CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

Research work pertaining to corrosion of steel rebar in concrete in the last twenty years is reviewed in this chapter. Only scant literature is available on the comprehensive study involving different protective coating systems and corrosion inhibitor in corrosion control of steel rebars.

2.2 STUDIES ON EXPERIMENTAL INVESTIGATIONS

The literatures related to the experimental investigation carried out by various researchers have been discussed.

Sanjay Narendra Pareek et al. (1991) investigated the adhesion of polymer-modified mortars to reinforcing bars. Polymer modified mortars using cationic, anionic and nonionic polymer dispersions were prepared with various polymer-cement ratios, and tested for bond strength through pull-out of vertically embedded reinforcing bars in the mortars. Retention of the bond strength of the polymer-modified mortars to the reinforcing bars through water immersion was also examined. It was concluded that bond strength of cationic polymer-modified mortars to reinforcing bars was much higher than that of unmodified, anionic and nonionic polymer-modified mortars. The retention of the bond strength of polymer-modified mortars to reinforcing bars after water immersion was 60 to 80% which compared well with unmodified mortar.
Effect of reinforcement corrosion on the bond strength between steel and concrete was investigated by Abdullah A. Almusallam et al. (1996). The bond behaviour of reinforced concrete elements, including the ultimate bond strength, free-end slip, and the modes of failure in precracking, cracking and postcracking stages were studied. The effect of different crack width and the rib profile degradation for various degrees of corrosion on the bond strength were also evaluated. The results indicated that in the precracking stage, (0 to 4% corrosion) the ultimate bond strength increased, whereas the slip at the ultimate bond strength decreased with an increase in the degree of corrosion. In the cracking stage (4 to 6% corrosion), the bond failure occurred suddenly at a very low free end slip. A large slip was noted as the ultimate failure of the bond occurred due to splitting of the specimens. Beyond 6% rebar corrosion, the bond failure resulted as a continuous slippage of the rebars. It was concluded that ultimate bond strength initially increased with an increase in the degree of corrosion up to 4% rebar corrosion after which there was a sharp reduction in the ultimate bond strength up to 6% rebar corrosion. Beyond 6% rebar corrosion the ultimate bond strength did not vary much even up to 80% corrosion. A crack width of 0.3 mm and a rib profile loss of 25% were observed beyond which a sharp reduction in bond strength occurred.

Yoshihiko Ohama (1996) discussed in detail the Japanese experience of polymer-based materials for repair and improved durability. The principle behind the deterioration of reinforced concrete structures was analysed. The parameters causing deterioration of concrete and degradation of reinforcing bars were listed. The various countermeasures to prevent deterioration of concrete and corrosion of reinforcing bars were studied. The role of polymers in modification of concrete surfaces to eliminate chemical degradation, corrosion-resistant reinforcements, repair materials for deteriorated reinforced concrete structures were also discussed. It was concluded that the cementious-polymeric composite materials used as
durability-improving materials and repair materials were considered to be very effective in improving the durability of reinforced concrete structures.

Ping Gu et al. (1998) discussed in detail the effective half-cell potential measurements in reinforced concrete structures. The importance and basic principle behind the half-cell potential measurements were explained. The various factors which influence half-cell potential readings such as oxygen concentration, carbonation, chloride ion concentration, use of corrosion inhibitors, use of coated rebars, dense concrete cover, concrete resistance, organic coatings and sealers, concrete patch repair, cathodic protection systems and stray current were analysed. It was concluded that half-cell potential data should always be validated by other measures such as visual inspection, delamination survey, chloride content measurement, concrete resistance measurement etc. before interpreting the probability of corrosion. It was concluded that the half-cell potential measurement revealed only the corrosion probability at a given location and time and long-term monitoring of the half-cell potential readings were more meaningful.

Han-Seung Lee et al. (2002) evaluated the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion. The effects of reinforcement corrosion on the bond behaviour between corroded reinforcement and concrete were evaluated by conducting pull-out tests. Accelerated corrosion method was employed to corrode the rebar inside the pull-out test specimen to the desired level. Pull-out tests were conducted on specimens with and without confinement reinforcement. The load versus free end slip behaviour was studied. A finite element analysis was also carried out on the basis of the results of the pull-out tests. It was found that the maximum bond strength and bond rigidity decreased in proportion with increase in corrosion percentage. The equations for calculating the
maximum bond strength and the bond rigidity necessary for a Finite Element analysis of reinforced concrete members with corroded reinforcement were obtained by the experiments.

Pech-Canul and Castro (2002) performed corrosion measurements of steel reinforcement in concrete exposed to a tropical marine atmosphere. Cylindrical concrete specimens of 78mm diameter and 150mm in height with centrally embedded reinforcement made of water-cement ratios 0.70, 0.50 and 0.46 were prepared and tested. Each specimen was embedded with activated titanium rod as reference electrode. For chloride penetration studies, concrete cylinders were made without reinforcement. The specimens were exposed to natural weathering in the marine atmosphere of the port of Progreso, located on the coast of the Yucatan peninsula, Mexico. Corrosion potential, linear polarization resistance and electrochemical impedance spectroscopy measurements were conducted on exposed specimens at regular intervals for a period of 56 months. Chloride concentration at the rebar level was also monitored at regular intervals. Test results indicated that the time for the onset of active corrosion was shorter for rebars in concretes with a high water-cement ratio compared to that for rebars in low water-cement ratio concrete. For the same exposure period, nominal corrosion current density values were generally higher for rebars in concrete with higher water-cement ratio than that for rebars in low water-cement ratio concrete. It was concluded that the results of potential measurements, LPR and EIS showed good agreement and it was concluded that these techniques can be used together to monitor the corrosion development in reinforced concrete specimens exposed to marine atmosphere.

Corrosion of steel reinforcement in concrete adjacent to surface repairs was investigated by Barkey (2004). Experiments were conducted to characterize the electrochemical macrocells that drive the corrosion process
near surface repairs. Reinforced concrete test specimens were prepared according to ASTM G 109-92 with some samples modified to incorporate simulated repairs. The repair mortar was a proprietary single-component, polymer-modified mortar. Test prisms were prepared in six different configurations representing a different repair or control geometry and chloride addition. Test results suggested that for chloride contaminated concrete with repair mortar, threshold potential difference between anode and cathode were observed initially without any induction time to the level of 25-30 mV. It was found that there was an existence of severe active/passive macrocell region near the repaired portion, i.e. 1 to 2cm inside the chloride contaminated concrete from the repair bond line. The current distribution within the macrocell was localized and controlled ohmically. It was concluded that corrosion macrocells were driven by heterogeneities in the repair zone which arises from the mismatch between concrete, mortar and from chloride remaining in the repaired material. It was also stressed that the repair material should be compatible with the original concrete and be prepared and applied uniformly.

Studies on the corrosion resistance of reinforcement steel in concrete with ground granulated blast-furnace slag was done by Song and Saraswathy (2006). The partial replacement of clinker, the main constituent of ordinary Portland cement by pozzolana or by products such as ground granulated blast furnace slag (GGBFS) effectively lowers the cost of cement by saving energy in the production process. It also reduces CO₂ emissions from the cement plant and offers a low priced solution to the environmental problem of depositing industrial wastes. The utilization of GGBFS as partial replacement of Portland cement takes advantage of economic, technical and environmental benefits of this material. Recently offshore coastal and marine concrete structures were constructed using GGBFS concrete because high volume of GGBFS can contribute to the reduction of chloride ingress. The
influence of using GGBFS in reinforced concrete structures from the durability aspects such as chloride ingress and corrosion resistance, long term durability, microstructure and porosity of GGBFS concrete has been reviewed and discussed in this study.

Ann and Song (2007) studied the Chloride Threshold Level (CTL) for corrosion of steel in concrete. The study discussed the state of art on the CTL for corrosion of steel in concrete, concerning its measurement, representation, influencing factors and methods for enhancement. CTL values reported in the majority of earlier studies were not in comparison with the test results. Using the corrosion initiation assessment method, a comparison was done with the results from different sets. It was concluded that total chloride by weight of cement or the ratio of chloride ions to hydrogen ions is the best presentation of CTL which shows the aggressiveness of chlorides (i.e. free and bound chlorides) and inhibitive nature of cement matrix. The key factor on CTL was found to be a physical condition of the steel concrete interface in terms of entrapped air void content, which is more dominant in CTL rather than chloride binding, buffering capacity of cement matrix or binders. The measures to raise the CTL values using corrosion inhibitor, coating of steel and electrochemical treatment were also studied.

The effectiveness of fly ash activation on the corrosion performance of steel embedded in concrete was studied by Saraswathy and Song (2007). It was found that the use of fly ash to replace a portion of cement has resulted in significant savings in the cost of cement production. Fly ash blended cement concretes require longer curing time and their early strength is low when compared to Ordinary Portland Cement (OPC) concrete. By adopting various activation techniques such as physical, thermal and chemical the hydration of fly ash blended cement concrete was accelerated and thereby improved the corrosion resistance of concrete. Concrete specimens prepared with 10,20,30
and 40% of activated fly ash replacement were evaluated for their open-circuit potential measurements, weight loss measurements, impedance measurements, linear polarization measurements, water absorption characteristics and the results were compared with those for OPC concrete without fly ash. All the studies confirmed that, up to a critical level of 20-30% replacement, activated fly ash cement improved the corrosion resistance properties of concrete.

2.3 STUDIES ON COATINGS

Rengaswamy et al. (1988) have studied the mechanical, electrochemical and corrosion resistance properties of the inhibited and sealed cement slurry coating system applied to steel rebars for its corrosion protection. Performance evaluation tests such as exposure studies on precracked model slabs, alternate wetting and drying tests and performance in the presence of chloride admixtures were also discussed elaborately. It was concluded that inhibited and sealed cement slurry coating lead to economy and efficiency higher than other coating systems.

Pull-out tests of epoxy-coated reinforcement in concrete were studied by Cusens and Yu (1992). Single pull-out and double pull-out tests were conducted and the results were compared with control uncoated bars. The size of the test specimen was 250 × 250 × 410 mm with 25mm bars and 150 × 150 × 200 mm with 12mm bars in compliance with BS 4449. The reinforcing bars were centrally embedded passing completely through the concrete prism through its longitudinal axis. In the single pull-out tests slip values at both ends were measured for each increment of load until failure. In the double pull-out tests, 20 cycles of load were applied at levels of steel stress between zero and 0.5 times the characteristic steel strength. Strains were measured by electrical resistance strain gauges glued inside the bars. Single pull-out test results suggested that epoxy-coated bars exhibited more
loaded end, free end slip as compared to equivalent uncoated bars. In double pull-out tests the epoxy-coated bars also exhibited more slip under load cycles accompanied by lesser stress gradient which indicated lower friction bond. It was concluded that epoxy coating was found to increase the slip in bond and thereby reduce the bond performance of coated bars.

Rasheeduzzafar et al. (1992) evaluated the performance of corrosion resisting steels in chloride bearing concrete by conducting seven-year site exposure tests. Performance of bare mild steel, galvanized, epoxy-coated and stainless steel clad reinforcing steels was evaluated by embedding them in concrete with three different levels of chloride content (0.6, 1.2 and 4.8% by weight of cement). It was concluded that bare mild steel bars suffer severe rust related damage in all the three chloride levels whereas the use of galvanized steel in concrete with high levels of chloride merely delay the concrete failure. Although barrier type epoxy-coated bars offer good corrosion resistant properties in low chloride levels, it offers finite toleration limit for chloride upon addition of chloride at higher levels. The best durability performance was exhibited by stainless steel clad reinforcing bars. There was no sign of corrosion observed after the exposure period.

Kayali and Yeomans (1995) evaluated the bond and slip of coated reinforcement in concrete. Galvanized, black and epoxy-coated rebars were embedded in reinforced concrete beams of size 1500 × 160 × 320 mm. The specimens were subjected to flexure test such that pure flexure occurred within the middle third of the beam. The test results revealed that ultimate capacity in flexure of beams reinforced with ribbed, galvanized or epoxy-coated bars was not statistically different to that of black steel reinforced beams. The results from load-slip measurements were indicative of the variation in bond for the different bar coatings. It was found that loads at a slip of 0.05mm was close to the ultimate load and accordingly loads at lower
slip levels such as 0.01 mm and 0.02 mm were considered for analysis. The mean critical load at these slip values for the ribbed galvanized bars was not statistically different from black steel. But for epoxy-coated ribbed bars about 20% reduction in load was observed. It was concluded that there was no significant loss in bond strength for galvanized bars, whereas there was significant reduction in bond strength for epoxy-coated bars.

Thangavel et al. (1995) studied the behaviour of protective coatings to steel reinforcement with respect to bond strength at the rebar concrete interface for the reliable performance of reinforced concrete structures. Pull-out tests were conducted on coated and uncoated rebars of 10mm diameter and 450mm in length, placed centrally in a 100mm concrete cube as per Indian standards. Bond behaviour of the galvanized, inhibited cement slurry coated and fusion bonded epoxy-coated bars with two different coating thickness was assessed and compared. It was observed that the coated rebars improved the bond strength as compared to the plain mild steel bars. Galvanizing and epoxy coating reduced the bond strength at higher thickness of coatings. On the other hand for inhibited cement slurry coated rebars, the bond strength improved further at higher thickness of coatings.

Protasio Castro et al. (1996) analysed the influence of protective coatings on the rebar-concrete bond. The value of the bar-friction co-efficient was obtained by testing a concrete tension strut reinforced with only one steel bar. The rebars include smooth and ribbed control bars, and bars manually coated with commercially available zinc based and epoxy resin coating to a thickness of 0.3 mm. The size of the concrete specimen was 820 x 54 x 54mm with centrally embedded rebars extended from both ends to a sufficient length to conduct tension test. The reinforcing bars were loaded in tension to 80% of its yield load and totally 72 tests were conducted. The average distance between cracks that form on concrete prisms was determined and bar-friction
co-efficient was also obtained. It was concluded that application of epoxy coating on ribbed bars had an appreciable influence on the friction co-efficient as compared to smooth bars. The zinc coating on smooth and ribbed bars had a significant influence on the friction co-efficient as compared to control rebars.

Kumar et al. (1996) discussed the various aspects relating to the mechanization of cement-polymer composite coating system for corrosion protection of rebars. Chemical resistance test, bond strength test and macrocell corrosion tests were conducted on coated rebars. Stress corrosion cracking tests and field exposure tests were conducted on coated prestressing strands. It was concluded that cement polymer composite coating offered excellent protection to steel bars and prestressing strands. Due to passivation-cum-barrier-nature of coating, localized defects in coating may not lead to severe undercutting.

The role of polymer cement inhibitor co-matrix in corrosion control of reinforcing steel was discussed by Manjrekar et al. (1996). Salt spray test, hydrogen embrittlement test and stress corrosion tests were carried out with coated rebars and prestressing wires. It was proved that polymer-cement-inhibitor co-matrix offered good corrosion resistance properties because of its ability to reduce chloride ion penetration towards steel and reducing transmission of gases like air, carbon dioxide, oxygen and water vapour.

Asthana et al. (1999) evaluated the performance of a novel Interpenetrating Polymer Network (IPN) coating for the protection of steel reinforcement in concrete exposed to aggressive environments. Physico-mechanical properties of the coating material along with chemical resistance against some acids, alkalies, fertilizers and water have been determined. Chemical resistance test, adhesion test and bond strength tests were conducted as per Indian Standards to study the corrosion resistance efficacy and
mechanical properties of the coated rebars. In the accelerated corrosion test, concrete specimens with embedded coated and uncoated rebars were subjected to 80 accelerated corrosion cycles to find the weight loss measurement. It was concluded that acceptable bond strength, improved flexibility and excellent chemical resistance properties were noticed for IPN coated bars and also satisfied the minimum codal requirements of Indian Standards. Accelerated test results revealed that IPN coated bars offered good corrosion resistance as compared to other tested coating systems. It was also concluded that IPN coated bars have much extended life in comparison to uncoated bars and the treatment cost was only about 15 to 20% of the cost of steel.

Kayali and Yeomans (2000) evaluated the bond strength of ribbed galvanized reinforcing steel in concrete by conducting beam end tests as per ASTM A944 to stimulate the behaviour of reinforcement in flexural members. The bond and slip behaviour of ribbed galvanized, epoxy-coated and black steel rebars were studied. Totally 30 specimens were cast with two different embedment lengths of 150 and 120 mm. In all the specimens, 16mm diameter rebar was used with 32 MPa concrete. From the tests conducted it was found that a slip value of around 0.4 mm has been associated with the bond failure of concrete. Test results also indicated that epoxy-coated bars have significant loss in bond strength of the order of 25% as compared to black steel and there was no adverse effects on bond with the use of galvanized steel. It was suggested that chromate treatment of galvanized bars was deemed unnecessary since there was no evidence of long term reduction in bond due to the possible effects of hydrogen gas evolution resulting from the reaction between zinc and wet concrete.

Vedalakshmi and Rengaswamy (2000) conducted quality assurance tests for corrosion protection systems which comprises of short-term tests
such as anodic polarization, peak potential, salt-fog and 2V impressed voltage tests. The long term tests included alternate wetting and drying, macrocell corrosion and precracked cantilever model slab tests. The results of quality assurance tests conducted on bars with inhibited cement slurry coating, cement polymer composite coating, fusion bonded epoxy coating and corrosion resistant rebars were discussed.

Vedalakshmi et al. (2000) evaluated the effect of prior damage on the performance of cement based coatings on rebar by conducting macrocell corrosion studies. The effect of prior coating damage produced during concrete pouring has been studied on inhibited cement slurry coating. To stimulate marine substructure environment, macrocell corrosion condition has been created through a chloride ion concentration gradient. Macrocell corrosion test was conducted as per ASTM G 109-92. Macrocell corrosion current and corrosion potential measurements were taken during the test period. It was concluded that inhibited cement slurry coating has better tolerance towards coating damage caused by pouring in chloride contaminated concrete as compared to epoxy based coating systems. It was also found that the performance of the coating was independent of the height of concrete pouring.

Andrade et al. (2001) studied the bond strength of galvanized rebars in concrete cured in sea water. Series of tests were conducted to compare the bond strength of bare rebars and galvanized bars embedded in concrete up to a period of 10 years in a chloride environment in natural sea water. The action of hydrogen inhibitor was considered in the case of galvanized rebars. It was found that galvanized rebars maintained bond characteristics throughout the test period with values much higher than the minimum requirements. The addition of hydrogen inhibitor or the use of high alkali cement on the performance of galvanized rebars was not effective in the long term.
Bond strength of galvanized reinforcement was studied by Belaid et al. (2001). Pull-out tests were conducted as per RILEM code for both ordinary and galvanized rebars. The type of rebars included ribbed rebar, smooth rebar and machined bar made of smooth rebar with constant rib spacing, thickness and four different rib heights. Cube and cylinder specimens were made. Rebars were placed horizontally in the cube specimens parallel to the direction of concrete pouring. In case of cylinder specimens, the rebars were placed normal to the direction of pouring. The pull-out load and the slip at the unloaded end of reinforcing bars were monitored during the test period. Test results revealed that galvanized coating improved the bond performance of smooth bars placed horizontally in the specimens. The galvanized coating did not affect the bond performance of horizontal ribbed bars and also the position of the reinforcing bar during casting. Whereas the rib height of galvanized bars affected the bond performance significantly. It was concluded that the bond performance of galvanized bars is dependent on the failure zone of concrete surrounding the reinforcement, the type of bar and the rib height of the reinforcing bar.

Omar Saeed Baghabra Al-amoudi et al. (2004) evaluated the long-term performance of fusion-bonded epoxy-coated steel bars in chloride-contaminated concrete. The effect of holidays, surface damage and chloride contamination on corrosion of fusion bonded epoxy-coated (FBEC) steel bars was evaluated by conducting linear polarization measurement and gravimetric weight loss technique. Reinforced concrete prisms measuring $102 \times 64 \times 305$ mm with a centrally placed 16mm diameter steel bar constituted the test specimen. Fusion bonded epoxy coating of thickness of 150 $\mu$m with surface damage levels of 0.5%, 1%, 1.5% and holiday levels of 1, 2, 3 per linear feet were studied. Chlorides were added at 0.4%, 1% and 2% by weight of cement to accelerate corrosion. Results of the electrochemical tests conducted periodically over a period of 7 years indicated that surface
damage is more deleterious to FBEC steel bars than the pinholes in terms of corrosion. No significant variation was found in corrosion current density with number of pinholes in the coating, but current density increased with an increase in degree of damage to coating. It was found that corrosion activity increased with an increase in the chloride concentration. A good correlation was also noted between the corrosion rates measured by the linear polarization method and the gravimetric weight loss technique.

Fanous et al. (2005) examined the performance of coated reinforcing bars in cracked bridge decks in USA. To study the effects of deck cracking on the performance of Epoxy-Coated Rebars (ECR), several concrete cores that contained reinforcing bars were collected from 80 bridge locations. The samples were collected from cracked and uncracked areas of the bridge decks. Concrete powder samples collected from the cores were analysed to find the chloride diffusion into the decks and the adhesion property of collected rebars were analysed by dry-knife adhesion test. The study revealed that there was no sign of corrosion from the rebars obtained from uncracked locations. Although signs of corrosion were observed from samples obtained from cracked regions, no delamination and spalling was observed. The collected rebar samples were rated according to the degree of corrosion and the condition/age relationship were developed. It was concluded that cracking in bridge decks had an impact on the performance of ECR and the adhesion of the coating was found to decrease with the increase in time.

Venkatesan et al. (2006) examined the corrosion performance of coated reinforcing bars embedded in concrete and exposed to natural marine environment. Corrosion behaviour of mild steel rebars coated with Cement Polymer Composite Coating (CPCC), Interpenetrating Polymer Network Coating (IPN) and Epoxy coating were studied and compared with the
performance of uncoated rebars. The size of the concrete specimen was 150 × 150 × 300 mm having embedded rebars. Open circuit potential test, gravimetric weight loss measurement, linear polarization test and AC impedance tests were conducted on specimens exposed to atmospheric, high tide level and seafloor level in the gulf of Mannar region near Tuticorin, India. It was concluded that coated bars offered excellent corrosion protection even in high chloride exposure conditions as compared to uncoated rebars. In the coated rebars, cement polymer composite coating possessed excellent corrosion resistance properties followed by epoxy coating and interpenetrating polymer network coating.

Saravanan et al. (2007) evaluated the performance of polyaniline pigmented epoxy coating for corrosion protection of steel in concrete environment. The corrosion resistant property of epoxy polyaniline system, coated on mild steel was evaluated by various techniques such as electrochemical impedance spectroscopy, potential time studies, cathodic disbondment test, anodic polarization study, salt spray test and chemical resistance test. The corrosion resistance of polyaniline coated rebars embedded in concrete was also studied by an accelerated time to cracking study. The formation of polyaniline was characterized using various techniques. Electrochemical impedance studies revealed that the resistance of the coating decreased initially and then increased due to passivating ability of the polyaniline pigment. It was concluded that epoxy coating with polyaniline pigment is effective in corrosion protection of steel in concrete environment.

2.4 STUDIES ON CORROSION INHIBITORS

Yoshihiko Ohama et al. (1991) have evaluated the effect of combined use of polymer-modified mortars and rust-inhibitor on corrosion inhibition of reinforcing bars. Cement mortar modifiers include Styrene-Butadiene Rubber latex (SBR), Ethylene-vinyl Acetate Emulsion (EVA) and
Polyacrylic Ester Emulsion (PAE). Calcium nitrite was used as rust-inhibitor. The size of the specimen is 160 × 40 × 40 mm embedded with a bar of length 130mm and 10mm diameter. Two types of specimens were prepared. In type A specimen, the rebar was completely embedded in polymer-modified mortar. In type B specimen, one half of the rebar was filled with base mortar and the rest was filled with repair mortar to replicate site conditions. The specimens were subjected to accelerated corrosion test. The corroded areas of the rebars were measured to evaluate the corrosion inhibiting properties of the polymer-modified mortars and rust-inhibitor. It was concluded that addition of rust-inhibitor improved the corrosion-inhibiting property of polymer-modified mortars. Addition of rust-inhibitor in the repair mortar remarkably reduced the corrosion rate of the embedded steel whereas corrosion rate of rebar embedded in the base mortar increased significantly. It was also concluded that the bonded mortar surfaces treated with rust-inhibitor exhibited less corrosion rate compared to the other untreated portion.

The behaviour of pre-rusted steel in concrete was evaluated by Gonzalez et al. (1995). Studies were carried out on the passivation characteristics of cement concrete on different levels of pre-rusted steel reinforcements. The corrosion rate behaviour was studied with inclusion of nitrite ions either by addition during concreting or by ponding it over chloride contaminated concrete. The effect of water proof coatings to concrete on the corrosion rate of pre-rusted steel in chloride contaminated steel was also studied. It was concluded that the mortar alkalinity which rapidly passivate a clear steel surface does not ensure passivation of highly pre-rusted steel. Inclusion of nitrite ions is inadequate for passivating strongly pre-rusted steel reinforcements. It was also derived that effectiveness of waterproofing treatment for diminishing reinforcement corrosion relied heavily on the timely application.
Experimental studies on penetrating-type corrosion inhibitor (based on bipolar inhibition mechanism) in reinforced concrete was conducted by Limaye et al. (2000). The effect of inhibitor addition on fresh concrete properties such as setting time, workability and hardened concrete properties such as compressive strength, bond strength were studied. Cylindrical concrete specimens of 40 mm diameter and 80 mm height with centrally embedded 8mm rebars were cast for electrochemical studies. The three type of specimens include control concrete specimen, specimen with corrosion inhibitor admixture and specimen with corrosion inhibitor coating over concrete surfaces. In the electrochemical studies, the specimens were impressed with a constant potential of 7.5V and subsequent current development versus time behaviour was followed until the failure of specimen. From the current values and time, total coulombs consumed were calculated which forms the basis for corrosion resistance efficacy of test specimens. It was concluded that incorporation of penetrating corrosion inhibitor does not impair any physical and mechanical properties of fresh and hardened concrete. Inhibitor admixed concrete and inhibitor coated concrete specimens exhibited significant reduction in corrosion rate and increase in bond strength as compared to control specimens.

Ramasubramanian et al. (2001) evaluated the inhibiting action of calcium nitrite on carbon steel rebars. Instantaneous and long term corrosion potential measurements and linear polarization measurements were carried out on polished carbon rebar specimens under different pH conditions and in the presence and absence of chloride ions in solution. Calcium nitrite inhibitor was added at four different dosage levels to study the inhibition mechanism of the system. Research studies indicated that there was a competition between the corrosion and passivation reactions, and the resulting open-circuit potential is dependent on the relative strength of the corroding and passivating environments. The corrosion rate is also dependent to a great extent on the pH
of the solution. It was also found that nitrite ions act as anodic inhibitors by increasing the rate of formation of a barrier oxide film. The protective action of the nitrite ions seemed to be more pronounced in highly corroding environment. The long-term studies confirmed that for a given amount of chloride, a minimum threshold concentration of nitrite was essential for protecting the steel.

Morris and Vazquez (2002) evaluated the performance of a migrating inhibitor in concrete containing various contents of admixed chlorides. A surface-applied Migrating Corrosion Inhibitor (MCI) based on alkylaminoalcohol was evaluated on concrete specimens containing reinforcing steel rebar segments. Concrete cylinders of size 150 mm in diameter and 200 mm in length containing four rebar segments with a cover of 15 mm was prepared. Two grades of concrete, three different chloride contents and two exposure conditions were investigated. The main electrochemical parameters such as corrosion potential, electrical resistance and polarization resistance were studied at regular intervals over a span of 1000 days. Chloride profile analysis were also carried out to study the chloride ingress behaviour. Test results revealed that when concrete was exposed to marine environment, the inhibitor was able to reduce the corrosion rate only when the initial chloride content was less than 0.16% by weight of cement. Efficiency increased as the water-cement ratio increased. There was no beneficial effect when the initial chloride content was greater than 0.43%. It was also found that when concrete was immersed in a saline solution, the use of inhibitor offered no significant effect irrespective of the water-cement ratio or initial chloride content in concrete.

Effectiveness of corrosion inhibitors in contaminated concrete was studied by Omar Baghabra Al-Amoudi et al. (2003). Performance of four types of corrosion inhibitors such as calcium nitrite, calcium nitrate and two
commercially available organic inhibitors were evaluated for five different levels of contamination. The type of contamination include addition of 0.8% chloride, 0.8% chloride with 1.5% SO3, sea water, brackish water and unwashed aggregates. The effect of corrosion inhibitors on the compressive strength of concrete and reinforcement corrosion was analysed. Cylindrical concrete specimens of size 75 mm diameter and 150 mm in height reinforced with 12mm diameter steel bar at the center were made. Corrosion inhibitor dosage varied for two different organic inhibitors, calcium nitrite and calcium nitrate. Corrosion potential measurements were observed for 180 days and corrosion current density using linear polarization technique were studied for 120 days at regular intervals. The results indicated that the tested inhibitors did not adversely affect the compressive strength of concrete. It was concluded that calcium nitrite was efficient in delaying the initiation of reinforcement corrosion in the concrete specimens contaminated with chloride, while both calcium nitrite and calcium nitrate mitigated the corrosion effects of chloride plus sulphate salts or sea water. In concrete specimens prepared with brackish water or unwashed aggregates, all the inhibitors were effective in reducing the rate of reinforcement corrosion. It was also stressed that the type and the dosage of corrosion inhibitor varied the nature and level of contamination.

Influence of corrosion inhibitors in reinforced concrete structures as a preventive technique was examined by Bolzoni et al. (2004). Effectiveness of three organic inhibitors such as amino-alcohols, alkanolamines and amine-esters were studied in addition to calcium nitrite based inhibitor. Test specimens of size 200 × 250 × 50mm made of M40 concrete embedded with 2 – 10 mm rebars were cast. Chloride was added to concrete during casting at 0.8% and 1.2% by weight of cement, and by ponding chloride solution in the case of control concrete specimens. Carbonation was achieved by passing pure CO2 through the carbonation chamber for 1hour every day. Corrosion
potential measurements, corrosion rate measurements using polarization techniques and carbonation depth measurement were followed at frequent intervals over the period of 3 years. It was concluded that addition of inhibitors enhanced the critical chloride content for carbon steel up to 0.8 to 1.2% by weight of cement. Addition of amino-alcohols and nitrite based inhibitors reduced the chloride penetration and corrosion rate appreciably compared to other tested inhibitors. In carbonated concrete no significant effect has been observed on CO₂ penetration or corrosion rate due to inhibitor addition.

Influence of calcium nitrite inhibitor on corrosion of steel in high performance concrete subjected to a simulated marine environment was investigated by Pedro Montes et al. (2004). Concrete made with 0.29, 0.37 and 0.45 water-cement ratio containing 0%, 20% and 40% fly ash and three different amounts of corrosion inhibitors were studied in pre-cracked specimens subjected to simulated and natural marine environments. Concrete prisms of size 230 × 55 × 300 mm reinforced with 2 – 15 mm diameter rebar with a simulated crack width of 0, 0.25 mm and 0.50 mm were used as test specimens. The specimens were placed in the marine environment simulation setup chamber to create the effects of artificial sea water conditions. The corrosion activity was monitored by using the linear polarization resistance method for the period of 12 months including visual observation. It was concluded that mere addition of calcium nitrite based corrosion inhibitors has no significant effect in decreasing corrosion since the crack condition of the specimens strongly affected the corrosion process. The effect of crack width was significant on corrosion. Non-detrimental effect of calcium nitrite based corrosion inhibitors on corrosion of specimens containing fly ash was also detected.
Yuichi Miyamoto et al. (2004) examined in detail the properties of polymer-modified mortars with nitrite-type hydrocalumite, a corrosion inhibiting admixture. Cement mortar modified with Styrene-Butadiene Rubber (SBR) latex as a polymeric admixture was prepared with various polymer-binder ratios and calumite contents, and tested for flexural and compressive strengths, adhesion, water absorption, drying shrinkage, accelerated carbonation, and corrosion inhibition. It was concluded that regardless of the polymer-binder ratio, the replacement of the ordinary Portland cement with the calumite causes a marked improvement in the corrosion-inhibiting property of the polymer-modified mortars but decreased their strengths and adhesion, and increased their water absorption, drying shrinkage and carbonation depth. It was found that the inferior properties are considerably improved with an increase in the polymer-binder ratio irrespective of the calumite content. It was also concluded that the polymer-modified mortars with the calumite can successfully be used as patch materials for the repair work for deteriorated reinforced concrete structures.

Ann et al. (2006) studied the effect of calcium nitrite-based corrosion inhibitor in preventing corrosion of embedded steel in concrete. A solution containing 30% calcium nitrite and 2% calcium nitrate was used as a corrosion inhibitor. The inhibition effect of calcium nitrite-based corrosion inhibitor using a polarization method and its influence on the chloride transport, compressive strength and setting time of concrete were studied. Rapid chloride penetration test was carried on concrete discs of size 50 mm thickness and 100 mm diameter. Mortar specimens of 75 mm diameter and 150 mm in height with centrally embedded rebar was used for polarization resistance measurement. Corrosion behaviour of specimens with five levels of chloride content and four levels of inhibitor addition were tested. It was concluded that calcium nitrite-based inhibitor significantly reduced the corrosion rate of steel in chloride contaminated mortar. There was a
remarkable increase in chloride threshold limit ranging from 0.22% to 1.95% as compared to 0.18% to 0.33% for control mortar specimens. Addition of inhibitor produced higher total charge passed in the rapid chloride permeability test. It was also observed that increase in the dosage of corrosion inhibitor resulted in a decrease in the concrete setting time. The compressive strength at early ages was increased by corrosion inhibitors whereas it decreased to a level of 28 day strength after a long term exposure of 900 days.

Saraswathy and Ha-Won Song (2007) conducted experiments to improve the durability of concrete by using inhibitors. The performance of anodic inhibitors (sodium nitrite and zinc oxide), cathodic inhibitors (monoethanol amine, diethanol amine and triethanol amine) and mixed inhibitors in controlling rebar corrosion were studied. Compressive strength test, tensile strength test, chloride diffusion test and macrocell corrosion test were conducted by varying the type and concentration of inhibitors. It was concluded that all the inhibitor admixed concrete at 2% addition showed maximum compressive strength as compared to control concrete. Whereas tensile strength and bond strength of concrete was not affected by the addition of inhibitor. Corrosion resistance properties of concrete was also improved and 2% addition was found to be optimum.

Tamizhselvi and Samuel Knight (2007) conducted electrochemical investigations to evaluate the performance of inhibitors to control rebar corrosion. Performance of sodium nitrite, zinc oxide and triethanolamine were studied by conducting harmlessness test, open circuit potential test and linear polarization technique. Cylindrical reinforced concrete specimens of size 70 mm diameter and 100 mm height were cast with centrally embedded 10 mm diameter CTD rebar of 50 mm height. The inhibitors were added at 1, 2 and 3% by weight of cement and chloride was introduced at 0, 0.75 and 1% by weight of cement. Test results exhibited that sodium nitrite and zinc
oxide offered higher corrosion resistance in harmlessness test and linear polarization test. Addition of 1% and 2% of inhibitors irrespective of the type offered significant corrosion resistance in the open circuit potential test. It was concluded that addition of 2% sodium nitrite offered higher corrosion resistance compared to control concrete in the presence and absence of chlorides.

From the above review of literature, it is clearly evident that corrosion of steel in concrete is inevitable but can be controlled. The usage of rusted steel rebars in concrete will affect the durability of reinforced concrete structures. Many other researchers have worked on the performance evaluation of individual protective coating systems and corrosion inhibitors. Extensive research work has been carried out in this area during the last three decades and as a result different coating systems and corrosion inhibitors have emerged. Central Electrochemical Research Institute (CECRI), Karaikudi, India, has developed inhibited cement slurry coating and cement polymer composite coating. These coating systems were not evaluated by other researchers for their performance. Galvanized rebars were used in different parts of the world in isolated locations. Only scarce literature is available on performance of galvanized bars in Indian climatic conditions. Not many researchers have attempted to develop simple anticorrosive coating system which can be adoptable even in minor construction sites. Moreover very few researchers have analysed the performance of damaged coated bar and their performance in inhibitor admixed concrete.

In India two types of High Yield Strength Deformed (HYSD) bars confirming to IS 1786 – 1985 are used in construction. These are Cold Twisted Deformed (CTD) bars and Thermomechanically Treated (TMT) bars. Comparative corrosion characteristics of protective coatings on these bars have not so far been evaluated. The present investigation is aimed at
evaluating the performance of cement polymer anticorrosive coating developed in the laboratory, inhibited cement slurry coating, cement polymer composite coating and galvanization on high yield strength CTD and TMT bars. The performance of coating with and without coatings damage in control and inhibitor admixed concrete were also studied.