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Review

Reinforcement corrosion in coastal and marine concrete: A review

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ABSTRACT

Concrete is used as a structural material for construction of buildings, jetties, harbors, etc. in many coastal and marine locations. The reinforcement used in concrete is susceptible to corrosion, resulting in loss of steel area, loss of bond, expansion of the reinforcement volume leading to cracking or spalling of concrete. Marine environment induces higher corrosion of reinforcement, compared to in-land locations. Concrete exposed to tidal fluctuations, or to the action of waves and currents are among the most severely affected. Corrosion of reinforcement in concrete is of major concern in coastal and marine environment. Control and monitoring of corrosion is a big challenge to engineers. In the recent years, different investigators reported their studies in this area. Depending on the severity of the exposure conditions, different corrosion inhibitors and protection methods have been attempted with varying degrees of success. The present article presents a generic review of the corrosion issues in marine concrete. Drawing from the experiences of the various researchers, the corrosion measurements, and corrosion control schemes, including use of coated reinforcements and corrosion inhibitors are discussed. The durability performance based design of concrete in the probabilistic framework and the life cycle cost analysis for durability design decisions have been identified as the future direction of corrosion protection of coastal and marine structures.

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1. Introduction

Concrete is cheap, versatile and durable building material, and it is used for many structures in coastal and marine areas. Due to the humidity, temperature and saline environment, reinforcement in such concrete is prone to corrosion. Corrosion results in loss of the reinforcement area and reduction in bond stress. Additionally, under the action of waves and currents, the corrosion of reinforcement is aggravated. The corrosion products are expansive and result in cracking of concrete cover or spalling. The chemical composition of the corrosion products of reinforcement in marine concrete was investigated by Vera et al. (2009). They concluded that lepidocrocite, goethite, akaganeite and magnetite mixtures were found both in natural and simulated marine environment whereas siderite was only detected in samples exposed to a natural marine environment. In literature, different models are presented for such estimation (Guzman et al., 2011; Wang et al., 2018) considering initiation and propagation of the chloride in concrete. These estimation models are supported by laboratory and field experiments by various researchers (Kondratova et al., 2003; Pradhan, 2014; Zhu et al., 2017; Wu et al., 2017). Repairing of concrete in marine locations, especially the submerged portions, is difficult and costly. Hence, corrosion of steel in marine concrete structures has received continued attention, in attempt to prevent, monitor and control corrosion. After introduction to the topic in the present section, the present study summarizes the issues of reinforcement corrosion in marine concrete in the following section. In the subsequent sections, a review of the various schemes of corrosion monitoring and control as reported in recent literature, is presented. This is followed by concluding remarks and references. The information provided in the article

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would help designers and project authorities in development of the strategies for monitoring and control of corrosion in their facilities according to the available resources, importance and service life of the concrete structures.

2. Factors Affecting Reinforcement Corrosion in Marine Concrete

Reinforcement is protected in alkaline concrete with a passive layer of corrosion products, which prevents further corrosion. This is the common situation in the concrete structures in general. To sustain this situation, some amount of moisture and oxygen would be required, and any phenomenon which upsets this balance might initiate corrosion. The peculiarity of corrosion in marine and coastal concrete lies in the physical damages which may occur to the concrete structure, and the chloride attack which is one of the main agents of corrosion of reinforcement in marine concrete. The diffusivity of the chloride in concrete, the diffusivity of sulfates in concrete, and the carbonation depth in concrete are among the major considerations. Other corrosion initiating factors may be chemical attack, salt weathering, and freeze-thaw attack among others (Neville, 1996).

2.1. Physical damages in marine concrete

The concrete may be affected by the passing currents, incident waves and splashes and sprays from breaking waves. In locations of strong wave and current action, abrasive effect of the sand, shingle and other debris in water may be significant. Surface of concrete just above ground or water level can experience salt crystallization, when salt water drawn up by capillary action evaporates, leaving behind the salt crystals – which can cause expansion damage. This problem is more pronounced in tropical climates. Horizontal slabs, when subjected to seawater spray, would be coated with salts, which move into concrete, a phenomenon known as salt scaling. The effect of these physical damages is detrimental to the durability as the cover to reinforcement is reduced, porosity of concrete is increased, and the chloride and other chemical ingress get enhanced. Any chemical deterioration of concrete like sulphate attack or alkali-silica reaction also have similar contribution to reinforcement corrosion.

Damage to concrete due to shock or impact might result in cover concrete cracking and subsequent ingress of seawater or saline air into concrete (Ramesht and Tavasani, 2013). The possible causes could be lack of using shock absorber devices or inadequate concrete cover. This assumes importance particularly for concrete the dock and jetty structures and should be given special attention.

2.2. Water level

Durability of concrete is largely influenced by its position with respect to the water level, with the maximum deterioration at average water level and above. Three zones have been identified for reinforcement corrosion in concrete, the atmospheric zone, the splash zone, and the submerged zone. In atmospheric zone, the concrete is exposed to humid and saline air, but not in direct contact with seawater. The submerged zone is where the concrete surface is saturated with limited access to oxygen. In between these two extremes, concrete is exposed to alternate wetting and drying cycles, with varying availability of oxygen (Allen, 1998). This zone may be split into tidal zone, where concrete is mostly wet, and splash zone, where concrete is mostly dry. The area of splash zone towards the drier (upper) side is most vulnerable to corrosion.

2.3. Chloride ingress

Presence of chloride ions in concrete may be due to salt contamination of the aggregates, or due to surface contamination of the reinforcing bars from air or salt-contaminated ground, or when reinforcement is inundated in low-lying areas. Chloride may also be absorbed from seawater in marine conditions. The factors governing the chloride diffusion to steel from concrete are depth of cover to reinforcement, presence of cracks in concrete, absorptivity and degree of saturation of concrete. There is difference of opinion of the mechanism of chloride ingress. The processes considered are diffusion, absorption due to capillary action and suction due to hydration of cement (Allen, 1998). After initial absorption over a few years, the chloride ingress is believed to stabilize. Roy et al. (1993) studied the chloride ingress in tropical marine concrete and reported that the diffusion coefficient calculated from field data agreed well with the earlier reported laboratory and field survey results. They further reported that the chloride ingress profiles matched with those computed from the diffusion theory. Luping (2008) proposed modeling free chloride transport taking free chloride as diffusion potential and then calculating the total chloride content taking into account the non-linear chloride binding along with the practiced empirical models based on error functions. They reported good agreement between the proposed model and the measurements though more studies for the pozzolona concrete were proposed. Such studies would help to generate additional data on which the different models could be generated and refined for further application.

2.4. Carbonation

Carbonation is the process of diffusion of carbon dioxide from air into concrete and reaction in presence of water results in carbonic acid, which reacts with the hydrated cement, starting with calcium hydroxide. This occurs even in low levels of carbon dioxide as present in the rural atmosphere. Carbonation results in lowering of the pH of concrete from around 13 and when it falls below 9, the passivity of the oxidation products on the reinforcement is broken and corrosion of reinforcement is initiated (Neville, 1996). However, carbonation is less of a problem in marine concrete compared to chloride attack. Carbonation can, of course, increase the propensity of the reinforcement in concrete to get corroded in cases where the chloride intrusion has already initiated the process of corrosion. So, it has to be considered in the overall plan of the monitoring and control of the corrosion of reinforcement of concrete in coastal and marine structures.

2.5. Resistivity

The process of corrosion requires an electrolyte between the anode and cathode on different parts of the reinforcement. Pore water with dissolved salts provide a low resistance pathway to electrical current, thus aiding corrosion. In dry concrete, which is highly resistive, corrosion is limited.

2.6. Degree of saturation, humidity and temperature

Diffusion of gases like carbon dioxide (which lowers the pH of concrete) and oxygen (which is required for oxidation) is limited in saturated concrete. Below 50% saturation, lack of electrolyte restricts corrosion. In between these limits, rapid corrosion is possible. In marine environment, concrete in the splash zone is subjected to alternate drying and wetting. During dry phase, carbonation and oxygen ingress is rapid and during wet phase, high humidity is present – this combined action aids corrosion and reinforcement corrosion rate is very high. Hussain (2011) explained the behavior of oxygen consumption rate of corroding steel reinforcement in chloride contaminated concrete under varying moisture environmental conditions, namely air dry, submerged, 95% relative humidity and alternate wetting–drying with the experimental studies. It was reported that the diffusion of oxygen is a significant factor only in the water saturated concrete and mentioned that it may be affected by the ratio of anode area and the total volume of concrete.

Alhozaimy et al. (2012) investigated the coupled environmental effects of high humidity and high temperature on chloride corrosion marine concrete structures. Laboratory controlled experimentation was carried out with 30°C, 40°C, and 50°C with 85% relative humidity. Samples with two 10 mm diameter bars, one completely and one partially embedded, with clear cover of 15 mm, were immersed in 99.99% pure sodium chloride solution. Tests carried out include half-cell corrosion potential using copper–copper sulfate reference electrode, macro-scale corrosion analysis, micro-scale corrosion analysis, and corrosion mass loss by gravimetric method. The corrosion reaction, after the breaking of passive layer, was observed to be both non-uniform and non-linear. It was also observed that there was a decrease in corrosion potential and corrosion mass loss at 50°C compared to that at 40°C. Possible reason identified was the reduction of oxygen solubility in the pore solution at high temperature and blockage of concrete pores at high relative humidity of 85%, under which another stable oxide layer may have developed. This was suggested as a potential method to passivate rebar in chloride environment.

2.7. Intense local corrosion

Some cases of severe local corrosion have been observed where a small area of reinforcing steel is exposed to seawater in submerged zone and linked to an efficient cathode above water (Allen, 1998). This condition would be dangerous in slender structures with few bars, like piles supporting jetties, which have been somehow damaged, resulting in large scale cracking and spalling.

2.8. Stray current corrosion

In certain marine structures, the additional steelwork like pipes and risers are protected from corrosion by cathodic protection and the reinforcement in concrete is left out of the system. If the reinforcement cage is not fully isolated, which is seldom the case, it might pick up stray current and corrosion would ensue in the anodic area when steel gives up its charge to the 'ground'. Hence, it is advisable to include all steel components, including complete reinforcing cage, for cathodic protection.

2.9. Use of supplementary cementitious materials

When replacing cement with other supplementary cementitious materials, special attention should be given towards the corrosion inhibition characteristics of the resulting concrete especially if it used in marine environment. Valipour et al. (2017) evaluated the durability performance of concrete specimens cast with various supplementary cementitious materials such as natural zeolite (0 - 30% cement replacement), metakaolin (0 - 15% cement replacement) and silica fume (0 - 10% cement replacement). The study investigated chloride diffusion when those specimens were exposed to tidal and splash exposures in a harsh marine environment, along with a parallel study under laboratory conditions. The authors concluded that optimum replacement level for zeolite in concrete between 10% and 20% resulted in 60% to 70% improvement in chloride penetration resistance in terms of concrete durability in aggressive environments.

3. Monitoring Reinforcement Corrosion

In addition to periodic inspection and maintenance of the structures, some innovative schemes of corrosion monitoring have been proposed by investigators in the recent years. Taking advantage of advancement of technology, acoustic emission, cost-effective sensors, and spectroscopy methods have found application in the monitoring process and they are discussed briefly in this section.

In their paper, Martinez and Andrade (2008) proposed a method of evaluating the efficiency of the cathodic protection by using linear polarization and electrochemical impedance spectroscopy (EIS). It was inferred from the results that the AC polarization resistance results can be applied for distinguishing cathodically protected steel from unprotected one, as the frequency value at which the maximum in phase angle appears for the faradic process would be moved towards higher values by around one to two orders of magnitude. The efficiency of the cathodic protection or verification of passivity can be checked by the recording of Bode plots of phase angles and verifying the frequency range of the appearance of the time constant of the faradic process. Influence of the electrolyte resistance was not noticed in any experiment. The results indicate that the impedance diagrams show important and consistent changes in shape and associated parameters when the steel is protected or unprotected and would be an efficient tool to monitor corrosion in steel exposed to saline water / environment.

Duffo and Farina (2009) developed an integrated and cost-effective sensor system for corrosion monitoring of reinforced concrete structures. It consisted of sensors, which would provide online measurements of various variables like the open circuit potential of reinforcement, the corrosion current density of bars, the electrical resistivity of concrete, the availability of oxygen, the chloride ions concentration in concrete, and the temperature inside the structure. These different electrodes, embedded in concrete were integrated with a software system that acquired and analyzed the data. Additionally, the software would generate alarms, to prompt the specialist to decide applicable mitigation strategies. From the results obtained, the promise of this particular sensor in determination of the corrosion state of existing as well as new concrete structures was established.

In salt environment, after corrosion of rebar is nucleated, the expansion of corrosion products results in corrosion-induced cracks in reinforced concrete. Kawasaki et al. (2010) evaluated acoustic emission (AE) technique for identification of the onset of corrosion and the nucleation of concrete cracking with a set of cyclic wet–dry tests of concrete specimens. Reinforcement provided was a single 13 mm diameter deformed bar embedded with 20 mm clear cover. Regular AE monitoring was performed during the wetting and drying cycle of a week each. The onset of corrosion and the nucleation of concrete cracking were clearly observed as two periods of high AE activity. Kinematics of micro-cracks was identified by SiGMA (Simplified Green's functions for moment tensor analysis) analysis of AE. The findings were corroborated with Scanning Electron Micrograph study of the cross-sections of corroded bars. It was concluded that AE techniques could be efficient tool for monitoring the corrosion process in marine concrete structures.

4. Control of Reinforcement Corrosion in Marine Concrete

There appears to be no single universal solution to the problem of reinforcement corrosion in marine concrete structures. Various approaches have been reported in literature and they would be required to be used either individually or in combination for efficient control for the corrosion scenario under consideration.

4.1. Dense compact concrete

No corrosion protection scheme would work without sound, dense and compact concrete. This would require proper mix design, workmanship, and adequate curing. There have been some studies on the effect some materials have on corrosion behavior, when they are added to the concrete mix. Asrar et al. (1999) reported that blending of sulfate resistant cement with microsilica gave better corrosion performance compared to ordinary Portland cement blended with microsilica when used for marine concrete.

In their study on predicting chloride penetration in fly ash concrete under long-term exposure in a marine environment, Chalee et al. (2009) presented empirical models developed based on two, three, four, and five year investigation of concretes in a marine site. The models were generated by regression analysis of the data, applying Fick's second law of diffusion. The model variables were the water to binder ratio, fly ash content, distance from the concrete surface, and exposure time. The prediction error of the models was around 25%-30%. The model also predicted the strong effect of fly ash and water to binder ratio on reducing chloride diffusion in concrete. It was concluded that a high volume (up to 50% of binder by weight) fly ash replacement and a low water to binder ratio would yield good chloride resistance in concrete under long-term exposure in a marine environment.

In their paper, Shekarchi et al. (2009) investigated how the strength and durability properties of concrete exposed to Persian Gulf conditions, got affected when silica fume was used as supplementary cementitious material in concrete. The chloride diffusion coefficient was also determined from samples taken at the ages of three, nine and thirty-six months. From the results, it was inferred that partial cement replacement up to 7.5% with silica fume reduces the chloride diffusion coefficient, while for higher replacement up to 12.5%, decrease in the diffusion coefficient was not significant. Though there was not much improvement in final strength, the initial rate of strength development was higher in silica fume concrete compared to ordinary Portland cement concrete. It was suggested that a silica fume content of 7.5–10% by weight of cement would be optimum for preventing chloride ingress in marine concrete for corrosion protection.

Chalee et al. (2010) investigated the effect of fly ash replacement in concrete and concluded that that the increase in fly ash clearly reduced the chloride penetration, chloride penetration coefficient, and steel corrosion in concrete. They presented an empirical model which could predict the concrete cover required to protect against corrosion initiation, within +15% of their experimental data and +25% of the last 10 years' data reported by other researchers for marine concrete.

In their study Lopez-Calvo et al. (2012) investigated the effect of calcium nitrite based corrosion inhibitor (CNI) and fly ash (FA) on the long-term compressive strength of high performance concrete (HPC). For twenty-eight day and one year strength, cylinders were tested while for nine year strength, concrete cubes were obtained from reinforced concrete slabs that had been exposed to a marine environment. It was observed that there was an enhancement on the compressive strength in concrete even after long-term exposure to a marine environment.

4.2. Cracking and cover to reinforcement

Cracks inevitably form on the concrete surface due to plastic shrinkage, drying shrinkage and thermal contraction. Possible remedies include low water-binder ratio, using low heat cement and supplementary cementitious materials of low heat of hydration, proper and adequate curing, lowering placement temperature and limit the temperature differential to around 20°C.

The importance of adequate cover to concrete in control of corrosion cannot be overemphasized. The cover provides a space to place and compact concrete where it is vital from durability point of view. The cover provides the minimum reservoir of alkalinity around reinforcement, and helps to maintain its passivity. Furthermore, cover acts as a barrier against chloride ingress and carbonation. For a certain crack width at surface of concrete, the crack width at the bar surface decreases with increasing cover depth, thus limiting chloride penetration, carbonation and corrosion.

4.3. Concrete surface treatments

There have been several studies on the corrosion protection by treating the surface of concrete with some coating material or mortar. The desirable properties of concrete surface coatings would include water impermeability, water vapor permeability, thermal stability, adequate adhesion, crack-bridging ability, and adequate elasticity.

Spainhour and Wootton (2008) investigated the performance of steel reinforcement embedded in concrete samples, encased by carbon fiber reinforced polymer (CFRP) wraps. Concrete samples were wrapped with 0 to 3 fabric layers impregnated with two different epoxies. Corrosion was accelerated by an impressed current through the samples kept in a high salinity solution. Corrosion was monitored dynamically during exposure by current flow measurements and reinforcement mass losses were measured after exposure. When comparing the theoretical predictions of total mass loss with actual corrosion mass loss values from experiment, it was found that in general the calculated mass loss under-predicts the actual amount of corrosion mass loss, though these two were well correlated. Test results indicated that CFRP wrapped specimens had decreased reinforcement mass loss, and lowered the corrosion rates. The performance of wrapped specimens was found superior to that of either control samples or those coated only with epoxy. Results indicated that in saline environment, the corrosion protection provided by the CFRP wraps improved with the more suitability of epoxy used, and the number of CFRP wrap layers.

Medeiros and Helene (2009) studied the efficacy of some surface treatments like hydrophobic agents, acrylic coating, polyurethane coating, and double systems in inhibiting chloride penetration in concrete. The efficiency of the coating was evaluated with tests like capillary water absorption test, pipette absorption test, chloride diffusion coefficient in saturated concrete, and rapid chloride penetration test. It was observed that the double systems presented greater capacity for reducing the capillary water absorption and chloride diffusion than all the single protection systems, with polyurethane coating as an exception. It was also noticed that all the tested surface protection coating provided significant reduction (>70%) in the sorptivity of concrete. In their effectiveness in reducing the chloride diffusion coefficient, polyurethane coating was the best with a reduction rate of 86%, followed by the double systems with best reduction of about 40%, and best reduction of other single coatings was around 20%. It was concluded that among the studied surface treatments, the polyurethane coating was the best corrosion protection surface treatment for marine concrete.

In their paper, Dai et al. (2010) examined the effectiveness of a water reducer and chloride barrier surface impregnation of the reinforced concrete in a marine environment with focus on how surface cracks created before and after impregnation influenced their performance. Reinforced concrete prisms and cylinders, treated with silane-based water repellent agents and sodium silicate-based pore blockers, were exposed to cyclic sea water shower under an outdoor environment for one year. Under such simulated accelerated subtropical marine wet-dry cycles, the time-dependent water absorption of all specimens was monitored. The penetration depths of the surface impregnation agents and the chloride penetration profiles were determined by splitting the samples. The areas with corrosion, evident in the steel reinforcement of the specimens were also measured.

From the results, it was observed that the sodium silicate-based pore blockers were not effective in preventing chloride penetration into concrete under simulated marine conditions. Under similar conditions, silane-based impregnation was found to be a highly effective in reducing water and chloride absorption, and the efficiency depended on the penetration depth, larger than 5 mm being advocated. When cracks (up to 0.2 mm) existed before impregnation, impregnation with silane-based cream and gel could resist corrosion even after one year of accelerated dry/wet exposure to salt water. However, if cracks formed after impregnation, chloride penetration could not be totally prevented, other than very fine cracks (< 0.08 mm).

Zhang et al. (2010a) explored geopolymer as an innovative inorganic coating for corrosion protection in marine concrete. The properties examined were setting time, permeability, anticorrosion, bond strength, and volume stability. A compound geopolymer was developed by adding 10% granulated blast furnace slag (GBFS) in metakaolin, and a beneficial effect of GBFS was observed in reducing the permeability of the geopolymer. From the study, it was confirmed that geopolymer had excellent anticorrosion property in seawater as well as marine atmosphere. Possibly due to the coexistence of calcium silicate hydrate (C–S–H) gels in both cement and geopolymer matrix, the average bond strength between geopolymer and cement paste or between geopolymer and mortar was found to be higher than 1.5 MPa. The large shrinkage of the geopolymer could be controlled with addition of polypropylene (PP) fiber and MgO expansion agent, and careful early age curing. It was inferred that geopolymer can be applied as an innovative protective coating for marine concrete structures.

The earlier study was followed by an investigation by Zhang et al. (2010b) on the microstructure of the interfaces between the geopolymer and cement paste and mortar, and the pore structure of geopolymers. The various tools applied included scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP) and Brunauer–Emmett–Teller (BET) nitrogen adsorption. It was found that the interface between the geopolymer and cement paste was very compact and its chemical composition changed due to the reaction between the geopolymer slurry and the cement. Open pores in the geopolymer were much smaller than that of ordinary Portland cement paste. The permeability decreased due to the compact microstructure of the geopolymer. The alumino-silicate geopolymerization products, unlike the hydration products of ordinary Portland cement, were stable both under sea water and in marine atmosphere, thus retaining their protective properties. It was suggested from the analysis that metakaolin-based geopolymers could be used as corrosion protection for marine concrete structures.

In their paper, Moradllo et al. (2012) explored six different concrete surface coatings, namely, acrylic modified cementitious coating, epoxy polyurethane, aliphatic acrylic (solvent based) with low viscosity silane/siloxane primer, acrylic modified cementitious coating, cementitious coating, styrene acrylate (solvent based) with low viscosity silane/siloxane primer on the surface of concrete and monitored their performance during 5 years of exposure in tidal zone of Persian Gulf region. Tidal exposure was at about 2.2 m from sea level, where the durations of exposure of concrete to dry and wet conditions were similar, like the tidal zone. The tests included chloride profile, chloride diffusion coefficient, surface chloride content, time dependent surface chloride content, and surface coating lifetime study. From the results, it was inferred that epoxy polyurethane and aliphatic acrylic were the most efficient coatings, which cause a reduction the chloride penetration and enhance the service life of concrete structures. However, performance of surface coatings is time-dependent and deterioration with time was observed.

Gong et al. (2012) evaluated the corrosion performance of marine concrete, with surface treatment by silane impregnation, using silane gel and silane solution. Effect of the type and amount of silane on the mechanical performance, capillary water absorption and chloride ion permeability of concrete were studied in the experiments. It was observed that, compared to untreated concrete, there was around 90% reduction of water absorption and chloride absorption of treated concrete. The chloride diffusion coefficient and electric flux was also found to decrease considerably. The reduction achieved was more in silane gel than silane solution treatment, and it also increased with amount of silane applied. It was inferred that surface treatment of concrete with silane was an effective chloride corrosion inhibitor in marine conditions.

Al-Majidi et al. (2018) presented a novel method of corrosion affected concrete repair using waste material rather than primary mineral product. They used strain hardening fibre reinforced geopolymer concrete for coating concrete which was subjected to accelerated corrosion and subsequent flexural tests of beam specimens. They concluded that surface coating with polyvinyl alcohol fibre reinforced geopolymer concrete significantly reduced corrosion damage in terms of mass loss, crack distributions and structural performance. A further observation was that the differences in surface coating thickness considerably affected the corrosion resistance of the repaired beams.

4.4. Coated reinforcement

Venkatesan et al. (2006) examined the performance of three different types of corrosion protection by specialty coatings to reinforcement bars, namely cement polymer composite (CPCC), interpenetrating polymer network coating (IP) and epoxy coating as corrosion inhibitors for marine concrete. They concluded that over the one year study period, the CPCC performed best for atmospheric, high tide and sea floor level, whereas epoxy performed better than IP for high tide level and the sea floor level.

The corrosion performance of epoxy/zinc duplex coated 13 mm diameter reinforcement, embedded in concrete was compared by Dong et al. (2012) with the black steel, galvanized and epoxy coated ones. The mechanical damages of epoxy coatings, which might occur during placement and casting of concrete, affect the corrosion protection performance and this aspect was also examined. The bars were placed with a cover of 12 mm, at the center of concrete cylinders, and immersion/exposure experiment was carried out on an ocean test platform, in the strait across Xiamen and Gulangyu, China. The specimens were subjected to two simulated accelerated tidal cycles per day. The corrosion potential of rebar embedded inside concrete specimens was measured by a digital multimeter with reference to saturated calomel electrode. The epoxy coated and epoxy/zinc duplex coated bars showed better anti-corrosion performance than others. While considering the mechanical damage of about 0.928% of the total surface area of coated rebar, more severe corrosion was observed in the damaged area of epoxy coated bar. In contrast, the epoxy/zinc duplex coating remained a good corrosion protection to steel in concrete even when suffering from similar mechanical damages to the epoxy coats.

Shubina et al. (2016) explored a new generation of reinforcement coatings for corrosion resistance. This was bio-molecules which was an eco-friendly option of reinforcement coating. The evaluation of the effectiveness of this coating was performed in simulated concrete pore solution using classical electrochemical measurements, microscope observations and X-ray Photoelectron Spectroscopy (XPS). They concluded that bio-molecules with the concentration of 1 g L^{-1} were demonstrated inhibition efficiency against corrosion of carbon steel in simulated concrete pore solution. For actual application, further investigation of inhibition properties of bio-molecules in the real mortar-embedded reinforcement bars along with evaluation of impact on the ecosystems would be required before the full-scale applications biomolecules.

4.5. Other reinforcement

There have been attempts at using other materials like stainless steel, galvanized reinforcement, and fibers as reinforcement in concrete in different research initiatives. However, due to some limitations, these have not been practically implemented. Stainless steel is prohibitively costly, and there are problems in large scale production of mild steel clad in stainless steel for corrosion protection. From their probabilistic life cycle analysis, Val and Stewart (2003) concluded that use of stainless steel reinforcement, which was six to nine times more expensive than carbon steel reinforcement, would be justified if the construction cost using stainless steel was no more than about 14% higher than the construction cost of using carbon steel reinforcement, for the splash zone. Galvanization of reinforcement may react with the alkaline concrete to give off hydrogen gas, which would pose fresh problems. Furthermore, research indicates that at high chloride levels, galvanization does not offer much benefit. Mild steel, stainless steel and polypropylene fibers have been used. Though they offer many benefits like strength equal to or greater than reinforcing bars, reduced weight and enhanced durability, their practical application have been limited to the armoring layers for abrasion protection of structural concrete. Further, they have found wide-spread application in the repair and rehabilitation of distressed concrete structures.

4.6. Cathodic protection

Prevention of corrosion of reinforcing steel has also been tried with cathodic protection devices, where sacrificial anodes are used. Bertolini et al. (2002) conducted experiments on reinforced concrete columns with steel embedded in chloride free and chloride contaminated concrete. They concluded that the sacrificial anodes were very effective in prevention of the initiation of the corrosion, and comparatively less effective in controlling any already initiated pitting corrosion. Orlikowski et al. (2004) established from their experiments that the proposed mix of pigmentary graphite and polymer matrix were very effective in cathodic protection of the reinforcement in concrete provided the graphite content was kept between 40% and 45%. Bertolini et al. (2004) reported the behavior of anode made of nickel-coated carbon fibres in a cementitious mortar used as cathodic protection. They further attempted patch repair on anode areas damaged by excessive current and concluded that such repairs were not effective.

A paper by Bertolini and Redaelli (2009) dealt with the determination of current and potential distribution in reinforced concrete elements partially submerged in seawater. The study was aimed at predicting the throwing power of cathodic prevention applied by means of sacrificial anodes. Throwing power means the height at which protection can be achieved with the particular anode location. It had been earlier reported that for cathodic protection, this height was limited to a few tens of centimeters above the water level, depending on the concrete resistivity. It was suggested that due to the higher polarisability of passive steel compared to that of active steel, the use of cathodic prevention, could be one option to overcome the limitation of cathodic protection. Experimental results from previous laboratory tests showed that the throwing power of cathodic prevention is higher compared to that of cathodic protection. Numerical simulations with finite element models of potential distribution were carried out for extending the results obtained on small-scale specimens to elements of larger dimensions, for both cathodic protection and cathodic prevention. The electrochemical behavior of steel bars, geometry of the pile, geometry of sacrificial anodes, concrete resistivity and water level were varied in the study. It was concluded that the throwing power of protection was influenced by the geometry of the pile, in particular its diameter, and by the amount of steel surface to be protected while other parameters such as concrete cover, position and dimension of submerged anodes showed no effects in the ranges of variation considered. Submerged sacrificial anode could inhibit corrosion up to 1.2 m above the water level.

Xu and Yao (2011) proposed a conductive overlay material made of carbon fiber filled cementitious mortar for cathodic protection of reinforced concrete structures. The main advantages of this scheme over the other anodic materials were noted as the similarity of thermal expansion to that of the underlying concrete and low contact resistance between the anode material and the concrete. Although there would be increase in cost by adopting this material and processing procedure, it would be compensated by the ease of installation, especially in inaccessible locations. The mechanical, electrical, and electrochemical properties of the material were investigated to evaluate the practicability. It was reported that the addition of carbon fibers enhanced the strength and toughness of the mortar, as well as the electrical performance. It was suggested that the optimum fiber content should be above but in the vicinity of the percolation threshold. It was ascertained from the accelerated anodic polarization tests and impedance measurements that both of the fiber content and pore solution composition influence the electrochemical property. The work confirmed the possible utilization of this type of anode material in cathodic protection of reinforced concrete damaged by chloride induced corrosion as in marine environment.

5. Life Cycle Analysis, Probabilistic and Durability Based Approaches

Zen (2005) discussed life cycle management for steel piles in sea water. Similar approach would be required to be adopted for efficient corrosion management of reinforced concrete structures too. In this regard, Meira et al. (2010) reported that the results of numerical extrapolations from their experimental data showed that chloride deposition rate on the wet candle can be used as an environmental indicator, helping to estimate the expectancy of service life of concrete structures or suggesting minimum concrete cover thicknesses for a required service life. Porsaee (2009) presented a measurement unit and a flexible program to facilitate the automated measurements of corrosion activity of reinforcement bars embedded in concrete, using a variety of electrochemical techniques. Such approaches must be further customized for application in corrosion monitoring of the coastal and marine concrete structures.

Val and Stewart (2003) presented the results of the probabilistic life-cycle cost analysis which could be applied to select optimal strategies for improvement of durability of reinforced concrete structures in marine environments considering the serviceability criteria like spalling and cracking. A probabilistic approach to durability was proposed for the design of reinforced cover of a concrete immersed in sea water by Deby et al. (2009). It considered non-linear chloride diffusion model, probabilistic parameter variability, and cement chemical composition, among others. The model was developed for ordinary Portland cement. Similar studies for other types of cement, and admixtures would be very useful. A design approach based on the verification of the serviceability (durability) limit states, such as de-passivation of reinforcement, cracking and spalling due to corrosion, and collapse due to cross section loss of reinforcement was advocated for marine environment by Ferreira (2010) based on the probability based durability performance analysis. The potential of the approach for assisting in durability design decision making process was highlighted.

When evaluating the possibility of corrosion in marine concrete or planning mitigation strategies, all possible causes and factors need to be considered. De Medeiros-Junior et al. (2015) demonstrated the practical approach with a case study of corrosion in an offshore platform. They concluded that the progression of corrosion depended on the orientation of the analyzed structure (sidewalls, towards wind / wave action or away) and this should be considered in studies of expected service life to be employed in real situations. They further mentioned the commonly found pathological manifestations in the structure under study as cracks, concrete detachment, marine growth and concrete displacing by reinforcement corrosion.

6. Conclusions

The major issues regarding reinforcement corrosion in marine and coastal concrete structures have been briefly discussed. The chloride attack is the main process governing corrosion with concrete in the splash zone being the most vulnerable. Higher humidity and higher temperature aid the process of corrosion. Physical damages by sand, shingles and debris carried by waves and currents as well as impact from vessels aggravate the problem. When cathodic protection is provided to additional steelwork, the reinforcement should also be cathodically protected to avoid stray current corrosion.

The main strategy for monitoring corrosion would be periodic and methodical inspection and maintenance. Other promising options like installation of sensors and advanced techniques like acoustic emission and spectroscopy have been identified by researchers and may be implemented as and when required. Automated measurement of the corrosion performance of reinforcement in marine concrete had been suggested. Dense and compact concrete, produced with low heat cement / cementitious material, low water-binder ratio, placed and compacted properly, and cured adequately would be indispensable in providing protection against corrosion. Depending upon the atmospheric aggression, adequate cover thickness should be provided. Use of stainless steel or galvanized steel as reinforcement has found limited practical application. The fiber reinforced concrete has been utilized, in majority of cases, as abrasion resisting armor for structural concrete. Epoxy-coated reinforcement and duplex coated reinforcements have also been proposed.

Majority of the work in the recent years have concentrated on various surface treatments of concrete like carbon fiber reinforced polymer, geopolymer, silane based coatings, among others. Some experiments have also been performed on cathodic protection schemes. It must be noted that there does not exist a single solution to the problem of reinforcement corrosion and systematic evaluation of the case under consideration should be performed to arrive at the most effective measure to prevent and limit corrosion of reinforcement in marine and coastal concrete structures. Keeping in view the variety of factors involved in the durability performance of marine concrete, and their complex non-linear interactions, probabilistic models had been proposed for predicting the performance. Further, performance based design and life cycle cost analysis which incorporates the stochastic nature of the variables would be essential in improving the design as well as the performance of the concrete structures in coastal and marine locations.

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