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Durability performance deterioration of concrete under marine environment from material to structure: A critical review

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Abstract: Corrosion induced deterioration of cementitious concrete and reinforced concrete (RC) is critical to durability, safety, and sustainability of infrastructures, especially for offshore concrete structures under marine environment. In this paper, the effects of marine environment on the deterioration mechanism, performance, and durability of concrete materials and structures are systematically reviewed. For the deterioration mechanism, the effect of the various chemicals in seawater and different marine exposure zones on the cementitious concrete and reinforced concrete is firstly analyzed and compared. At material level, this paper discusses the characterizations of cementitious concrete, including compressive strength, chloride diffusion, carbonation depth, and pore structure. Besides, the performance of cementitious concrete with the addition of supplementary materials was also compared when exposed to marine environment. While at structure level, the durability of RC structures, including beams and slabs, and its structures with corrosion protection under marine environment, is evaluated. This paper also assesses some cases of RC structures after many years of exposure to marine environment. Furthermore, prospectives are proposed for further applications on concrete under marine environment. The conclusions are of great benefit to the researchers and enginners in the concrete-related industry who aim to develop durable and sustainable concrete structures under marine environment.

Keywords: Cementitious concrete; Marine environment; Durability; Performance; Deterioration

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1. Introduction

With its commonality and comparatively low cost, concrete has currently turned into the most extensively used human-made construction materials all over the world and also becomes the preferred material for civil and infrastructure construction in the marine environment [1]. With the increase of offshore structures (including civil and military terminals, offshore airports, offshore wind power stations, sea lighthouses, radar stations, island reefs, and fortifications, etc., some of which are shown in Fig. 1 [2-4], it is critical to comprehend the durability deterioration of concrete under marine environment. Concrete exposed to marine environment is vulnerable to a variety of physical and chemical degradation procedures [5]. For example, chemical action of seawater composition on the hydration products of cement and crystallization pressure of salts within concrete if one side of the structure is affected by moisture and dry conditions, corrosion of embedded steel in reinforced or prestressed members, and physical erosion as a result of wave action and floating objects [6]. Therefore, it is necessary to study the behaviour of cementitious concrete and reinforced concrete (RC) under different seawater exposure conditions to evaluate seawater degradation of buildings working in the marine environment.

Various chemical substances in seawater have both beneficial and unfavourable impact on the performance of cementitious concrete under marine environment. The primary existence of chloride ions, sulphate ions and magnesium ions in the seawater can cause complex chemical reactions between cementitious concrete and those solutions [7-10]. The average content of dissolved salt in seawater is about 35 g/L [11]; however, the concentration of specific salt changes with the geographical location, which is especially different from the ions in the freshwater taken from rivers. Therefore, the ions in the seawater have a chemical attack in all the exposed cementitious concrete. Chlorides are able to be incorporated in calcium chloroaluminate hydrates such as Friedel's salts or Kuzel's salts, which can be attached to calcium silicate hydrate (C–S–H) and preserved in the pore solutions. Moreover, cementitious concrete in contact with seawater is corroded by sulphate, which can also cause deterioration to the structures [12]. The higher content of magnesium ions in seawater cannot be saturated in seawater to form brucite ($Mg(OH)_2$) because the pH of seawater is low. However, when seawater encounters high pH value, such as in one of the porous solutions (pH of 12.5-13.5) of typical concrete, brucite precipitates [13].

In addition, for the reinforced concrete, when the concentration of chloride in the RC reaches a certain threshold value, the chloride ion is absorbed on the surface layer of the steel bar, which accelerates the corrosion rate. In the case of sufficient oxygen and moisture, steel rebar starts to corrode with the existence of chloride ions [14]. As the corrosion occurrence, the extension volume of the corrosion product can be as high as two to six times of the original steel volume, which produces an increasing expansive pressure on the interfaces among concrete and reinforcements. Afterward, tensile stresses loss lead to surface cracking, delamination, spalling of concrete, a decrease of the transverse-sectional area of reinforcement, and loss of the bond between the concrete and steel reinforcement [14]. In construction industries, different corrosion protection and maintenance methods of RC are usually adopted when being in the marine environment. One of the most typical methods is the addition of mineral admixtures in cementitious concrete, which can facilitate the enhanced performance of the concrete and RC, such as strength, durability, and bio-deterioration resistance through a pozzolanic reaction [15-18]. The cementitious concrete and reinforced concrete structures, used in marine projects, usually need to be added by some supplementary materials to improve its performance.

Therefore, this paper reviews the performance of cementitious concrete under marine environment, at both the material and structural levels. At the material level, the impact of different salts contained in seawater on the chemical reaction of cementitious concrete (with or without additives) is summarised. The effects of major characterizations such as the compressive strength, chloride diffuse, and carbonation depth and pore structure are detaily discussed. Besides, the performance of concrete with the addition of supplementary materials was also compared when exposed to simulated or practice seawater environment. At the structural level, the properties of reinforced concrete structures and their evolution under marine environment are compared. Finally, the conclusions and suggestions are proposed in providing the basis for further studies on the durability of cementitious concrete and reinforced concrete structures under marine environment.

2. Deterioration mechanism of concrete and reinforced concrete

The service lifespan of concrete in the marine environment depends on the interaction of change of its physical characteristics and chemical reaction mechanisms [10]. It is well recognized that deterioration of concrete composites and construction under marine environment is principally controlled by permeability performance of concrete, which might be related to the different exposure marine environments and chemical reactions [19, 20]. Multiple chemicals in seawater possess a beneficial or secondary action on the characteristic of concrete in seawater environments, which has also been studied. Table 1 presents the chemical concentrations in seawater as specified by ASTM D1141-98 (Standard Practice for the Preparation of Substitute Ocean Water) [11]. It can be seen that the main chemical compositions contain KCl, $MgCl_2$, Na_2SO_4, $CaCl_2$, and NaCl and so on. In particular, chloride ions in seawater corrode steel bars are seriously influenced. The effect of $NaHCO_3$ and KBr is not discussed in this paper for its low content in seawater. In addition, the deterioration mechanism of different exposure marine environments on cementitious concrete is discussed. The effect of marine environments on the properties of cementitious concrete is mainly caused by the different salts with high concentrations, whose effects will be further discussed in the next subsection.

2.1 Effect of chloride salts on cementitious concrete

As can be seen from Table 1, the chloride ions from seawater environment are mainly originated from sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$) and potassium chloride (KCl). Chloride ions can permeate into cementitious concrete exposed to chloride salt solutions through diffusion, wicking and absorption processes [19, 20]. In the procedure of chloride ions' migration, a specific proportion of chloride ions is bound by the cement matrix, and some free chloride ions are left in the pore solution [21]. Fundamentally, chloride ions can trap in C-S-H. Meanwhile, chloride ions from NaCl, $MgCl_2$, $CaCl_2$, KCl can react with calcium aluminate (C_3A) and monosulfoalunimate (AFm) to form Friedel's salt ($Ca_4Al_2(OH)_{12}Cl_2 \cdot 4H_2O$) [22, 23] and Kuzel's salt ($Ca_4Al_2(OH)_{12}Cl(SO_4)_{0.5} \cdot 5H_2O$) [23, 24], the X-ray diffraction (XRD) results shown in Fig. 2.

Concrete exposed to NaCl or KCl solutions usually changes its microstructure owing to various chemical reactions, such as the formation of Friedel's salts [25, 26]. Suryavanshi et al. [27] revealed that in the existence of sodium chloride solution, Friedel's salt was formed through two independent mechanisms: adsorption and anion-exchange mechanism. Farnam et al. [28] confirmed that with the coexistence of NaCl and calcium sulfoaluminate phases in the cement matrix, there is an additional chemical phase transition to Friedel's salt. Jiang et al. [29] studied the effect of KCl as a chloride source on the steel reinforcement corrosion. The decalcification from Portlandite and C-S-H is a reaction in slow processes. The leaching of calcium leads to the increase of porosity and larger pores. In the existence of NaCl or KCl, Friedel's salt is constituted from a calcium aluminate hydrate and a soluble chloride origin after Eq. (1) and Eq. (3), or Eq. (2) and Eq. (4), as shown in Table 2.

Cementitious concrete exposed to $MgCl_2$ solution usually changes its microstructure owing to chemical reactions, including the formation of $Mg(OH)_2$, Friedel's salts, magnesium silicate hydrate (M–S–H), magnesium oxychloride, and/or calcium subordinate oxychloride; these changes may be followed by critical ruptures [30, 31]. Peterson et al. [32] reported the formation of $Ca(OH)_2$ and related ripping through cementitious concrete under the solution of $MgCl_2$ exposure. Farnam et al. [33] showed that the conformation of calcium oxychloride follows the phase diagram of $Ca(OH)_2$–$CaCl_2$–H_2O, which results in the deterioration in cementitious concrete under chloride ion and magnesium ion environments. $MgCl_2$ can react with Portlandite in cementitious concrete to generate $Mg(OH)_2$ and $CaCl_2$, as displayed in Eq. (5). When $Mg(OH)_2$ and $MgCl_2$ exist together in the ternary system on account of the $Mg(OH)_2$–$MgCl_2$–H_2O, magnesium oxychloride ($3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$

and 5 $Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$) are formed as shown in Eq. (6). As shown in Eq. (5), if $Ca(OH)_2$ is left in the matrix, $CaCl_2$ created as Eq. (5) results in the formation of calcium oxychloride. Sutter et al. [34] reported that calcium oxychloride was formed in detected specimens under the $MgCl_2$ solution owing to the reaction between calcium hydroxide and calcium chloride. In some cases, calcium ions can be substituted by the magnesium ions resulting in the transformation from C-S-H to M-S-H [35]. M-S-H can only be stabilized at a low pH range (7.5–11.5), while C-S-H can be stabilized in a pH range (10–12.5), which is mainly determined by the molar ratio of Ca/Si for C-S-H) [35].

Cementitious concrete under $CaCl_2$ solutions exposure shows different phases, resulting in deterioration during a reversely short time. Concrete exposed to $CaCl_2$ solutions showed significant damage due to the formation of calcium oxychloride [36]. The deterioration mechanism of calcium oxychloride on the cementitious concrete has also gained attention [37]. The phase diagrams of both $Ca(OH)_2$-$CaCl_2$ solution systems [38, 39] and cement paste-$CaCl_2$ solution systems [40] have been established. Concrete exposed to $CaCl_2$ solutions showed significant damage, which is because the formation of calcium oxychloride is able to react with calcium hydroxide ($Ca(OH)_2$) to form $CaCl_2$, as shown in Eq. (8). Additionally, Friedel's salt is formed from calcium aluminate hydrate and the source of $CaCl_2$ after Eq. (9). All the equations of Friedel's salt and Kuzel's salt are shown in Table 2.

2.2 Effect of sulphate salts on cementitious concrete

From the view of the chemical attack, the deterioration of concrete made with ordinary Portland cement (OPC) is partly or principally because of the existence of Portlandite (CH), which is the hydration product most susceptible to sulphate attack [41]. The sulphate ions from seawater environments are mainly from Na_2SO_4. Bellmann et al. [42] examined the impact of sulphate on gypsum conformation of mortar immersed in Na_2SO_4 solutions of different concentrations. Ogawa et al. [43] determined the performance of ordinary and mixed types of cement under the attack of 10% Na_2SO_4 through the loss of compressive strength of cubic specimens. When the external sulphate ions (Na_2SO_4) enters the porous cement and interacts with the hydration products of cement, the attack of external sulphate in the seawater environment will continue. Portlandite ($Ca(OH_2)$) can absorb sulphate ion and become gypsum ($CaSO_4 \cdot 2H_2O$), as shown in Eq. (10). The combination of monosulphate ($3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$) and external sulphate forms ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), as shown in Eq. (11). Both products (gypsum and ettringite) occupy a greater volume after crystallization in the pores of concrete than the compounds they replace.

The growth of pressure with the increasing ettringite crystals results in surface cracking known as the softening type of crack. Gypsum formed as a result of cation exchange reactions can also lead to expansion [44]. It is reported that the process of metamorphism of silicate cement paste hardening due to gypsum formation results in a reduction in stiffness and strength, followed by expansion, cracking, and ultimately the transformation of the material into a paste or non-cohesive material. Thus, the sulfate attack in seawater is associated with a progressive loss of strength and loss of mass of structural concrete. Sulfate constitutes the second not characterized by expansion caused due to a large amount of ettringite formed as a result of sulfate attack. According to Nehdi et al. [45], concrete attacked by sulfates has a characteristic whitish appearance. The damage was initially found at the edges and corners of the structure, followed by the gradual cracking and peeling of the concrete.

2.3 Effect of seawater on reinforced concrete

When RC is exposed to marine environment, many elements (sulphate, carbon dioxide, chloride, silicate, oxygen, water) participate in chemical reactions in different ways, there are various reactions that contribute to the corrosion process [46]. Corrosion starts by attacking the preventive layer on steel bars after the destruction of that layer concrete becomes highly reactive or ionize for the electrochemical corrosion process [47]. Corrosion is not constant at all over reinforcement because at different cross-section and environmental condition (ionic behaviour, water, oxygen salts, etc.), ions concentrations are different, which make the different intensity of corrosion at different places [48]. Because of chemical and salts reactions, anions and cations are formed at a different portion of the

RC system, which makes a full circuit for electrical current supply from one end to another (cathode and anode end). Due to the difference in ions (anode and cathode), salts react in the presence of oxygen and creates a heterogeneous environment and water solution, which acts as an electrolyte and starts an electrochemical process [49]. Fig. 3 demonstrates the fundamental reaction mechanism of corrosion activities.

Dispersion of passive film embedded over the reinforcement and occurrence of corrosion reaction occurs due to two reasons: chloride salt or carbonation (or combination of both processes) [49]. Chloride salt also participates in corrosion reactions. Typically, it reacts with cement to form calcium chloro-aluminates and calcium chloro-ferrites. However, chloride-hydroxides ($[Cl^-]/[OH^-]$) ratio reduces and causes the devastation of the negative protective film, and initiation of corrosion occurs. After this, either chloride makes threshold concentration or pH solution reduces steel with the carbonation process [49]. In the case of carbonation, carbon-dioxide (CO_2) reacts with water present in pores because of the ingression of moisture from the atmosphere or soil. It decreases the pH of concrete from 13.5 to around 9 [50].

2.4 Effect of marine exposure zones on reinforced concrete structures

The RC structures under marine environment are mainly exposed to three different environments, including atmospheric, tidal, and submerged zone. Different exposure conditions under marine environment are shown in Fig. 4 [51]. The primary transport processes under marine environment are usually included by the following parts: capillary absorption, permeation, ionic diffusion, migration, and convection, etc. [52]. In the atmospheric zone, structures are exposed to airborne chloride. The steel reinforcement corrosion, mainly caused by chloride, maybe a deterioration mechanism of this condition [53]. Furthermore, the RC structures can withstand deterioration due to carbonization, which may be related to other factors, including relative humidity or changing of temperature. However, corrosion caused by chloride is the main degradation mechanism compared with deterioration corrosion caused by carbonization [54]. As for the transport mechanism, both gas and water vapor diffusion can occur under such exposure conditions. In addition, absorption is one of the most common transport mechanism under atmospheric conditions, as rain occurs, resulting in alternate wetting and drying. Meanwhile, the RC structures may undergo physical degradation due to salt crystallization.

RC structures exposed to the tidal zone are generally considered in the worst state of deterioration [55]. The aggressiveness of the tidal exposure zone should be characterized, taking into account other factors, including climatic conditions, spatial variability, and frequency of the high and low tides. All mechanisms, such as diffusion, absorption, core-absorption, and osmosis, play an indispensable part in the transport of invasive kinds in the region. In addition, the mechanical action of waves may lead to visible wear. The deterioration caused by such wear can interact with the wetting-drying cycle resulting in salt crystallization. As for the cementitious concrete and RC structures wholly immersed in the seawater (submerged zone), no absorption occurs compared to the most common transport mechanism in atmospheric and tidal conditions. However, the permeability of the concrete is more important than in other conditions, resulting in the fact that the characteristics of diffusion can be a significant role [56-58]. Therefore, in this exposure condition, it is increasingly significant to evaluate the permeability of cementitious concrete and reinforced concrete structures than that of strength. Cementitious concrete may mainly deteriorate as a result of individual and combined chemical deterioration procedures such as sulphate erosion or leaching and deterioration by chloride, etc., which has already been discussed in detail in the above subsections. In addition, corrosion of steel has been reported to progress at different rates in the tidal and atmospheric marine environments, with very limited corrosion activity being reported in the submerged zone.

3. Cementitious concrete under marine environment

The effect of marine/seawater environments on the cementitious concrete is mainly manifested in the mechanical properties, durability, and microstructural characteristics. This section presents the compressive strength, durability including chloride permeability and carbonization of concrete under marine environment. The microstructure and pore structure changes of cementitious concrete under marine environment are also discussed. In addition, the performance of concrete exposed to marine environment with mineral admixtures was also compared.

3.1 Compressive strength

Compressive strength of cementitious concrete can be significantly influenced by marine environment. It is well known that concrete performance is associated with the characteristic of raw material, including cement types [59] and aggregate [60]. In addition, investigations have also been concerned with the beneficial impact of mineral admixtures on the performance of cementitious concrete under marine environments, mainly including fly ash (FA) [61, 62], pulverised fuel ash (PFA) [63], bark ash (BA) [64], metakaolin (MK) [65], ground granulated blast furnace slag (GGBFS) [66], silica fume (SF) [67], and also pumice [59], etc. Table 3 summarizes the compressive strength of cementitious concrete under marine environment.

As shown in Table 3, Hossain [59] observed the compressive strength of concrete cast with distinct ordinary cement (ASTM Types I, II, and V). Among them, Type I has the highest content of C_3A, while Type V has the lowest content of C_3A. After the cement replaced by the pumice used in casting concrete, it was noticed that the strength of concrete with Type I and Type II cement enhances with the addition of pumice content, with a maximum of about 20%, while the strength of concrete with Type V cement decreases with the increase of pumice under marine environment. Ramachandran et al. [60] examined the compressive strength of recycled aggregate concrete in seawater corrosion for 16 months, which indicated that with the enhancing of substitution rate and corrosion period, seawater had a considerable impact on the mechanical strength of recycled aggregate concrete.

When mineral admixtures are applied as partial substitutes for cement, the strength reduction of cementitious concrete under seawater exposure conditions can be reduced. Bose et al. [65] prepared different mortars immersed in seawater, replacing 0% and 30% of OPC with MK, and found that the specimens exposed to seawater displayed reduced strength, but the delay in compressive strength was smaller for the mortars with MK. Jau et al. [66] used GGBFS to replace OPC for up to 50% by weight to make GGBFS-OPC concrete, which has experienced wetting-drying cycles accelerated test for over one year under seawater corrosion. The compressive strength of concrete without GGBFS began to drop after half-year exposure, while the compressive strength for GGBFS concrete kept on increasing with time. Duan et al. [67] examined the effects of pozzolanic materials, including GGBFS, SF, and MK, on the compressive strength in a seawater condition for up to half-year exposure, and concluded that with the supplement of GGBFS, SF and MK, the strength of concrete would progressively increase without considering exposure conditions. Chalee et al. [64] utilized BA as a mineral admixture to be a substitute for OPC after 5-year marine conditions exposure, and found that there was no strength loss for the BA concrete in the marine environment. Hence, the seawater had a little influence on the strength reduction of the concrete containing BA.

Some studies also examined the concrete properties by replacing OPC with binary or ternary mineral admixtures blends under marine environments. Bai et al. [63] manufactured the concrete with 10%, 20%, 30%, and 40% replacements of OPC by MK and PFA, and immersed the specimens in synthetic seawater for 18 months. Both binary (OPC-PFA) and ternary (OPC-PFA-MK) blends can obviously improve the strength of concrete immersed in seawater, while further mixing the control and OPC-PFA concrete with MK greatly reduced the strength delay of specimens exposed to seawater environments. Seleem et al. [68] investigated the deterioration ratios (strength deterioration factor, SDR) of concrete incorporating SF, GGBFS, and MK in binary and ternary combinations and exposed them to synthetic seawater for more than 1 year. Except for mineral mixtures containing GGBFS, the SDR of all specimens increased with age increasing apart from the specimens containing GGBFS, which appreciates GGBFS as the most effective additive to maintain the strength of concrete in marine environments, compared to OPC–SF specimens exhibiting reversely higher strength values in the whole ages with rarely suitable as GGBFS in retaining strength. Yue et al. [61]

studied the mechanical behaviours of FA concrete with or without superplasticizer (SP) immersed in seawater environments for a year. Although the strength of OPC concrete is higher than concrete with FA and with only SP in the early stage, the strength of OPC concrete reduces slightly after exposure to marine environments.

Additionally, Mohammed et al. [69] investigated the mechanical behaviours of concrete with distinct binders of OPC, high early strength cement (HESPC), moderate-heat cement (MHPC) and B-type slag cement (SCB) under tidal environment for up to 20 years. It was noted that only after 5 years, the compressive strength of concrete has increased. Then it decreases gradually after 10 years, and after 20 years, it is equal to or less than the compressive strength of concrete at 28 days. Fig. 5 displays the compressive strength at different testing ages. It can be seen that with the increase of immersion time in a seawater environment, the strength of concrete declines, and the mineral admixture can delay the decrease of compressive strength. In conclusion, when mineral admixtures are used as partial replacements for cement, the strength reduction of cementitious concrete under marine environments can be reduced. High-quality aggregate used in casting concrete under the marine environment is an essential choice.

3.2 Chloride diffusion

Intuitively, permeability influences concrete durability, the reason of which is that it evaluates the ability of both harmful ions and salts to penetrate the cementitious concrete. Generally, Fick's diffusion law is applied to simulate the transport of chloride through concrete, one of the identification parameters of which is the chloride diffusion coefficient (D_c). The D_c is determined by fitting the error function solution to Fick’s diffusion law, which has been pointed out to be a time-varying parameter [70-72]. The corrosion degree of concrete due to chloride transport are different for the vary marine environments (environmental temperature, humidity, and lots of sulfate ions exist in the seawater), which lead to the difference of the chloride diffusion coefficient. Currently, many investigators have reported that several concrete mixtures differ in D_c under the seawater environment, as shown in Table 4.

As can be seen from Table 4, the primary factors influencing the D_c of cementitious concrete under marine environment include W/B ratios, type of mineral admixtures, exposure time and locations, etc. Bader [70] reported the influence of W/B ratio of D_c on OPC concrete exposed to underground conditions in a coastal area. The chloride concentration is generally reduced as a reduction in the ration of water to binder. Chalee and Jaturapitakkul [71, 72] investigated the effect of water to binder ratios and FA replacements percentage on D_c under marine environment for up to 5 years. It is reported that D_c of all mixes were reduced with the extension of curing time, and the reduction of water to bind ratio led to the reduction of D_c. When the water to bind ratio decreased, the D_c in all mixes just with OPC was lower than that in FA-concrete. Jau and Tsay [66] used GGBFS to replace OPC for up to 50 wt.% to manufacture OPC-GGBFS concrete and tested the D_c of the OPC-GGBFS concrete immersed in seawater environment. Under the same exposure condition, the coefficient is smallest when the GGBFS substitution ratio is up to 20%, compared to relatively high permeability when the GGBFS substitution ratio is up to 50%. This is possibly because the pozzolanic reaction of proper GGBFS can optimize the pore structure of concrete, while the calcium hydroxide provided by cement is not sufficient for full pozzolanic reaction for high GGBFS substitution. In addition, the D_c of OPC-GGBFS concrete decreases with the increase of time due to pozzolanic reaction, compared to an increase in OPC concrete. Bamforth, Dhir, and Mohammed et al. [56-58] also determined the effects of SF, GGBFS and PFA on the concrete immersed in tide environments. The appropriate SF, GGBFS, and PFA replacement for OPC reduced the D_c in tide environment. Besides, the D_c of the concrete with appropriate content of SF, GGBFS, and PFA could be decreased as the exposure time increased from 3 to 8 years [56, 57].

Additionally, chloride transport levels can differ remarkably being up to the site of the cementitious concrete, the level of exposure to the different concentrations of chloride ions solutions environments, and efflorescence conditions related to temperature and moisture. Consequently, the situation of climate has an essential effect on the transport speed of chloride. Song et al. [73] evaluated chloride convey of concrete from three different coastal regions: Japan, Britain and Venezuela, concluding that cementitious concrete under tropical environment were more vulnerable to chloride ions penetration and indicating that tropical climates were poor conditions for chloride ion penetration as a result of high relative moisture, temperature, and chloride ion concentration. Mustafa and Yusof [74] studied the influence of different distances from the coastline on the D_c of concrete. The longer was the time in exposure, the greater was the surface chloride content, and the smaller was the noticeable diffusion coefficient. Jin et al. [75] tested the D_c of concrete with different contents of mineral admixture in the marine atmosphere zone, splash zone, tidal zone, and submerged zone for up to 13 months. The effect of FA and GGBFS on the migration and binding capacity of chloride ion was examined, and the optimum substitute ratios of mineral admixture in the marine environment were also put forward. The decreasing trend of chloride ion binding capacity was more evident in the submerged and tidal area. Safehian and Ramezanianpour [54] assessed the effects of exposure conditions, including atmosphere, splash, and tidal zones on the D_c of concrete containing SF of 7 wt.%. It should be noted that D_c in most normal specimens is approximately the same, and the curing conditions do not show a significant on them for up to 5 years. Wu et al. [55] studied the influences of exposure conditions, including atmosphere zones, tidal zones, and splash zones on chloride ingress and the D_c of concrete, indicating that the difference in D_c value caused by exposure conditions is not apparent.

From the result of the chloride diffusion mentioned above, the primary factors influencing the time-dependent D_c of cementitious concrete under marine environment include W/B ratios, type of mineral admixtures, exposure time, and locations. The D_c of concrete could be decreased by the reduction of water to bind ratio and appropriate content of mineral admixtures. Compared to the marine exposure zones, the concentrations level of chloride ions and efflorescence conditions related to temperature and moisture would have more profound influences on the change of D_c. Therefore, it is very necessary to select the appropriate concrete with appropriate content of mineral admixtures to cast offshore structures according to the location related to multiple concentrations, temperature, and efflorescence degree.

3.3 Concrete carbonation

Carbonation is a process in which carbon dioxide (CO_2) in the atmosphere reacts with water in the pores of the concrete to form carbonic acid. The acid reacts with alkaline in the pores and neutralizes the alkaline environments. This reaction decreases the pH of concrete pore solution in freshwater from 12.6 to below 9, while some test results show that when the seawater pH was less than 7, CO_2 in seawater corroded the concrete [76-79]. However, little concrete deterioration took place when the pH of the seawater outpaced 7.5. Table 5 summarizes the impact of the seawater environment on the carbonation changing of cementitious concrete. Some of the carbonation depth results are also shown in Fig. 6.

Duan et al. [76] investigated the carbonation resistance of concrete consist of MK under seawater and freshwater, respectively. During the early days, the carbonation depth of specimens in seawater was less high than that in freshwater. With the increase of MK, the carbonation depth of specimens decreased slightly regardless of the exposure conditions. Uthaman et al. [77] measured the carbonation depth of four different types of FA based specimens with or without nanoparticles exposed to the marine atmosphere for one and six months. Compared to FA based specimens, the nanophase modified FA specimens have a higher carbonation depth. For all of the nanomodified groups, the nanoparticles modified FA group with nano-TiO_2 and nano-$CaCO_3$ show the minimum carbonation depth.

The carbonation depth of cementitious concrete could be affected by the curing conditions and types of aggregate. On the coast of the northern Mediterranean sea, Ragab et al. [9] collected concrete specimens from the wave's repellent blocks. The specimens cover a wide range from 4 to more than 60 years. The erosion starts from the transition zone of aggregate cement slurry interface as the weak point and then expands around the coarse aggregate, which protrudes from the concrete block. Therefore, the erosion depth is the average erosion depth around the coarse aggregate resulting in that the carbonation depth enhances with the decrease of concrete quality. Safehian and Ramezanianpour [54] presented the results of carbonation depth and concrete protect magnitude. Carbonation of concrete protects, which emancipates chemical bounded chlorides, would enhance chloride penetration.

Additionally, Jena and Panda [78] observed the increased depth of carbonation with age. It is found that the carbonation depth can be enhanced with the increase of FA replacement percentage. Under identical conditions, the carbonation depth of OPC concrete was 5 mm, while that of coral concrete was 2 mm [41]. Experimental data on the South China Sea showed that after 25 years of testing, the carbonation depth of the coral concrete garage floor was 35–55 mm. The coral concrete seawall was 10–20 mm after 19 years, while the coral concrete in the tidal area was 8 mm after 25 years.

As the curing situation changes, Cheng et al. [80] found that the carbonation depths of specimens at 20 $^{\circ}$C, which were immersed in high concentration seawater of 10 times, were the thinnest of that in different concentration seawater. With the decrease of seawater concentration, the carbonation depths of specimens increased. For 10 times of high concentration seawater, with the increase of seawater temperature, the carbonation depths of specimens were reduced.

In general, carbonation depth of concrete composites under marine environment can be changed by exposure environments, aggregate types, and mineral admixtures types, etc. The addition of FA will increase the carbonation depth, compared to a decrease by using MK. The carbonation depth of concrete in marine environment was less high than that in freshwater and can be reduced with the rising of seawater concentration. It is better to choose types of concrete that are less affected by the carbonation because carbonation can release chemical bounded chlorides and increase the penetration of chloride ions.

3.4 Microstructure and pore structure

The microstructure and pore structure of concrete consists of pores, capillary pores, and gel pores. As one of the crucial properties of cementitious concrete, the pore structure accounts for a certain percentage in cementitious concrete, and it is of considerable significance to the transmission characteristics [81, 82]. Specifically, pore structure parameters, consisting of porosity and pore size distribution, are essential constituent parts of microstructure. It is worth noting that different exposure conditions will affect the formation and destruction of the microstructure of cementitious concrete. When encountering marine environments, inorganic salts could accelerate the hydration of cement hydration to some extent and improve the early strength of concrete. Nevertheless, for long curing time, with the in-depth hydration, the cementitious concrete are slightly densified, and there is no gap between the expansion product and the internal stress, resulting in the gradual change and degradation of the pore structure of the concrete in the seawater environment. Currently, the majority of researches associated with the influence of mineral admixtures on the pose structure of concrete under marine environment. Fig. 7 shows some results of the pore size distribution of concrete with mineral admixtures substitutes in a seawater environment.

As can be seen from Fig. 7, the durability is greatly improved as a result of the reduction of large amounts of pores when pozzolanic materials are used as part of cement substitutes. Memon et al. [83] studied the influences of mineral and chemical admixtures, namely FA, GGBFS, SF, and superplasticizers on the porosity, pore size distribution of high-strength concrete in seawater curing condition. Three grades of cement substitutes (0, 30%, and 70% by weight) were used. Compared with OPC concrete, the pore size distribution of both high-strength concrete (FA-SF concrete and FA-SF-GGBFS concrete) was remarkably finer, and the average volume pore radius at the age of 6 months were dropped by around three times. Duan et al. [67] discussed the evolution characteristics of the pore structure of concrete under the seawater environment with time. The effects of mineral admixtures including GGBFS, SF and MK on pore structure, are also evaluated. Compared to concrete with mineral admixtures, the OPC concrete under simulated seawater conditions in early age has higher porosity. The pore characteristics of concrete under marine environment are greatly improved by mineral admixtures. The order of influence of mineral admixtures on the microstructure is: MK > SF > GGBFS. The pore structure of OPC concrete in seawater became worse gradually with time, while minerals admixtures have a positive impact on pore refinement of concrete regardless of the curing environment.

Besides, Duan et al. [76] indicated the pore structure of MK concrete under marine environment. The results display that the porosity of MK specimens is lower than that without MK. The seawater curing condition further leads to a relevant low porosity in the early stage and the similar high porosity in the later stage. Jau and Tsay [66] measured the pore size distribution of OPC-GGBFS concrete exposed to seawater at different ages. It has been reported that with age, the pore volume decreases, that is, the macropores gradually become finer pores and the cumulative pore volume decreases, the reason for which is that the cement hydration and the pozzolanic reaction caused by the increasing formation of hydration productions, filling the voids and decrease the number and quantity of pores. Especially, when the GGBFS substitution rate is 20%, the pore volume is the lowest.

The different cement types may also affect the pore structure of concrete under the seawater environment. Hossain [59] investigated the porosity of concrete made with different plain (ASTM Type I, II, and V) or blended cement with up to 30% pumice substitutes under the marine environment for one year. Compared to OPC concrete, the porosity of concrete mixed with pumice is lower in seawater. Under the curing condition of freshwater, the porosity of both plain concrete and blended concrete decreases as the increase of immersed time. With the rise in pumice content, the porosity of blended concrete will decrease, which is lower than that of OPC concrete. Under the seawater environment, the porosities of plain and blended concrete increase with the increase of curing time. The best performance can be obtained by mixing type I cement with 20% pumice, which shows low porosity and high resistance to chloride ion corrosion in seawater.

Overall, the porosities of concrete under seawater environment could be increased with time period. However, the pore characteristics of concrete under marine environment could be significantly improved by the appropriate addition of mineral admixtures for the reason that the cement hydration and the pozzolanic reaction caused by the increased formation of hydration productions, thus optimizing the pore structure. The pore structure of the concrete should be taken into consideration for the offshore building design.

4. Reinforced concrete and infrastructure

In marine environments, high humidity, sulphate attack, and chloride ion concentration and air lead to much more severe corrosion to offshore structures than structures in inland areas. As illustrated in Fig. 8 [84], the corrosion causes tremendous mass loss of reinforcement bars, cracking of concrete protective layer [85], and a decrease in the binding capacity of the interface between concrete and reinforcement [86]. For the structural part, as a result of the sustain aging and deterioration of marine environments in the service life, the strength [87, 88], stiffness, ductility [89], and energy consumption capacity [90] is decreased. Beams and slabs are two types of primary constituent parts of concrete structure, such as coastal bridges and harbours. This section generalizes the previous findings of structures and productions based on reinforced concrete structures under seawater environment, including beam and slab, and protection coating or repairing materials.

4.1 Concrete beam under marine environment

Up to now, some studies have investigated the capacity decrease of aging RC beams in the marine environment. In the initial stage, the flexural strength of RC beam is not significantly affected by the corrosion of longitudinal reinforcement. In contrast, the stiffness and flexural strength are remarkably reduced owing to the deficit of the longitudinal section [91, 92]. Some results showed that the RC beams under the marine environment using supplementary cementitious materials showed slight influences on the performance change. Weerdt et al. [93] submerged concrete beams using different binders, including OPC, SF, FA, or GGBFS in seawater environment for 16 years and examined the chloride ingress. Fig. 9 displays the chloride profiles after 16 years of exposure evaluated by titration. There were limited significant differences in physical-mechanical properties and chloride ingress between those different types of concrete, which indicate that either the substitution content of OPC is too low or the ingress of chloride is primarily controlled by the corresponding physical properties. Otieno et al. [94] prepared the concrete beam with different binders containing GGBFS and FA and different W/B ratios of 0.40 and 0.55 and curing those specimens under accelerated laboratory corrosion or went through physic corrosion in a tidal zone. The results displayed that the coverage depth, crack width, and partial substitute of OPC with FA or GGBFS lead to a reduction in the corrosion rate. However, there was no significant discrepancy in the corrosion rate between the two curing conditions owing to the replacement of OPC by FA or GGBFS.

The effect of the exposure conditions on the properties of the geopolymer concrete beam was also considered. Darmawan et al. [95] studied the behaviour of high geopolymer concrete beam (GCB) in a splashing zone for up to 28 days. Compared to those cured at room temperature, geopolymer concrete in seawater environment showed lower compressive strength, higher porosity and lower concreter resistivity. According to the load test of the geopolymer concrete beam under the action of shear load, the seawater environment has no effect on the crack pattern and crack growth of the GCB. Reddy et al. [96] reported an experimental evaluation of low-calcium FA-based geopolymer concrete beam under a marine environment. The results pointed out that the geopolymer concrete beam is additionally uniform, well-bonded to the aggregate, and shows more excellent resistance to seawater attack than OPC concrete. Consequently, geopolymer concrete beam can obtain improved crack resistance and enduring durability regardless of marine environment.

The influence of the location is also a vital factor in the durability of the RC beam under the marine environment. Poupard et al. [97] presented the diagnostic results of chloride-induced corrosion damage of RC beam for 40 years exposed to marine environments and concluded that the chloride was responsible for the corrosion attack by the physicochemical measurements, and the corrosion activity in the beam varies depending on the position. It was also concluded that the location of both "high corrosion zone" and "low corrosion zone" distinguished by the result data did not change over time. Zhu et al. [98] studied the corrosion-induced cracking procedure of RC beam with sustained load under marine environments for 26 years. In the compression region caused by the sustained load, the crack for the corrosion appears first, while the length and width of the crack for the corrosion increase significantly, which is related to the top-bar impact and the top-surface-ponding impact.

The influence of moisture is also a vital factor in the durability of the RC beam under marine environment. Medeiros et al. [99] studied the chloride-ion contents of RC beam under the marine environment for 40 years, where located about 700 m away from a coastline. The result showed that the relationship between the position of the concrete columns and the seawater has limited effect, and the concrete located in the wet and dry cycle area is more susceptible to chloride attack. Yin et al. [100] examined the durability of the RC beams under the coupling effect of loads and a chloride wetting-drying cycle and freeze-thaw cycle and concluded that the coupling effect of corrosion and loads environment has a munificent impact on the RC beams, resulting in failure mode, and changes in the bearing capacity and deflection of the beams. Generally, the properties of RC beams could be strongly affected by the exposure of marine environment. It is very necessary to choose suitable raw materials and low-corrosive steel for offshore construction taking the location into consideration.

4.2 Concrete slab under marine environment

Up to now, the capacity decrease of aging RC slabs has also been examined by some studies. Akiyama et al. [101] presented the time-dependent dependableness analysis of RC slab in the marine environment. It is concluded that it can assess the impact of marine environment by time-dependent analysis, inspection results and inspection times on the latest estimates of the reliability of one-way plates, resulting in decision applications that consider dependableness based acceptance criteria and / or cost-benefit analysis of risk. Gao et al. [102] established a practical method to predict the diffusion coefficient, staring time and flexural failure possibility of RC slabs with load-induced cracks under the marine environment. The results showed that the crack caused by the load significantly affects the prediction accuracy of the change of the ability to withstand the corrosion failure of the reinforcement.

Kondratova et al. [103] investigated the influence of the pre-crack and corrosion inhibitors on the corrosion rate of the RC slabs with a 20 mm cover. In the process of casting, a 0.2 or 0.4 mm wide simulated crack was formed transversely to the steel axis and two commercial corrosion inhibitors (organic corrosion inhibitor (OCI) and anodic calcium nitrite-based corrosion inhibitor (CNI)) were added to the concrete mix to prevent corrosion. After 12, 24 and 36 months of exposure to the marine environment in natural marine exposure site, the corrosion damage of concrete slabs were evaluated. As shown in Fig. 10, in terms of reducing the corrosion rate of concrete with no inhibitors, OCI is more effective than CNI. In contrast, the efficiency of both corrosion inhibitors is relatively low in cracked concrete. Additionally, Heede et al. [104] conducted a series of tests on the effect of crack width on the chloride penetration of RC slabs using FA and SF. The results show that to reduce the inevitable cracks in these slabs; it is necessary to include additional reinforcement throughout the life cycle to decrease the property crack width to 0.05 mm. As aforementioned, simulating crack development and predictive models are effective ways to ensure the safety of RC slabs under seawater environments.

4.3 Concrete structure with corrosion protection under marine environment

Different corrosion protection and maintenance methods of RC in the marine environment have been studied. [105, 106]. Lists of protection methods for RC under the marine environment are shown in Table 6. There are five main ways to deal with the corrosion of RC in the marine environment: repair or partial reconstruction; corrosion inhibitor; protective coating; cathodic protection; replacement of reinforcements.

Swamy and Tanikawa [107] considered the utilize of preservative operation in structures. In concrete structures contaminated with chloride ions, partial or patching can just solve this trouble and is merely applicable when the damage is relatively slight. Asrar et al. [108] replaced OPC with microsilica to provide better corrosion protection to the RC under seawater environment. It has been noted that its protective effect on the sulphate resistance cement is better than that with OPC. Besides, Malik et al. [109] pointed out that migratory corrosion inhibitors as possible chemicals for rehabilitating can indeed protect reinforcement concrete in a seawater environment.

Electrochemical chloride extraction (ECO) is a proverbially used protective method [110-112], to reduce existing chloride levels and prevent further damage. Kim et al. [113] prepared slab specimens to evaluate the effectiveness of cathodic protection under the seawater environment. The Zn-mesh sacrificial anode has been used as an anti-static protection system. Bertolini et al. [114] introduced the productiveness of immersion sacrificial anode in preventing pitting corrosion in marine piles. The results show that, at least under the current test conditions, the sacrificial anode is additionally efficacious in avoiding the start of corrosion (i.e., providing cathodic protection) than in controlling the ongoing pitting (i.e. ensuring cathodic protection). Steven et al. [115] used cathodic protection to control the corrosion of RC structures under the marine environment. Moradllo et al. [116] used six different concrete surface coatings on concrete surfaces and studied the properties of those coatings during 5 years of exposure in a marine tidal area of the Persian Gulf. In terms of the results obtained, it has been proved that epoxy polyurethane and aliphatic acrylic acid are the most effective coatings, which can reduce chloride penetration and prolong the service life of cement-based structures. However, the properties of the surface coating relies on the time and the concrete have to be coated again with a different surface coating within the appropriate time, which means before the coating deteriorates. Erdoğdu et al. [117] prepared the concrete slabs with no damage, 1% damage and 2% damage epoxy-coated bars. It is shown that reinforcement with a damaged epoxy coating has no proof of adequate rust build-up at the surface of steel concrete to cause concrete cracking. Venkatesan et al. [118] carried out a one-year study of RC specimens exposure to three different levels. The properties of three different types of corrosion protection against cement, namely cement polymer composite, interpenetrating polymer network coating, and epoxy coating, were assessed stately by measuring open circuit potential measurements. Hawary et al. [119] evaluated the bond strength properties of epoxy coated bars by a battery of axial tensile tests of epoxy coated bars embedded in concrete cylinders and undergone drawing tests of epoxy coated bars in the marine environment. Dong et al. [120] assessed the corrosion behaviour of epoxy/zinc-coated steel bars embedded in concrete compared to black steel, galvanized, and epoxy-coated steel bars in the marine environment.

Zhou et al. [121] used glass fiber reinforced polymer (GFRP) to replace the rebar to cast concrete owing to its exceptional corrosion resistance to seawater environment. Li et al. [122-126] also utilized the fiber-reinforced polymer (FRP), GFRP, basalt fibre-reinforced polymer (BFRP), carbon fibre-reinforced polymer (CFRP) to replace the rebar in the RC under seawater environment, indicating that CFRP has the highest strength and elastic modulus in both longitudinal and transverse directions. The CFRP may be a better alternative to cast concrete in marine environments.

In general, a partial or partial repair can only solve this problem in concrete structures, and only in the case of minor damage. Corrosion inhibitors are modifiers because they are mixtures of compounds or have been applied to the interface of concrete [109]. The protective coating provides an impermeable layer on the concrete to prohibit the entry of chloride ions [113, 116]. Electrochemical chloride extraction is a proverbially used measurement methodology to reduce existing chloride levels and prevent further damage [117-120], which is a cost-efficient and enduring method to remove large quantities of contaminated chlorine ions. Using FRP to replace the rebar in casting concrete under the seawater environment is also an effective method [127].

5. Case studies on assessment of concrete structure

Currently, with the increase of offshore structures (including the power plant, wharf, and bridge, etc.), it is of significance to describe the assessment of structure after many years of exposure in marine environments. Table 7 summarizes some cases for RC structures under marine environment. The engineers and investigators showed more attention to the technical and economic risks associated with the aging offshore structures under the marine environment. Some researchers concerned the current or existing state of the offshore structures using the field test or conventional and non-destructive tests [128-132], while others considered the environment conditions and its likely deterioration rate of the concrete structures under the marine environment by using probabilistic assessment frameworks, field, and laboratory tests [133-138]. In addition, the prediction of structural deterioration and possible promotion in natural and applied loadings by numerical simulations is also concerned [139-141]. Overall, there is additional attention to the long-term investigations and the whole service life cycle of the cement-based structure under marine environment.

Taking the RC canal structure of a power plant in Indonesia exposed to the coastal area for up to 20 years, for example, Bayuaji et al. [137] used deterministic and probabilistic assessment frameworks to assess the service life of the structure. By visual inspection, it is found that the cracks of the structure are mainly formed outside the expansion joint, and the strength is relatively low at or very close to the expansion joint. As shown in Fig. 11 [142], according to the strength decrease of RC caused by corrosion and the worst-case scenario, it is concluded that only small repair work is required to be complied with avoiding ingress up to 2025.

Additionally, a RC bridge of Hornibrook Highway crossing at Bramble Bay, north of Brisbane, Queensland, Australia, located adjacent to the Pacific Ocean with more than 75 years in service, for example, was investigated by Melchers et al. [133-136]. Fig. 12 displays the visual appearance of the Hornibrook Highway Bridge from structure to the longitudinal cross-section. It can be seen from Fig. 12 that although the steel bars or concrete have slight local cracks, there is a small amount of external rust in the case of severe corrosion of steel bars, indicating that local alkali leaching is an essential component of the development of high local corrosion. Overall, the accessible proof from the discernible appearance of piles and testing of stochastic specimens shows that the concrete is of high quality, indicating a high degree of natural incorruptness, elevated strength, low permeability, and no voids.

Melchers et al. [133-136] indicated that structural engineers are ought to focus on the discovery of probable localized areas with high localized corrosion instead of the total concrete chloride content of RC structures. This locally severely corroded area is related to slight but profound hairline cracks or cognate defects. It should not constantly be easily detected by visual examination, especially in the tidal or splash areas where the corrosion product might be washed away from the cracks and seepage. According to the results in Table 7, the assessment of offshore structures should focus on the local areas with severe corrosion rather than the whole structure. Additional concentrations should be paid to the effect of multiple factors on the construction of RC, including the synergistic effects of carbonization and chloride and the impact of the wetting-drying cycle. The durability and service life of buildings under marine environments is mainly determined by the quality of the materials used. It is also essential to establish a systematic monitoring and assessment system for the RC structure under marine environment.

6. Conclusions

The seawater corrosion of cementitious concrete and reinforced concrete structures is a major issue for coatal infrastructures all over the world. This review evaluates the durability performance of concrete under marine environments at both the material and structural levels. Based on the present literature review, some conclusions are as follows:

(1) The effects of marine environment on reinforced concrete structures are mainly reflected in different exposed areas of the ocean, the interaction of physical and chemical mechanisms, and the corrosion of steel. In particular, chloride and sulfate attacks are the most common

environmental attack in the marine environment, where structure exposed to saltwater and wetting-drying cycles gives rise to corrosion of reinforcement and deterioration of concrete composites.

(2) Under marine environment, corrosive chemicals enter through interconnected concrete pores. The key to the durable concrete system is the use of low water to binder ratio and the addition of supplementary cementitious materials that exhibit excellent performance in the marine environment, particularly constituted with ground-granulated blast-furnace slag and silica fume.

(3) The cause of corrosion must be detected and determined before any solution is selected to repair or reduce corrosion in the structure under marine environment. Therefore, in the case where solutions require the introduction of new materials into cement or steel bars, it is necessary to determine the possibility of those chemical compounds reacting with chloride ions existed in the concrete to determine whether their reactions cause further damage.

(4) Reinforced concrete exposed to the marine environment can reach its useful life even at tides and splatters by using traditional concrete-making materials (including mineral admixtures and possible corrosion inhibitors), with appropriate protection and practices. In addition to preventing corrosion caused by chloride ions, concrete must be compounded in order to avoid harmful carbonization of concrete and other corrosion.

(5) Given the future challenges of marine concrete strcuttures, the related impacts of global warming and climate change are likely to be among the most severe issues. Global temperatures and sea levels have risen, and extreme weather events have increased. When they affect coastal infrastructure, they are incredibly destructive and destructive. Coupled with the possible population growth in coastal areas, designers, builders, and operators of concrete infrastructure in marine environment will face significant challenges.

7. Future prospectives

The discussion shows that current studies on reinforced concrete structures in offshore construction are gaining additional attentions because the corrosion of concrete and steel reinforcement is a major concern. While there are some measures to protect marine structures, additional investigations are needed. Therefore, the following research prospects are summarized:

(1) At the material level, the carbon footprint of concrete depends to a great degree on the amount of cement clinker it has, because the output of clinker will release a large amount of CO_2. By increasing the percentage replacement of supplementary cementing materials (SCMs) for cement, the clinker content of concrete can be extremely decreased, which also helps enhance the durability of concrete. Geopolymer concrete, only using SCMs to casting concrete, may be an alternative to cement concrete used in the marine environment.

(2) Extending service life to more than required years need complementary methods or a comprehensive strategy (including SCMs and corrosion inhibitors). Nevertheless, no matter how long chloride takes to reach the steel, the corrosion happens sooner or later. Therefore, the simply practicable option for supplying corrosion protection continuously is to utilize corrosion-resistant reinforcement materials, for example, advanced stainless steel or non-ferrous metal steel materials (such as fibre-reinforced plastic bars).

(3) For monitoring techniques, offshore structures are often under the environment with erosive salt, where wetting-drying cycles in tidal exposure conditions can speed up the chloride corrosion. Conspicuous injures resulting in the corrosion of chloride ions are rusting and peeling, which affects the service life and durability of offshore buildings. Under certain circumstances, some surveys, usually having video reports, have been utilized to monitor the "health" of structures in the ocean. However, the technology is rapidly evolving, and specialist companies can provide preliminary structural assessments and tests to set up the rank of corrosion preservation needed to improve service life, as mentioned in previous studeis [143-145]. Finally, customized corrosion preservation methods are provided, which possibly includes mosaicked sacrificial anodes or impressive present systems that can be monitored in the long term.

(4) Predicting the deterioration of offshore structures is a challenge, but considerable research investigations are still needed. A representative instance is a comprehensive forecast of conveying and degradation mechanisms in both cracked and uncracked concrete. For cracked concrete, more investigations should be required to find out the necessary transport process of the concrete in the first place. Another challenge that engineers possibly prolong to confront is the requirements to continually evaluate the applicability of novel types of cement to meet progressively stringent durability prerequisites, containing extended preservation-free life. Undoubtedly, a large amount of challenges will demand the growth of reliable tests and flexible inspection and standards to satisfy them.

Abbreviation

BA	Bark ash	GFRP	Glass fiber-reinforced polymer
BFRP	Basalt fibre-reinforced polymer	HESPC	High early strength cement
C_3A	Calcium aluminate	IPN	Interpenetrating polymer network coating
CFRP	Carbon fibre-reinforced polymer	MHPC	Moderate-heat cement
CH	Calcium hydroxide	MK	Metakaolin
CNI	Anodic calcium nitrite-based corrosion inhibitor	M–S–H	Magnesium silicate hydrate
CPCC	Polymer composite coating	OCI	Organic corrosion inhibitor
C–S–H	Calcium silicate hydrate	OPC	Ordinary Portland cement concrete
CPCC	Polymer composite coating	PFA	Pulverised fuel ash
D_c	Chloride diffusion coefficient	RC	Reinforcement concrete
EC	Epoxy coating	SCB	B-type slag cement
ECO	Electrochemical chloride extraction	SCMs	Supplementary cementitious materials
FA	Fly ash	SDR	Strength deterioration factor,
FRP	Fiber-reinforced polymer	SF	Silica fume
GCB	Geopolymer concrete beam	SP	Superplasticizer
GGBFS	Ground granulated blast furnace slag	XRD	X-ray diffraction

Conflict of Interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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with layer-distributed conductive rubber fibres, Sensors and Actuators A: Physical 301 (2020) 111763.

List of Tables

Table 1 Main chemical composition of seawater [11]

Chemical	NaCl	$MgCl_2$	Na_2SO_4	$CaCl_2$	KCl	$NaHCO_3$	KBr
Concentration (g/L)	24.53	5.20	4.09	1.16	0.695	0.201	0.101

*Chemicals at concentrations below 0.1 g/L are not included.

Table 2 Formation of Friedel's salt and Kuzel's salt

Item	Salt	Equations	References
1	NaCl	$2NaCl(aq)+3CaO{\cdot}Al_2O_3{\cdot}6H_2O(s)+Ca(OH)_2(s)+4H_2O\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O(s)+2NaOH(aq)$	[27]
2		$2NaCl(aq)+3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O(s)\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O(s)+2Na_2SO_4(aq)+2H_2O$	
3	KCl	$2KCl(aq)+3CaO{\cdot}Al_2O_3{\cdot}6H_2O(s)+Ca(OH)_2(s)+4H_2O\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O(s)+2KOH(aq)$	[29]
4		$2KCl(aq)+3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O(s)\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O(s)+2K_2SO_4(aq)+2H_2O$	
5	MgCl₂	$Ca(OH)_2(s)+MgCl_2(aq)\rightarrow Mg(OH)_2(s)+CaCl_2(aq)$	[30, 31]
6		$(3or5)a(OH)_2(s)+MgCl_2(aq){\cdot}H_2O\rightarrow(3or5)Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O(s)$	
7	CaCl₂	$3Ca(OH)_2(s)+CaCl_2(aq)+12H_2O\rightarrow 3Ca(OH)_2{\cdot}CaCl_2{\cdot}12H_2O(s)$	[39]
8		$3Ca(OH)_2(s)+CaCl_2(aq)+12H_2O\rightarrow 3Ca(OH)_2{\cdot}CaCl_2{\cdot}12H_2O(s)2$	
9		$CaCl_2(aq)+3CaO{\cdot}Al_2O_3{\cdot}6H_2O+12H_2O\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O(s)$	
10	Na₂SO₄	$2Na_2SO_4(aq)+Ca(OH)_2(s)+H_2O\rightarrow 2NaOH(aq)+CaSO_4{\cdot}2H_2O(s)$	[41, 42]
11		$3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O(s)\rightarrow 2CaSO_4(aq)+20H_2O\rightarrow 3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O(s)$	

Table 3 Effects of compressive strength of cementitious concrete under marine environment

Item	Replacements	Exposure conditions	Age (years)	Important notes	References
1	MK	Seawater	0.5	1) The compressive strength of concrete decreases in seawater 2) The defect in strength was pretty smaller for the specimens with MK	[65]
2	PFA, MK	Synthetic seawater	1.8	1) MK greatly reduced the strength retardation of the specimens exposed to seawater environment 2) Both PC–PFA) and OPC-ML-PFA blends cause significant improvement in compressive strength	[63]
3	GGBFS, Type I, II, V cement	Tidal environment	20	1) The exact mechanism is related to the increase of the compressive strength in the early stage of exposure 2) The decrease of the compressive strength in the middle stage 3) The stability of the compressive strength in the later stage of exposure	[69]
4	GGBFS	Artificial seawater	1	1) After accelerated test, the compressive strength of OPC concrete without GGBFS began to decline 2) The strength for GGBFS concrete continued to increase	[66]
5	SF,GGBFS,MK	Synthetic seawater	1	The strength of the concrete with pozzolanic mixtures was higher than that of the specimens with only OPC	[68]

6	Pumice, Type I, II, V cement	Seawater	1	The minimum compressive strength development was found in concrete mixed with sea condition	[59]
7	BA	Tidal environment	5	No compressive strength loss was found in concrete made with BA.	[64]
8	GGBFS, SF, MK	Artificial seawater	0.5	The compressive strength of the concrete can be increased by adding the mineral admixture regardless of curing environment	[67]
9	FA, superplasticizer	Seawater	1	1) The compressive of FA concrete decreased in the early stage 2) Increased significantly by the end of one year even when exposed to seawater	[62]
10	Recycled aggregate	Seawater	1	When the replacement rate and corrosion time increase, seawater has a significant effect on the compressive of recycled aggregate	[60]

Table 4 Diffusion coefficients D_c of cementitious concrete exposed to marine environment

Item	Detail of specimen		Times	Environments	Detection	Diffusion coefficients	References
	Binder	W/B	(years)		method	D_c ($\times 10^{-12}$ m^2/s)	
1	OPC		5	Exposed to the tidal zone of Gulf of Thailand.	Fick's second law	3.10, 4.00, 5.60	[71]
	15% FA	0.45				1.20, 1.50, 2.10	
	25% FA	0.55				0.98, 1.30, 1.90	
	35% FA	0.65				0.80, 1.10, 1.20	
	50% FA					0.45, 0.55, 0.95	
2	OPC	0.60	1	Immersed in artificial seawater according to ASTM D1141	Fick's second law	6.20	[66]
	10% GGBFS					4.90	
	20% GGBFS					4.70	
	30% GGBFS					4.80	
	50% GGBFS					6.50	
3	OPC	0.40 0.50 0.65	4.5	Along the Arabian Gulf	Fick's second law	1.18, 5.95, 6.92	[70]
4	OPC	0.50	1	Different distance to seashore	Fick's second law	4.41-4.91	[74]
5	OPC	0.66	3, 8	A tidal environment	Fick's second law	6.53, 7.85	[56, 57]
	30%PFA	0.54				0.89, 0.78	
	70% GGBFS	0.48				0.76, 0.56	
	8% SF	0.72				3.98, 3.25	
6	OPC	0.45	15	A tidal environment	Fick's second law	2.14	[58]
	GGBFS					0.48	

7	PFA OPC 50%GGBFS+FA	0.35	1.25	Atmosphere, Splash, Tidal and Submerged zone in Wheat Island	Fick's second law	0.55 0.76,1.30,4.50,3.70 0.73,2.00,3.70,5.60	[75]
8	7% SF	0.35	5	Atmosphere, Splash and Tidal zone in Persian Gulf I zone Atmosphere, Splash and Tidal zone in Persian Gulf II zone	Fick's second law	0.96, 0.88, 0.86 0.31, 0.34, 0.75	[54]
9	OPC (C40 concrete)	0.40	3	Atmosphere, Splash and Tidal zone in the Beibu Gulf I zone (Fangcheng) Atmosphere, Splash and Tidal zone in the Beibu Gulf II zone (Qianzhou) Atmosphere, Splash and Tidal zone in the Beibu Gulf III zone (Tieshan)	Fick's second law	0.70, 0.83,0.75 0.74,1.01,0.91 0.84, 1.18, 1.07	[55]
10	OPC	0.56	0.5	In artificial seawater	Darcy's law	1.81	[72]

Table 5 Effect of seawater environment on the carbonation depth changing of cementitious concrete

Item	Detail of specimen	Exposure conditions	Important notes	References
1	MK	Artificial seawater, up to 180 days	1) In both early and later days, the carbonation depth of concrete in seawater is lower than that in freshwater 2) Adding MK can decrease carbonation depth of concrete	[76]
2	OPC	In situ, up to 60 years	1) The carbonation depth increases with the decrease in concrete quality 2) A higher reduction of the carbonation depth with the increasing concrete grade	[9]
3	SF	In situ, Persian Gulf region	1) Carbonation of concrete surface increase chloride permeability 2) The marine exposure environment can affect the carbonation of concrete	[54]
4	FA, Nano-$CaCO_3$	Marine atmosphere for 1 and 6 months	1) Nano-$CaCO_3$ can reduce the carbonation depth of FA based concrete in the marine environment. 2) The carbonation depth can be increased by adding FA	[77]
5	FA, GGBFS,MK, recycled aggregate	Artificial seawater, up to 49 days	1) FA, GGBFS and recycled aggregate can increase the carbonation depth of concrete 2) MK can decrease the carbonation depth of concrete under marine environment	[80]
6	OPC	High concentration seawater, up to 180 days	1) With the increase of seawater, the carbonation depths of concrete decreased in the same concentration seawater 2) With the temperature increase of seawater, the carbonation depths of concrete decreased in the same concentration seawater	[79]
7	FA, Coral concrete	Tidal environment, up to 25 years	1) The carbonation depth of concrete is increased with the increasing exposure time 2) The carbonation coefficient increases with increasing FA content	[78]

Table 6 Protection methods for reinforced concrete under marine environment

Item	Name of method	Conditions of use	Important notes	Country	Ref.
1	Surface coatings	Epoxy polyurethane and aliphatic acrylic	1) Reduce the chloride penetration 2) Enhance the service of life 3) Surface coatings is time-dependent	Iran	[116]
2	Coated Reinforcing bars	Patch with an epoxy compound	1) Extend the service life 2) Cannot provide total protection	Turkey, Canada	[117]
3	Coated Reinforcing bars	Polymer composite coating (CPCC), interpenetrating polymer network coating (IPN) and epoxy coating (EC)	1) Different types of coating have different effects 2) Less visual inspection on coated rebar	India	[118]
4	Epoxy-coated bars	An active single component epoxy zinc primer	No significant difference in bond strength for both coated and uncoated bars	Kuwaii	[119]
5	Coated rebar	Epoxy/zinc duplex	1) Higher anti-corrosion performance 2) More serious corrosion once coating is mechanically damages	China	[120]
6	Cathodic Protection	Protection method/system	Expanding pressure and tensile stress	Korea	[113]
7	Electrochemical	Open circuit potential (OCP), linear	Have self-catalysis effect of chloride	China	[112]

	Methods	polarization resistance (LPR) and electrochemical impedance spectroscopy (EIS) methods.			
8	Cathodic Protection	Cathodic protection and sacrificial or galvanic anodes	1) Provide long-term corrosion control 2) Stop further corrosion		[115]
9	Partial replacements	Microsilica added concrete	Decrease the corrosion rates	Saudi Arabia	[108]
10	Corrosion inhibitors	Migratory corrosion inhibitors	1) Show in general little corrosion 2) Less corrosion rates	Saudi Arabia	[109]
11	Alternative reinforcements	GFRP	1) Enhance the ductility 2) Slight deterioration in load capacity	China, USA	[121]
12	Alternative reinforcements	FRP	1) Exhibit excellent residual strength 2) Slightly compromised by seawater environment	Korea	[127]
13	Alternative reinforcements	FRP, GFRP, BFRP, CFRP	1) The ultimate strain of CFRP is much less than that of BFRP and GFRP 2) Sightly enhance the concrete and lower axial strain	Australia	[122-124]

Table 7 Case studies for reinforced concrete structures under marine environment

Item	Structure	Method of test	Exposure duration (year)	Important notes	Country	Ref.
1	RC canal	Deterministic and probabilistic assessment frameworks	20	1) 85% higher compressive strength than that of the specified 2) No signs of rebar corrosion 3) No sign of structural distress	Indonesia	[137]
2	Reinforced concrete structures	Meteorological data collection	1.5	1) Low or no one corrosion process started 2) In a passive state of corrosion	Brasil	[131]
3	Reinforced and pre-stressed concrete dock	Field test	10	1) Deterioration rate depends on exposure conditions 2) Very high deterioration rates leading to serious damage in very short time periods	Portugal	[128]
4.	RC beam	Electrochemical measurements, complementary destructive methods	40	1) Chloride ions are the only responsible of corrosion attack. 2) Including low-corroded regions and high-corroded	France	[97]
5.	RC plant	Field and laboratory test	25	1) Aggregates show little influence on the chloride levels 2) Little deterioration observed in the concrete with	USA	[138]

				good quality, despite its high carbonation rate.		
6.	RC bridge	Field and laboratory test	75	1) pH around 12 for high strength and low permeability of the concrete 2) The detection of the highly localized corrosion regions than over concrete chloride content	Australia	[133-136]
7.	RC beam	Non-destructive measurement	0.3	1) Reduce uncertainty in durability parameter evaluation by a combination of techniques 2) Technique results linearly correlated with durability parameters	France	[129]
8.	RC structures	Non-destructive measurement	20	1) Possibly identify corrosion by using an image processing based damage classification methodology 2) Possibly improve the detection process of non-destructive measurements	France	[132]
9.	RC jetty	Conventional and non-destructive tests	30	1) Extensive deterioration mainly caused by chloride-induced corrosion 2) Synergistic effects accelerating corrosion of the reinforcing steel	Iran	[130]
10.	RC structures	Comprehensive numerical method	—	1) Carbonation eliminating CH and the C-S-H resulting in decrease of physical chloride binding capacity	Australia	[139]

11.	RC structures	Numerical simulations	—	1) Avoids the problematic assessment of the intrinsic permeability 2) Little influence on the chloride ingress by intrinsic permeability value	France	[140]
12.	Reinforced Concrete	Numerical simulations	—	1) Successfully predict data at locations through the combination of curve-fitting methods and the kriging methods	Ireland	[141]

List of Figures

Fig. 1. Types of concrete structures under marine environment [2-4]: (a) Docks, Ireland, UK; (b) Longest sea bridge, connecting mainland China to Hong Kong and Macau; (c) Wharf, Victoria, Australia; (d) Gigantic Troll field, Norway

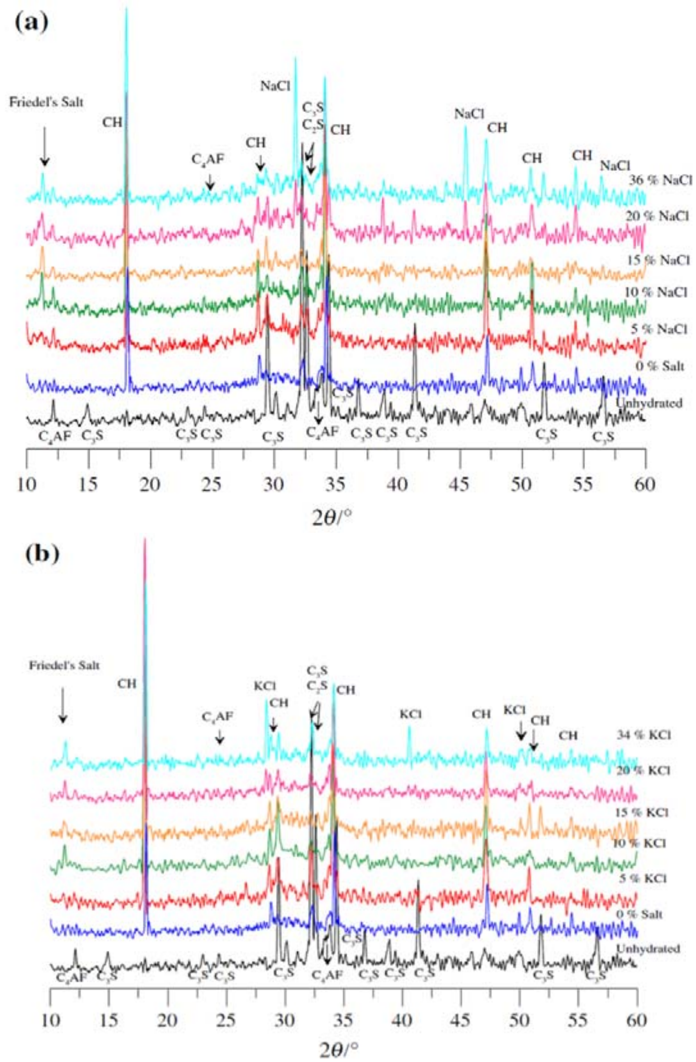


Fig. 2. XRD results of cement paste with (a) NaCl and (b) KCl [23]

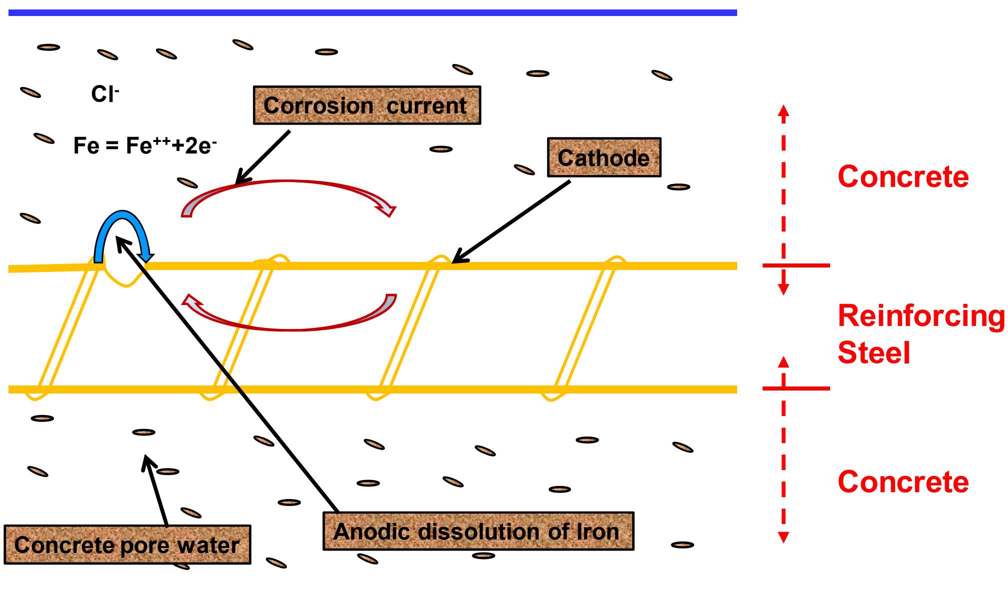


Fig. 3. Chloride induced corrosion mechanism surrounding zone of reinforcement [84]

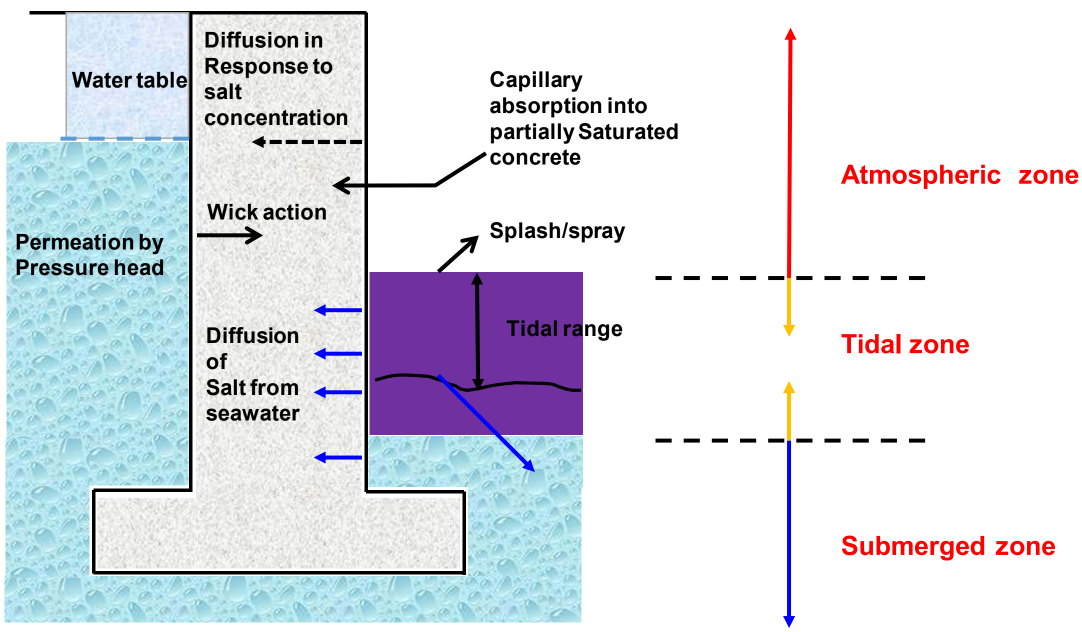


Fig. 4. Different exposure conditions under marine environment [51]

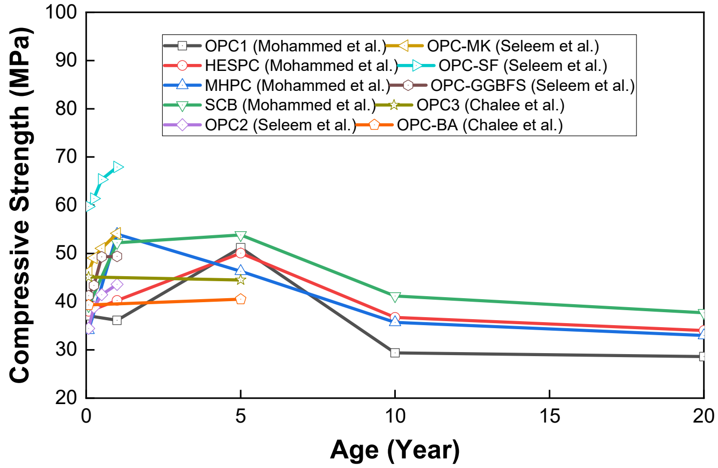


Fig. 5. Changes of compressive strength of concrete at different ages of seawater corrosion [30,40,41]

Note: All the test results in the figure are caring for concrete, and the numbers are used to distinguish the test results of different authors on the same cement. The group with mineral admixtures indicated that some cement was replaced. Figs. 6 and 7 are the same.

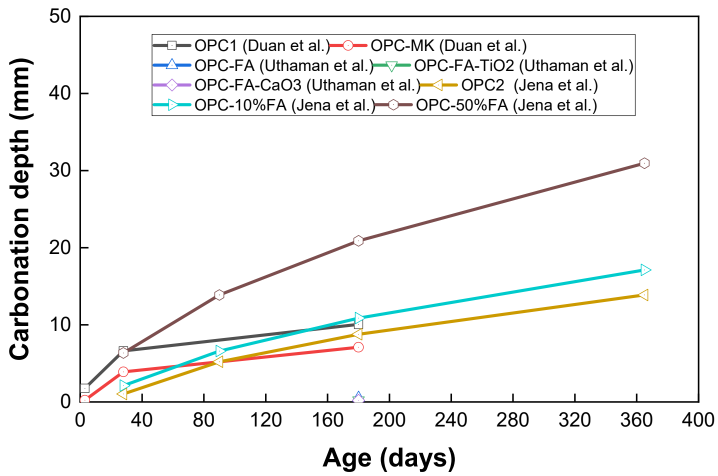


Fig. 6. Changes of concrete carbonation depth at different ages of testing [76-78]

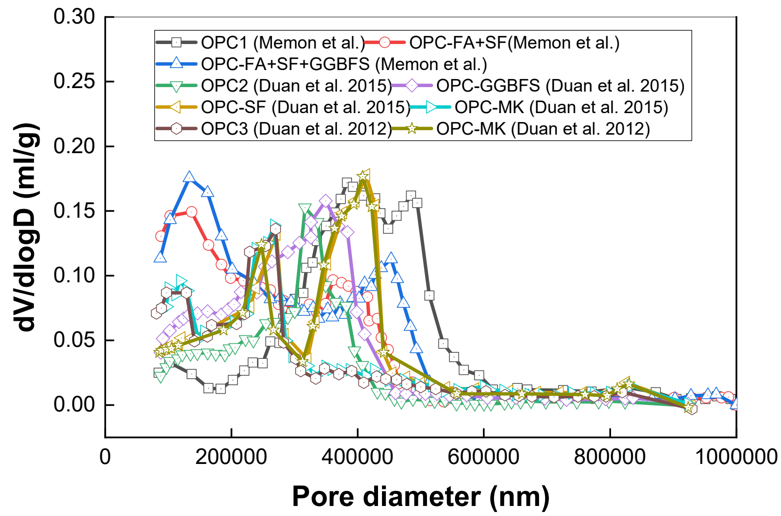


Fig. 7. Pore size distribution of concrete in seawater environment [67, 76, 83]

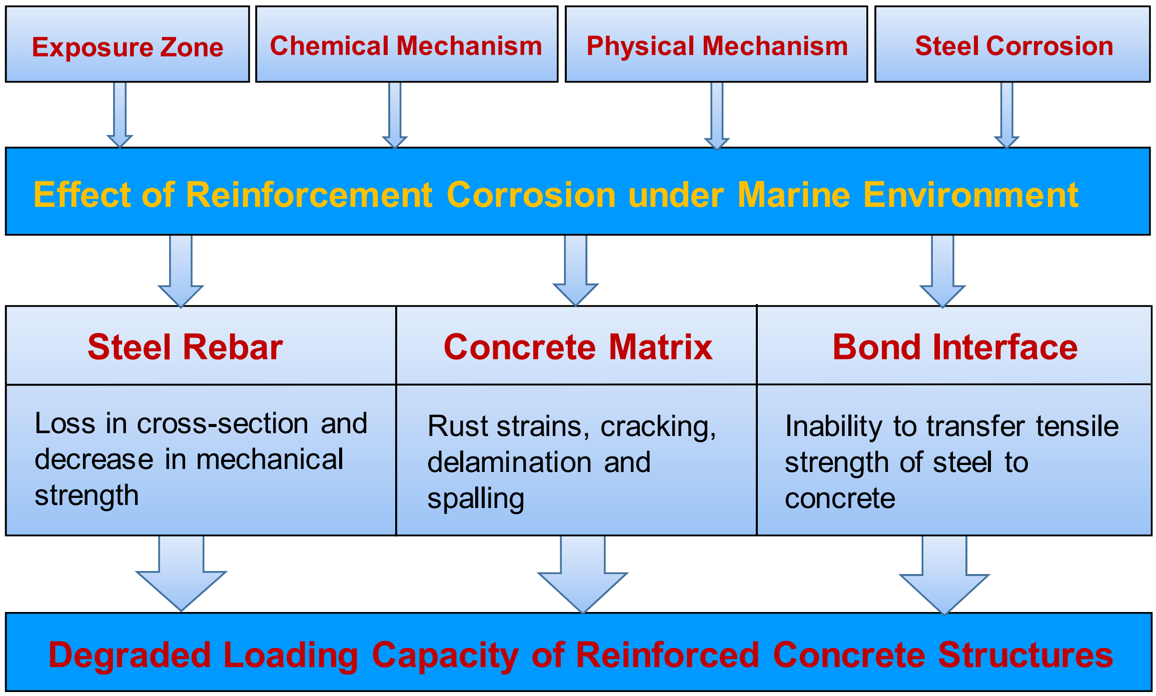


Fig. 8. Effects of steel reinforcement corrosion on reinforced concrete structures under marine environment [84]

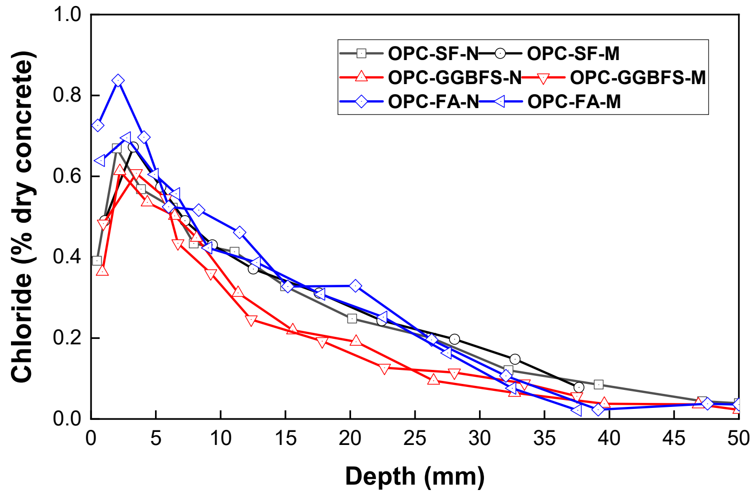
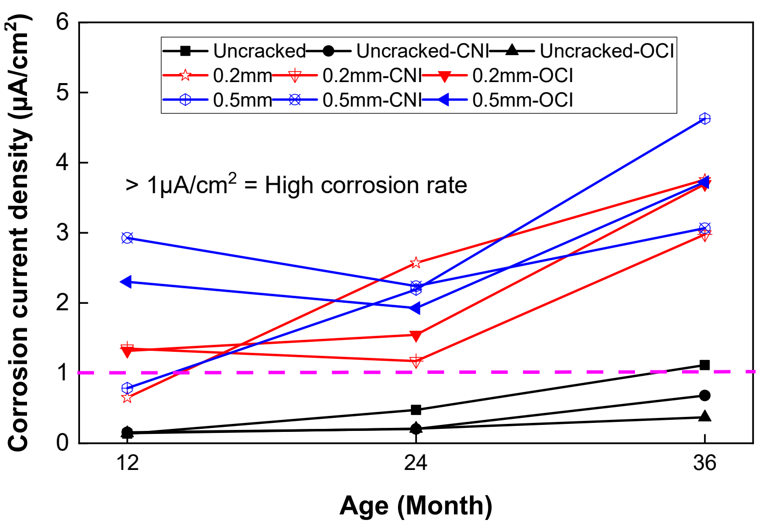


Fig. 9. Comparison of chloride profiles from reinforced concrete beams [93] (N: laboratory environment; M: marine environment)



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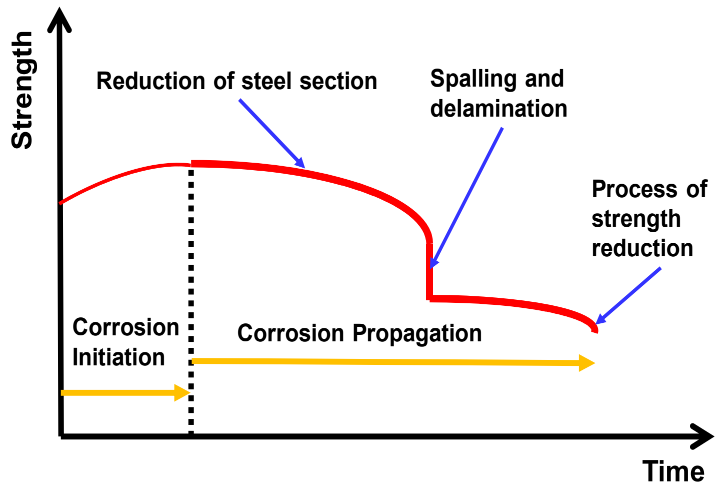

Fig. 11. Strength reduction of reinforced concrete structure due to steel corrosion [142]

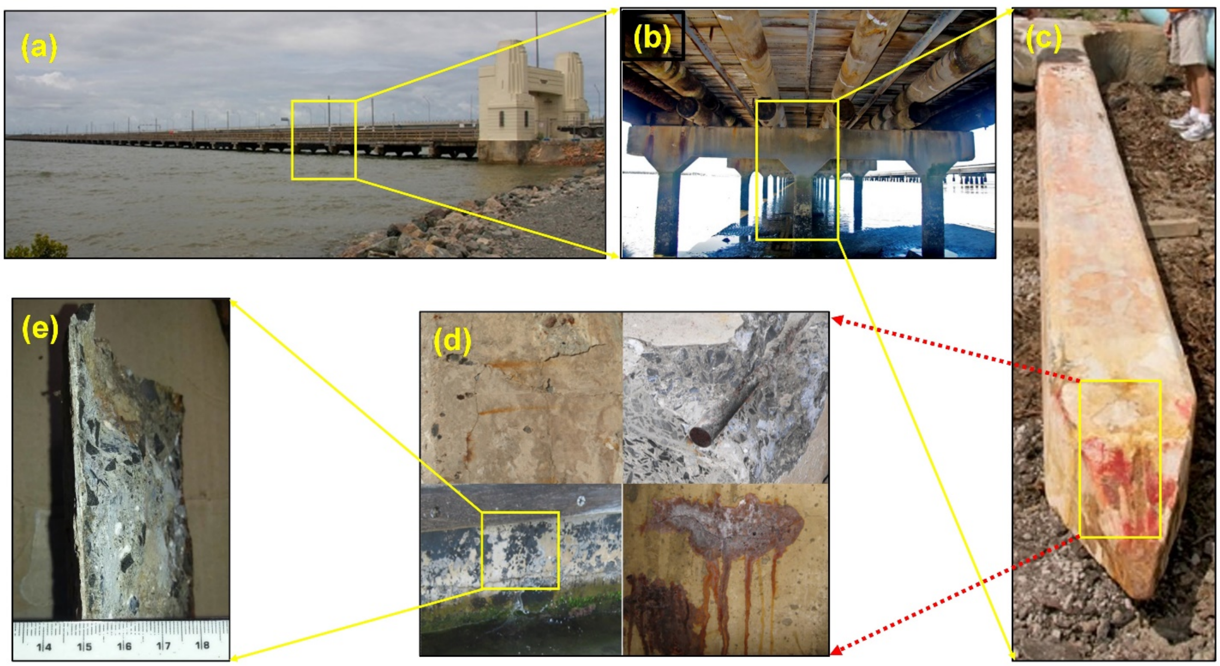

Fig. 12. Deterioration of Hornibrook Highway Bridge, Australia [133-136]: (a) Hornibrook Highway Bridge; (b) Underside of bridge; (c) Typical complete pile recovered; (d) Minor longitudinal and transverse concrete cracking; (e) Longitudinal cross-sectional.