Surface Engineering of Construction Steel
for Corrosion Protection – A Review

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Abstract

Corrosion of rebars is a major problem faced by structures, especially in marine environments. Reinforcing bars are subjected to pitting corrosion from chloride attacks. Furthermore, structures are also susceptible to acid rain and attack from sulphate species. To overcome such challenges, surface engineering can be an effective option. Recent studies have shown rising focus of engineers and scientist on preventing corrosion from rebars and reinforcing steels, by applying a layer of coating. Such coatings include enamel, epoxy, duplex enamel and epoxy, galvanization, electroless Ni and self-healing coatings. They effectively shield the rebars by providing either barrier or passive protection. Therefore, the present work aimed to summarize different coating variants used for corrosion prevention of rebars, and present recent trends. Further research directions to make the coatings more cost-effective were also reviewed.

Keywords: concrete; corrosion resistance; electrochemical corrosion; reinforcing steel; surface coating.

Introduction•

Presently, ocean resources are being exploited, and steel structures subjected to marine environments undergo degradation caused by corrosion [1-3]. Due to the attack of chloride species, dimensional changes take place, and the structures' longevity is affected [4-6]. Furthermore, because of aggressive environments and pollution, there is stress corrosion cracking of structural steels [7-10]. Dynamic conditions to which the structures are exposed also influence their corrosion behavior [11]. Initially, when corrosive media seep in through the pores of concrete and reach steel reinforcements, a passivating layer is formed. Nevertheless, de-passivation of this layer takes place, leading to further severe corrosion of the embedded steel [12, 13].

In this regard, various grades of steel have been investigated. Thermo-mechanically treated (TMT) rebars possess high corrosion resistance [14-16]. Austenitic grade stainless steels have high corrosion resistance, due to the

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• The abbreviations list is in page 453.

formation of a passivating oxide layer [17-20], which can be further enhanced by using duplex steel with ferritic/austenitic microstructures [21-25]. Cr-modified low alloy steel also has shown higher corrosion resistance in a simulated concrete pore solution [26-28]. Most of the studies have revealed formation of a passivating layer responsible for the corrosion prevention of structures over a long period of time. The use of admixtures has been also recommended for maintenance of long-term passivity in reinforced concrete [29-31].

Different surface coatings play a key role in mitigation of corrosive agents attacks on embedded steel. Widely reported variants include epoxy and enamel coatings [32-35]. Enhanced bond strength between mortar and reinforcement steel has been obtained in case of enamel coatings. Recent studies have also reported self-healing enamel coatings [36]. Though careful handling of enamel coatings has been suggested, due to its susceptibility to damage during transportation [36]. Excellent corrosion resistance has been achieved for galvanized rebars, due to the ability of the coatings to provide barrier and sacrificial protection [37, 38]. Electroless Ni-P coatings have also been found to be suitable candidates to prevent corrosion of embedded steel against simulated marine environments, as well as on sulphate attacks [39, 40].

Therefore, the current scenario suggests that overwhelming attention is being given to studies on the corrosion behavior of steel and the ability of surface engineered steels, in the long run. This would enable prevention of significant economic losses arising out from the maintenance of structures in coastal/marine environments, chemical industries, agriculture related infrastructure, etc. The present review aims to have a broad understanding of the corrosion behavior of construction steel, the associated corrosion mechanisms and several coatings that have been successfully applied onto rebars. Future research directions are also suggested in the review.

Steel variants used for construction and their corrosion behavior

Super high strength steels are good candidates for use in offshore structures. E690 steel, with fine grained bainitic structure obtained after high heat input welding and rapid cooling, has been recommended for offshore structures [41]. Austenitic stainless steel, such as AISI 304 or 316 steel, has been found to remain passive towards chloride attacks [21]. High strength and corrosion resistance has been achieved for duplex stainless steel [21]. A709-50CR steel has been considered for girder replacement [42], and it has been found to have higher reliability and economic benefits compared to carbon steel, which suffers from pitting, with an increase in corrosion and results in brittle failure [43]. A steel bar exposed to natural corrosion for 19-36 months has shown dimensional losses proportional to corrosion crack width [44].

Enhanced corrosion resistance has been observed in Ni advanced weathering steel, due to formation of corrosion products [2]. In general, formation of corrosion products and passivity improves weathering steel performance in harsh

condition and chloride attacks. The new weathering steels has been subjected to harsh conditions in Maldives. Ni-enriched $NiFe_2O_4$ has been formed, resulting in a passive protection [2]. In fact, Ni content in weathering steel has a marked effect in the formation of corrosion products. In simulated marine environments, weathering steel with 1.2% Ni has shown enhanced corrosion resistance [45]. In another study, Ni content has been progressively increased for weathering steel (0.92%, 1.69% and 2.83%), and it has been seen that corrosion rate has decreased [46]. Subsequently, optimal Ni quantity has been confirmed to be 3.5%, by [47], which has been further supported by indoor acceleration tests [48].

Addition of a small amount of Cr to Ni reduces steel corrosion rate [4], although an increase in chloride concentration occurs, due to a decrease in pH at the interface [49]. However, Ni and Mo addition improves the corrosion behaviour of steel [50, 51]. Cr addition improves Fe^{2+} and OH^- within the formed oxide layer, resulting in rust compaction [26]. In fact, the durability of Cr-modified steel is higher than that from HRB400 steel, with higher threshold of chloride concentration [27]. Therefore, it has been observed that steel used in harsh conditions is mostly Cr-modified, with Ni or Mo addition, to form weathering steel, and gain resistance against marine or acidic environments.

Use of admixtures

Cement and additives determine the structures' quality. A thick passivating layer of ferric oxide is formed in alkaline environments. The corrosive agents penetrate concrete through the pores present in it. Above a certain threshold limit, the passivating layer is destroyed, and steel corrosion initiates. Alkalinity of concrete may be increased, and concrete porosity may be reduced, by addition of admixtures to cement. Admixtures are added during mortar preparation.

Phosphates are good admixtures, being quite effective as corrosion inhibitors [52-54]. On addition of trisodium phosphate, galvanostatic potential has increased with higher phosphate concentrations, while, in its absence, it has dropped to -0.15 V, showing active corrosion [52]. Phosphate and chloride ions have a combined effect on corrosion [53]. Corrosion resistance was due to formation of ferric phosphate and maghemite, and phosphate ions concentration should be greater than chloride content. Also, in another study, it has been seen that, when phosphates and chloride content were equal, pitting corrosion was prevented [55]. Corrosion rate has decreased for a one-year period. However, the efficiency of inhibitors has decreased with an increase in time, i.e., after two years of immersion in a chloride-contaminated solution. Some other reported inhibitors were sodium monofluorophosphates, calcium nitrites and amino alcohols [56]. The performance of trisodium phosphate (Na_3PO_4) as inhibitor, in a pH 12.5 solution, has been investigated, and two methodologies have been adopted [57]. In the first one, Na_3PO_4 has been added to the pore solution, and in the second case, a pre-treatment has been given to the rebar in the inhibitor solution. Better corrosion protection, which has resulted in pre-passivation, has

been seen for the second method. The performance of phosphate ions as inhibitors has been also reported in concrete pore solutions. However, the capability of passive layers has also depended on the duration of pre-treatment given to steel in the 0.5 M Na_3PO_4 solution [58].

In a study by [59], steel rebars have been immersed in calcium hydroxide with and without chlorides, for 30 days, with sodium phosphate acting as anodic inhibitor, which has reduced corrosion activity. The inhibitor's performance was compared with tetra sodium pyrophosphate and hydroxyethylidene-diphosphonic acid, and the efficiency of the latter was lower.

In the work of [60], steel reinforcement in mortar has been immersed in 3% NaCl with phosphate as admixture. Portland cement with sand has been used to prepare concrete specimens. A ratio of 0.5:0.3 has been taken for water cement and cement sand, respectively. Two types of specimens have been prepared, i.e., with and without sodium phosphate as inhibitor in water. For the second specimen, a significant improvement in corrosion potential has been observed compared to the blank. Three anodic polarizations have been carried out, as shown in Table 1. Corrosion protection ability has been attributed to the formation of iron phosphate and iron(II) phosphate at anodic sites, and visual inspection has corroborated well with experimental results. Thus, phosphates have corrosion reduction capabilities and are non-toxic, but their long term performance may not be satisfactory, especially when chloride concentration increases.

Table 1: Corrosion potential of mortar with and without inhibitor in a 3% NaCl solution [60].

Mortars	Reference mortar	Mortar + Na_3PO_4
Cycle 0 (C_0) E_{corr} +10 (mV/SCE)	-337	-246
Cycle 1 (C_1) E_{corr} +10 (mV/SCE)	-537	-210
Cycle 2 (C_2) E_{corr} +10 (mV/SCE)	-	-530

In recent years, pozzolanic material, i.e. fly ash, is being commonly used, being obtained as a by-product of several industries, such as power plants, and formed due to coal combustion [61]. Several research works have been carried out to study the effect of fly ash in preventing chloride attacks [62, 63]. Addition of fly ash to concrete increases its electrical resistivity [62], leading to a consequent decrease in chloride diffusion coefficients. Low quality fly ash, added to normal Portland cement and eco-cement, resulted in mortars with lower ingress of chloride [63]. Corrosion resistance of reinforced concrete structures has been measured using half-cell potential for 10, 20 and 30% fly ash content. It has been seen that 30% fly ash had the highest corrosion resistance [64]. Also, when cement was replaced by 20% fly ash, flexural strength of corroded reinforced concrete structures increased. However, it decreased as corrosion level increased from 10 to 15%. Thus, corrosion resistance and load bearing capacity are affected upon addition of fly ash and occurrence of corrosion.

Other candidates for inhibiting steel corrosion are natural pozzolan, silica fume and slag [65]. Corrosion resistance and chloride diffusivity of volcanic ash

blended with mortar has been studied by [66]. The curing time has been varied up to 1 year. Water/binder ratio was 0.55 to 20 and 40% volcanic ash. Electrochemical and accelerated chloride ion diffusion tests have indicated the long term beneficial effect of 20 and 40% volcanic ash addition. Diffusion coefficient has decreased and passivation period has increased. Natural pozzolans have been investigated by [67] as partial substitute to ordinary Portland cement. Corrosion rate decreased and induction time increased for 20% cement replacement by pozzolan.

Calcium nitrate-based inhibitors in concrete have also resulted in an increase in threshold of chloride, and higher concrete compatibility [68]. Both early and later stage corrosion performance have been improved by calcium nitrate in calcium sulphoaluminate cement [69].

Benzotriazole (BTA) has been found by [70] to be a possible corrosion inhibitor for carbon steel. Electrochemical tests have been performed with BTA concentration of 1.5 wt.%, having showed much lower corrosion current density. BTA has also been found to be an attractive alternative to nitrites as corrosion inhibitor for reinforcement steel in concrete, with lesser environmental impact. BTA has also successfully inhibited corrosion of galvanized steel in an alkali-activated fly ash solution, due to formation of a protective complex film in the medium [71].

Therefore, inhibitors or admixtures in concrete successfully delay corrosion initiation. However, long-term performance is not satisfactory after corrosion initiation. Surface engineering can thus be an effective alternative, which has been discussed subsequently. In the absence of corrosion inhibitors, unacceptable corrosion performance can be seen, even for chloride percentage of 0.8% or higher. However, inhibitors can reduce corrosion rate at chloride percentages of 0.8 or 1.2%, due to maintenance of a passive state [72], although, above 1.6%, corrosion initiates.

Coating variants for corrosion protection
Epoxy coatings

Epoxy coatings are widely used for corrosion protection of rebars embedded in concrete. Mechanical and corrosion behavior of epoxy coated TMT rebars has been investigated using electrochemical tests. A clear decrease in corrosion current and rise in polarization resistance have been observed for epoxy coated TMT rebars, indicating a rise in corrosion resistance [73].

X-ray diffraction study of corroded surfaces has revealed formation of oxides, hydroxides and oxy-hydroxides, leading to enhanced corrosion resistance in alkaline and acidic environments.

Nevertheless, it has been found out that cracks in epoxy coated rebars decrease thermal insulation compared to uncoated ones [74]. So, damage of epoxy coatings is inevitable. Electrochemical tests have been conducted on damaged epoxy coated rebars, after 30 days of accelerated corrosion [75]. It has been seen

that the extent of damage and electrolyte concentration has a significant effect on the rebars corrosion. However, most electrochemical studies indicate lower corrosion current and higher potential of epoxy coated rebars compared to bare mild steel, over a long duration of two years, in harsh environments such as 3.89% NaCl [76].

One of the major concerns in bridges is chloride infiltration, which results in damages, especially where deicing salts are used [77]. Electrochemical polarization tests have been carried out for bridge concrete, and a clear improvement in corrosion resistance has been observed for epoxy coatings [77]. Since highways and rail bridges are constructed for long term usage, fusion bonded epoxy coatings have been investigated as potential candidates [78]. Apart from chloride infiltration, they are also subjected to ultraviolet rays from sun. Based on electrochemical studies, it has been concluded that fusion bonded epoxy coatings are adversely affected by ultraviolet rays, and their exposure should be minimized.

Furthermore, epoxy coatings are prone to damages during transportation. Epoxy coatings with pinhole defects have been investigated by [33]. There are three stages to corrosion of coated rebars in uncarbonated/carbonated simulated pore solutions. Competitive adsorption of Cl^- and OH^- and O_2 concentration had effect on the first two stages, respectively, whereas corrosion has occurred under the coating around the pinhole, in the third stage. Local electrochemical impedance mapping has been carried out by [79]. It has been seen that corrosion has also occurred beneath the coating away from the defect.

Pitting corrosion is dependent on the electrode size. Therefore, small defects in epoxy coatings, in the order of 200 μm in diameter, have been investigated by local electrochemical impedance spectroscopy plots, and a blocking effect by corrosion products has been found by [80], whereas the same has not happened with bigger defects, in the order of 1000 μm in diameter.

Electrochemical study, along with scanning vibrating electrode technique, has revealed a uniform corrosion in coated steel with micro cracks [81]. However, in harsh sulphuric acid and hydrogen sulphide media, periodic investigation of epoxy coatings has been suggested by [82]. Fusion bonded epoxy coatings with 300 μm thickness had higher service life compared to 200 or 100 μm ones [83]. It has been further suggested that fusion bonded epoxy coatings should be avoided if sufficient thickness of the coatings cannot be achieved. To prevent any damage, careful handling is required. In another study by [84], it has been proposed that concrete structures lifespan can be prolonged with epoxy coated rebars.

In a recent study, epoxy coatings have been modified with graphene oxide/carbon nanotubes [85]. From electrochemical studies, it was concluded that such coatings have superior corrosion resistance compared to epoxy ones.

Graphene nanoplatelets and silica nanopowders in epoxy coatings can also shield rebars from corrosion [86]. Hybrid graphene nans-platelet and silica nanopowder reinforced coatings had almost three times higher coating resistance to corrosion

compared to single reinforcements. Furthermore, this has remained unchanged, even after 200 h exposure. Added benefits, such as abrasion resistance, have also been obtained. It has also been seen that a blend of graphene derivatives, such as graphene oxide, reduced graphene oxide and carbon nanotubes, have performed well in corrosive environments, and have not shown signs of corrosion up to 150 days [87].

In a recent study, cement based and Zn-rich epoxy coatings have been investigated and compared to uncoated rebars [88]. Concrete specimens with uncoated rebars have cracked at 113 h exposure. Cement-based epoxy coatings have cracked at 282 h exposure, while Zn-rich rebars have cracked at 110 h. Average corrosion potential was -350 mV for the uncoated rebar and more negative than that from cement-based or zinc-rich coatings.

Therefore, it is evident that epoxy coatings can effectively shield steel rebars from corrosion, although their major disadvantages are damages caused during transportation and the size of defects, which play a major role in corrosion control. Furthermore, most of the research works have also concluded that electrochemical methods, such as electrochemical impedance spectroscopy and potentiodynamic polarization, are the most recommended techniques for detecting corrosion on epoxy coated rebars. Also, it has been reported that hybrid epoxy coatings have superior corrosion performance.

Enamel coatings

To overcome associated problems with epoxy coatings, enamel coatings have been widely investigated, as they are less prone to damages during handling [34], and do not suffer under-film corrosion. Composition of alkali borosilicate glass frit used for pure enamel coatings is given in Table 2.

Table 2: Composition of alkali borosilicate for developing pure enamel coatings [34].

Element	SiO_2	B_2O_3	Na_2O	K_2O	CaO	CaF_2	Al_2O_3	ZrO_2	MnO_2	NiO	CoO
Wt.%	44	19.3	15.8	2.8	0.1	4.7	4.6	5.3	1.5	1	0.9

A very high degree of corrosion resistance has been observed for pure and double enamel coatings investigated through electrochemical methods. Compared to intact fusion bonded epoxy coatings, enamel coatings had higher corrosion resistance. When these coatings were embedded in concrete and tested for a period of 173 days, passivity has been observed for pure and double enamel coatings [35], as shown in Fig. 1. Corrosion potential was nobler for double enamel coatings, while corrosion current density was also lower in 3.5% NaCl [89]. On the other hand, bond strength of a mixed coating, i.e. 50% enamel and 50% calcium silicate, was has shown higher tension strength [90]. This has been attributed to higher roughness and stronger bond with the surrounding matrix formed by calcium silicate.
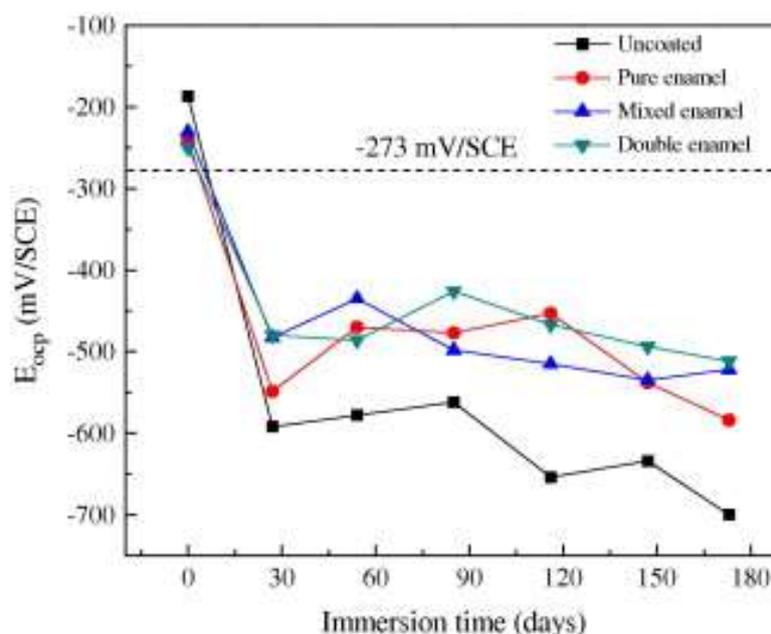
Figure 1: Open circuit potential of enamel coatings over a period of 173 days [35].

Further investigation of 50% enamel and 50% calcium silicate coatings has been done using pull out test, and the interface has been observed [91]. A higher bond strength has been observed for enamel coating compared to epoxy coatings.

Duplex enamel and epoxy coatings with outer epoxy and inner enamel layer have been investigated by [92]. In 3.5% NaCl, duplex coatings had higher average corrosion resistance, as revealed in open circuit potential, compared to individual ones. In calcium hydroxide, damages in duplex coating have reduced corrosion resistance of the duplex coatings by 10 times. In fact, sintering temperature also affects corrosion resistance of 50% enamel and 50% calcium silicate coatings [93]. With an increase in sintering temperature, corrosion current density decreases, as shown in Fig. 2.
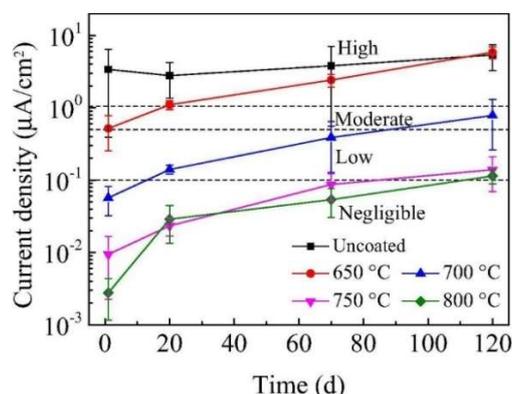

Figure 2: Variation of corrosion current densities of sintered 50% epoxy and 50% calcium silicate coating in 3.5% NaCl [93].

An optimal sintering temperature of 750°C was thus established. Furthermore, the susceptibility of this coating to cracking and deformability has also been

reduced, due to a dense structure and uniform hole distribution. Silicon nitride modified enamel coatings have been seen to have further better corrosion resistance and thermal shock resistance (more than 100 cycles of thermal shock), compared to enamel coatings [94]. However, the porosity of the coatings has increased, due to addition of silicon nitride. Nevertheless, the protection ability was better during initial stages of corrosion, compared to enamel coatings. At the later stage, corrosion rate was 10 times lower compared to bare steel.

In another study, sand particles with 0, 5, 10, 20, 30, 50 and 70wt% have been added to enamel coatings [95]. Though enamel coatings have wetted well with sand particles, corrosion resistance has decreased, due to formation of concentrated air bubbles around them. In this regard, inclusion of silicon carbide (SiC) has proved to be beneficial [96], reducing residual stresses and eliminating micro cracks, which has resulted in enhanced corrosion resistance. After immersion in 3.5% NaCl, for one day, a nobler corrosion potential of -0.680 V, was observed compared to uncoated samples with -0.750 V. Thermal expansion of the SiC reinforced coatings has matched well with steel, which has helped in reducing the residual stresses.

Composite coatings of SiC and enamel coatings have been seen to have self-healing behavior [97]. Salt spray test, potentiodynamic polarization, electrochemical impedance spectroscopy and open circuit potential have been performed for long term corrosion tests. Over a period of 210 days, 7.5% SiC reinforcement had 5 times greater charge transfer resistance, compared to pure enamel.

Thus, enamel coatings have shown better corrosion resistance and less proneness to damages compared to the epoxy coatings. Also, to achieve adherent enamel coatings, surface roughness of the substrate, i.e., rebar, should be controlled. Higher surface roughness has resulted in improved adhesion strength and impact strength [98].

Electroless nickel coatings and galvanizing

One of the metallic coatings which is recently being given attention is electroless Ni variant. The potential of electroless Ni-P, Ni-W-P and Ni-Cu-P coatings in 3.5% NaCl have been investigated by [39]. Enhanced corrosion protection has been observed for Ni-W-P coating, in electrochemical tests. On the other hand, severe pitting corrosion has been seen for the substrate, i.e., TMT rebar. Further, Taguchi's method has been utilized to optimize Ni-W-P and Ni-Cu-P coatings corrosion performance in 3.5% NaCl [99, 100]. The optimized bath led to a shift in corrosion potential to a more positive side, i.e. -258 and -350 mV, for Ni-W-P and Ni-Cu-P coatings, respectively. A decrease in corrosion current density has been also observed compared to bare rebar. Fig. 3 shows corroded surfaces. Initiation of passivation was observed in both coatings, which may prove to be beneficial for long-term applicability of the coatings.

Electroless Ni coatings have also been investigated in a sulphate medium [40, 101]. Accelerated tests have been carried out using electrochemical technique. Severe damage has been observed on TMT rebars. On the other hand, Ni-W-P coating had nobler corrosion potential and corrosion current density, due to formation of passive corrosion products. Ni and P oxides may induce protection for Ni-W-P coated rebars.
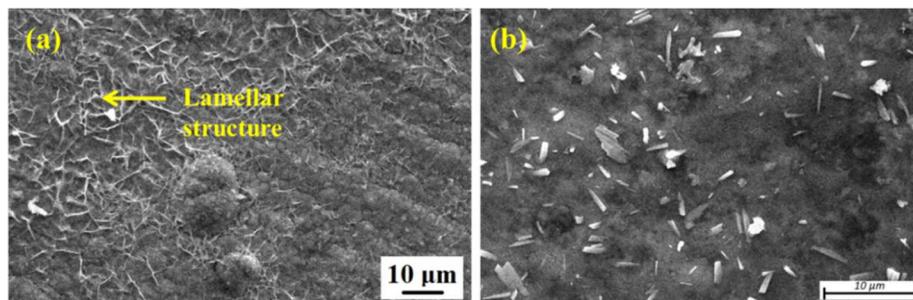

Figure 3: Corroded surface of optimized **(a)** Ni-P-W and **(b)** Ni-Cu-P coating deposited on TMT rebars in 3.5% NaCl [99, 100].

Electroless Ni-P coatings have also been found to provide enhanced corrosion resistance in a simulated concrete pore solution [102]. Ni-P coating deposited at pH 4.0 has attained passivity. Further, heat treated crystalline mid-phosphorus Ni-P coatings have developed a passive layer of Ni_2O_3 and Ni_5P_2. However, an increase in pH of concrete pore solution has resulted in higher corrosion of the coating following chloride attack [103]. Furthermore, higher P may result in smoother surface, leading to a decrease in bond strength with mortar.

Electroless Ni coating with three different thicknesses (10, 20 and 30 µm) has been investigated by [104]. Over an exposure period of 1 month, the 30 µm thick coating had higher resistance to cracking in a chloride medium. In fact, electroless Ni coatings' corrosion current density has been lower than 0.01 µA/cm^2, after 40 months [105]. The coating has also been considered to be fit for coastal structures, as per ASTM standards [106].

The addition of multi-walled carbon nanotubes and TiO_2 particles to Ni-P coatings has been investigated by [107]. Electrochemical studies have been carried out. It has been seen that, compared to bare TMT rebars, Ni-P coatings and TiO_2 with multi-walled carbon nanotubes had 22.5 and 10.63% higher corrosion resistance, respectively, as shown in Fig. 4.

Another widely investigated surface engineering method is galvanization, which provides passive protection on steel. Hot dip galvanized coatings on rebar in ordinary Portland cement have been investigated by [38]. Calcium hydroxyzincate has given sufficient protection to steel, while dilute chromic acid treatment of rebar has resulted in Zn passivation. Zinc oxide and zinc carbonate formation has been reported, due to steel weathering, and an insignificant loss of depth was seen for rebars in ordinary Portland cement. Corrosion protection of hot dip galvanizing could be improved by alloying with Al [108].
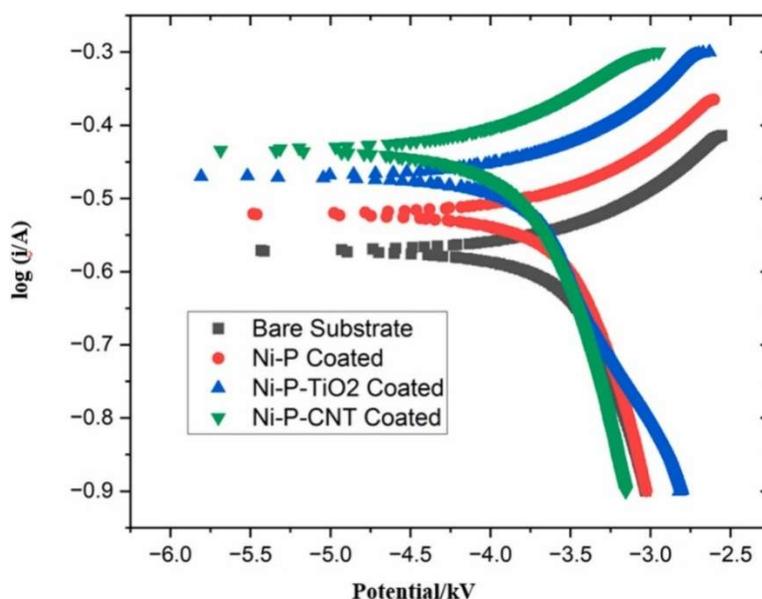
Figure 4: Tafel polarization curves of uncoated and coated substrates in a 3.5 wt% NaCl aqueous solution [107].

The 10%Al-90%Zn (10AZ) has provided the best result compared to pure Zn. Formation of passive products can be seen in Fig. 5.
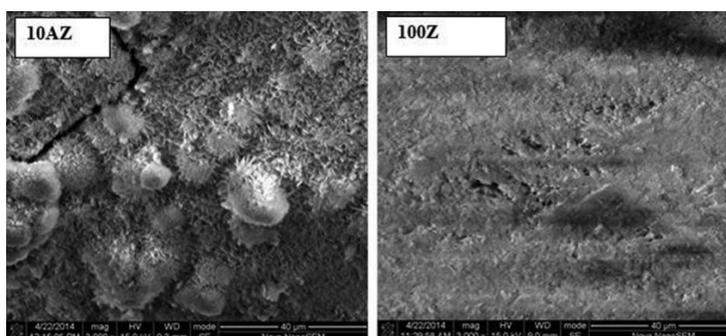

Figure 5: Corrosion products formed on 10AZ- and Zn-coated rebars after 20 wet/dry treatment cycles [108].

A study of major reduction reactions during passivation has revealed oxygen as the main oxidizing agent, which rapidly has led to passivity formation [37]. In fact, even if the coating is cut or damaged at places, galvanizing provides sacrificial protection to steel [109]. Linear polarization and electrochemical impedance spectroscopy were utilized to periodically investigate hot galvanized low carbon steel in chloride-contaminated concrete [110]. Initially, the coating corrosion was higher, due to Zn dissolution, but after 18 months' exposure, corrosion resistance has improved. This was due to the associated Zn coating. If the pore solution is highly alkaline, i.e., pH < 11.4 or ≥ 13.3, Zn dissolution takes place [38, 111]. This is the situation generally observed in fresh concrete mix where galvanized reinforcement is laid [112]. Hot dip galvanized coating thickness also plays an important role. For thickness below 50 μm, effective

corrosion protection could not be provided [113]. Thus, thickness below 50 μm has not been recommended.

Hence, both electroless Ni and galvanization play a significant role in corrosion protection of reinforcement rebars. Galvanized coatings exhibit passive protection, while electroless Ni variants provide barrier protection. Also, electroless Ni has the advantage of the coating's deposition uniformity. Thus, ribbed rebars can be easily coated, and they would precisely follow contours.

Self-healing coatings

Self-healing intelligent coatings with micro-encapsulated corrosion inhibitors have received significant attention for corrosion protection of structures. Since epoxy coatings have the disadvantage of getting damaged, their corrosion inhibition capability can be improved by encapsulating Tung oil [114]. When coatings are damaged, encapsulated Tung oil is released, which cures the damaged area, and provides 3 times longer durability compared to conventional epoxy coatings in accelerated corrosion tests. In fact, after accelerated corrosion for 150 days, 83% of the coatings have not shown signs of damage. Furthermore, pull out tests have suggested similar bond strength with mortar, compared to epoxy coatings. Epoxy coatings have been further modified by being encapsulated with nano-clay and Tung oil [115]. Hydrophobic alumina-silicate clay platelets have provided endurance to water molecules, and have improved corrosion resistance by 3 order. Furthermore, Tung oil micro-capsules act as 'smart coatings'. Similar results have also been obtained by [116]. Hybrid nano-clay and Tung oil microcapsules have also been reported by [117]. Corrosion resistance has been delayed by nano-clay, while Tung oil microcapsules have hindered corrosion. This was possible for hybrid coatings, compared to the other singular variants, i.e. plain epoxy or nano-clay incorporated coatings. This has also taken care of damages during handling, since Tung oil provides the pre-damaged spot with a healing mechanism. Other organic and inorganic containers include micro/nano polymer capsules, hallo site nanotubes, cellulose nanofibers, TiO_2 nano containers, hollow glass fibres, etc. [118]. Thus, self-healing coatings with Tung oil core material and different carriers deposited with epoxy coatings have proven to be effective corrosion inhibiting agent [118].

Conclusions

Surface engineering plays a critical role in extending the durability of reinforcement steel in coastal areas and harsh environments. Efforts have been made to investigate different steel variants. Cr-modified steel with Ni and Mo has produced high corrosion resistance. However, such grades of steel are costly. Admixtures may be also added to concrete, for inhibiting corrosion, though their long term performance has not been found to be satisfactory.

In this regard, epoxy coatings have been widely investigated, but they have the disadvantage of being brittle and prone to cracks during transportation. Enamel

coatings, along with epoxy ones, may effectively inhibit corrosion in rebars. Metallic coatings recently investigated, such as electroless Ni-P based alloy coatings, show initiation of passivation in accelerated electrochemical corrosion towards chloride and sulphate attacks.

Hot dip galvanization also provides a barrier and sacrificial protection. Recent trends include incorporation of Tung oil as core material in nano-capsules and deposition, along with epoxy coatings. They haves the advantage of epoxy coatings, and healing of damages by Tung oil leads to the formation of smart coatings. Further research may be carried out, to incorporate such nano-capsules in electroless Ni coatings, which have the advantage of deposit uniformity, allowing for ribbed rebars to be uniformly coated. Hence, to achieve enhanced corrosion resistance and bond strength, electroless Ni coatings with nano-fillers as capsules have tremendous potential in the future for smart coatings.

Authors' contributions
Arkadeb Mukhopadhyay: Data collection, review of literature, writing first draft. **Sarmila Sahoo**: Data collection, review of literature, review of first draft.

Abbreviations
BTA: Benzotriazole
NaCl: sodium chloride
SiC: silicon carbide
TMT: thermo-mechanically treated

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