ENVIRONMENTAL CONSIDERATION FOR THE USE OF EPOXY-COATED REBARS (FBECR) IN THE GULF REGION

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ABSTRACT

The aggressivity of the environmental conditions of the Arabian Gulf region impose additional measures and precautions to be implemented for the use of epoxy coated reinforcing steel.

The salt-laden humidity blown from the Gulf side on hot summer days with relative humidity reaching about 100%, accelerates corrosion at location of coating damage due to improper handling or from cutting and bending at job sites. The long and improper storage of such materials at sites where they come into contact with soil and water and are left exposed to humidity and sunlight cause corrosion at imperfections and deterioration to the coating film. Also, high temperature and humidity affect the property of the coating powder and the quality of the coating thereafter.

This paper will discuss the effect of the local environment on the quality and performance of epoxy-coated rebars in the region to increase the awareness about such effects and improve the overall handling practices.

KEYWORDS

Durability; epoxy; corrosion; debonding; deterioration.

INTRODUCTION

The early deterioration of concrete structures due to corrosion of steel reinforcement is a major and serious problem facing the concrete industry. In the Arabian Gulf region concrete structures show distress due to corrosion of reinforcement in the first 5-10 years of their service life (Rasheeduzzafar et al., 1982).

The early deterioration of concrete structures in the Gulf region is due to several interactive parameters. The aggressivity of the climatic and geomorphic conditions with lack of appropriate specifications and construction practices are the main factors (Rasheeduzzafar et al., 1984).

The use of Fusion Bonded Epoxy-Coated Reinforcement (FBECR) in concrete is one of the emerged solutions to arrest the premature rebar corrosion problem in concrete. The FBECR was introduced in the USA in the early 1970s as a measure for preventing the corrosion of reinforcement in concrete by providing a direct shield for the rebar against the corrosive agents. It was widely used in construction of bridge decks subjected to deicing salts and which suffered from chloride-induced corrosion of the reinforcement.

As a result of good performance of the FBECR, its use grew very rapidly in the USA and Europe in the 1980s. Fig. 1 summarizes the shipments of FBECR in the USA and Canada during the period 1984-93 for 70-80% of total production as compiled by CRSI (Manning, 1996).

A survey for 92 bridge decks constructed with FBECR in eleven states and three Canadian provinces, showed an overall good performance. The overall condition of the bridge decks was considered to be good with no evidence of any significant premature concrete deterioration that could be attributed to corrosion of FBECR. The use of good quality concrete with adequate cover, inspection, finishing and curing of the concrete and the proper manufacturing and handling of FBECR, complement the use of FBECR in providing effective corrosion protection for concrete bridge decks. FBECR has provided effective corrosion protection for up to twenty years of service (Smith and Virmani, 1996).

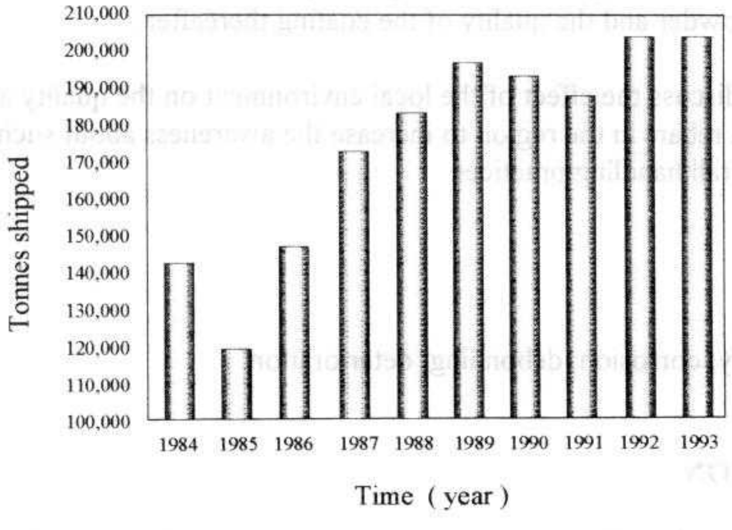


Fig. 1. Shipments for epoxy-coated reinforcing steel in North America, 1984-1993

However, major corrosion cases were reported by the Florida Department of Transportation in 1986 in several bridges in the Florida keys. As a result of such reports, considerable research was launched by different agencies to evaluate the performance of FBECR of different quality and under different exposure conditions. The performance came in a very wide range from excellent to poor/not recommended for use (Zayed et al., 1989; Sagues and Powers, 1990; Sagues et al., 1990; Sagues, 1994).

Since the failure reports, there have been significant improvements made in the quality of FBECR, in terms of adhesion, reduction of holidays and minimum thickness requirements. Such improvements are expected to improve the corrosion performance of FBECR along with appropriate adaption of construction practices at site (ASTM, 1996).

USE OF FBECR IN THE ARABIAN GULF REGION

The concrete structures in the Arabian Gulf suffer from early cracking and spalling due to the corrosion of reinforcements. As there is indeed a need for a means to prevent the early corrosion of reinforcement, the FBECR was used in construction in some projects in the U.A.E. in the mid 1980s and several coating plants were set up thereafter. Between 1991-1992 three coating plants were constructed in the Eastern Province of Saudi Arabia. In 1996-97 a new coating plant was also constructed in the State of Qatar. At present, there are five coating plants in the U.A.E., which make a total of nine plants in the Arabian Gulf countries.

The use of FBECR in construction is increasing as the prices of the FBECR are being reduced in comparison with uncoated rebars. Fig. 2 shows the total sales for the three plants in Saudi Arabia (Saudi Iron and Steel Company, 1998).

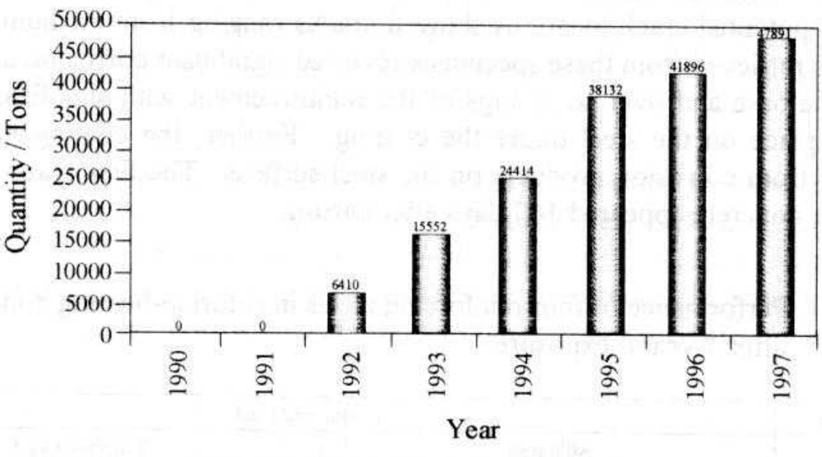


Fig. 2. Total sales of rebar to epoxy factories (1990-1997)

PERFORMANCE OF FBECR IN THE GULF REGION

There is no actual field performance data available for the used FBECR in the Gulf region. A limited number of research projects have been carried out at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia and Dubai Municipality, U.A.E.

Exposure Site Study at KFUPM

At KFUPM, the performance of FBECR has been evaluated in comparison with stainless-clad, galvanized, and mild steel deformed rebars (Rasheeduzzafar et al., 1992). The different steel reinforcements were placed in good quality, chloride-bearing concrete with different degree of chloride contaminations. The concrete prisms contain four bars placed at the corners of the prism with a clear cover of 25 mm on each side. Three concrete prisms were made for each type of rebar and each chloride contamination. Three different dosages of chloride were added to the concrete mix as sodium chloride through the mix water: 2.40, 4.80 and 19.20 kg/m^3. The specimens were exposed to the outside environment at the exposure site and about one meter above the ground surface. The environment represents the typical Gulf environment, which is characterized by saline sea influences, intense heat often associated with high humidity and strong persistent dry winds. Summer temperatures are mostly in the range of 40-50°C, with concrete temperatures of up to 70°C due to the effects of solar radiation.

The corrosion performance of the different reinforcements was measured by:

a- The onset and propagation of concrete cracks
b- Weight loss of the rebars after removal of corrosion products
c- Condition of steel rebars in terms of rust coverage of the rebar and pitting spots.

At the end of the 7-year exposure to the Gulf environment at Dhahran, the rebars were retrieved and evaluated, and the results are summarized in Table 1. Visual examination of the FBECR rebars, after removal from concrete, showed them to be clean and corrosion free and the coating appeared shiny and damage free for the concrete specimens with 2.4 and 4.8 kg/m^3 chloride content. However, for the 19.2 kg/m^3 chloride concrete specimens, all potential crack locations showed cracks ranging from medium to heavy in width. Rebars retrieved from these specimens revealed significant corrosion attack, which occurred at the base and over some lugs of the reinforcement with significant corrosion having taken place on the steel under the coating. Further, the coating had breached systematically from corrosion products on the steel surface. The first crack on the 19.4 kg/m^3 chloride concrete appeared 163 days after casting.

Table 1. Performance of four reinforcing steels in chloride-bearing concrete after 7 years' exposure

Added Chloride		Reinforcing Steel							
		Mild steel				Galvanized steel			
lb/yd^3 (kg/m^3)	Cement, percent by weight	Average weight loss per unit length, gm/cm	Crack classifi-cation	Rust coverage, percent	Time of first crack after casting	Average weight loss per unit length, gm/cm	Crack classifi-cation	Rust coverage, percent	Time of first crack after casting
4 (2.4)	0.60	0.780	Medium (3)	100	–	0.480	Fine (2)	60	–
8 (4.8)	1.2	1.050	Heavy	100	–	0.602	Medium (3)	100	–
32 (19.2)	4.80	1.632	Spalling	100	65	0.965	Wide (4)	100	172
		Epoxy-coated steel				Stainless-clad steel			
4 (2.4)	0.60	–	No crack (1)	–	–	–	No crack (1)	0	–
8 (4.8)	1.2	–	No crack (1)	–	–	–	No crack (1)	0	–
32 (19.2)	4.80	–	Wide (4)	–	163	–	No crack (1)	0	–

Laboratory Accelerated Testing at RI-KFUPM

In another evaluation of FBECR performance carried out by the Research Institute at KFUPM (Saricimen et al., 1997), the effect of fabrication bending of FBECR on the corrosion process was investigated. The study also investigated the bond strength at elevated temperature conditions and determined the effect of epoxy film thickness; the effect of holidays/damages; and ultraviolet exposure on the corrosion performance of FBECR produced by local manufacturers.

In this investigation, prisms of 100×62.5×305 mm were used for straight bars and prisms of 202×62.5×305 mm were used for J-bend bars. A concrete cover of 25 mm was maintained in all specimens. The specimens were placed in tanks with 5% sodium chloride solution for the accelerated corrosion testing in laboratory room temperature. The FBECR rebars were procured from local manufacturers and they were in compliance with the ASTM A775/A775M-90. Then the specimens were subjected to an induced current using potentiostat to shift the potential of the steel to anodic state. The applied potential was 4.0 volts versus a silver/silver chloride reference electrode.

The corrosion data were recorded every 2-hour for the first 82 hours. On the basis of change in corrosion current readings over a given time period, the intervals for recording the corrosion data were later changed to 4-hour and 8-hour periods after 783 hours and 3,519 hours, respectively. The changes in corrosion current readings are indicated by sudden increases in current that are associated with increased corrosion activities that, quite often, produce cracks on the concrete surface of the specimen. At the onset of crack appearance on the concrete specimen surface, the specimen was taken out of the test and set aside for later retrieval of the FBECR steel bars. After observations and recording of corrosion data, the specimens were broken open and the FBECR steel bars were retrieved, cleaned and visually examined for corrosion stains and epoxy-coating cracks.

It was noted that once corrosion cells form at perforations or at epoxy-coating cracks locations, they become points at which epoxy coating and steel surfaces disbond, thus allowing the corrosion process to spread on the steel surface of the rebar beneath the coating rather than penetrate through its thickness as previously stipulated. The corrosion process is of pitting type corrosion and produces black granular corrosion product.

The corrosion process in the J-bend bar initiated at the patch repair of the cut-ends and advanced beneath the epoxy coating through a major portion of the surface area of the bar. The corrosion started on the deformation pattern, particularly along the axis of the bar, where the epoxy coating is presumably very thin due to the sharp geometry (i.e., sharp edge). Also, it was noted that spots of corrosion stain developed on the FBECR steel bar surface, the corrosion appeared very severe with black corrosion products.

Performance of FBECR in U.A.E.

Dubai Municipality conducted a research study on FBECR exposed to aggressive environmental conditions of the United Arab Emirates since December 1991 (Sharafi et al., 1996). The study covers rebar coating systems and different products comprising pore blocking admixtures and a penetrating surface sealer. The parameters included in the study were two water cement ratios of 0.44 and 0.6, two types of curing regimes, two concrete rebar covers (10 mm and 30 mm) and three site exposure conditions (above ground, below ground and in the tidal zone). Table 2 shows the exposure conditions for the specimens. The effectiveness is assessed through accelerated laboratory tests and site exposure tests. The tests performed at different ages include compressive strength, water absorption, water penetration, capillary rise, chloride ingress and crack mapping. Also, electrochemical testing comprising half-cell potential, resistivity, linear polarization, corrosion current and AC impedance were conducted.

Table 2. Salinity condition of the exposure site at U.A.E.

Exposure Site Location	NaCl ppm	SO_4 ppm	pH
Soil at ground level	140	504	8.5
Soil below ground level	2291	2424	8.8
Soil in tidal zone	2052	372	9.0
Groundwater	26216	37212	8.14
Seawater	34702	3036	7.64

Specimens with FBECR after three years of exposure in the tidal and below ground zones were found to be in good conditions, but some showed rust stains at random locations. No signs or symptoms of corrosion were noticed for the above ground specimens with FBECR. Inspection of the exposed rebars of several specimens from the tidal zone and below ground level revealed that there were areas of coating which did not adhere to the rebar surface. Cutting these areas with a knife revealed that the disbondment of coating was associated with corrosion of the steel surface, and where the coating adhered well, there was no corrosion under coating. However, it was not clear to the researchers if the coating had been disbonded before testing or disbonded after exposure. Tests conducted on the FBECR obtained from construction sites showed that they were far from satisfactory with respect to ASTM standard (ASTM A775/A775M-91) at the time of the test.

CORROSION MECHANISMS OF FBECR

The adhesive state of the coating to the bar is essential to the corrosion protection performance of FBECR as is the magnitude and type of coating damage. There are two possible situations for the corrosion of FBECR in chloride laden environments (Manning, 1996):

I- If FBECR is placed in poor quality concrete, the chloride ions penetrate the concrete quickly and corrosion takes place only at bare, holiday and thin coating areas until the coating loses adhesion by water dissociation and undercoating corrosion takes place.

II- If FBECR is placed in good quality concrete, the chloride ions arrive at the bar when the coating has debonded and corrosion takes place primarily as undercoating corrosion.

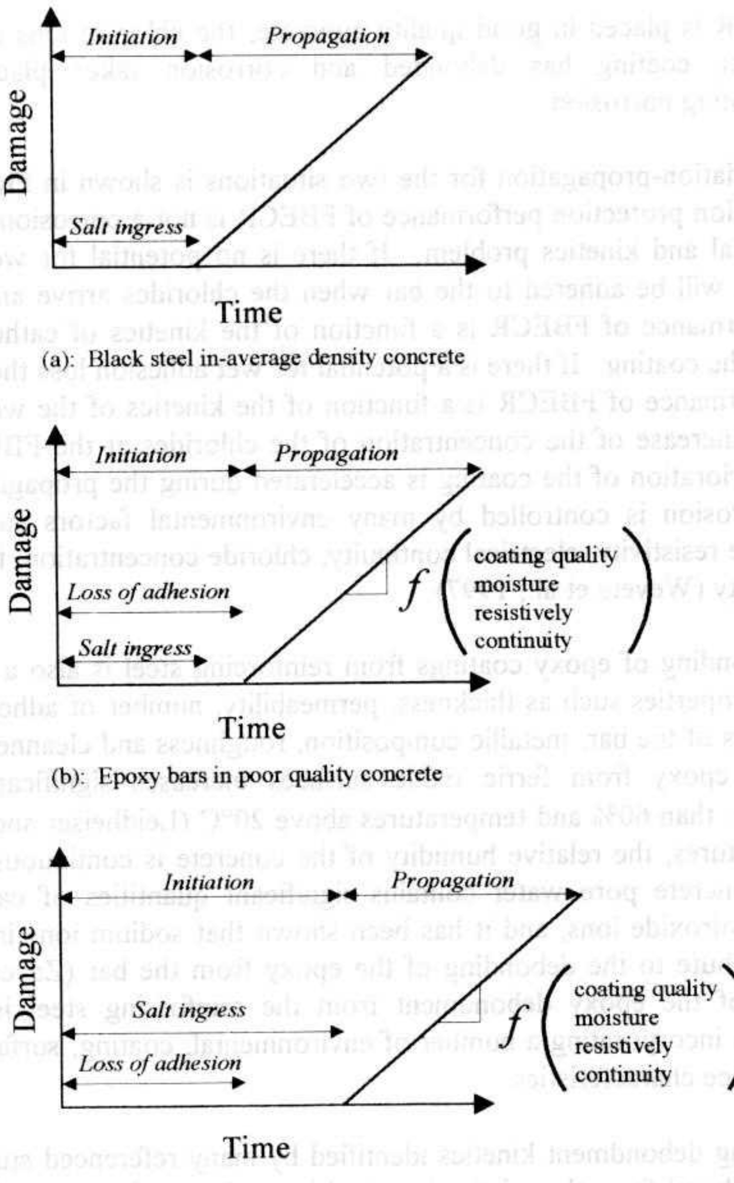
A model for initiation-propagation for the two situations is shown in Figs. 3(b) and (c). Thus, the corrosion protection performance of FBECR is not a corrosion problem but an adhesion potential and kinetics problem. If there is no potential for wet adhesion loss then the coating will be adhered to the bar when the chlorides arrive and the corrosion protection performance of FBECR is a function of the kinetics of cathodic and anodic debondment of the coating. If there is a potential for wet adhesion loss then the corrosion protection performance of FBECR is a function of the kinetics of the wet adhesion loss and the rate of increase of the concentration of the chlorides at the FBECR depth. In both cases, deterioration of the coating is accelerated during the propagation phase, and the rate of corrosion is controlled by many environmental factors such as moisture content, concrete resistivity, electrical continuity, chloride concentration, temperature and oxygen availability (Weyers et al., 1997).

The rate of debonding of epoxy coatings from reinforcing steel is also a function of the epoxy coating properties such as thickness, permeability, number of adhesive bond sites, surface properties of the bar, metallic composition, roughness and cleanness. The rate of debondment of epoxy from ferric oxide surfaces increases significantly at relative humidities greater than 60% and temperatures above 20°C (Leidheiser and Funke, 1987). For marine structures, the relative humidity of the concrete is continuously greater than 80 percent. Concrete pore water contains significant quantities of calcium, sodium, potassium and hydroxide ions, and it has been shown that sodium ions in concrete pore water may contribute to the debonding of the epoxy from the bar (Zayed et al., 1989). Thus, the rate of the epoxy debondment from the reinforcing steel is an extremely complex function incorporating a number of environmental, coating, surface preparation, and metallic surface characteristics.

The epoxy coating debondment kinetics identified by many referenced studies show that the epoxy will debond from the reinforcing steel in marine environments in about 4 to 7 years and in bridge decks in 12 to 15 years. Also, the rate of debondment is a function of the quality of the concrete. The rate of debondment is less in high quality concretes (Weyers et al., 1997).

Leidheiser and Funke (1987) presented a hypothesis for the debondment of continuous organic coatings from metal surfaces under the following conditions:

1. Water disbondment is a consequence of the formation of many molecular layers of water at the metal/coating surface.
2. Water moves through the coating by diffusion through the polymer or through capillaries or pores in the coating.
3. The driving force for directional water transport through the coating to the interface is diffusion under a concentration gradient.
4. Water accumulation at the interface is made possible by the presence of non-bonded areas of sufficient dimension for the formation of liquid water.
5. The local water volume grows laterally along the metal/polymer interface under a concentration gradient force.



(a): Black steel in-average density concrete

(b): Epoxy bars in poor quality concrete

(c): Epoxy bars in good quality concrete

Fig. 3. Initiation-propagation models for uncoated and coated steels

For the FBECR system, the liquid concrete pore water is separated from a ferric oxide layer by the epoxy coating and thus provides the concentration gradient or the diffusional driving force. Also, water absorption of iron oxide increases exponentially at relative humidities greater than 60 percent.

The field and laboratory investigation has identified two factors that appear to be critical to the development of severe corrosion in FBECR (Sagues, 1994). The first factor is the presence of breaks in the coating that expose some of the metal surface to direct contact with the surrounding electrolyte. Coating breaks relevant to corrosion initiation can range from holidays invisible to the naked eye, produced at the time of manufacturing, to narrow cracks in the coating produced during fabrication bending of the rebar, to macroscopic abrasion, gashes and cuts caused during transportation, field handling and vibration while concreting. The second factor is the development of extensive loss of adhesion between the coating and the base metal after relatively short service times in concrete, even in the absence of chloride ion contamination. And once corrosion of FBECR begins when the coating has debonded, the corrosion propagation time period from initiation to cracking and spalling of the concrete cover is expected to be more or less the same with FBECR as for black steel.

LOCAL CONSTRUCTION ENVIRONMENT

As it is known, the rate of corrosion of rebars is directly related to the availability of oxygen and moisture at the cathodic areas. The rate also depends on the level of chloride concentration at the rebar level, resistivity of the concrete, continuity of the reinforcement and environment temperature. FBECR provides additional protection for rebars as long as it remains intact and free of damage. Adhesion of coating to the steel bar depends on the degree of cleanliness and anchor pattern of the rebar at the coating stage. The adhesion loss rate is also dependent on the degree of saturation or moisture availability within the concrete. It was shown that the degree of FBECR corrosion is proportional to the level of damage in the coating.

The Gulf environment is very aggressive and characterized by hot and humid weather with a wide range in temperature and humidity fluctuation between days and nights. Fig. 4 shows the range of temperature and humidity over the year. The temperature often exceeds above 35°C daily from May to September, with a wide variation in relative humidity which ranges from 20-100% depending on the wind direction. Table 3 shows the contamination level of the humidity moisture blown from the Gulf side. Such conditions enhance the corrosion of the uncoated as well as the coated reinforcement.

The current construction practices in the Gulf region for the use of FBECR are still far from satisfactory. Unskilled construction laborers handle the coated rebars in the same manner as the uncoated rebars, causing many scratches and damage to the coating film. Fig. 5 shows a typical construction site storage where bars are laid directly on the ground soil with debris all over. Bending equipment for uncoated bars is used for the bending of FBECR, creating serious damage to the coating surface as shown in Fig. 6.

Patching of damage is not done in time and damage area is left to rust, and then patching is applied without any cleaning or removal of the rust. Patching materials are mostly left open, thicken before they are applied at locations of damage. Such repair is totally ineffective in providing any protection.

In many construction sites, coated and uncoated rebars are used together in the same structural element without consideration of the possible macrocell action between the two sets of reinforcement. Fig. 7 shows a typical construction site for such situation. In many other situations, construction is interrupted for a long standing period where FBECR is left for months to deteriorate before the next casting of concrete takes place. Some construction sites visited were in dormant situation for more than one and a half years. FBECR used in foundations will be subjected to severe exposure conditions and high salinity of the ground soils in sabkha, which covers a large portion of the Gulf coastal region. The high level of groundwater with its high salinity would accelerate wet adhesion loss of the FBECR. Reinforcement at the surface of the ground will be subjected to ideal corrosion condition due to salt accumulation just above the ground surface from capillary action and continuous wet/dry cycles. Fig. 8 explains the situation which caused actual cracks at the lower portion of columns. The chemical composition of sabkha soil is shown in Table 4 (Al-Amoudi, 1995).

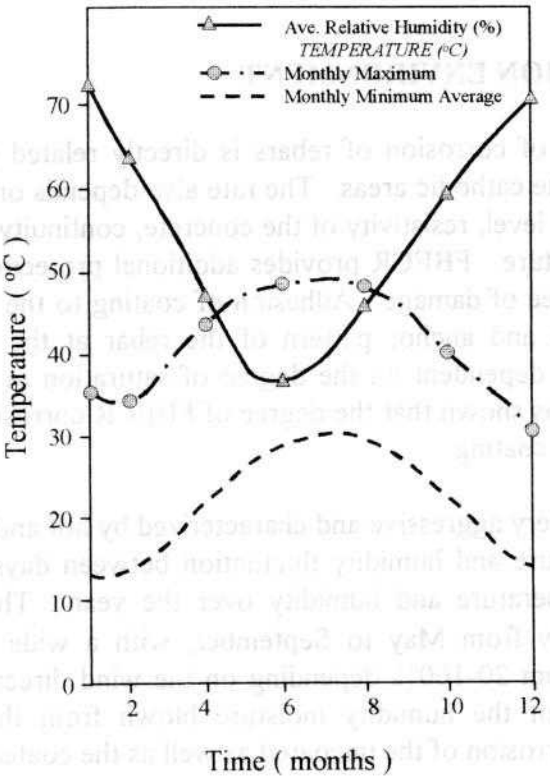


Fig. 4. Climate of Dhahran

Table 3. Analysis of air moisture in Dhahran area (Sept. 1998)

Chemical	Value
Cl^-	36.8 ppm
SO_4	25 "
Mg	8.3 "
Ca	3.2 "
pH	6.4
Conductivity	390*

*μmhos/cm

Coated rebars sometimes have sharp edges which makes maintaining the required coating thickness difficult. Adjustment by the local rebar manufacturer is required to produce more suitable rebars for coating. Fig. 9(a) shows typical damage on the coating due to improper handling and (b) sharp edges and seems found in the rebars supplied for coatings.

Fig. 5. Storage of FBECR at construction site

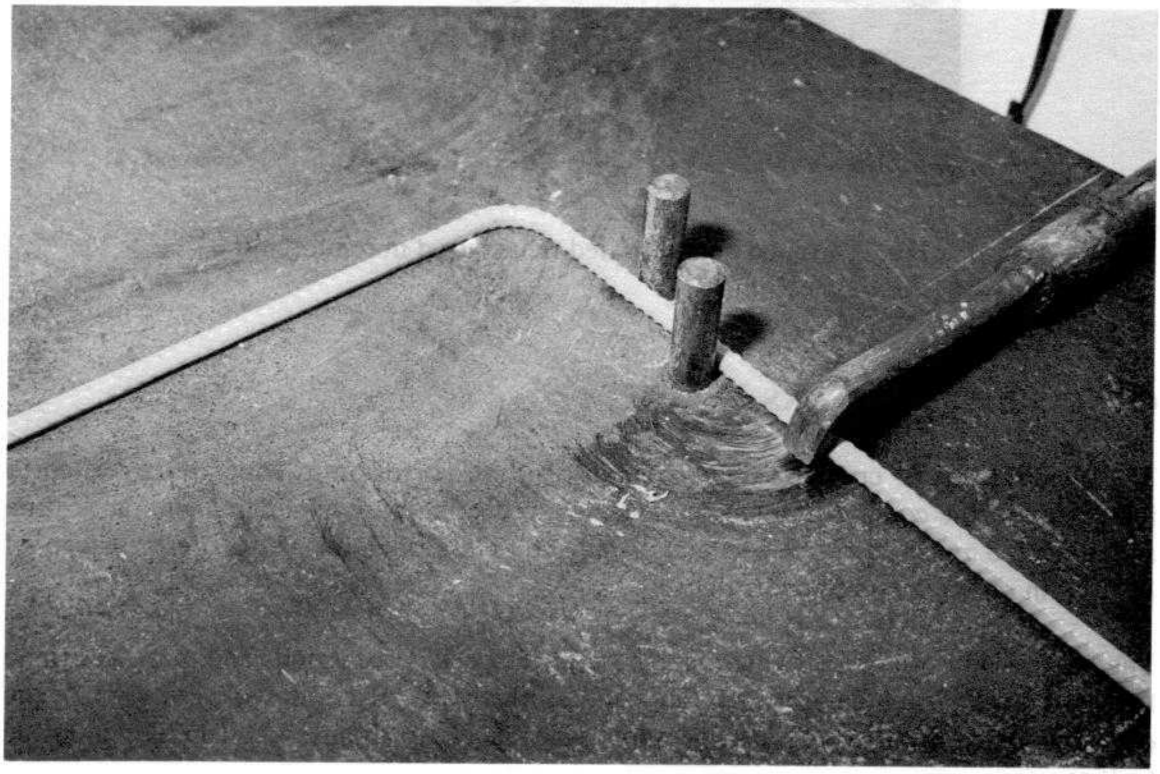


Fig. 6. Bending tools used in construction site

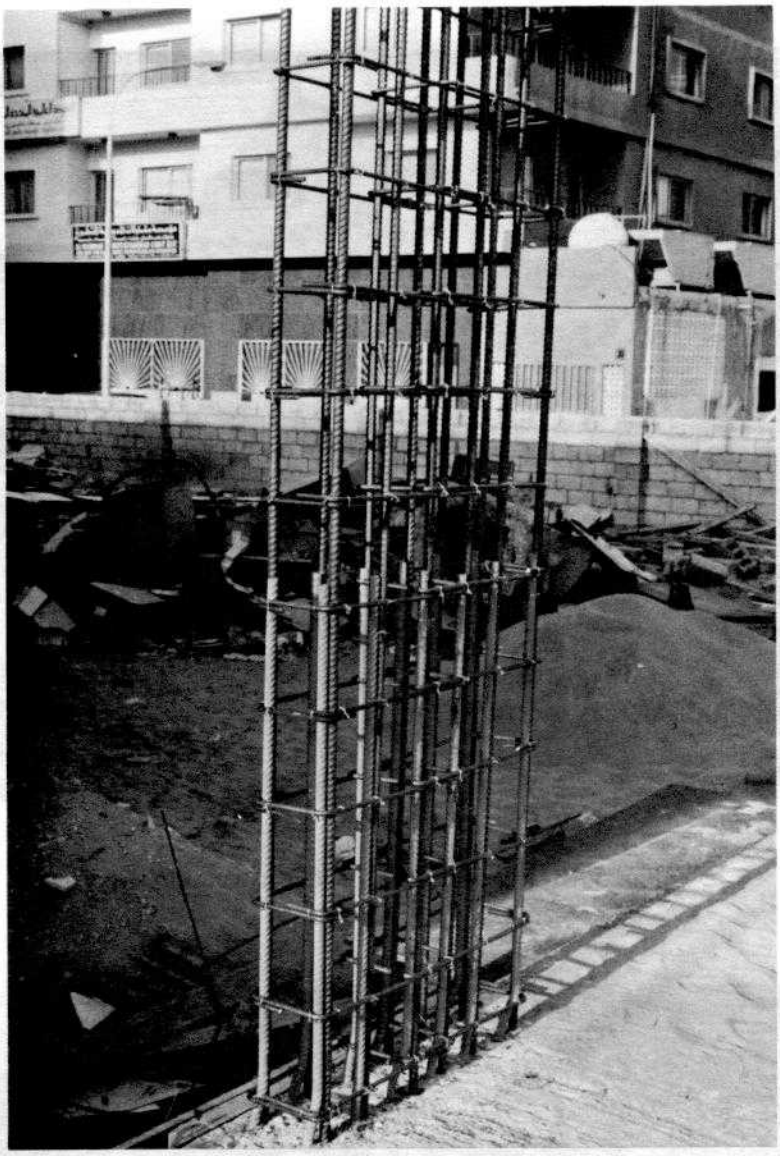


Fig. 7. Coated and uncoated rebars used in reinforcing a column

CONCLUDING REMARKS

The effectiveness of epoxy-coated rebars in resisting corrosion in concrete is related to the quality of the coating. Minimizing damage to coating during handling and fabrication and effective repair for any accidental damage is essential for better performance of FBECR in resisting corrosion.

The aggressivity of the Gulf environment requires special precautions and measures to be followed during manufacturing and fabrication of FBECR. The following are some of the concerns which need careful consideration with respect to the use of FBECR within the Gulf region:

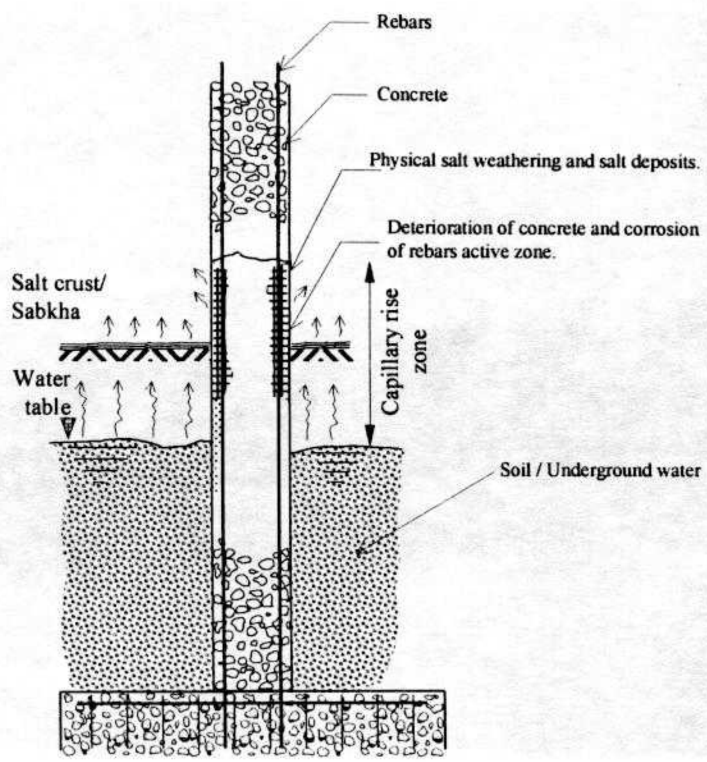


Fig. 8. Location of concrete deterioration due to high water table and capillary rise zone

Table 4. Chemical analyses of typical sabkha brine and seawater, ppm

Ions	Sabkha Brine	Arabian Gulf Seawater
Na^{+}	78800	20700
Mg^{++}	10320	2300
K^{+}	3060	730
Ca^{++}	1450	760
Fe^{++}	Trace	Trace
Sr^{++}	29	13
Cl^{-}	157200	36900
Br^{-}	490	121
$(SO_4)^{--}$	5450	5120
$(HCO_3)^{-}$	87	128
pH	6900	8300
Conductivity*	208000	46200

*µmhos/cm

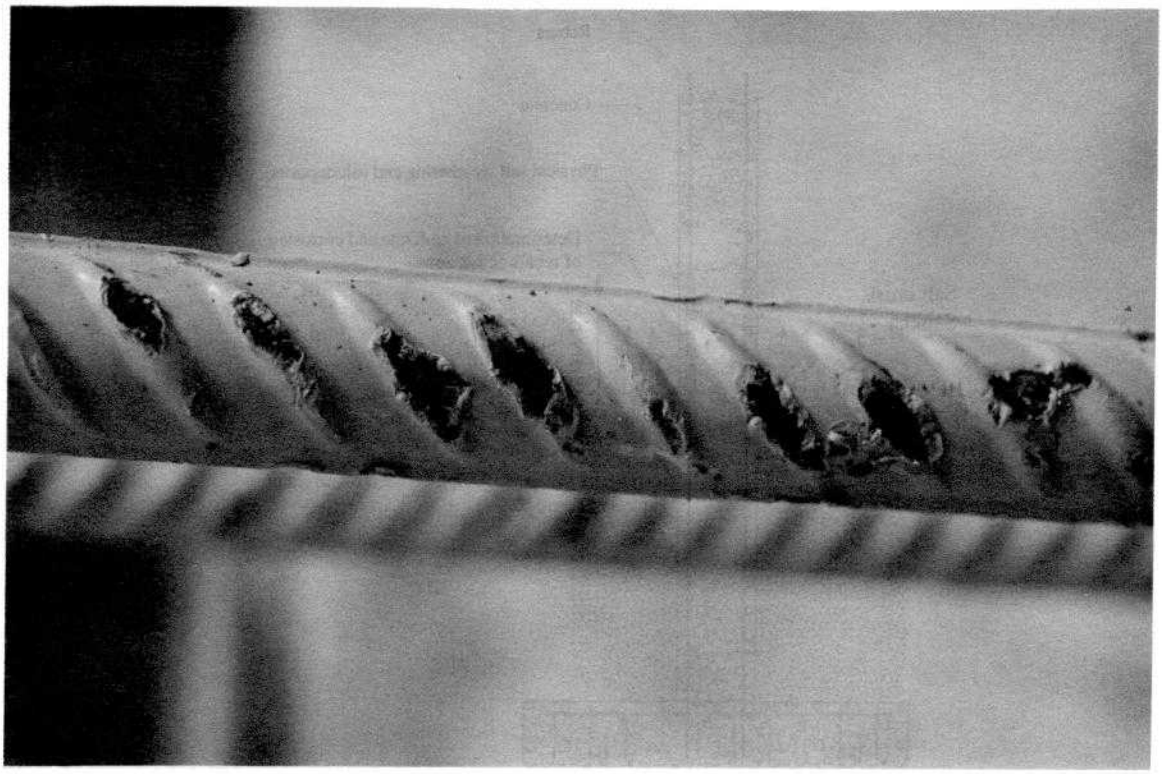


Fig. 9(a). Typical coating damages due to improper handling at job site

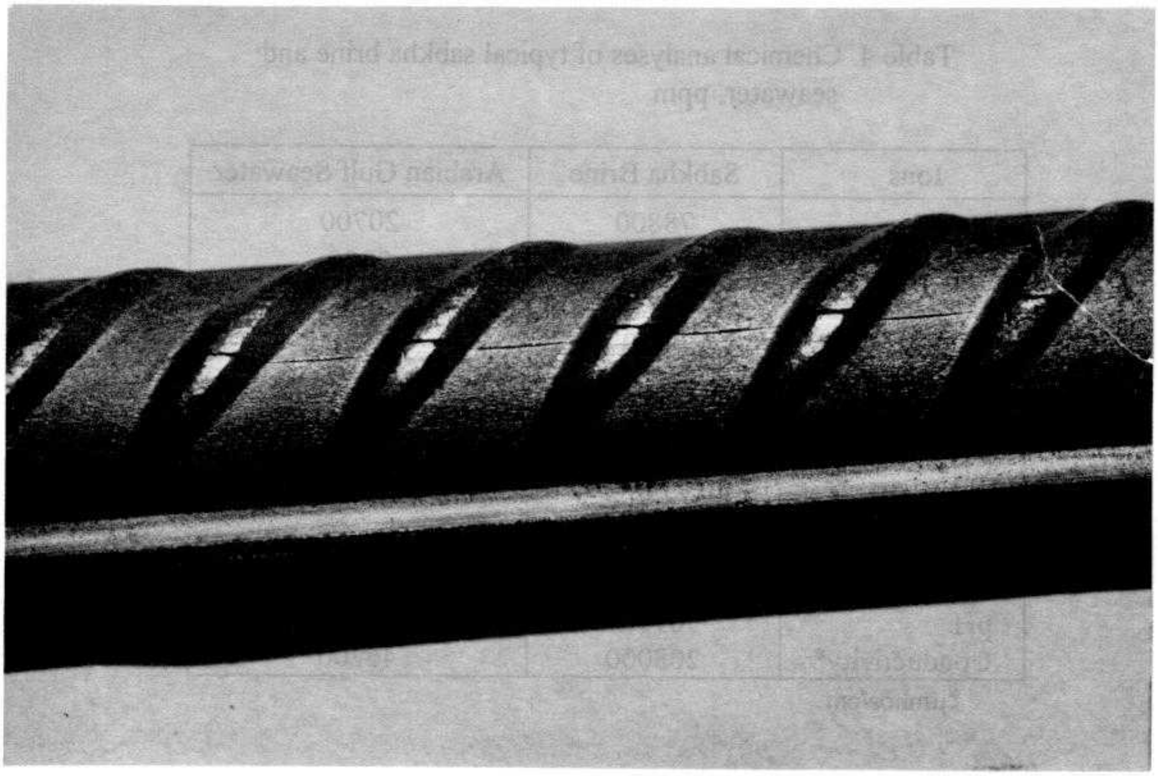


Fig. 9(b). Sharp edge and seem (crack) in rebars supplied for coating

1. Good quality FBECR with appropriate handling would provide satisfactory protection performance against corrosion of rebars if constructed with good quality concrete.

2. The level of moisture and temperature of the exposure conditions are key factors for the debondment of coating from the rebar surface.

3. Epoxy-coating powders shall be handled during transportation and storage without exposure to high temperature (above 30°C) for a time exceeding 2-3 hours. Long exposure affects the properties of powder and the quality of the coating thereafter.

4. Long time storage for reinforcement to be processed for coating should be avoided as they would develop surface rust in a relatively short period of time due to high humidity and temperature and it will be more difficult to achieve the high level of cleanness prior to coating.

5. The time between cleaning and coating should be minimized to avoid the development of flush rust at the cleaned steel surface.

6. Storage time at the construction site should be limited to reduce the FBECR exposure to sunlight, heat and humidity and the degradation of the coating and loss of flexibility and adhesion.

7. Repair of damaged coating by touch-up material should be done immediately in accordance with manufacturer's instruction for the touch-up materials. Damaged areas should be cleaned till rust is removed before touch-up material is applied for effective repair.

8. Plant fabrication is highly preferable as it is done according to standards with minimum damage to the coating.

9. Bending at site, if necessary, should be carried out by proper equipment and tools to minimize the damage in the coating.

10. Mix of uncoated and coated reinforcement should be avoided to reduce the possible macrocell action between the two types of reinforcement.

11. The need for high-quality concrete does not need to be emphasized as it is necessary to provide a protection for the FBECR from early corrosion.

12. Construction interruption should be minimized to avoid the long exposure of FBECR to weathering conditions and loss of its protection property.

13. Manufacturers of rebars should produce a more suitable product for coating with fewer sharp edges and seems.

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