

ANTI-CORROSIVE STEEL REBAR COATINGS: AN OVERVIEW

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Reinforced concrete is one of the most versatile construction materials used for the construction of several strategic structures like long-span highway bridges, pavements, off-shore structures, multi-storied framed structures and many other mega- industrial structures. Some engineers still believe that once the reinforced concrete structures are designed and built, it will remain durable and maintenance free and they can fulfill the intended purpose and function for the whole of its designed life. This is not true. The microstructural properties and permeability of concrete to various aggressive ions are responsible for corrosion of embedded steel in concrete. This paper presents in brief, the mechanism of steel corrosion in concrete and the state of the art of anti-corrosive steel rebar coatings used so far to protect the steel embedded in concrete against corrosion.

CORROSION OF STEEL IN CONCRETE

The phenomenon of widespread deterioration of reinforced concrete structures during the past two decades has become a matter of global concern, and therefore the long-term durability of concrete structures has assumed great importance today [1]. Corrosion of steel in concrete is one of the major causes of the premature failure of reinforced concrete structures [2-6]. Enormous amount of money is required for repair measures to improve the durability of new structures as well as to guarantee the durability of existing structures after repair or strengthening [7].

The deterioration of reinforced concrete structures is mainly due to the corrosion of embedded reinforcing steel in concrete. Corrosion of steel in concrete occurs when the outside environment influences the change in the composition of pore solution present in concrete. Permeability of concrete is one of the main reasons by which the change in pH of pore solution takes place. Aggressive chloride ions, carbon dioxide, moisture and oxygen can easily diffuse into concrete through the pores and cracks present in concrete from the outside environment and thus lower the pH of the pore solution from high alkalinity. This reduction in pH destroys the passive oxide film formed over the surfaces of the embedded steel. The process of corrosion starts when once the passive oxide film is broken or destroyed. On onset of corrosion, the rust products are being formed around the steel bars. These rust products are many

times in volume than that of the original metal lost from the steel bars. Therefore, these rust products exert pressure on the cover concrete. When this pressure exceeds the tensile strength of concrete, the cover concrete cracks and subsequently spalling of concrete takes place by exposing larger area of steel bars to the environment directly which accelerates further serious corrosion damages to the structures. As a result of this corrosion damage, loss of structural integrity and safety arise. Many reports presented in various International Congresses afford many examples of such serious damages to reinforced concrete structures with in a relatively short period after construction.

A SHORT HISTORY OF DEVELOPMENT OF COATING MATERIALS

Primitive men first used paints about 25,000 years ago [8] Chemical analysis of cave paintings discovered at Altamira (Spain) and Lascaux (France) showed that the main pigments used were of iron and manganese oxides. Some earth pigments were ground to a fine powder using stone mortar and bone pistons and mixed with bone marrow, animal fats, egg white or vegetable sugars to form paints. Although these paints were of very poor durability, they survived because of their shelter in deep caves which were subsequently sealed off.

Egyptians developed the art of paint-making with wider colour range considerably during the period Circa 3000-600 B.C. The first synthetic pigment, known today as Egyptian Blue, was produced almost 5000 years ago. During this period, red lead was used in wood preservative paints, but was more extensively used by the Romans. First resins used were almost all naturally occurring gums and waxes. During 600 BC— AD 400, Greeks and Romans were known to preserve and decorate objects with paints. Varnishes incorporating drying oils were introduced during this period. By the late eighteenth century, owing to increased use of iron and steel by industrial revolution, all types of paints and coatings were developed for construction and engineering purposes. The use of turpentine as a paint solvent was first described in 1740. The basis of formaldehyde resin chemistry was laid down between 1850 and 1890, although it was not used in paints until the twentieth century. During 1877, the nitrocellulose was discovered and used safely by plasticizing it with camphor. In 1918, a new white pigment, TiO_2 , which was to replace white lead completely, was introduced. During 1949-1951, epoxy resins were developed in Switzerland and in the United Kingdom (UK) and became available in the United States of America (USA). These resins could be applied in heavy coatings, from 75 to 500 microns per coat. By the end of 1950, usage of epoxy coatings had developed in volume, and various formulators were trying to correct some of the disadvantages of these coatings in several applications [9]. As far as coatings on steel reinforcements in concrete are considered, most cases serve as a means of isolating the embedded steel from the surrounding environment. Thus, an intact coating shields the steel from various adverse

conditions occurring at the concrete/steel interface which can cause corrosion of the steel and subsequent failure of the structure. More specifically, a coating on steel reinforcement is generally used to eliminate the effect of some anticipated factor which could promote corrosion.

ORGANIC COATINGS

A stable organic coating on reinforcing steel, to serve as a barrier for isolating the steel from moisture, chlorides and oxygen was first sponsored by Federal Highway Administration (FHWA), Washington D.C., USA, during early 1970's, and the project was sponsored at the National Institute of Standards and Technology, and then the National Bureau of Standards, to search for organic coatings for this application [10].

Coal-tar epoxy coatings have been used in numerous applications with good results. Their tolerance for poor cleaning, strength, excellent bond characteristics with steel surface and quick curing properties made them more satisfactory. But coal-tar epoxy coated bars cannot be fabricated without serious damage to the coatings and also it provides poor bonding property with concrete.

Asphalt coatings have been used for coating reinforcing steel, but some significant drawbacks are inherent in the system. The tendency towards cold flow and the intolerance towards poor surface cleaning are significant drawbacks [11].

Chlorinated rubber coatings offer substantial advantages in bond characteristics with concrete and steel. No major fabrication problems would be anticipated. But unstabilised chlorinated rubbers have the tendency to liberate hydrochloric acid [11].

Various vinyl coating systems are acceptable for rebar coatings, if sufficient efforts are made for adequate surface preparation, and to assume sufficient coating thickness. They require either high build vinyl or a two coat minimum application. They are suitable for application prior to fabrication of reinforcement.

Epoxy-coated reinforcing steel is being used extensively in the United States for corrosion protection in concrete structures. The first full scale application of this material was in four-lane bridge in Pennsylvania in the year 1973 [12-15]. Since then, tens of thousands of structures have been constructed with this material. Epoxy-coated rebars have gained widespread acceptance as a means to extend the service life of parking garages, bridges, pavements and other reinforced concrete structures susceptible to corrosion. Since its first use in 1973, the cost of epoxy-coated rebars has dropped significantly. As use and production grew, the cost decreased. For most

structures, coating all the reinforcing steel will usually only increase the total structural cost by between 1% and 3% [13]. Epoxy coatings to steel reinforcements are either applied by brushes or electrostatically using a bisphenol-amine epoxy powder over the hot, freshly sand blasted surface [16,17].

Initial laboratory tests have suggested that the epoxy product could provide good corrosion protection. Corrosion performance over the long-term in bridge decks applications has been reported to be satisfactory [12]. To date, there are a few published data of significant corrosion failure of epoxy-coated rebar in bridge decks with United States. But observations of severe corrosion damage of epoxy-coated rebar in sub-tropical marine environment have been reported [18].

LABORATORY PERFORMANCE OF EPOXY COATED REBARS

According to FHWA report [10], out of 47 non-metallic coatings studied for corrosion protection of steel rebars in concrete, four fusion-bonded epoxy powders emerged as the most promising coatings studied. Performance of epoxy-coated rebars has been evaluated by many workers under laboratory test conditions, in aqueous as well as in concrete environments. Aqueous environment mainly included saturated and chlorides.

Studies carried out by Sagues and Powers [19] in Florida, USA, concluded that cathodic disbondment and delamination of coating occurred at freely corroding and lower potentials when exposed to 3.5% NaCl solution. Exposure under anodic polarization resulted in pitting, but little disbondment of the coating. When the coating was exposed to $\text{Ca}(\text{OH})_2 + \text{NaCl}$ solution, it did not result in extensive disbondment at cathodic potentials. However, under anodic polarization, both pitting and delamination were observed.

In another study, Zayed and Sagues [20] at the University of South Florida, investigated the corrosion of epoxy coated rebars with intentional surface defect in a naturally aerated 3.5% NaCl solution for 140 days, using straight and bent coated rebars. It was concluded that the straight and moderately bent epoxy-coated rebars showed similar corrosion behavior when damaged.

In 1992, in a final report for the Canadian strategic Highway Research Programme [21], it was pointed out that the epoxy-coated steel rebars exhibited coating disbondment, blisters and cracks under long-term corrosion and structural performance tests.

In another report of Federal Highway Administration, Washington [22], it was reported from pull-out tests conducted with intentionally induced disbondment in coatings, bars with good

coating and uncoated rebars, that the critical bond strength of disbonded coating showed very poor values compared to grid epoxy-coated rebars. However, even with 20 to 30% coating disbondment, the bars developed 80% of the mean critical bond strength of bare bars.

Kahhaleh et al. [23] concluded in their report that even the smallest damage in the coating will initiate corrosion of rebar in a severe environmental condition, Vibrating equipments used during compaction of concrete at site may cause considerable damage to the coating. It is also reported that the holiday detectors cannot be considered as reliable device to monitor coating defects; and the quality of coating can be effectively identified by hot water immersion test. In this test, deliberately damaged bars were immersed in hot water having a temperature around 80°C for 7 days. After the test period, bars were retrieved from the hot water bath and visually examined for any corrosion damages.

Kahhaleh et.al.[24] from the University of Texas at Austin have investigated the current US specification limits on acceptable damage to fusion bonded epoxy-coated bent bars Following are the conclusions drawn from this study:

- (i) Corrosion of damaged epoxy-coated rebar in concrete was delayed and initiated when the chloride concentration reaches around twice the levels associated with the on-set of corrosion of uncoated steel.
- (ii) Under macrocell action, even damaged epoxy-coated rebars reduce the severity of reinforcement corrosion; however, the corrosion resistance is governed by degree of damage to the coating.
- (iii) The limits of allowable coating damage in the current US specification are not strict enough. Damage close to these limits causes breakdown on the coating adhesion and underfilm corrosion.
- (iv) The quality of concrete at the coated bar interface has a significant effect on corrosion protection when concrete contains high chlorides. The epoxy coating has a tendency to develop blisters at voids in contact with the bar surface.
- (v) Repairing the coating damage with patch coating material reduces the corrosion activity, but is not always effective.
- (vi) Smaller diameter coated rebars exhibited less corrosion than the larger diameter bars.

Makhlouf et al. [25] carried out experiments to verify and compare the bond strength of epoxy-coated deformed bars, using beam specimens. It was found that the epoxy-coated bars developed bond strength as low as 74% as that of uncoated bars.

Sharafi et al. [26] carried out chemical resistance tests on epoxy-coated rebars as per ASTM A775/775M-1992. It was reported that the coating did not show blistering or

softening. However, at the patched ends, softening had occurred due to adhesion loss in most of the specimens tested. From the chloride ponding test, it was found that even with high chloride levels at the rebar locations, there was no threat to rebar corrosion. This could be due to the fact that the reinforced concrete specimens were totally immersed in chloride solution and there was no oxygen available for the galvanic cell operation.

Jiro Satake et al. [27] from Simitomo Metal Industries Ltd., Japan, carried out a detailed study on the long-term performance study of epoxy-coated steel rebars, With three different coating thicknesses, varying from 100 to 300 microns, with concrete of compressive strength 240 kg/cm^3 . The prisms were subjected to static tensile test to generate cracks in concrete prior to exposure test and loaded gradually to a value of 3000 kg/cm^2 and specimens were loaded to constant stress of 2000 kg/cm^2 in the reinforcing bars. The crack width varied from 0.11 to 0.12 mm, from 0.16 to 0.19 mm, and from 0.22 to 0.25 mm at the covers 20, 40 and 70 mm respectively. All the specimens were subjected to alternate wetting and drying for 6, 12 and 24 consecutive months. It was concluded from the test results that after 24 months of exposure, 200 to 300 micron epoxy-coated rebars remained unaffected and retained all the original properties of the coating even with a minimum concrete cover thickness of 20 mm.

FIELD PERFORMANCE OF EPOXY COATED REBARS

In the early 1970's many concrete bridges in North America had shown signs of deterioration after only 2 to 3 years of construction and frequently required extensive repair after 5 to 10 years [28]. Fusion bonded epoxy-coated rebars (FBECR) were found to provide corrosion resistance combined with flexibility and abrasion resistance, and therefore in 1977 seventeen American states had adopted the use of epoxy-coated steel in bridge construction. The use of FBECR also spread rapidly in Canada between 1979 and 1981 [28].

While EBECR was becoming an established product in North America and Middle East, the use of the material in Europe and UK was relatively limited and confined to small applications in the road bridges. The largest application of FBECR in the mid-eighties was at Candiff peripheral distribution link road built by South Glamorgan Country Council. The majority of the structures using FBECR in the UK are for marine applications, water retaining structures and chemical plants.

In Japan, epoxy-coated reinforcing steel has been used frequently in concrete structures built in water front areas, highway bridges, and foundations of airport facilities constructed on artificial islands.

Field evaluation studies carried out by some researchers [29, 18, 30] during late 1980's reported that the epoxy-coated rebars are generally rated in excellent condition despite high chloride content in surrounding concrete. It is also reported that, based on deterioration rate and life expectancy, epoxy-coated rebar decks have performed better than the calculated rates and however, the rating is not a true indicator of the performance because there are so many variable factors influencing the performance. In Florida, severe corrosion of epoxy-coated reinforcing steel has been documented at some major construction projects in subtropical manne environments. Sagues et al. [15] reported that the damage took place in the form of extended metal loss with additional localized pitting. Low pH water accumulated at the resulting coating crevices, and the coating disbondment extends beyond the areas of high metal loss. Spalling of concrete cover was observed before ten years of service. In Japan, Jirosatake et al. [27] carried out a long-term corrosion study on epoxy-coated rebars at the tidal zone of Kashima Harbour. It was concluded that after 24 months marine exposure, extensive deep rusting had occurred in plain bars. When 200 micron thick epoxy-coated rebars were used in the same environment, the reinforcements were protected against corrosion and the coating itself remained intact irrespective of concrete cover thickness.

However, in some positions of United States, especially in Florida, some concerns about potential problem of long-term durability of epoxy-coated bars were raised during 1993 with the following objectives[22].

- To re-examine the effectiveness of the epoxy coating on steel rebar under simulated marine environment and to identify the cause of the problem.
- To determine the up-to-date overall performance of epoxy-coated reinforcement bars in concrete bridge decks exposed to actual service conditions.
- To search for the most corrosion-resistant organic coating system for the steel rebars.

A report of 10 years experiment [31] on reinforced concrete beams exposed at the sea coast of Hokkaido, showed that even with beams using epoxy-coated rebars, longitudinal cracks were formed along the reinforcements. It was also reported that the corrosion spread from the ends of the bar or from defects in the coating, eventually stopping along the line of a circumferential rib, some distance from the origin of corrosion. It further stated that there was very little bonding between the steel and the coating in the areas where the steel was corroded.

Many researchers reported [26, 32-34] that more negative potential values were recorded on the epoxy-coated bars, indicative of more severe corrosion condition. But post exposure examination

indicated that they were in good condition with corrosion limited to isolated pitting attack and some under film attack.

During 1996, eleven state highway agencies in the United States and Canadian State Highway Research Programme conducted investigations to evaluate the performance of epoxy-coated rebars on 92 bridge decks, which are exposed to harsh service conditions, to give some light on the controversy regarding performance Of epoxy coated rebars. Federal Highway Administration (FHWA), Washington D.C., [15] analysed the data obtained by the investigators and concluded as follows.

- Most of the epoxy-coated rebars found to have holidays of 202 rebar segments extracted, 81% did not have any corrosion present. Rebar segments extracted from lower concrete cover areas only should presence of corrosion.
- In many bridge decks, loss of coating adhesion with rebar was found.
- Defects and holidays in the coatings reduce the effectiveness of epoxy-coated rebar in protecting steel from corrosion.
- From the core test data, it was found that the concrete surrounding the rebars in many structures had accumulated sufficient chloride to exceed 0.6 kg/m^3 , which is considered by many researchers as the threshold level. In 33 decks the chloride level was exceeding this threshold level. In 11 decks the chloride content was greater than 3.0 kg/m^3 , with the highest content being 6.8 kg/m^3 .

Fusion bonded epoxy coated rebars has been used by most highway agencies including the Pennsylvania Dept. of Transportation (Penn DOT) and the New York State Dept. of Transportation (NYS DOT), to protect reinforcing steel in concrete from corrosion. However, research from recent research activities [35-37] cast doubt on the ability of epoxy coating to provide long-term corrosion protection of steel in concrete exposed to chlorides. A recent Summary Report from FHWA, Eastern Resources Center, USA [38] suggests necessary precautions to be taken while using epoxy coated rebars at site.

Study completed by Krauss et al [39] on corrosion investigation of four bridges built between 1973 and 1978 using epoxy coated rebars confirmed good performance of epoxy coated rebars. However, this report indicates significant softening and disbondment of coating on some samples due to exposure to wet chloride environment.

Many recent technical reports on the performance of epoxy coated rebars in bridge decks (40-451) concluded that the epoxy coating on steel rebars performed well with occasional evidence of

(IJAER) 2015, Vol. No. 10, Issue No. VI, December

e-ISSN: 2231-5152/ p-ISSN: 2454-1796

coating disbondment and corrosion. These observed failures were minor and did not show any pattern to cause any major concern. Another recent report (461 based on laboratory evaluation with epoxy coated rebars and uncoated rebar in various environments including high saline conditions indicated excellent performance of epoxy coating. Though there are few drawbacks with the epoxy coated steel rebars, they can be corrected 147,481 by improving the film adhesion with the steel substrate, by reducing the holidays and damages in the coating and by increasing the coating thickness.

OTHER TYPES OF ORGANIC COATINGS

Shreekant Patil and Shenoy [49] formulated polyurethane coating based on acrylic resin and aliphatic isocyanate for rebar coating. It is claimed to possess excellent chemical resistance, adhesion, toughness and abrasion resistance. The addition of cyclohexanone in the formulation helps in leveling the film and ensures uniform coating thickness and pinholes.

L.K. Aggarwal et al. [50] of Central Building Research Institute, Roorkee, India has developed epoxy-phenolic interpenetrating polymer network (IPN) system to protect steel reinforcements from corrosion in concrete. IPN coating system is a two component system, consisting of two or more polymer alloy. It is claimed that the polymer phases are devoided of chemical linking between them interwoven to each other by permanent entanglements. A medium viscosity epoxy resin, based on epichlorohydrin and bisphenol as base and an aromatic amine adduct as the cross-linker and a phenolic resin obtained from an indigenous phenol with its cross-linker has been used in this formulation.

S.K. Manjrekar et al. [51] reported that polymer-cement-inhibitor (PCI) coating on steel rebar provided an impermeable membrane as well as effective passivating environment for embedded steel rebar. It is reported that the PCI is a highly alkaline emulsion coating compatible with concrete environment, provides extraordinary tensile and flexural properties to the film, highly impermeable to water and possesses chemical resistance.

K. Kumar et al. [52] of Central Electrochemical Research Institute (CECRI), Karaikudi, India, has developed cement-polymer composite coating (CPCC) for corrosion protection of steel in concrete. The salient feature of this coating system is the rapid curing of primer and sealing coat. It is also reported that the bond strength of the coating is enhanced as the top coat being a cement based system, is quite compatible with concrete to improve bond strength.

S.X. Wang et al. [53] developed an acrylic latex coating system to protect steel bars in concrete against corrosion. Addition of inhibitive pigments such as zinc yellow or red in the coating system provides passivation of the steel surface against aggressive agents.

L.G. Andion et al. [54] developed a phenol polymer coating for steel rebars embedded in concrete. It is reported that the phenol and its substituted derivatives can be electropolymerised by oxidation in aqueous and non-aqueous solution giving polymeric film. This has been substantiated by several authors [55-61]. In this system, polymeric film is deposited on steel surface as thin film by electrochemical oxidation of phenol (concentration 0.06M) in solution of sodium carbonate of 0.1M. This coating system has been tested by measuring corrosion current densities and compared with bare steel rebars, under different chloride concentrations in concrete. This system is reported to protect the embedded steel rebars against corrosion in chloride environments.

INORGANIC COATING SYSTEMS

Two types of inorganic coating systems were developed at CECRI, Karaikudi, India [62-65] for corrosion protection of steel rebars in concrete. The first one is an inhibited and sealed cement slurry coating, is obtained by an in situ process to be carried out after all bending and shaping operations are completed at the construction site. This coating has been evaluated under different field conditions and also under different accelerated laboratory test conditions. It has a minimum durability factor of 25. This system obviously has multifarious sequential operations and hence laborious and time consuming. The second coating is an inorganic alkali-silicate coating, found to have the durability factor of 10 to 300, in terms of galvanic current measured. Even with 1% prior damage on coating, the coating was found to have a durability factor of 10. In situ patch repairing is easy to perform in these systems. However, the long-term performance in the field is yet to be assessed in the case of alkali-silicate coating system.

Silicon and Si-Ti based coatings were developed [66-68] to coat the steel rebars by chemical vapour deposition in fluidized bed reactor (CVD-FBR). The coating material such as silicon or mixture of silicon + titanium particles is loaded as a powder in an FBR. An inert gas is used to fluidise. With a coating temperature ranging from 500-600 °C, a very thin diffusion coating thickness of 1-10 micron is obtained which is quite adherent, compact and conformal. The main portion of the coating composed of Fe_3Si and FeSi when silicon was the only coating material used. AC Impedance measurements showed the protective nature of coating when tested with 5% NaCl solution. Best coatings were obtained when silicon and titanium were co-deposited at a temperature around 550 °C.

METALLIC COATINGS

Metallic coatings on steel rebars provide protection against chloride-induced corrosion in concrete. Metallic coatings presently under serious consideration are of zinc, nickel and copper. Metallic coatings can be classified into the categories. Sacrificial or non-sacrificial (noble) coatings made of metal like zinc, which has more negative potentials than steel, can provide sacrificial protection to steel. When this sacrificial coating on steel is broken, a galvanic cell is formed whereby the coating is slowly sacrificed. Noble metals like copper and nickel can also be coated over steel. However, the protection exists only as long as the coating is unbroken, since any exposed steel is anodic to this coating. Of these, hot dip galvanizing (zinc coating) has gained most widespread use for reinforcing bars.

LABORATORY PERFORMANCE OF GALVANISED REBARS

Galvanising of steel is done by number of ways such as hot-dip galvanizing, zinc spraying, sherardizing and electrolytic coating, Hot-dip galvanizing of steel rebars is normally used in construction practices. Considerable controversy exists in respect of the efficiency of hot-dip galvanizing for protection of steel in concrete. The reason is that the efficiency of protection depends on the one hand on the steel composition and on the other hand on the pH value of the concrete especially in the case of chloride attack.

The corrosion behaviour of galvanized steel in concrete has been studied extensively in the laboratory and in the field [69-71]. The reaction of zinc with concrete is quite superficial and the reaction products may not induce damaging stresses [72]. However, 100% pure zinc can react with wet concrete to form insoluble salts, which crack concrete in the presence of hydrogen gas evolution [73,74] A report [75] indicates that zinc has low tolerance limit for chloride. Some other test results (761 have revealed the unpredictable behaviour of galvanized steel in concrete.

Macias and co-workers [77-81] studied the corrosion behaviour of galvanized steel in simulated aqueous environment of cement in the presence of various soluble components of Na^+ , K^+ , Ca^{2+} , SO_4^{2-} , Cl^- by conducting polarization experiments. It was concluded that at the threshold pH of 1.355 ± 0.1 , corrosion of galvanized steel had occurred. It was reported that at pH of 13.2, a protective layer of calcium hydroxy zincate $[\text{Ca}(\text{Zn}(\text{OH})_3\text{2H}_2\text{O})]$ was not formed uniformly. Compared to NaCl , CaCl_2 produces more adverse effect. It was concluded that sulphate ions did not causes the dissolution of zinc as chloride, as long as their presence in pore solution causes the passivity of zinc and more importantly sulphate ions did not promote pitting corrosion of galvanized rebars, A total dissolution of zinc was observed when the pH of the medium was greater than 13.4 ± 0.1 . Above this pH, there was a porous layer of calcium hydroxy zincate thus causing the dissolution

of Zn with the formation of $Zn(OH)_2$ and ZnO, Galvanized rebars embedded in slag and fly ash cements which had low pH value around 12.1, showed a higher i_{corr} of around $0.8\mu A/cm^2$.

Stresses produced by the corrosion of galvanized and bare steel embedded in cement mortar was studied [82]. At equal corrosion rates bare steels produced larger stresses than galvanized rebars. This is because, the Fe_3O_4 layer formed on bare steel was continuous, adherent and locked in place at the interface causing expansive pressure. Whereas ZnO layer was powdery, much less adherent, had some degree of mobility and was able to into concrete, thus reducing the expansion at the interface.

Hildebrand and Schwenk [83] reported that only at partial immersion conditions the corrosion susceptibility was more, because in this condition, chlorides, water and oxygen passed together towards the rebar. Zinc coating was removed up to 25 micron in aggressive condition, which indicates that the hot-dip galvanizing can only delay the corrosion and hence it can give only temporary protection.

Hime and Machin [84] reported that $Zn_5(OH)_8Cl.H_2O$ was found to be a corrosion product of zinc coating of galvanized steel embedded in concrete contaminated with a large amount of chloride. Cracking of mortar or concrete can occur due to corrosion of Zn layer if $Zn_5(OH)_8Cl.H_2O$ was formed.

Thangavel et al. [85] have studied the influence of coating thickness on bond strength using galvanized, chromated-galvanised rebars with different coating thicknesses. Pull-out strength tests carried out as per BIS:2770:1979 revealed that the galvanized rebars had more bond strength compared to uncoated rebars. It is also reported that if the thickness of the coating is increased, the bond strength is reduced. Chromate treatment on galvanized rebars has no beneficial effect with regard to bond strength.

FIELD PERFORMANCE OF GALVANISED REBARS

Field performance of hot-dip galvanized steel rebars is being evaluated in many countries (particularly in the USA). In most cases, the performance has been compared with bare steel as well as epoxy coated steel [86].

Swamy et al. [87] had carried out long-term field exposure studies on hot rolled galvanised rebars in off-shore environment at Tokyo Bay, Japan. It was concluded that the delaying of

concrete cracking due to corrosion of galvanized steel couldn't be expected in most corrosive off-shore environments.

Norimoto Kashino [88] has evaluated the long-term performance of galvanized rebar in concrete under various environmental conditions with three types of concrete mixes. It was concluded that the galvanized rebars performed well in low chloride concrete.

The Building Research Establishment, UK had undertaken field exposure studies on galvanized rebars at different sites for a period of 5 years 1891. From this extensive study, it was reported that the galvanized bars in 5.4% NaCl concrete, corroded completely and the measured weight loss was 13.9 gms, which was very much higher when compared to bare steel, whose weight loss was only 5.9 gms. Only in chloride free concrete, the weight loss of galvanized bar was less, i.e, 0.31 gm, when compared to bare steel i.e.0.50 gm.

Swamy [90] had evaluated corrosion resistance of plain and galvanized rebars at stressed condition in a tidal zone of sea water. Specimens were stressed up to 200 N/mm^2 . It was concluded that the performance of galvanized coating mainly depends on concrete cover thickness and the chloride ion concentration.

The performance of galvanized rebars in concrete are conflicting, perhaps the conflict pointed to possible influence of experimental techniques on the results and there is a need to develop an evaluation method that can be standardized.

OTHER TYPES OF METALLIC COATINGS

Some of the noble metals such as copper, nickel, stainless steel and titanium were coated over the bare steel surface of rebars and evaluated for their corrosion resistance performance in concrete.

Copper-clad reinforcing steel rebars were initially tested during 1980 and 1984. Re-evaluation of copper-clad rebars has been undertaken recently by FHWA, Washington [91]. It was reported that the copper-clad rebars are more resistant to corrosion, and provide better protection against corrosion than calcium nitrite inhibitors. Copper-clad rebars in concrete with chloride level 8.5 to 10.32 kg/m^3 , which is at least 14 times more than the corrosion threshold level of chloride, did not show any corrosion failure when tested in reinforced concrete slabs, but it discoloured the surrounding concrete to a gray-green colour, due to significant amount of unhydrated cement around these rebars. As the copper can retard the hydration of cement, a detailed study on

structural effects on retardation of cement hydration is required, prior to using these rebars in bridge structures.

Nickel cladding of steel rebars received attention in the late 1960's and has been shown to be capable of delaying in some cases and preventing corrosion of rebars in concrete [92-94]. Wrought nickel, at least 0.025 mm thick with underlying diffusion zone of alloyed nickel and iron provides additional corrosion protection. It is reported [95] that even in the event of break in the nickel coating, corrosion of steel is not appreciably accelerated. Results of 11 year testing of nickel coated bars in marine environment showed [94] that the coating was effective in delaying or sometimes completely preventing corrosion of rebars. However, nickel coating on steel rebars is still expensive.

Use of stainless steel rebar was encouraged by the British Standards Institution (BSI) specifications [95] in 1986. The solid stainless steel appears to be a potential alternative to bare steel bars due to its high polarization resistance [96]. Due to high cost of stainless steel bars, alternatively, cost-effective stainless steel coated rebars were tried as rebars in concrete. Stainless steel was sprayed on bare steel surface by the technology called twin-wire electric arc (TWEA) and high pressure/high velocity oxygen fuel processes (HP/HVOF) [97]. The stainless steel coating processed by HP/HVOF process has superior polarization resistance compared to that TWEA process. The former process produces a dense, low-oxide content coating, while the latter produces relatively more porous coating. Galvanic coupling corrosion is a problem in this stainless steel coating. Elimination of open porosity, cracks, surface defects and minimizing oxide content in the coating are very important for long term performance.

Jayaweera et al. [98] reported that alloy metal coating using Si, Ti and Ni can be used for coating steel rebars in concrete. Ti-Ni coating can be formed by fluidized bed chemical vapour deposition (FBR-CVD), paint and heat or FBR-plasma spray techniques. It is reported that these metallic powder coatings provide non-sacrificial, superior corrosion protection for long time, Ti: Ni (70:30 by weight percent) coating on steel rebars provides a 20 fold increase in corrosion resistance over uncoated steel.

REFERENCES

1. N.P. Mailvaganam and G.G. Litvan, Ind. Concr. J., 70(1996)471
2. N.S. Berk and M.C. Hicks, "Predicting Times to Corrosion from Field and Laboratory Data" Techniques to assess the corrosion activity of steel reinforced concrete structures, ASTM STP 1276, Neal S. Berke, Edward Escalante, Charles K.

(IJAER) 2015, Vol. No. 10, Issue No. VI, December

e-ISSN: 2231-5152/ p-ISSN: 2454-1796

Nmai and David Whiting, American Society for Testing and Materials, 1996, pp.41-57.

3. C. Andrade and C. Alonso, "Progress on Design and Residual Life Calculation with regard to Rebar Corrosion of Reinforced Concrete" Techniques to assess the corrosion activity of steel reinforced concrete structures, ASTM STP 1276, Neal S. Berke, Edward Escalarite, Charles K Nmai and David Whiting, American Society for Testing and Materials, 1996, pp.23-40.

4. C.E. Lock, "Corrosion of steel in Portland Cement Concrete : Fundamental Studies", Corrosion effect of stray currents and the techniques for evaluating corrosion of rebars in concrete, ASTM STP 906, V. Chaker, Ed. American Society for Testing and Materials, 1986, pp.5-14

5. J.G. Keer, J.R. Chadwick and D.M. Thompson, "Protection of Reinforcement by Concrete Repair Materials against Chloride-induced Corrosion", Corrosion of reinforcement in concrete, Ed. C.L. Page, K.W.J. Treadaway and P.B Bamforth, Elsevier Applied Science, Essese, England, 1990, pp.420-432.

6. E.J. Wallbank, "The Performance of Concrete in Bridges", Her Majesty's Stationery Office, London, April (1989).

7. P. Schiessl, "Corrosion of Steel in Concrete", Report of the Technical Committee 60-CSE RILEM (The International Union of Testing and Research Laboratories for Materials and Structures), Chapman and Hall, New York (1988).

8. R. Lambourne, "Paint and Surface Coatings • Theory and Practice", Ellis Horwood Ltd., Chichester, West Sussex, England (1987) pp.23-40.

9. Stanley L. Lopata, "Evolution of steel protection • A personal view", New concepts for coating protection of steel structures, ASTM STP 841, D.M Berger and R.F. Wint Eds., American Society for Testing and Materials (1984) pp.5-9.

10. J.R. Clifton, H.F. Beeghly and R.C. Mathey, "Non-metallic coatings for concrete reinforcing bars", Report No. FHWA-RD-74-18, Federal Highway Administration, Washington, D.C. (1974).

11. G. Ganesh Babu, "Corrosion behaviour of steel in concrete : An Overview" Protection of reinforcement in concrete an update, published by India Lead Zinc Information Centre (ILZIC), New Delhi (1995) pp.1-32.

12. R. Wayers and P. Cady, Concr. Intl, 9 (1987) 15.

13. "Corrosion Protection: Concrete Bridges, Federal Highway Administration, U.S. Dept. of Transportation Publication No. FHWA-RD-98-088, September 1998 (for New Bridges)

14. "Performance of epoxy coated rebars in bridge decks", Federal Highway Administration, US Dept. of Transportation Publication No. FHWA-RD-96-092 (1996).

15. Alberto Sagues, Rodney Powers and Abla Zayed, "Marine environment corrosion of epoxy-

coated reinforcing steel", Corrosion of reinforcement in concrete, C.L. Page, K.W.J. Treadway and B.Bamforth, Eds. Elsevier Applied Science, Essex, England (1990) pp.539-549.

16. B. Mc Fadden, "Application and fabrication of epoxy coated reinforcing steel in solving ebar corrosion problems in concrete", Seminar Reprint, NACE, Houston (1983) p.8/1.

17. L. Salparanta, "Epoxy coated concrete reinforcements", Research Report No.525, Technical Centre of Finland, Espoo, March 1988.

18. R. Kessler and R. Powers, Interim Report, Corrosion evaluation of sub- structures, Long Key Bridge, Corrosion Report No. 87-9A, Materials Office, Florida, Dept. of Transportation, Gainesville, 1987.

19. A.A. Sagues and R.G. Powers, Effect of concrete environment on the corrosion performance of epoxy-coated reinforcing steel", Paper No.311, CORROSION 90, April 23-27 (1990) Lasvegas, Nevada, pp.311/1 - 311/15.

20. A.M. Zayed and A.A. Sagues, Corros. Sci., 30 (1990)1025.

21. K.C. Clear, "Effectiveness of epoxy-coated reinforcing steel", Final Report submitted to Canadian Strategic Highway Research Programme, Toronto, Canada, 1992.

22. S.B. Chase, "Structural effects of epoxy coating disbandment", Federal Highway Administration, US Dept. of Transportation, Report No. FHWA-RD-93-055 (1993).

23. K.H. Kahhaleh, H. Y. Chao, J.O. Jirsa, R.L. Carrasquillo and H G. Wheat, "Inspection and deterioration of damage to epoxy-coated reinforcement", Research Report No. 1265-1, Dept. of Transportation, Texas, USA (1993)

24. K.H. Kahhaleh, J.O. Jirsa, R.L. Carrasquillo and H.G. Wheat, "Macro cell corrosion study of fabricated epoxy coated reinforcement", Proc. of International Conf on Corrosion and Corrosion Protection of steel in concrete, Swamy, R.M., Ed., Sheffield Academic Press, UK, July 24-28 (1994) pp.1244-1254.

25. H.M. Makhlof, A. Al-Tamini and A.H. Akbari, "Bond carrying capacity of epoxy coated reinforcement", Proc. of Intl. Conf. on Corrosion and Corrosion Protection of steel in concrete, Swamy, R.M. Ed., Sheffield Academic Press, UK, July 24-28 (1994)pp.1218-1230.

26. E. A. Sharafi, M. Shahrour and S.M.K. Chetty, "Short and long-term effectiveness of rebar coating systems in concrete exposed in aggressive environmental conditions in the United Arab Emirates", Proc. of Intl. Conf. on Corrosion and Corrosion Protection of steel in concrete, Swamy, R.M. Ed Sheffield Academic Press, UK, July 24-28 (1994) pp. 1184-1198

27. Jiro Satake, Masahi Kamakura, Kiyoshi Shikakawa, NatoMikami and Narayanaswamy, "Long-term corrosion resistance of epoxy coated reinforcing steel bars" Corrosion of reinforcement in concrete construction, Crane, A.P Ed., Ellis Horwood Ltd., Chiechester, England (1983) pp.357-378

28. N.S. Rengaswamy and K. Saravanan, "Field performance of epoxy-coated rebars in concrete structures", Protection of reinforcement in concrete: An update, published by India Lead Zinc Information Centre (ILZIC), New Delhi (1995) pp. 121-132.
29. Robert Turgeon, "Evaluation of epoxy and galvanized reinforcing bars in Pennsylvania bridge decks", Corrosion of metals in concrete, NACE, Houston, Texas (1987) pp. 200-217.
30. G.J. Malasheskie, D. Maurer and J. Arellano, "Bridge deck protective systems", Research Project 85-17, US Dept. of Transportation, Washington, DC (1988) Final Report.
31. K. Kobayashi, "Present state of development of use of epoxy-coated reinforcing steel in Japan", Proc. of Intl. Conf. on Corrosion and Corrosion Protection of steel in concrete, Swamy, R.M. Ed., Sheffield Academic Press, UK, July 24-28 (1994) pp. 1142-1154.
32. Sakir Erdogan, Theodore W. Bremner and Stephen Clarke, "Nine year programme of epoxy coated rebar in a tunnel structure", Proc. of Intl. Conf. on Corrosion and Corrosion Protection of steel in concrete, Swamy, R.M. Ed. Shemeld Academic Press, UK, July 24-28 (1994) pp. 1 199-1209.
33. Ziad G. Mat. Perf., 33 (1994) 52
34. D. Gustafson, Epoxy update, Civil Engg., 58 (1988) 38
35. A.A. Sagues, Corrosion of epoxy-coated rebars in Florida bridges, Final Report of Florida Dept. of Transportation, WPI No. 0510603, University of South Florida, Tampa, Fla, May 1994.
36. K.C. Clear, W.H. Hartt, McIntyre and S.K. Lec, Performance of epoxy-coated reinforcing steel in Highway bridges, NCHRP Report No. 370, Transportation Research Board, Washington, D.C. (1995).
37. R.E. Weyers, W. Pye, J. Zemajtis, Y. Liu, D. Mokarem and M.M. Sprinkel, "Field Investigation of corrosion protection performance of bridge decks constructed with epoxy-coated reinforcing steel in Virginia", Transportation Research Record No. 1597, Transportation Research Board, Washington, DC (1992) pp. 82-90.
38. Epoxy coated reinforcing steel: Summary Report, Eastern Resource Centre, Federal Highway Administration, Region-3, Office of Structures Technology Exchange Forum, August, 1998.
39. Paul D. Krauss, David B. Mc Donald and Mathew R. Sherman, "Corrosion investigation of four bridges built between 1973 and 1978 containing epoxy-coated reinforcing steel, Minnesota Dept. of Transportation, Report No. MN/RE-96-25, (1996).
40. G.R. Perregaux and DR Brewster, "Service performance of epoxy-coated steel in reinforcement in bridge decks", Technical Report No. 92-3, New York, Dept. of Transportation, Albany, NY (1992).

(IJAER) 2015, Vol. No. 10, Issue No. VI, December

e-ISSN: 2231-5152/ p-ISSN: 2454-1796

41. H.J. Gillis and M.G Hagen, "Field examination of epoxy coated rebars in concrete bridge decks", Report No.NOURD-94-14, Minnesota DOT, St. Paul, MN(1994).
42. R. W. Reves, "The performance of epoxy coated reinforcement steel in substructure of coastal bridges in North Carolina", Presented at the ASTM Epoxy coated reinforcement workshop, June 21-22, 1995, Hyatt Regency, Denver.
43. Evaluation of bridge decks using epoxy coated reinforcement. Research Report MIR 1261603, West-Virginia DOT, Charleston, WV (1994) .
44. H.O. Hasan, J.A. Ramirez and D.B. Cleary, "Field evaluation of concrete bridge decks reinforced with epoxy-coated steel in Indiana" Paper No.950200, 74th Annual Meeting, Transportation Research Board, Washington, DC(1995).
45. D.G Manning, J. of Cons. and Bldg Mat. , 10 (1996)349.
46. I. Kondratova and T. Bremner, "Effectiveness of epoxy coatings and corrosion inhibitors in concrete containing embedded steel — An experimental study", Presented at Corrosion Conf. on Understanding Corrosion mechanisms in concrete, July 27-31 (1997) MIT, Cambridge, M.A.
47. R.E. Weyers, W. Pye and M.M. Sprinkel, ACIMat.J., 95(1998)546 .
48. S. Erdogdu, T. W. Bremner and I.L. Kondratova, Cement and Conc. Res., 31(2001)861.
49. ShreekantPatil and M.A. Shenoy, Trans. Met. Fin.Ass.India,2(1993)31.
50. L.K. Aggarwal, K.K. Asthana and Rajni Lakhani, Indian Concrete Journal.,69(1995)269.
51. S.K. Manjrekar, R.S. Manjrekar and P.R.C. Nair, Indian Concr. J., 70 (1996) 389.
52. K. Kumar, R. Vedalakshmi, S. Pitchumani, A. MadhavaMayandi and N.S Rengaswamy, Indian Concr. J. , 70 (1996) 359.
53. S.X. Wang, W.W. Lin, S.A. ceng and J.Q. Zhang, Cement and Conc. Res., 28 (1998) 649.
54. L.G. Andion, P. Graces, R. Lapuente, J.L. Vazquez and F. Cases, Corros. Sci., 44 (2002) 2805.
55. J. Wang, S.P. Chen and M.S. Lin, J. Electroanal. Chem., 273 (1989) 231.
56. P. Mourcel, M.C. Phan, P.C. Lacaze and J.E. Dubois, J. Electroanal. Chem., 145 (1983) 467.
57. M. Gattell and D.W. Kirk, J. Electrochem. Soc., 140 (1993) 903.
58. R. Lapuente, F. Cases, P. Garces, E. Morallon and J L. Vazquez, J.Electroanal. Chem., 451 (1998) 163.
59. I. Sekine, K. Kohara, T. Sugiyama and M. Yuasa,J.Electrochem. Soc., 139(1992) 3090.
60. S. Tag, M.F. Ahmed and S. Sankarapapavinasam, J. Appl. Electro-chem., 23 (1993) 247.
61. R. Bertoncello, F Furlanetto, A. Glisenti and M.M. Musiani, J.Electrochem. soc., 142 (1995) 410.
62. N.S. Rengaswamy, S. Srinivasan and T.M. Balasubramanian, Trans. SAEST, 23 (1980) 163.

(IJAER) 2015, Vol. No. 10, Issue No. VI, December

e-ISSN: 2231-5152/ p-ISSN: 2454-1796

63. N.S. Rengaswamy, K.I. Vasu and B. V. Renganathan, Proc. Of Second Confon Dock and Harbour Engg., Madras, India, Dec. 1987, p.455.
64. N.S. Rengaswamy, V. Saraswathy and K. Balakrishnam J. of Ferrocement, 22 (1992) 359.
65. N.S. Rengaswamy, R. Vedalakshmi and K. Balakrishnan, Anticorr. Meth. Mar., 42 (1995) 7.
66. A. Sanjurjo, M.C.H. Mc Kubre and G.D. Craig, Surface Coating Technology, 39/40(1989) 691.
67. A. Sanjurjo, S. Hettiarachchi, K.H. Lau, Philip Cox and Bernard Wood, Surf. Coat. Tech., 54/55 (1992)224.
68. A. Cabrera and J.K. Kirner, Surf Coat. Tech., 39/40(1989)43
69. H.Arup, Mater.Perf.,18(1979)41.
70. B. Lansly, Corros. Prev. Control, 34 (1987) 10.
- 71.K. Thangavel, N.S. Rengaswamy and K. Balakrishnan, Mat. Perf., 34 (1995) 59.
72. Editorial, Indian Concr. J., 59 (1985) 141.
73. D.F. Griffin, "Effectiveness of zinc coating on reinforcing steel in concrete exposed to a marine environment", Technical Note No. 1032 (Porthueneme, CA: US Navy, July 1969).
- 74.W. Hubert, Symp. on Significance of tests and properties of concrete and concrete making materials, ASTM STP 169 A (1966) p.230. American Society for Testing and Materials, Philadelphia.
75. N.S. Rengaswamy and V.S. Muralidharan, Corros.Bull.4 (1984)189.
76. N. Wilkins, Materials Performance, 19 (1980) 52.
- 77.A. Macias and C. Andrade, British Corros. J., 18 (1983)82.
- 78.A. Macias and C. Andrade, Corros. Sci., 30 (1990) 393.
- 79.A. Macias and C. Andrade, Cem. Conc. Res., 17 (1987)307.
80. A. Macias and C. Andrade, British Corros. J., 22 (1987)113.
- 81.A. Macias and C. Andrade, British Corros. J., 22 (1987) 163.
82. Thomas J. Kinstler, "An update of galvanized reinforcing steel-stresses produced by the corrosion of reinforcing bars embedded in cement mortar (ZE-271)", Seminar reprints on solving rebar corrosion problems in concrete, NACE, Houston Texas, Paper No. 10 (1982).
83. H. Hildebrand, und W. 'Schwenk, Werkstoffe und Korrosion,37(1986)163.
84. W.G. Hime and M. Machin, Corrosion, 49 (1993) 858.
85. K. Thangavel, N.S. Rengaswamy and K. Balakrishnan, Indian Concr. J., 69 (1995)289.
86. N.S. Rengaswamy and R. Vedalakshmi, "Field Performance of galvanized reinforcement in concrete structures" in Protection of reinforcement in concrete an update, published by Indian Lead Zinc Information Centre (ILZIC), New Delhi (1995) pp.53-66).
87. R.N. Swamy, S. Koyama, J. Arul and T. Mikami, "Durability of steel reinforcement in marine environment", Ed. By V.M. Malhotra, ACI SP 109, American Concrete Institute, Detroit, USA (1988) pp. 147-162

(IJAER) 2015, Vol. No. 10, Issue No. VI, December

e-ISSN: 2231-5152/ p-ISSN: 2454-1796

88. Norimoto Kashino, "Applicability of newly developed corrosion resistant Second Australia-Japan rebars in reinforced concrete construction"

Coordinated Workshop on Durability of reinforced concrete, Australia, Nov 28-30, 1988, pp.7.33-7.41.

89. K.W.J. Treadway and H. Davies, *The Struct. Engr.*, 67(1989)99.

90. R.N. Swamy, "Resistance to chlorides of galvanized rebars", *Corrosion of reinforcement in concrete*, Ed. By C.L. Page, Elsevier Science Publisher Ltd. England (1990) pp.586-600.

91. D.B. Mc Donald, Y.P. Virmani and D.F. Pfeifer, *Concr.Intl.*, 18(1996)39.

92. A.B. Tripler, E.L. White, F.H. Haynie and W.K. Boyd, "Methods of reducing corrosion of reinforcing steel", National Cooperative Highway Research Programme, Report No.23, Highway Research Board, Washington, DC(1966).

93. I. Cornet, T. Ishikawa and Bresler, *Mat. Prot.*, 7 (1968)44.

94. E.A. Baker, K.L. Money and C.B. Sanborn, "Marine Corrosion behaviour of bare and metallic-coated reinforcing rods in concrete", *Chloride corrosion of steel in concrete*, ASTM STP-692, American Society for Testing and Materials, Philadelphia(1977)pp.30-50.

95. BS:6744, British Standard specification for Austenitic stainless steel bars for the reinforcement of concrete, British Standards Institution, London, 1986.

96. P. Gu, B. Arsenault, J.J. Beaudoin, J.G. Legoux, B. Harvey and J. Fourier, *Cement and Conc. Res.*, 28 (1998)32.

97. P. Gu, B. Arsenault, J.J. Beaudoin, J.G. Legoux, B. Harvey and J. Fourier, "A Study of the polarization resistance of thermal sprayed stainless steel coatings for rebars", Third CANNfET/ACI, International Symposium on Advances in Concrete Technology, Auckland, New Zealand, August 27-29(1997).

98. P. Jayaweera, D.M. Lowe, A. Sanjurjo, K.H. Lau, and L. Jiang, *Surf. Coat. Tech.*, 86-87/2 (1996) 522.