrete. Samples are used to test the properties of fresh concrete or to fabricate specimens to determine the properties of hardened concrete.
2	2016	Testing of concrete — Part 2: Properties of fresh concrete	ISO 1920-2: 2016 specifies test procedures for fresh concrete. It specifies the following test methods: determination of consistency (slump test, Vebe test, degree of compactability, flow table test for high flow concrete and flow test), determination of density at l 'fresh state and determination of the air content by the manometer method and by the water column method.
3	2019	Testing of concrete — Part 3: Making and curing test specimens	This document specifies the shape and dimensions of concrete specimens for strength testing and the methods of fabrication and hardening of such specimens.
4	2020	Testing of concrete — Part 4: Strength of hardened concrete	This document specifies the test procedures for the strength of hardened concrete.
5	2018	Testing of concrete — Part 5: Density and water penetration depth	This document specifies methods for testing the density and depth of water penetration in hardened concrete.
6	2019	Testing of concrete — Part 6: Sampling, preparing and testing of concrete cores	This document specifies a method for taking core samples from hardened concrete, their examination, preparation for testing and determination of compressive strength. This document does not provide guidance on the decision to drill core or on drill locations, and does not provide procedures for interpreting core strength results. It is recommended that before coring, all parties agree on the need for a core test and how the results should be interpreted.

7	2004	Testing of concrete — Part 7: Non-destructive tests on hardened concrete	ISO 1920-7: 2004 specifies non-destructive testing methods to be used on hardened concrete. The methods included are: a) determining the number of bounces; b) determining the ultrasonic pulse velocity; and c) determining the breakout force.
8	2009	Testing of concrete — Part 8: Determination of drying shrinkage of concrete for samples prepared in the field or in the laboratory	ISO 1920-8: 2009 specifies a method for determining the variations in length of concrete specimens due to air drying, as well as the method of preparing and curing the concrete specimens to be tested.
9	2009	Testing of concrete — Part 9: Determination of creep of concrete cylinders in compression	ISO 1920-9: 2009 specifies a method for determining the creep of standard concrete test cylinders subjected to a sustained longitudinal compressive load.
10	2010	Testing of concrete — Part 10: Determination of static modulus of elasticity in compression	ISO 1920-10: 2010 specifies a test method for the determination of the static modulus of elasticity in compression of hardened concrete, on specimens cast or taken from a structure.
11	2013	Testing of concrete — Part 11: Determination of the chloride resistance of concrete, unidirectional diffusion	ISO 1920-11: 2013 specifies a method for determining the parameters of unidirectional penetration of non-permanent chlorides in conditioned specimens of hardened concrete. The test method determines the penetration of chloride at a specified age, e.g. for the classification of the quality of concrete by comparative tests.
12	2015	Testing of concrete — Part 12: Determination of the carbonation resistance of concrete — Accelerated carbonation method	This procedure specified in ISO 1920-12: 2015 is a method for evaluating the carbonation resistance of concrete using an accelerated carbonation test. After a preconditioning period, the test is performed under controlled exposure conditions using an increased level of carbon dioxide to which the vertical sides of the sample are exposed. The test results are not intended to define performance requirements but to compare the carbonation resistance of different concretes of the same strength class, which are used under the same environmental conditions.
13	2018	Testing of concrete — Part 13: Properties of fresh self compacting concrete	This document specifies procedures for testing fresh self-compacting concrete. It specifies the following test methods: determination of consistence (slump flow test), V funnel test, L box test, sieve segregation test, J-ring test and self-compactability test.

14	2019	Testing of concrete — Part 14: Setting time of concrete mixtures by resistance to penetration	This document discusses the method of determining the setting time of a concrete with greater than zero slump, by testing the sieved mortar of the concrete mixture. The initial setting time and the final setting time are the necessary time intervals. so that the sieved mortar of the concrete mixture reaches the specified values of resistance to penetration after the initial contact of cement and water. The method can be used to determine the effect of variables such as temperature, type and content of cement, proportions of the concrete mix and admixtures, on the setting time and hardening characteristics of concrete. This test method is applicable under controlled laboratory conditions, as well as under field conditions.