Materials and Structures

Long-term field exposure of structural concretes in marine environment: state-of-the-art review by RILEM TC 289-DCM

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Long-term field exposure of structural concretes in marine environment: state-of-the-art review by RILEM TC 289-DCM

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Abstract:

This paper reviews the technical aspects related to the long-term field exposure practice in marine environments, based on the return of experiences of major marine exposure sites in world-wide scope. The long-term exposure practice helps both the research on durability mechanisms of structural concretes under real environments and the calibration of durability models to support the life-cycle management of concrete structures. The presentation of the field exposure data can be categorized into the information relevant to exposure sites, the data related to the exposed materials and specimens, the information of environmental actions, and the data related to the performance of materials. A standardized presentation of these data can help the efficiency of data sharing and exploitation. The exploitation of exposure data employs various models to represent the chloride ingress and the induced corrosion risk of the embedded steel bars. There are needs for models addressing the strong environment-material interactions, and simple yet reliable durability indicators for engineering use. The design and operation of exposure stations need the careful choice of exposure sites and specimens, the appropriate scheme for monitoring and inspection of exposed specimens, the systematic recording and management of exposure data, and the regular maintenance of exposure facilities. The support of exposure data for life-cycle management is demonstrated through the durability planning of a real project case. The good practice of long-term field exposure is summarized in the end.

Keywords:

Marine environment, Structural concrete, Field exposure, Durability, Modeling, Data management

1. Introduction

Nowadays, structural concretes are required to fulfil their expected performance during long service lives, e.g. 50 years for buildings and more than 100 years for large-scale infrastructures [1]. The knowledge on their long-term durability is crucial for the design and management of these structures and infrastructures, especially for those exposed in aggressive environments such as the marine environment. The durability performance of structural concretes in marine environments is highly complex, involving such actions as chloride ingress, carbonation, freeze-thaw, seawater erosion and their coupled effects [2]. The marine exposure practice provide unique data sources to investigate the long-term performance of concretes, and to support the design, assessment and prediction of long-term durability of concrete structures and infrastructures. That is the very reason that the engineering community values the practice of long-term field exposure.

The systematic exposure of concrete materials in marine conditions started in 1930's. The United States built exposure stations in four typical marine climates in the coastal areas of US [3-5], and the collected data served to investigate the surface chloride content and the chloride diffusion coefficient in terms of concrete mixtures, exposure conditions and time [6]. Latin America began the practice of exposure in 1991 with the first sites established in Mexico [7]. The DURACON project quantified the chloride ingress and carbonation of concretes in the Iberoamerican urban, marine and rural environments [8]. The Punta Matamoros site in Cayo Santa María, Cuba was set up in 2015 to study the performance of concretes incorporating LC3 binders [9]. Spain established four concrete blocks in a beach site (Huelva) before 1990 to study the main characteristics related to the chloride penetration [10]. Sweden established Träslövsläge site in 1990 to study the chloride diffusion in concretes and its influencing factors [11], helping the calibration of ClinCon model [12] and the service life prediction of concrete structures. A French exposure study was initiated in 1996 including the tidal zone of one marine site (La Rochelle), and the observations helped to quantify the long-term performance of concretes with different binders [13]. In Asia, Japan has established marine exposure stations since 1980 [14-15] with the obtained data helping to study the durability mechanisms of reinforced concretes with coatings [16-17]. China begun the marine exposure practice in 1980s by stations built in marine ports [18]. These data help to upgrade the Chinese technical standards for concrete durability (JTS 152-2015, GB/T 50476-2019). Especially, the data from Zhanjiang station were used to calibrate the durability model for the Hong Kong-Zhuhai-Macau sea link project [19]. In South Africa, long-term studies have been undertaken since the 1990s at exposure sites around Cape Town and Durban to measure chloride ingress, rebar corrosion, and durability index characteristics for different types of concretes [20].

Albeit these achievements, the exploitation of long-term field data is not yet satisfactory, and the added value of these data has not been fully generated. The data collection from exposure stations is rather intuitive, and a systematic format for data collection/presentation is missing; more deepened interpretation of these data, obtained through labour/budget demanding procedures, are expected to provide more information for durability performance; and more formalized guideline is expected for the operation of exposure stations and the support for life-cycle management of concrete structures and infrastructures. Aiming at these lacks, the RILEM TC 289-DCM is committed to providing solutions and tools for these needs. This paper gives a comprehensive review on the state-of-art of the durability mechanisms of concretes in marine environments, the presentation of long-term filed exposure data, the interpretation and modelling from these data, and the exploitation of these data. From the return of experiences of major exposure sites, it is expected that the practice of field exposure in marine environments can be shared in wider scope for both research and practice purposes.

2. Concretes exposed in marine environments: mechanisms and factors

2.1 Basic mechanisms

Concrete is a heterogeneous composite incorporating different phases such as fine and coarse aggregates, porous hardened cement paste, and the interface between them. Exposed in marine environments, the structural concrete will undergo physical and chemical changes due to both the environmental actions and the service loadings [1]. These changes depend highly on the local exposure conditions with marine chlorides and atmosphere. As the concrete is permanently immersed in seawater, e.g. elements under sea level, the internal pores of concrete are in connection with the external seawater, resulting in the transport of chemical substances, such as Cl^-, Mg^{2+}, SO_4^{2-}, from seawater into concrete and/or the outward transport of pore species, such as Na^+, Ca^{2+} and OH^-, from pore solution to seawater (calcium leaching). All these transport processes will in return alter the liquid-solid equilibria between the pore solution and the solid phases in the matrix of concrete [21]. As the concrete is exposed to air-borne chlorides, these transport processes are less active but the CO_2 in the atmosphere will induce carbonation on the concrete surface. As the concrete is alternatively exposed to seawater and atmosphere, e.g. elements in tidal or splashing zones, the involved processes are intermediate to the above two cases, except that the transport at the concrete surface will be dominated by strong capillary absorption (suction) under the drying-wetting cycles [22]. In addition, the direct contact with seawater can induce pure mechanical damage of concrete surface from erosion (seawater flow) or abrasion (sediments or/and flowing ice) [23]; under cold climates, the frost damage may occur on highly saturated concrete surfaces as well [24].

Figure 1 illustrates the involved durability processes for concrete under different exposure conditions. Under each exposure zone, these processes always include complex material-environment interactions on the concrete surface and diffusion-dominating ones in the inner (bulk) part of concrete. As a consequence, these processes can both alter the concrete properties and disturb the electrochemical stability of steel bars in concrete [25-26]. So far, the steel corrosion is the major durability concern for reinforced concrete (RC) structures in marine environments, and the following will be focused on the corrosion of reinforcement steel in concrete.

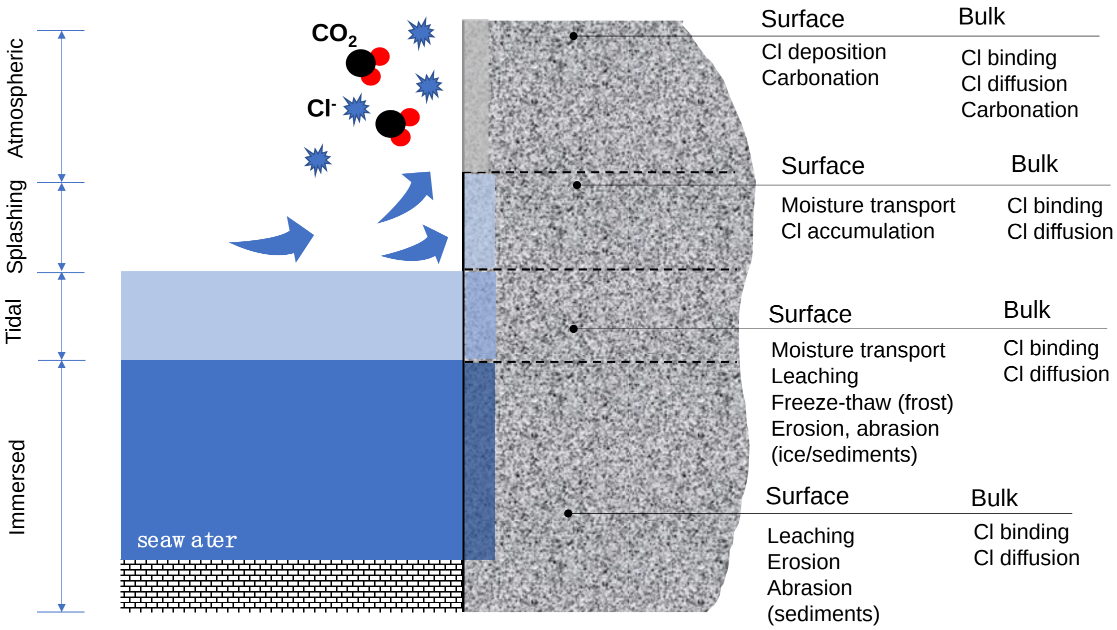


Figure 1: Illustration of general durability processes of concrete in marine environments

2.2 Influential factors and consequences

The structural concretes are subject to both environmental actions and service loadings. Thus, the durability processes mentioned above involve influential factors such as environmental and climate factors, material factors and loading factors in service.

Environmental factors

The environmental factors include mainly the salinity of seawater, its temperature, and the drying-wetting/freeze-thaw cycles induced by the local climates. *The salinity of seawater* refers to the total concentration of soluble ions such as Na^+, Cl^-, Mg^{2+}, SO_4^{2-}. These ions are active in the physical diffusion, capillary absorption, and chemical reactions with cement hydrates. The ionic concentrations in the seawater change with the atmospheric precipitation, inflow of fresh water from river mouths and melting glaciers, and the rate of evaporation [27]. The temperature of seawater depends on the local climate and influences the chemical activities of ions, increasing the diffusion rate but decreasing the chloride binding of concrete [28]. The drying-wetting cycles may result from natural precipitation or alternative contact with air and seawater. Under these cycles the capillary absorption is active and can transport the external ions into concrete more efficiently, and its intensity is highly dependent on the concrete saturation and the drying/wetting periods [29]. The freeze-thaw cycles come into action for the concrete concurrently saturated and exposed to frost climates. Under these cycles, the external liquid can also be brought into concrete by the "pump-effect" [30], and the number of cycles plays a significant role in the chloride penetration [31]. Besides, the surface erosion by flowing seawater and the abrasion by seawater sediments and/or ice are also relevant factors.

Material factors

The material factors include the composition (proportioning) and the properties of concrete. *The mineral composition of binders* (Portland cement and supplementary cementitious materials) will determine the hydration products and pore solution chemistry, which are the basis for pore transport and reactions. *The water to binder (w/b) ratio* is one crucial proportioning parameter determining largely the hydration extent and the pore structure of material. *The pore structure* (porosity and tortuosity) will in turn determine the durability related properties, depicting the resistance of concrete to mass transport, represented mainly by the gas permeability, ion (chloride) diffusivity, water permeability and water absorption rate [32]. One important factor is the near-surface zone of concrete which differs from the bulk concrete and is sensitive to the concreting operation and curing practice. This zone shows "skin effect" and could be the weakest link against chloride ingress [33-34].

Loading and service state factors

Structural concretes work under certain loading levels. *The loading*, if excessive, can induce cracking in concrete and facilitate the ingress of aggressive agents. The impact of loading on durability processes is due to the induced cracking [35]. Moderate cracking opening, e.g. less than 0.3 mm, was observed to have rather limited influence on the corrosion risk of embedded steel in concrete [36-37]. The cracking due to severe early-age or drying shrinkages was regarded more harmful for steel corrosion [38]. Still, more field and laboratory data are needed to confirm these observations. Under accidental actions, such as ship impact or release of aggressive chemicals in port structures, the induced damage can accelerate the corrosion of embedded rebars [39].

Consequences

The consequence of the durability processes includes two basic aspects: for the near-surface concrete, the solid matrix will be significantly altered and the relevant properties will be affected including mechanical strength, transport properties, sulfate resistance and frost and abrasion/erosion resistance; for the bulk concrete, the mass transfer will transport aggressive agents, e.g. chlorides or sulfates, into the inner part of material and initiate the related chemical reactions. Both aspects will enhance the corrosion risk of the embedded steel bars and the cracking of concrete cover by steel corrosion [40], affecting the bearing capacity of RC structures eventually. Table 1 illustrates the correlation between these above-mentioned factors and the consequences.

Table 1: Relevance of different factors to the deterioration of concrete durability in marine environments (n.r. stands for "not relevant", ↑ for increasing and ↓ for decreasing)

Factors		Consequence				
		Mechanical resistance	Transport resistance	Carbonation resistance	Frost resistance	Corrosion risk
Environmental	Salinity (Cl) (seawater, higher)	n.r.	n.r.	n.r.	n.r.	↑
	Temperature (seawater, higher)	n.r.	↓	n.r.	n.r.	↑
	Drying-wetting (splashing/tidal)	↓	↓	↓	↓	↑
	Freeze-thaw (frost)	↓	↓	n.r.	↓	↑
Material	Binder type (using SCM)	n.r.	↑	↓	n.r.	↓
	w/b ratio (smaller value)	↑	↑	↑	↑	↓
	Pore structure (compact)	↑	↑	↑	↑	↓
	Surface quality (good)	↑	↑	↑	↑	↓
Service	Loading level (compressive, moderate range)	n.r	n.r	n.r	n.r.	n.r.
	Cracking (within 0.3 mm)	n.r.	↓	↓	↓	n.r.
	Impact and aggressive chemicals	↓	↓	↓	↓	↑

3 Presentation of long-term field exposure data: information and format

3.1 Information relevant to marine exposure sites

The environmental conditions of exposure sites describe the natural envelope for the concrete specimens under long-term observation by the surroundings. These conditions constitute the first group of information relevant to the field exposure practice. From the experiences so far [8,41], the following information is regarded as necessary: (a) the geographical location and orientation, (b) the atmosphere classification according to ISO-9223:2012, (c) the planning of exposure area and positioning for different types of specimens, (d) the meteorology of atmosphere such as temperature, relative humidity, CO_2 concentration, time of wetness and chloride deposition rate, (e) the hydrology of seawater such as waves and tides, temperature, salinity, pH value and ion concentrations, and (f) the methods to collect/record these environmental data.

The exposure sites in unshielded conditions, exposed to open seawater and stormy actions, need accurate hydrology data, such as waves and tides, to define the different exposure zones. The exposure sites in shielded conditions, protected from strong stormy actions, need to specify clearly the different exposure zones created by the shielded conditions, using the regional hydrology only for reference. Figure 2 illustrates two exposure sites, one on the Mexican coast in atmospheric exposure (Port Progresso, Mexico) and the other on the west artificial island of HZM project (Ling'ding ocean, China).

Figure 2: Marine atmospheric exposure site in Mexican gulf, Port Progresso, Mexico (left) and unshielded exposure station for HZM project in Ling'ding Ocean, China (right). Courtesy of Dr. Pedro Castro-Borges and Mr. Su Quanke (HZMBA)

3.2 Information relevant to long-term exposure

The central information of long-term exposure pertains to the behaviors of concrete specimens under the environmental actions. This group of information can be further divided into factors related to the materials and specimens, the environmental actions and the performance of materials. The factors of materials and specimens refer to the composition of concrete, the applied protection materials (if any) and the loading/cracking states of specimens. The environmental factors are the actual actions of seawater or atmosphere on the concrete specimens, including the effect of specimen orientations and the dominating wind directions. The performance factors depict the measurable changes of specimens during field exposure. Moreover, the random and statistical nature of these factors is also relevant to the interpretation and use of exposure data.

Material and specimen factors

The types of cement have notable impact on the concrete resistance to chloride ingress: slag cement > fly ash (FA) cement > silica fume (SF) cement > ordinary Portland cement [42]. The apparent chloride diffusion coefficient and the critical chloride content for corrosion initiation decrease with increasing FA content in the binder [43]. Compared to Portland cement concrete, the alumina-cement concrete during marine exposure was reported to have a denser microstructure on the surface than the interior, and also a more porous steel-concrete interface [16]. The *w/b ratio* has also notable effect on chloride ingress: lowering *w/b* effectively reduced the apparent chloride diffusion coefficient, and the diffusion coefficients all decayed with the exposure age [44]. *The supplementary cementitious materials (SCM)* enhanced the chloride ingress resistance by incorporating 5-10%SF [11] or 15-35%FA [45], and using SCM increased both the long-term strength and the corrosion resistance of reinforced concrete [46]. For *aggregates*, concretes using lightweight and conventional aggregates have basically the same resistance to chloride penetration [47].

On the specimen level, the *silane impregnation* was observed to improve effectively the resistance to chloride ingress, and the hydrophobicity remained valid after 12 years of exposure [48]. The organic coating applied on the concrete surface usually comprises of primer and finish layers, and the epoxy-resin coating still showed good resistance to chloride ingress after 19 years of exposure in the splashing zone [49]. The cracking was also intentionally created in exposed specimens, and the self-healing was observed for cracks with openings less than 0.5 mm and the healing capacity of concrete incorporating different cements followed: OPC > FA cement > slag cement [15].

Environmental factors

The temperature of seawater will directly affect the chloride diffusion rate in concrete structures, and a higher temperature promotes the chloride penetration [50]. *The seawater salinity* determines the intensity of action of chlorides ingress, and a higher salinity increases also the apparent chloride diffusion coefficients, but the influence is weaker than the seawater temperature [50]. *The contact conditions with seawater* on different heights of exposure gave different values of apparent chloride diffusion coefficients: splashing < tidal zone < immersed zone [51]. *The distance from the coastline* determines the deposit quantity of chlorides on the concrete surface, and the chloride content of the concrete surface was observed to follow a power function of the distance from coastline [52]. The wind speed will determine the reach of chloride aerosol: the concentration of air-borne chlorides in marine air increased significantly as the wind exceeded the critical speed of 3.0 m/s [53].

Performance factors

The strength of concrete materials provides a first engineering indicator of performance under marine exposure. According to Chalee et al. [54], the compressive strength of OPC concretes decreased slightly but concretes incorporating rice husk-bark ash gained in compressive strength after 5 years' exposure. *The physical properties and appearance* of concrete specimens, including the cracking and pore structure, can be characterized as the affected performance of concrete [15]. *The electrical resistivity* is among the easily measured physical properties and can be related to the corrosion resistance of reinforced concrete [55] though the nature of this relationship is yet to be explored. *The chemical and electrochemical factors* refer to the chemical composition in concrete, such as the contents of chlorides and sulfates, and the electrochemical state of embedded steel rebars, such as the AC-impedance and potentiodynamic polarization [56].

Uncertainty and statistical properties

Most of the above information is by nature associated with uncertainties. Three sources of uncertainties can exist for exposure data: physical, statistical and model uncertainties. The physical uncertainty refers to the inherent randomness and variability of physical quantities such as the recorded seawater temperature and the measured cement content in hardened concrete. Each physical quantity has its own variability and can be described through statistical laws [57]. In determining the statistical properties for a certain quantity, sampling is necessary. Since sampling number cannot be infinite, the sampling is always insufficient for the complete description of statistical properties, where the statistical uncertainty arises. This uncertainty can be decreased by more sampling. When using exposure data to regress physical properties, models are sometimes needed, e.g. solution of Fick's second law used in regressing apparent chloride diffusion coefficient [58], and uncertainty will be introduced when the model used is not accurate. This uncertainty can only be decreased through the improvement of modeling. Whatever the source, a high degree of uncertainty will need more specimens and more data to support a valid interpretation. Thus, it is important to clarify the sources of uncertainties and narrow them down.

3.3 Essential information for presentation of marine field exposure data

On the basis of the above review, it is attempted to establish the minimum ensemble of information for a marine exposure dataset. Table 2 summarizes the factors already reviewed and divides the factors into three groups: the environment, the material and the performance groups. The material factors refer to the information and characteristics of concretes prior to the exposure operation. Note that this table provides a minimum collection of information relevant to marine field exposure and more information would be necessary for specific exposure purposes.

Table 2: Dataset for standard presentation of long-term marine field exposure data

Group	Factors and indexes	
Environment	Exposure station description	station owner/operator (ID), exposure location (ID), opening year, status of station, exposure conditions provided, capacity of exposure station
	Meteorological and hydrological conditions	Atmospheric temperature, relative humidity, wind speed, precipitation, exposed zones (atmospheric, splash, tidal submerged), seawater salinity, temperature, chloride concentration and sulfate concentration
	Additional environmental conditions	ambient temperature variation, relative humidity variation, additional seawater chemistry, chloride deposition rate
Materials	Concrete specimen label	specimen ID, mix ID, specimen geometry, casting date, exposure date, exposure location/station (ID)
	Concrete mix proportioning and properties	mix proportion, air content and chloride content of the fresh concrete, density and slump of fresh concrete, laboratory production and curing, compressive strength of concrete at 28d
	Raw materials and other properties	type, chemical composition and physical properties of cement and mineral admixtures; type, maximum size and grade curve of aggregates; specimen surface cracking (if apply)
Performance	Concrete mechanical properties	compressive strength; dynamic modulus of elasticity (if apply)
	Chloride profiles	chloride profile, test method of chlorides
	Steel profiles (for reinforced concrete)	corrosion potential, corrosion rate, resistivity tensile strength (if apply)
	Additional performance data	profiling of other ion species, carbonation/leaching depth, microclimate of specimen surface, concrete cover compactness, concrete surface cracking

3.4 Sampling and testing

The complete presentation of field exposure data needs to specify the sampling procedure and test methods so that the obtained data can be interpreted correctly, and compared and shared among different exposure stations.

Sampling and conditioning

Samples of concrete for characterization analysis are usually obtained from the surface to the inner part of the exposed specimens by dry-coring or dry-cutting, to avoid any dilution of chlorides [54, 59]. For chemical composition analysis, e.g. chloride profiling analysis through titration and acid-soluble testing, an amount of at least 10g of powder sample should be collected from each specimen at different depths, and sieved through 100-125μm to obtain a homogenous sample of particles [60]. Prior to testing, the cores, prisms and powder samples are usually oven-dried under mild temperature of 50 °C, to preserve the microstructure below micrometer scale and minimize the possible thermal damage [59].

Testing

General standards for testing exposure specimens have not yet been established. For chloride content measurements, the profiling method is usually applied using the powder samples collected from different depths of specimen, and the chloride content can either be determined through water soluble method (RILEM TC178-TMC) or acid soluble methods (ASTM C1152, AASHTO T260). The corrosion-related properties can include the half-cell potential of embedded bars (ASTM C876, NMX C495), the corrosion rate of steel (ASTM G102, NMX C501), and the concrete resistivity (NMX C514). A handheld non-destructive equipment, of RapiCor type, was used to measure simultaneously the half-cell potential, corrosion rate and resistivity of the cover concrete [61]. The carbonation depth is usually determined by the spray of phenolphthalein solution (NMX C515) or other reagents (EN 12390-12).

4. Interpretation and exploitation of long-term data: modeling and needs

So far, a considerable amount of exposure data has been obtained from long-term exposure sites and real structures in marine environments [10, 13, 59, 62-63]. Modeling is needed to interpret these data, especially the chloride ingress, providing the basis for durability design of RC structures. There are various models for chloride ingress in concrete exposed to marine environments [64], and a recent review of models can be found in the work of RILEM TC 270-CIM. These models are briefly summarized as follows.

4.1 Models based on analytical solutions to Fick's 2nd law

The model of general ERFC (Error-function solution to Fick's 2nd law) with constant diffusion coefficient is widely used for chloride ingress since Collepardi et al. [65]. This model obtained the chloride diffusion coefficient and the surface chloride content by curve-fitting the ERFC to measured chloride profiles. *The model ERFC with time-dependent diffusion coefficient* adopts an age factor to make the apparent chloride diffusion coefficient decrease with time, adopted by the "DuraCrete" project [66] and by *fib* [67]. *The false ERFC model with time-dependent diffusion coefficient and surface chloride content* was proposed as the simplest empirical model considering the time-dependence of both diffusion coefficient and surface chloride content [68]. *The Mejbro-Poulsen model with time-dependent diffusion coefficient and surface chloride content* was based on a sophisticated mathematical solution to Fick's 2nd law [69-70], too complex to be used conveniently. And the time-dependent chloride diffusion coefficient in this model refers to its instantaneous quantity. The ACI Life 365 software [71] employed also the instantaneous diffusion coefficient to predict chloride ingress with time-dependent diffusion coefficient and surface chloride content. For comparison, the diffusion laws in Duracrete [66] and *fib* [67] used the apparent diffusion coefficient averaged over the given exposure duration, which is different from the instantaneously measured one at specific exposure age [72]. These models focus on the chloride ingress and are convenient to use for engineering, but the chloride ingress is greatly simplified as pure diffusion [73]. So, these models cannot provide accurate prediction for complex chloride transports in Figure 1.

4.2 Models based on physical and chemical processes

There are also models considering the physical and chemical processes during the chloride ingress other than pure diffusion, including the convection, the interaction between chlorides and other aqueous ions, and interaction between aqueous ions and solid phases. *The ClinConc (two-steps) model* used Fick's law to describe free chloride transport firstly and then calculate the bound chloride by non-linear binding law [12]. The material parameters include the mixture proportioning and the environmental factors of the chloride concentration and the temperature of seawater. The output results include free and total chloride profiles. *The Multi-species models* used the Nernst-Planck equation for multi-species transport and interactions [74-75]. So far, these multi-species models can consider more complex equilibria between the pore solution and the solid phases [76-80]. *The models with convection transport* were also developed to consider the capillary absorption under drying-wetting cycles or under non-saturated conditions [63, 80-82]. The multi-phase or multi-component models used 2D or 3D numerical solutions to simulate the chloride transport among different phases or components [83].

4.3 Other models

The models of chloride ingress with concurrent carbonation were proposed analytically through moving boundary problems [84] and numerically through multi-species scheme [85]. These models can be used to predict the chloride ingress of concrete exposed to the marine atmosphere. Different chloride diffusion coefficients should be specified for carbonated concrete and non-carbonated concrete, and the humidity of medium range (roughly 75%) will have the most pronounced effect for impact of carbonation on chloride ingress. *The square root model* was proposed to denote the time dependent penetration depth of chlorides into concrete surface in marine exposure conditions. This model originated from the ''square root observation'' of a linear relationship between the depth of a reference chloride content and the square root of exposure duration [86-87]. *The model based on electrical resistivity* introduced additional factors to relate the measured electrical resistivity to the apparent chloride diffusion coefficient of concrete [88]. These models provide good complements to the foregoing two groups of models.

4.4 Benchmark of various models

In the past decades, several benchmarks were conducted to evaluate various models against the exposure data of chloride ingress. The first benchmark was performed in 2001: eight models were benchmarked using the 2-years data from the field exposure site (western coast of Sweden) as input for calibration of the models and then prediction of chloride profiles after 100 years [68]. The second benchmark was carried out in the EU-project ChlorTest: some 16 models covering the models in 4.1/4.2 and the resistivity model in 4.3 were involved, using the short-term (2-10 years) field data from Sweden and Spain as input for calibration and for predicting the chloride profiles after 100 years [89]. The results of these two benchmarks are given in Figure 3 and Figure 4 with dramatic scatters among different models. The most recent benchmark was carried out by RILEM TC 270-CIM. Some 14 models covering those described in 4.1 to 4.3 (except the resistivity model) were involved in this benchmark. Again, the field data from Sweden were used to calibrate the 14 models which were then used to predict chloride profiles after 100 years. The scatters among predicted results after 100 years are found to differ significantly in the range of depth at 0-10 mm, as shown in Figure 5.

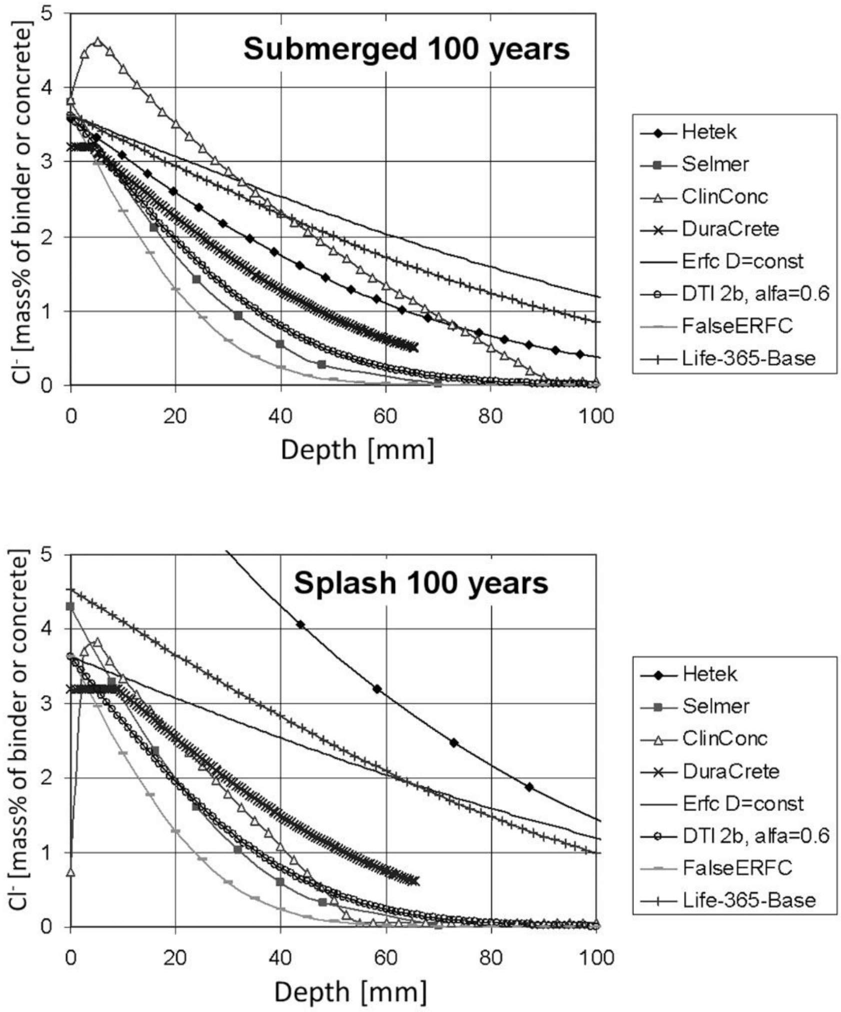


Figure 3 – Predicted chloride profiles for concrete with 95%PC (CEM I)+5%silica fume, w/b 0.40, after 100 years under the submerged marine condition in the 1st benchmark. Data from Nilsson [68]. Hetek - Mejbro-Poulsen model; Selmer - ERFC with Selmer's own age factor; DTI 2b – ERFC with age factor 0.6; Life-365 – A numerical solution. The model users were supplied with concrete mix proportion, D-values measured at 6 months by both the immersion test (NT BUILD 443) and the rapid chloride migration test (NT BUILD 492), chloride profiles measured from the submerged concrete in the Swedish west coast seawater after 0.6, 1 and 2 years, and the annual average chloride concentration and temperature in the seawater as well.

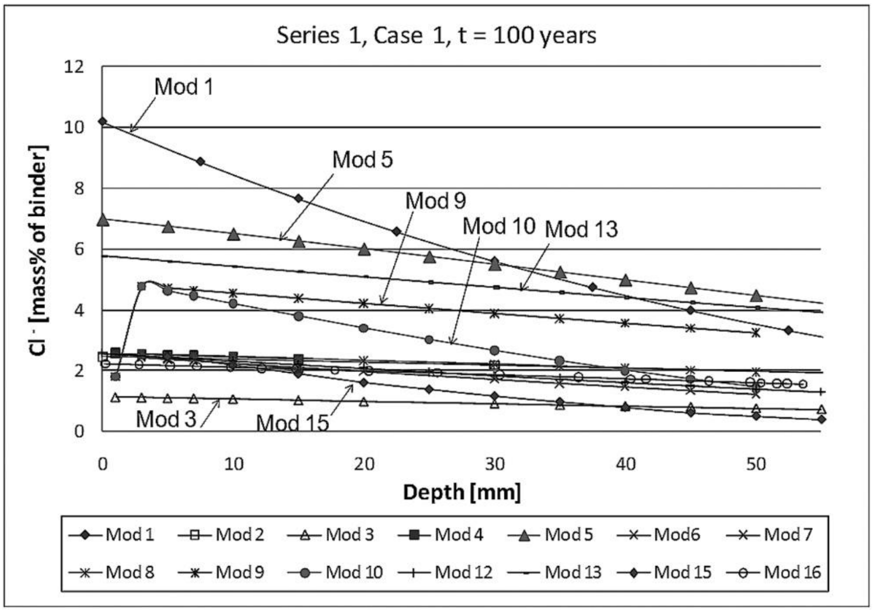


Figure 4 – Predicted chloride profiles for concrete with 100%PC (CEM I), w/b 0.40, after 100 years under the submerged marine condition in the 2nd benchmark. Data from Andrade [89]. The model users were supplied with cement compositions, concrete mix proportion, D-value measured at 6 months by the rapid chloride migration test (NT BUILD 492), chloride profiles measured from the submerged concrete in the Swedish west coast seawater after 0.8 years, and the annual average chloride concentration and temperature in the seawater as well.

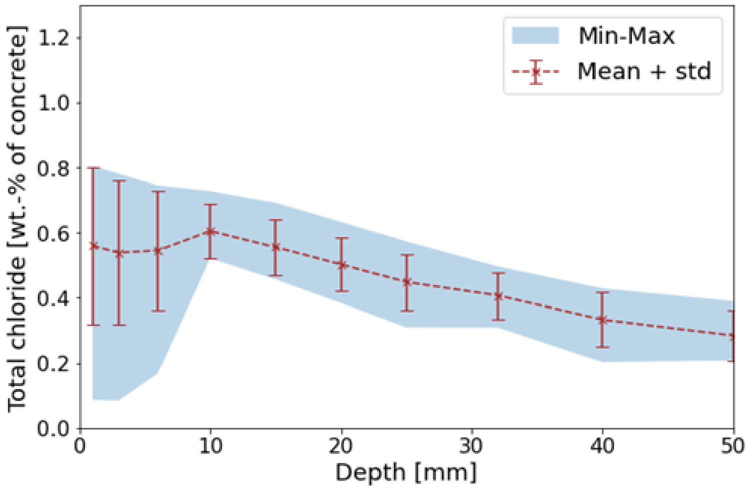


Figure 5 – Predicted chloride profiles for concrete with 95%PC (CEM I)+5% silica fume, w/b 0.40, after 100 years under the submerged marine condition in the recent benchmark. Data from Soive et al. [63]. The model users were supplied with the same information as given in Figure 4.1, and the additional data including moisture profile after 2 years' exposure, and the surface chloride contents curve-fitted after 0.6-2 years' exposure as well. In total 14 model users participated in the benchmark evaluation.

4.5 Need for new engineering indicators and exploitation of long-term data

The benchmark results in section 4.4 illustrate the large scatters in the predicted long-term chloride profiles. This situation is, at least partly, due to the incomplete description of the boundary conditions and the strong environment-material interaction in the outmost surface. Concerning the boundary conditions, Flint et al. [90] demonstrated the importance of the actual exposure conditions and its impact on the long-term hygrothermal conditions and chloride ingress in reinforced concrete. The environment-material interactions involve such processes as chloride ingress, carbonation, drying-wetting cycles, leaching, freeze-thaw cycles and abrasion/erosion actions, cf. Figure 1. The interaction between the marine environment and the near surface resulted in an elemental zonation feature [91-92]. Fjendbo et al. [93] show that the near surface zone of the concrete undergoes gradual and systematic changes in the composition in the marine tidal and submerged zones. Systematic changes were observed within 10mm from surface after ten years marine exposure and resulted in non-monotonous profiles with a maximum near the depth of phase changes. For concrete in the marine atmospheric exposure, Li et al. [94] demonstrated the importance of carbonation along with the chloride ingress. These results confirm the need to account for these near-surface changes and upgrade the prediction capacity of these models.

In parallel to the development of more advanced models, simplified indicators for engineering are equally expected. As such, the square root time-dependent ingress depth of a reference concentration was proposed [86] and further documented as a general feature from the chloride profiles from North European exposure stations [87]. This penetration (or ingress) depth, if linked to data for chloride thresholds for corrosion initiation, could be a direct indicator to judge the corrosion risk of embedded steel bars. Finally, to explore the global use of long-term exposure data, both valid and reliable prediction models and sufficiently detailed environmental data are at need. If such system can be established, the practice of exposure sites can be greatly optimized in the global scope by applying the long-term exposure observations from one site for design at other exposure conditions.

5. Long-term exposure stations: technical requirement and support for management

5.1 Design and operation of exposure sites

Establishing exposure stations involves the design and operation phases. The design phase should consider the geographical location, facility support, the support structures and the specimens placing and protection. The operation phase includes the monitoring of specimens, the sampling and tests on the concrete specimens, and the maintenance of facilities as well.

Design of exposure sites

Most of available exposure stations in marine environment have been established for general use. The choice of these sites mainly considers the representativity for hydrology and meteorology for a given region, accessibility of transportation and power supply, easiness for construction and the minimized impact on the surrounding environments. Usually, these sites are built in facilities sheltered, by natural bay or breakwaters, from direct actions of waves and tides of seawater for safety consideration of supporting structures and the concrete specimens. The support structures are either newly designed or situated in existed facilities, such as wharfs and floating pontoons, and create locally different exposure conditions for concrete specimens, i.e. atmospheric, splashing, tidal and immersed zones.

The concrete specimens or elements are fabricated and cured in laboratory after a given scheme and then transported and placed to different exposure conditions. The geometry of concrete specimens is adapted to the exposure purposes. These specimens are either tested on site or taken to laboratory on predetermined time basis for chloride ingress, corrosion state of steel and other analysis. For exposure sites built for specific projects, they are expected to represent the exposure conditions of real projects, not necessarily sheltered. The other aspects remain the same as the sheltered stations while the fixation of concrete specimens in support structures should be considered specially for stormy climates. Table 3 summarizes the main technical considerations of major exposure sites in world scope.

Monitoring, sampling and testing

The exposure stations depend heavily on the sensors, equipment and probes to record the environmental conditions, the behaviors of concrete specimens and the safety of support structure. The collected data should be stored and managed properly to support relevant technical activities. The environmental conditions to be recorded can be referred to Section 3.1. These data can be acquired directly by equipment and sensors installed in exposure sites or be procured from meteorology and hydrology stations. Table 4 summarizes the main sources of data procurement and data management.

The recording of the durability performance of concrete specimens is the central issue in exposure site operation. The concrete specimens, after standard laboratory curing to given ages, are normally subject to their initial laboratory characterizations before being placed into different conditions. With the exposure time, the specimens are either measured in-situ through pre-installed sensors or taken out and sampled for laboratory tests. These measurements target mainly at the ingress of aggressive ions (chlorides and sulfates), the carbonation, and the corrosion-related properties of RC specimens. The relevant methods are reviewed in Section 3.4. Calcium profiles can be used to correct the variation in cement paste content if the aggregates do not contain acid-soluble calcium. If protective coating is applied, additional tests for the effect of the coating can be included. The sampling and testing frequency are predetermined for specific purposes, cf. Table 3. The data management evolves rapidly, using more and more electronical formats and computerized tools, and the good management of these data promotes their sharing and reuse.

Lastly, the service state of support structures is of equal important if the structure is specially designed to hold the concrete specimens. To master the safety of these structures, the operator should monitor the marine hydrodynamics, including hydrology, seawater erosion, sediment flux and floating mud, to evaluate their service state on timely basis. These results provide technical basis for the maintenance and repair for the support structures.

Table 3: Main technical considerations for design of marine exposure sites

Exposure site	Climate	Siting conditions	Support structure	Specimen		
				Fabrication	Positioning and protection	Sample collecting
Zhanjiang Port (China)[18]	Subtropical marine, southeastern coast of China	Marine coast, Shielded conditions	Wharf structure, RC frame	150 mm×150 mm×300 mm; 28 d laboratory curing; Labelling after zone- concrete-purpose	Specimens placed in different exposure conditions relative to seawater, positioned and protected by stainless steel cages; facilities designed to withstand typhoons and ship collisions.	Samples collected at pre-determined intervals; numbers of samples collected according to specimen size and purpose: corrosion of rebars, chloride ingress, ageing of coatings.
Hong Kong-Zhuhai-Macau Bridge (China)[19]	Subtropical marine, southeastern coast of China	Offshore, unshielded conditions	Independent RC frame, built for exposure	150 mm× 150 mm × 150 mm (plain concrete), 150 mm×150 mm×300 mm (RC specimen); 28 d laboratory curing; Labelling after zone- concrete-purpose	Same as above	Same as above
Träslövsläge (Sweden)[11]	Nordic marine, west coast of Sweden	Marine coast, shielded by breakwater in harbor	Floating pontoons [11]	1000 mm×700 mm×100 mm; 14 d laboratory curing; Labelling with stainless steel plate	Specimens mounted on the floating pontoon with the half of the length submerged in the sea	Chloride profiles after exposure for 0.5-1a/2a/5a/10a/20a, and corrosion conditions after exposure for 13a/20a [95]
Fehmarn Belt (Denmark)[42]	Nordic marine, south coast of Denmark	Marine coast, shielded by breakwater in harbor	Steel rigs fixed on sheet pile wall [42]	2000 mm×1000 mm×200 mm; 43-49 days curing; Labelling with imprint on top and marking on stainless steel eyebolts for lifting	Specimens mounted in steel rigs with the 700mm above and 1300mm below normal water level.	Chloride and calcium profiles for 15 mix designs after exposure for 0.5a/2a/5a/10a, and continuous monitoring of corrosion for 3 mix designs.
Cape Peninsula (South Africa) [20]	Temperate, eastern (Granger bay) and western (Simonstown) peninsula	Marine coast: shielded by a dockyard (Simonstown), unshielded with strong wind (Granger	Sea wall	Plain concrete block specimens; different curing methods; 28 days (age at the start of exposure)	Secured through chains; specimens exposed to upper tidal and spray zones, oriented towards the worst combination of drying and seawater spray	Chloride content and durability indicators, on predetermined time basis

		bay)				
Wheat Island, Qingdao (China)	Temperate monsoon climate, northeast coast of China	Marine coast, Shielded conditions	Natural reefs and RC frame	100 mm×100mm×100 mm (plain concrete); 100mm×100mm×300/400mm (RC specimen); 28d laboratory curing; Labelling after zone-concrete-purpose	Same as Zhanjiang Port	Same as Zhanjiang Port
Progreso Port, Yucatán, (México) [7]	Tropical climate, Coast of Mexico Gulf	50-780m from the coast, total exposure to marine air	Aluminum frames	150mm×150mm×300mm (plain concrete/RC); 28d laboratory curing; Labelling after Number-w/c ratio-prevailing or Non Prevailing wind	Specimens with one 150mm×300mm surface oriented toward the prevailing winds.	Carbonation depth, profiles of chlorides and sulfates measured on predetermined basis; Half-cell potential and corrosion rates measured monthly using the rebars in RC prisms
NPRA (Norway)	Nordic marine, Norwegian coast	Marine coast, shielded by breakwater in harbor (Solsvik, Austefjorden)	Quay	300mmx300mmx3000mm (Sandnessjøen, Solsvik), 190mmx390mmx2700mm (Austefjorden); minimum 14d curing; Labelling according to composition	Specimens placed partially submerged in seawater with parts in air, tidal zone, and submerged; secured through chains (Sandnesssjøen, Solsvik) or steel frame (Austefjorden)	Core extraction and determination of chloride content (profiles) at predetermined intervals; Regular measurements (Sandnessjøen) or instrumental monitoring (logging) of signals (Solsvik, Austefjorden) for corrosion activity above, in and below the tidal zone.
Huelva (Spain)[10]	Mediterranean climate, Southwest coast of Spain	Marine coast, shielded beach of 200m long, closed to public	No	Reinforced concrete blocks of 50x50x2000cm made with different cement types and reinforcements	Blocks half-buried in sands (1m), half-exposed to tidal actions (1m)	Cores drilled and chloride profiles determined by grinding powder; Corrosion rate and resistivity measured since some years ago

Table 4: Main data sources and data management for specimens on marine exposure sites

Exposure site	Test methods and measured indexes				Data management	
	Concrete	Rebar	Coating/silane	Others	Recording and storage	Implementation and use
Zhanjiang Port (China) [18]	Chloride profiling from ground powder (ASTM C1152); Measured Indexes: chloride content, apparent chloride diffusion coefficient, surface chloride concentration	Corrosion rate of rebars in concrete (ASTM C876); Measured indexes: corrosion potential, corrosion current, polarization resistance	Bonding force coating/concrete (ASTM D7234), Depth of silane and water absorption of concrete (ASTM C1585); Measured Indexes: bonding force, impregnation depth, water absorption	Resistance to chloride penetration in concrete mixed with hydrophobic pore-blocking agent (ASTM C1585/C1152) Measured Indexes: water absorption, apparent chloride diffusion coefficient	Manual recording and file storage on paper formats (before 1990's), and computerized recording and storage in specific database developed (after 1990's)	Data centralized Storage and implementation by CCCC; Data accessible to authorized parties; Support to update relevant technical specifications.
HongKong-Zhuhai-Macau Bridge (China)[19]	Same as above	Same as above	Same as above	Same as above	Computerized recording and storage in specific database; included into integral HZM project mega-database of service state control.	Data storage and implementation by CCCC (owned by HZMBA); Data accessible to authorized research units; Support to HZM project.
Träslövsläge (Sweden) [11]	Chloride profiling from ground powder (NT BUILD 443) Measured Indexes: chloride content, apparent chloride diffusion coefficient, surface chloride	Corrosion condition of rebars in concrete (ASTM C876; RapiCor); Measured indexes: corrosion potential, corrosion rate, resistivity of cover	Not included	Not included	Manual recording and file storage	Data published in technical reports; data accessible to public in form of electronic tables

	content	concrete				
Fehmarn Belt (Denmark) [42]	Chloride and calcium profiling from ground powder (NT BUILD 443) Measured Indexes: chloride and calcium content, apparent chloride diffusion coefficient, surface chloride content, compressive strength, microstructure by petrography	Corrosion condition of rebars in concrete (3 mixes) (ASTM C876); Measured indexes: corrosion potential, corrosion rate	Not included	For three mixes: Corrosion initiation on anode ladders. Self-healing of cracks and corrosion initiation of intersecting rebars.	Automatic monitoring and file storage of corrosion data. Manual recording and file storage of concrete exposure data.	Data published in technical reports; data accessible to public in form of electronic tables. Data available at: www.concreteexpertcentre.dk
Wheat Island, Qingdao (China)	Chloride profiling from ground powder (JTS/T 236-2019); Measured Indexes: Same as Zhanjiang Port	Same as Zhangjiang Port	Depth of silane and water absorption of concrete (ASTM C1585); Measured Indexes: impregnation depth, water absorption	Same as Zhangjiang Port	Recording and storage in specific database developed (built in 2010)	Data storage and implementation by QUT; Data accessible to authorized units; Support to project (Qingdao Bay Bridge)
Port Progreso, Yucatán, (México) [7]	Carbonation front (NMX-C-515); Profiles of water-soluble chlorides (RILEM TC 178-TMC); Resistivity (NMX-C-514) Measured indexes: Carbonation depth,	Corrosion conditions for rebars in concrete (NMX-C-501, NMX-C-495); Measured indexes: corrosion potential, corrosion current, polarization	Not included	Physical properties of concrete [96] Measured indexes: Water absorption rate, effective porosity	Manual recording and file storage on paper formats, then computerized recording and storage in specific database developed	Support to Mexican NMX standards and projects in the same region

	Chloride diffusion coefficient, resistivity	resistance				
NPRA (Norway)	Chloride profiling from ground powder (spectrophotometric or potentiometric method); Measured Indexes: Same as Träslövsläge station	Corrosion conditions of rebars in concrete Measured indexes: corrosion potential, electrical resistance	Not included	Resistance to chloride penetration in (1) pre-cracked beams, (2) concrete mixed with corrosion inhibitor, (3) concrete mixed with hydrophobic agent, (4) concrete mixed with latex (Sandnesssjøen) Measured Indexes: Same as concrete tests	Manual recording and file storage on paper formats, then computerized recording and storage	Data used for revision of NPRA rulebooks; chosen data published in technical reports and/or journals
Huelva (Spain) [10]	Chloride and XRD profiling Measured indexes: chloride content, apparent chloride diffusion coefficient, surface chloride content	Corrosion rate through Linear polarization Measured indexes: corrosion rate	Not included	Several cement types and concrete mixes with galvanized and stainless steel rebars	Data recorded every year until around 20 years	Data collected by authors and support for general research and engineering projects.

Maintenance of exposure facilities

The regular inspections and proper maintenance of facilities in exposure stations are crucial to keep the functionality of stations. The routine and regular inspection consists of checking the components in the support structures, the defects of the monitoring equipment and cables, and the position and integrity of exposure specimens. After stormy events for unshielded sites, special inspections should be arranged. If any defect or failure is detected, a maintenance should be planned and performed. The regular maintenance includes replacing the defective components, removing marine biological growth, placing supplementary specimens, and retrofitting the support structures if necessary. Special inspection and maintenance are to be activated after accidental events such as ship impact, typhoon and earthquake. Under such situations, a comprehensive inspection is required for the structural safety, monitoring system, and operation states of the exposed station.

5.2 Support for service life management

The exploitation of field exposure data has two-fold purposes: to understand the underlying durability mechanisms and to calibrate durability models to support the life-cycle management of concrete structures. The former has been handled in Section 2 and Section 4, and this section focuses on the latter aspect. A large-scale sea link project, Hongkong-Zhuhai-Macau (HZM) bridge, is retained to demonstrate the support of long-term exposure practice to the life cycle management.

Overview of HZM sea link project

The HZM project was built on the southeastern coast of China, linking the cities of Zhuhai and Macau to the Hong Kong city, cf. Figure 6. The design working life of the whole project is 120 years, and the project was open to traffic in 2018. Concrete was extensively used in the structures of the project, including sea bridges, immersed tube tunnel and the offshore artificial islands. The main RC elements are summarized in Table 5. These RC elements were subject to a model-based durability design using a chloride ingress model calibrated on local long-term exposure data [57]. The durability performance of these RC elements was further assessed in the construction phase using the in-situ measurements [97]. On this basis, a preliminary maintenance plan was proposed. Table 5 lists the main durability requirements with the corresponding maintenance plan for typical RC elements. The inspection and monitoring are planned for the service phase of the project using pre-installed sensors and long-term exposure to monitor the chloride ingress and the corrosion of rebars. An exposure station was thus built on the west artificial island, cf. Figure 6 (right). From the inspections and monitoring, the model-based durability assessment is to be performed on regular basis, and the assessment results will further adjust, if necessary, the maintenance plan. It is through this interactive scheme that the long-term durability of RC structures can be ensured [19].

Table 5: Durability requirements, measures and maintenance planning for RC elements in HZM project

Construction	Element	Exposure	Concrete			Protection measures	Preliminary maintenance planning	
			Class	Cover (mm)	Cl diffusivity (10^{-12} m^2/s)		Techniques	Period (year)
Navigable spans, Cast-in-place	Pylon	Salt fog	C60	60	3.5 (2.2)*	Stainless bars Silane impregnation	Chloride extraction Silane impregnation	40
	Pier (exterior)	Salt fog	C50	60	3.5 (2.2)	Silane impregnation	Chloride extraction Silane impregnation	20
		Splashing	C50	60	3.5 (2.2)	Stainless bars Silane impregnation		40
	Pier (interior)	Salt fog	C50	50	3.5 (2.2)	-	Chloride extraction Silane impregnation	20
		Splashing	C50	50	3.5 (2.2)			20
	Bearing platforms	Splashing	C45	80	3.5 (2.2)	Stainless bars Silane impregnation	Chloride extraction Silane impregnation	40
		Immersed	C45	80	3.5 (2.2)	Stainless bars Silane impregnation	-	-
Non-navigable spans, Prefabricated	Pier (exterior)	Salt fog	C50	60	3.5 (2.2)	Silane impregnation	Chloride extraction Silane impregnation	20
		Splashing	C50	70	3.5 (2.2)	Epoxy-coated bars Silane impregnation		20 (*40*)**
	Pier (interior)	Salt fog	C50	50	3.5 (2.2)	- (>+8.00m) Silane impregnation (<+8.00m)	Chloride extraction Silane impregnation	20
		Splashing	C50	60	3.5 (2.2)			20
	Bearing platforms	Immersed	C45	60	3.5 (2.2)	Silane impregnation	-	-
Tunnel, Prefabricated	Tunnel segment (exterior)	Splashing	C45	70	3.5 (2.2)	Cathodic protection	Cathodic protection	100
	Tunnel segment (interior)	Salt fog	C45	50	3.5 (2.2)	-	-	-

* values out of parenthesis stand for 28d apparent chloride diffusivity and values in parenthesis for 56d diffusivity.

** the period in parenthesis is updated from the durability assessment using long-term exposure data.

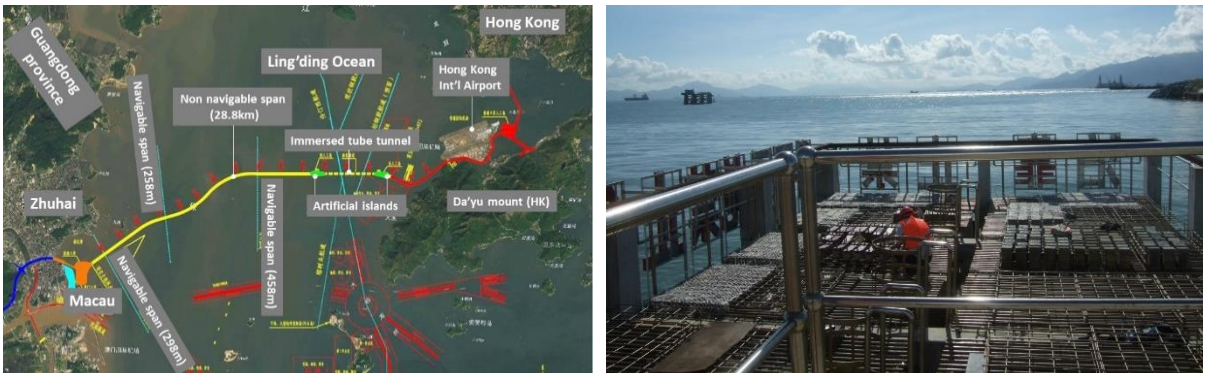
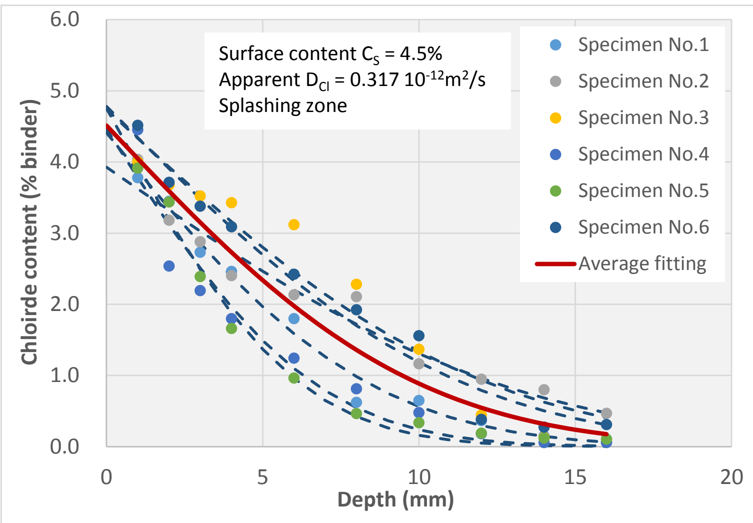


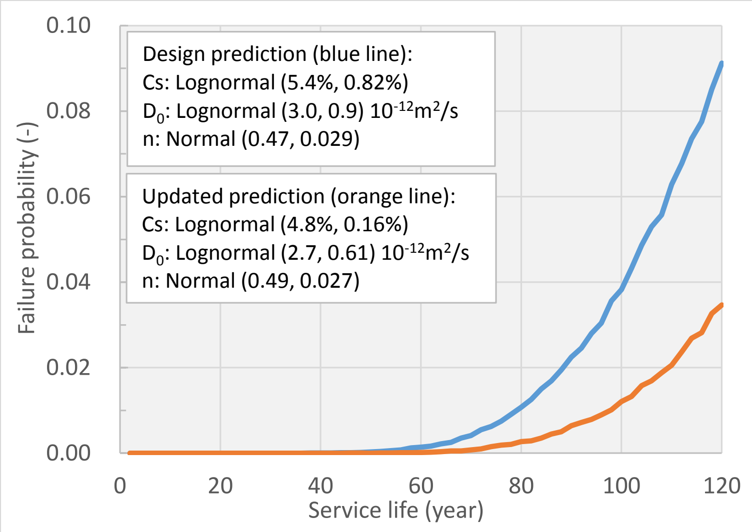
Figure 6: Overview of Hong Kong-Zhuhai-Macau sea-link bridge (left) and the long-term exposure station built on the west artificial island of the project (right). Source: Courtesy of Mr. Su Quanke (HZMBA)

Support of field exposure data

The exposure of concrete specimens started in 2014, cf. Table 4. On a pre-determined basis, the specimens are taken to laboratory for analysis of the following characteristics: the surface chloride content, the apparent chloride diffusivity and their time-dependence. The exposure data from the sampling of specimens, in 1 year and 3 years, are used here to demonstrate the updating procedure. Figure 7(a) gives the regressions of apparent chloride diffusivity from the measured chloride profiles in 3 years for splashing zones. The updating of the apparent chloride diffusivity and surface chloride content leads to the updating of the predicted durability performance of the RC elements. Figure 7(b) provides the durability assessment results in terms of failure probability with respect to the corrosion initiation of rebars. Using these results, the preliminary maintenance planning can be updated accordingly. Take the piers in non-navigable bridges for example: the first maintenance of surface silane impregnation can be adjusted from 20 years to longer periods, e.g. 40 years, for the part of piers in splashing zones. Though more data are needed to reinforce this recommendation, the interaction has been demonstrated clearly for the input of exposure data, the model-based assessment, and the dynamic planning of maintenance actions.



(a)



(b)

Figure 7: Regression of exposure data for chloride ingress after 3 years of exposure (a) and updating of durability assessment for RC piers in non-navigable bridges (b) for exposure in splashing zones. The updating scheme considers the change of surface chloride content C_s, the initial chloride diffusion coefficient D_0 and the ageing factor of diffusivity n.

5.3 Good practice for exposure stations

For design of marine exposure sites, the sites for general use should better be shielded from strong hydrological and meteorological actions, and the sites should have easy access to transportation of specimens and facilities. For sites built in projects, reliable protection should be assured for both support structures and the positioning of concrete specimens since they are usually unshielded from stormy climates. For operation of these exposure stations, the positioning, sampling and testing of concrete (RC) specimens should be planned before exposure tests. A clear and durable labelling of concrete specimens is important for sampling and testing. It is better to perform a complete characterization of concrete materials in laboratory just before the exposure. The obtained data are recommended to be stored in centralized and computerized manner, in parallel to the paper format documentation. Collaboration among different exposure stations and the related data interpretation are greatly encouraged to make the maximum use of available data.

6. Summary and Perspective remarks

1. The practice of long-term exposure of structural concretes in marine environment provides an important and precious data source for durability mechanism investigation and supports the mastering of long-term durability performance of concrete structures and infrastructures. So far, the major exposure sites in the world-wide scope, built either for general use or for specific projects, have played an important role in these two aspects. However, the practice needs to be improved to promote the efficiency of exploitation and sharing of these field exposure data, including the systematic presentation, interpretation and further exploitation of the exposure data.

2. The presentation of long-term exposure practice needs the information on the marine exposure sites and the information on the long-term performance of specimens. The information on exposure sites includes mainly the geographical location, local meteorological and hydrological conditions, and the exposure area planning. The long-term performance information involves the description of materials and specimens, and the quantified performance of exposed specimens. A preliminary dataset is proposed and integrates data groups of environment, materials and specimens, and performance. Two aspects merit attention: first, the test and sampling methods are not unified, so the comparison of data from different exposure site should check the test/sampling methods used; second, the dispersion of exposure data is due to uncertainties of different natures, and there is a strong need to quantify and narrow down these uncertainties.

3. The durability mechanisms of concrete exposed in marine environments involve both the environment-material interaction in near surface and the diffusion-dominating process in bulk concrete. Various models have been developed so far. A big family of models are derived from the analytical solution of Fick's 2^{nd} law, and how to handle the time-dependence of chloride diffusion coefficients and surface chloride content have been highlighted. Other models consider more sophisticated aspects for the physical and chemical processes during the chloride ingress to improve the predictions. The benchmarking of available models shows large scatters for predicted chloride profiles. This situation calls for more advanced mechanism-based models and more robust durability indicators for engineering use.

4. The exposure sites of general use are mainly for understanding the deterioration mechanisms of structural concretes under marine environments whilst the project-dependent sites provide the real durability performance of structural concretes and support the life-cycle management of the project. The design of exposure sites should consider the representativity for hydrology and meteorology, the accessibility of transportation and power supply, the easiness for construction and the minimized ecological impact. The operation of exposure sites should assure monitoring, sampling and testing of the concrete specimens, maintain a consistent strategy on the data management, and perform sufficient maintenance for the exposure facilities. From the available exposure results of HZM project, the updating for main durability parameters is demonstrated and the recommendation for maintenance planning is made. The life-cycle management of such projects necessitates incorporating systematically the exposure data into durability planning.

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Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

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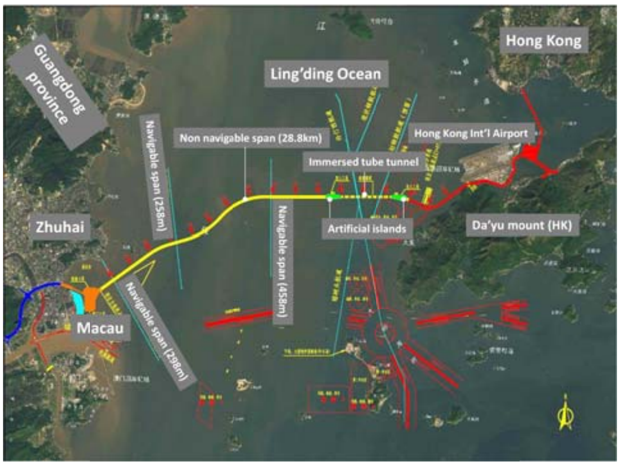

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