CORROSION RESISTANCE PERFORMANCE OF FUSION BONDED EPOXY COATED REBARS

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Corrosion resistance properties of fusion bonded epoxy coated rebars (FBECR) directly exposed as well as under embedded condition in concrete mortars in simulated concrete pore solution (SPS) and 3.5%NaCl have been studied. Electrochemical techniques (Direct current and A.C. impedance spectroscopy) have been employed to assess the performance of the coatings. The results show that the FBECR is extremely stable in contact of aqueous solutions having no trace of chloride ions. In the presence of chloride ions, however, deterioration of the coating has been noted. EIS studies have been used to determine as water absorbability, loss of electrical insulation properties and change in resistances and capacitance of the coated interface with the passage of time.

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Corrosion of reinforcement bars especially in coastal areas is a serious problem and is responsible for premature failures of many structures. The passivity imparted by the alkalinity of the cement to the reinforcement steel surface becomes ineffective when chloride concentration at the steel surface exceeds a critical threshold value. Under such a situation, the total loss of the steel thickness per unit area is negligibly small in comparison to penetration rate at certain susceptible part of the reinforcement bars. As a result of increase in stress intensity factor at the tip of localized pits formed on the surface of rebars, the tensile strength of the concrete structures which is mainly imparted by the steel reinforcement bars, is severely affected and results in collapse of the structures. Many techniques have been developed to control the above mentioned corrosion problems. These include the use of corrosion resistant alloys, corrosion inhibitors, cathodic protection and use of organic / metallic coatings on steel bars ⁽¹⁻⁹⁾. Out of these techniques, the application of fusion bonded epoxy coating on steel bars FBECR⁽¹⁰⁾ had been guite popular and in use at many places since last three decades. The FBECR was developed in USA in1960s and its use was strongly recommended in coastal areas. It was proposed that the FBECR imparts resistance to the permeation of moisture and aggressive anions, acts as electrical insulator and provides physical barrier between the steel bars and corrosive electrolytes. During the 1980s, the FBECR became extremely popular in USA and National standard for the material was formulated⁽¹¹⁾. Thereafter the production of FBECR started in many countries such as Japan, North America, the middle east and in India. The failure of the structures incorporating FBECR, however started occurring within 10 years of their erection^{02/131}. The failure investigations revealed that these failures took place either at the defect sites (cracking/mechanical damages caused in coatings prior to/ during the erection of the structures) of the coating or at the places where although the coating was intact but corrosion took place beneath the coating. These observations created a great concern and had casted doubt on the ability of FBECR in withstanding the corrosive attack. This led researchers to have a re-look on the performance of FBECR. During the last few years a number of

research papers on corrosion resistance performance of FBECR have appeared in literature and a great deal of disagreement exists amongst the researchers on the durability of the FBECR exposed to saline environment⁽¹⁴⁻²⁵⁾. The present study was taken up at the National Metallurgical Laboratory, Jamshedpur, India to have more authentic data on performance of FBECR using electrochemical impedance spectroscopy (EIS) and D.C. corrosion techniques. The present paper is a part of this study and incorporates the results obtained for FBECR exposed directly to simulated pore solution (SPS), 3.5% sodium Chloride solution and embedded in concrete mortars blended with chloride ion.

EXPERIMENTAL DETAILS

FBECR used for the study were in the form of thermo-mechanically treated bars of 16 mm dia having plain ribs. The epoxy coating was applied on the surface of rebars in the factory and they were collected from the construction site. The samples of 1 meter length were taken and were again cut in required length. These bars having sound and defect free only selected for the studies. The coating thickness on the bars was in the range of 130µ. The mortars embedded with FBECR were prepared by using cement (ordinary Portland cement) + water + sand (conforming to Bureau of Indian Standard BIS-650 (1966), Grade I) mixed in the proportions of 1:0.5:3 respectively. They were blended with different concentrations of chloride ion in the form of sodium chloride. The concentration of chloride ions was calculated on the basis of weight of cement taken for casting of mortars. Out of 210 mm length of the rebar samples, only 160 mm length was cast in cylindrical mortars in such a way that a concrete cover of 16 mm thickness was available to the steel bars from all sites of the casting. To avoid the effect of geometry of counter electrode on polarisation data, 304 stainless steel (SS) bars of similar dia (16 mm) were cast in mortars maintaining equal distance from the sample of FBECR. This SS bar was used as the counter electrode during the electrochemical studies. The cut end of the FBECR was kept out of the mortar. This avoided the patching work on the cut end of the cross sectional area which could have resulted in bringing of a different type of surface in contact with the corroding electrolyte-Two type of mortars were prepared. One had intact FBECR embedded in the mortar whereas the other had 40 numbers of holidays created on the hill part of the ribs at equal distances. The holidays had diameter of 1 mm which were created by using a sharp knife. Thus the total exposed area of the embedded FBECR in such mortars was 0.314 cm². To avoid the formation of crevices at the two ends, the bars were provided with thick coat of Feviseal putty *. For direct exposure of the FBECR, the bars of 16 cm length were fixed in plastic container. The two cut edges were again kept out of the cell as mentioned in the case of mortars. The electrical contacts were made through a copper wire soldered at the two free ends of the electrode.

* A trade name of water resistant sealer formulated by fast setting epoxy and supplied by M/S Pidilite, India.

The casting and curing of mortars were carried out as per ASTM-C192-90a. They were demoulded after 24 hours of casting and cured for 28 days in humidity chamber maintained at 95% RH at 25°C temperature. After curing, the mortars were exposed for 10 days in 3.5% sodium chloride solution followed by drying at 65°C for 5 days. This treatment was counted as one cycle. It is reported that the cyclic wet/dry treatment to mortars has an accelerating effect on onset and propagation of corrosion on the steel surface and provides actual conditions of field applications.⁽¹⁻⁴⁾ The embedded bars were then evaluated for changes in their corrosion rate and corrosion potential with passage of time by using DC polarisation resistance technique as specified under ASTM STP 1065. The potential values during the polarisation studies were scanned between \pm 20 mv of open circuit potential of the embedded rebars at the rate of 0.015 mv/sec. Corrosion rate of the

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steels have been evaluated by determining the polarisation resistance (Rp) of the corroding interface by using Stern-Geary equation :

Breaker and Kingsbury⁰⁸⁰ have shown that the capacitance of gR/H = riol ace exposed in

Where $B = \beta a \cdot \beta c / 2.3(\beta a + \beta c)$ and Rp is the polarisation resistance determined by linear polarisation resistance technique, βa and βc are anodic and cathodic Tafel slopes whose values were taken 0.12 V/decade of current for the shake of simplicity. Since the polarisation studies of the embedded rebars were limited in the range of ± 20 mv of open circuit potential, it was expected that these polarisations would leave least effect on the surface conditions of the embedded rebars. The same mortars, therefore, were repeatedly used to have kinetic data on change in corrosion rate and corrosion potential with the passage of time.

The FBECR were directly exposed in chloride blended simulated concrete pore solution (SPS) having the chemical compositions as follows :

resistance and increa

KOH = 0.06Mfound true in case of rebars embedded in mortars having chM2.0 = HOaN the absence of chloride ion, however a decrease in corresion rate with $M100.0 = _{c}(HO)a2.d$. (Fig.6a and

The kinetic data were collected for the exposed bars after different intervals of time. The reference electrode was a saturated calomel electrode (SCE). A luggin capillary was used to provide electrolytic contact between the calomel electrode and electrochemical cell. EIS studies were performed by imposing 10 my of sinusoidal voltage (with reference to open circuit potential) at the working electrode (embedded and directly exposed FBECR) and varying the frequency from 100 KHz to 0.001 Hz. All the electrochemical studies were performed by using a Gamry Potentiostat * supplied by M/S. Gamry Instruments of USA. All the experiments were performed in air conditioned room having the temperature in the range of 22-28°C. avionable doidy abixorbyd orretorique as at

Results and Discussion

FBECR directly exposed to SPS : It is well known that the epoxy coating on rebars provides a barrier type of protection to the steel surface. The electrical properties of the coated surface exposed in an aggressive solution, therefore, provide very vital informations on the efficacy of the coating for a particular system. The coated rebar surface exposed in an electrolyte comprises of resistance components such as uncompensated metallic circuit and solution resistance (Ru), pore resistance of the coating (Rp), charge transfer resistance(Rct) and capacitance components eg. Capacitance resulted due to double layer formed at coating/electrolyte interface (Cc) and metal/electrolyte interface (Cdl). A schematic diagram for such a system is shown in fig. 1. The change in properties of these parameters with passage of time, therefore, is expected to provide the informations related to the corrosion resistance of the coating. Fig.2 shows the change in uncompensated resistance (Ru) of the corrosion circuit exposed in SPS having 0.5% Chloride ion. It is noted that (Ru) decreases with increase in exposure time. Since other uncompensated resistance components of corroding cell (solution, metallic conductor etc.) are kept constant during the period of tests, the decrease in Ru values may be attributed to the loss in electrical resistance of the coating. A similar trend has also been noted for the charge transfer resistance (Ret) and polarisation resistance of FBECR (Fig.3 and Fig.4). The most adverse effect of the exposure time has been noted on polarization resistance (Rp) where after 16 days of the exposure of FBECR samples, the Rp has decreased by about 8 times. The capacitance of the coating-metal interface on the other hand, is observed to increase with passage of time (Fig.4). These observations clearly indicate that the epoxy coating, when exposed directly to SPS, is not very resistant to the penetration of moisture and

aggressive ions. The above observations get further support from the fact that the absorption of water by FBECR exposed in SPS solution increases with the passage of time. Brasher and Kingsbury⁽²⁶⁾ have shown that the capacitance of a coated surface exposed in aqueous solution is related by the equation

$Ct Co = 80^{x}$ (1)

where Co and Ct are the capacitance values of the system at zero period of exposure (before exposure of the coating in the electrolyte) and after time t respectively. 80 is the dielectric constant and x is the volume fraction of water in the coating. In view of the fact that the capacitance values determined for the system is dominated by the capacity of water absorbed coating the above equation can be used for the present system. The percentage volume fraction of absorbed water with passage of time is shown in Fig.5. The figure clearly reveals that a gradual increase of water content of the coating takes place with passage of time.

The loss in electrical resistance and increase in water absorption by the coating with passage of time is expected to increase the corrosion rate of rebars with time. This is found true in case of rebars embedded in mortars having chloride ions. In the absence of chloride ion, however a decrease in corrosion rate with time has been noted. (Fig.6a and 6b). These aspects can be explained by considering the fact that in the absence of any chloride ion, alkalinity of concrete helps in the formation of protective iron oxide film on the steel rebars. In the presence of chloride ions, the protective oxide reacts with chloride ion to form soluble iron complex⁽²⁷⁾. When iron chloride complex diffuses away from the bar to an area of greater alkalinity and concentration of oxygen it reacts with hydroxyl ions to form $Fe(OH)_2$, which frees the complexed chloride ions to continue the corrosion process in the presence of moisture and oxygen⁽²⁸⁾,

$$FeCl_{2} + 2H_{2}O \rightarrow Fe(OH)_{2} + 2HCl -----(2)$$

Since $Fe(OH)_2$ is an amphoteric hydroxide which dissolves quickly in acid solution to release fresh $FeCl_2$ at the sites of pores,

 $Fe(OH)_2 + 2HCl \rightarrow Fecl_2 + 2H_20$ ------(3)

This sets a chain of reactions causing an increase in corrosion rate. In the absence of chloride ions, however, a dacrease in corrosion rate with passage of time appears to be controlled by different mechanism. Due to the non avialability of chloride in mortars, instead of hydrolysis reaction as shown in eqn.(2), a stable oxide phase (Fe₂O₃) is found which blocks the pores⁽²⁹⁾

$$2Fe(OH)_2 \quad O_2 \Rightarrow Fe_2C_3 + H_2O -----(4)$$

The above mechanism of reaction at the pore sites of epoxy coating suggests that very fast rate of penetration of corrosion attack should take place at these sites. It is mainly due to the presence of very large cathode to anode area ratio (pore sites acting as anode and rest of the coated surface ladden with chloride acting as cathode). This was indeed observed for the rebars embedded in mortars having chloride ions (Fig.7a and 7b). Considering the fact that the corrosion activities on FBECR was restricted only at the pore sites of the coating, the actual corrosion rate was determined by taking area of pores instead of total embedded area of the coated rebar. The results showing apparent corrosion rate (calculated on the basis of total embedded area) and actual penetration rate (determined by considering only the total area of pores) with passage of time are shown in figure 7(a). It is evident from the above figures that after an exposure period of 250 days, the actual penetartion rate is about 25 times higher than the apparent corrosion rate. This corrosion rate (actual) is also many times higher than corrosion rate of an ordinary mild steel having no coating, embedded in mortar and exposed under identical test conditions (fig.7b).

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The fact that the defects in epoxy coating are increasing with the passage of time of exposure is also evident from the corrosion potential-time plot for various systems. It is reported that a coated interface maintains the outstanding corrosion protection if it attains the corrosion potential in an electrolyte very similar to that of the base metal in the same medium⁽³⁰⁾. The systems exhibiting a nobler potential after exposure to an aggressive electrolyte indicate the development of defects in the coating. In the presnt system of FBECR directly exposed to SPS or embedded in mortars in the absence and the presence of chloride ions, have a definite trend of change in corrosion potential with passage of time, (fig.8). It is evident from fig.8 that the FBECR exposed in SPS has more stability of corrosion potential in comparisn to the solution having chloride ions. In pure SPS solution, bare steel exhibits corrosion potential of the order of -300 mv (SCE). It is evident from the fig. 10 that after a period of 263 days of exposure in the solution, the corrosion potential has drifted to - 87my. In the presence and the absence of chloride ions, the onset of enobling in potential takes place within 07 days. After a continuous increase in potential, it again starts to move in negative direction and ultimately after a certain period of exposure the potentials attain the values of bare steel. It is interesting to note that the exposure time for onset of negative movement of the potential after moving in positive direction varies with chloride content in SPS. For pure SPS, this time is 140-days where as for SPS having 0.15%, 0.3% chloride ions and 3.5% NaCI solutions, the values are > 263 days, 62 days and 21 days respectively. These changes in potential are directly related to the cathode/anode surface area ratio of a coated material. An increase in cathode / anode area ratio results due to the poorer performance of the coating and moves the potential in positive direction. A larger cathode area is a consequence of a delamination process which results in due to the weakening of coating/substrate bond. A shift in potential, therefore, more nobler than the corrosion potential of base metal is an indication of deterioration of the coating.

A similar trend as noted for FBECR directly exposed to SPS solution has also been observed for the coated bars embedded in mortars having different concentrations of chloride ions(Fig.9). This is true for the coated bars with and without holidays. The only difference is that the bars having holidays develop the nobler potential at a faster rate than those having no holidays. However, non of the samples exhibit the turning point from noble direction movement to active direction indicating that the process of development of defects is still continuing even after 308 days of exposure. The final exfoliation of the coating may take more time to happen.

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Variation in aparent corrosion rate with time for FBECR embedded in mortars having 0.5% Cl⁻



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STUDIES ON PERFORMANCE OF GALVANNEALED COATINGS AND OTHER TYPE OF ZINC COATINGS



Fig : 8 Change in corrosion potential with passage of time for FBECR immersed in chloride blended SPS and 3.5% NaCl solution.



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Laterature survey has revealed that very limited informations are available on the correction resistance performance of galvannealed coatings in different types of correstive environments. The present work, is a part of a programme of evaluation of comparative performance of galvannealed vis-a-vis other zinc coatings in acidic, alkaline and neutral environments.

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