Proceedings, Structural Faults and Repair Conference, Edinburgh, 10-12 June 2008.

CORROSION OF FUSION-BONDED EPOXY COATED BARS IN CHLORIDE-CONTAMINATED PLAIN AND SiLICA FUME CEMENT CONCRETES EXPOSED TO VARYING TEMPERATURE

By

A. S. **AI-Gahtani and M. Maslehuddin**

King Fahd University of Petroleum and Minerals
Dhahran, Saudi Arabia

Abstract

Fusion bonded epoxy coated (FBEC) bars are being utilized by the construction industry in several regions of the world to minimize corrosion damage to the reinforced concrete structures. While the use of FBEC bars in concrete is debated among the concrete technologists, contractors and owners are using them as one of the methods to enhance the useful service-life of reinforced concrete construction. Several studies have been conducted at King Fahd University of Petroleum and Minerals to develop methodologies for enhancing concrete durability under severe environmental conditions of the region. One of the studies has been to evaluate the usefulness of FBEC bars under local conditions, which are characterized by high chloride contamination in concrete and elevated environmental temperature. The effect of high chloride concentration and elevated temperature in conjunction with damage to the FBEC on the corrosion of the substrate metal was studied in plain and silica fume cement concretes. The corrosion current density on mild steel and damaged FBEC bars was noted to increase with an increase in temperature. The performance of FBEC bars in the silica fume cement concrete was better than that in the plain cement concrete at both normal and elevated temperatures. The long-term performance of FBEC bars was satisfactory at elevated temperatures in the silica fume cement concrete specimens even with up to 2% chloride, by weight of cement.

Keywords: Fusion-bonded epoxy coated steel bars, Plain and blended cement concretes, Reinforcement corrosion, Surface damage, Temperature.

INTRODUCTION

The reduction in the useful service-life of reinforced concrete construction is caused mostly due to corrosion of reinforcing steel. A variety of solutions have been proposed to protect the reinforcing steel from corrosion in order to minimize concrete deterioration. However, it is postulated that concrete reinforced by good quality fusion bonded epoxy coated (FBEC) steel bars perform better than that reinforced with galvanized steel or coated with surface coatings. [1,2]. Field observations indicate that FBEC gets damaged during handling operations as a result of lack of supervision and unskilled laborers at the construction sites [3]. Several investigators [4-9] have reported the beneficial effect of FBEC bars in extending the useful service-life of reinforced concrete structures. However, few studies [10-12] reported limitations of FBEC bars in marine structures and those serving in highly concentrated chloride environments. Erodogdu and Bremmer [10] conducted field and laboratory testing on coated bars with different levels of surface damage (0, 1 and 2%). The epoxy-coated bars removed from the slabs after one and two years of exposure exhibited no propensity to cause cracking and spalling and signs of reinforcement corrosion were not observed on the surface of concrete. Al-Amoudi et al. [13] conducted a study to evaluate the effect of holidays, surface damage and chloride contamination on corrosion of FBEC bars. They concluded that the surface damage is more deleterious to FBEC bars than the pinholes in terms of corrosion. No significant variation was observed in the corrosion current density on steel bars with the number of pinholes in the coating while it increased with an increase in the extent of surface damage. Similarly, the corrosion activity increased with an increase in the chloride concentration [13].

The reported research program was conducted to study the effect of coating damage on the corrosion-resistance of FBEC bars in chloride-contaminated (2%) plain and silica fume cement concrete specimens exposed to varying temperature.

EXPERIMENTAL PROGRAM

Preparation of Concrete Specimens

Deformed mild steel bars 20 mm in diameter, coated with FBEC of a thickness of 170 μm were used in the study. Although there is not enough information in the literature about the degree of surface damage, ASTM A775 [11] permits a maximum damage of 1% in each 0.3 m of the bar. Therefore, surface damages of 1.5% and 3% were selected to assess the influence of this parameter on corrosion of FBEC bars. The prescribed level of surface damage was achieved by manually removing the coating using a scriber. Crushed limestone, with a maximum size of 12.5 mm, bulk specific gravity of 2.43, and water absorption of 2.57% was used. Dune sand with a specific gravity of 2.64 and water absorption of 0.57% was used as fine aggregate. A coarse-to-fine aggregate ratio of 1.6 and effective water to cement ratio of 0.5 were kept invariant in all the concrete mixtures.

All the concrete mixtures were prepared with a cementitious material content of 370 kg/m^3. Silica fume cement concrete contained 7.5% silica fume by weight of the cementitious materials. All the specimens were contaminated with 2% chloride ions to accelerate reinforcement corrosion.

Thirty six reinforced concrete specimens, 75 mm in diameter and 150 mm high, were prepared from plain and silica cement concrete mixtures. The specimens were divided into three groups. These specimens were placed in 5% NaCl maintained at 25, 35 and 48 °C.

Monitoring Reinforcement Corrosion

Reinforcement corrosion was monitored by measuring corrosion potentials and corrosion current density (I_{corr}) at periodic intervals. Corrosion potentials were measured using a saturated calomel reference electrode (SCE) and an high impedance voltmeter. Corrosion potentials more negative than –270 mV SCE indicate more than 95% probability of reinforcement corrosion while a value more positive than –120 mV SCE indicates a 95% probability of no corrosion, while values between –270 and –120 mV SCE are not easily interpreted, and probability of reinforcement corrosion is uncertain. I_{corr} was measured using the linear polarization resistance method (LPRM). The polarization resistance was determined by conducting linear polarization scan in the range of ± 10 mV of the corrosion potential. A scan rate of 0.1 mV/s was used. The Ohmic drop between the steel bar and the reference electrode was compensated using a positive feed back technique.

Steel is considered to be in a passive state if I_{corr} is less than 0.1 $\mu A/cm^2$ [15]. Erdogdu and Bermner [10] suggest that for a long-term maintenance-free performance, I_{corr} should be less than 0.01$\mu A/cm^2$. In this study, an Icorr value of 0.3 $\mu A/cm^2$ is taken as a threshold value.

RESULTS

Corrosion Potentials

The time-corrosion potential curves for steel in plain and silica fume cement concrete specimens exposed to temperatures of 25 °C, 35 °C and 48 °C are shown in Figures 1 through 6. Figure 1 shows the corrosion potentials of steel in the plain cement concrete specimens exposed to a temperature of 25 °C. The corrosion potentials decrease, i.e., become more negative with time and the corrosion potentials on the uncoated steel bars are more negative than those on the FBEC steel bars.

Figure 2 shows the corrosion potentials on steel in the silica fume cement concrete specimens exposed to a temperature of 25 °C. The corrosion potentials were maximum (more positive) on the FBEC steel bars without any damage while those on the FBEC bars with 1.5% and 3% damage were marginally more positive than the uncoated steel bars.

Figure 3 shows the corrosion potentials on steel bars in plain cement concrete specimens exposed to a temperature of 35 °C. The potentials were low (less negative) on the uncoated steel bars while they were the highest (more positive) on the undamaged FBEC steel bars. The corrosion potentials on all the steel bars decreased with the time of exposure. The corrosion potentials on steel in the silica fume cement concrete specimens exposed to a temperature of 35 °C are shown in Figure 4. The potentials were more negative on the uncoated steel bars while they were more positive on the undamaged FBEC steel bars. The potentials on FBEC steel bars with

1.5% and 3% damage tended to be between potential values for uncoated and undamaged FBEC steel bars.

Figures 5 and 6 show the corrosion potentials on the uncoated and FBEC bars in the plain and silica fume concrete specimens exposed to a temperature of 48 °C. As expected, the corrosion potentials on the uncoated steel bars were more negative than those on the FBEC steel bars.

The corrosion potentials depicted in Figures 1 through 6 were utilized to assess the time to initiation of reinforcement corrosion according to ASTM C 876 criteria. These data are summarized in Table 1. The data in Table 1 indicate that the time to initiation of reinforcement corrosion was influenced by the exposure temperature, extent of surface damage and the cement type. The time to initiation of corrosion decreased with the extent of surface damage and increasing exposure temperature. Further, corrosion initiation was noted later in the silica fume cement concrete specimens compared to the plain cement concrete specimens.

Corrosion Current Density

The variation of corrosion current density, I_{corr}, with time on the uncoated and FBEC steel bars in the plain and silica fume cement concrete specimens exposed to 25, 35, and 48 °C temperature is depicted in Figures 7 through 12. The values at each age are the mean of measurements conducted on three similar specimens.

Figures 7 and 8 depict the I_{corr} values on steel in the plain and silica fume cement concrete specimens exposed to a temperature of 25 °C. The data in these figures show that the I_{corr} increases with time. The I_{corr} was generally less in the concrete specimens with FBEC steel bars.

Figure 9 shows the I_{corr} values on steel in plain cement concrete specimens exposed to a temperature of 35 °C. The I_{corr} was generally the least on FBEC steel bars with a value less than 0.1 $\mu A/cm^2$. The I_{corr} values on the uncoated bars was more than 0.3 $\mu A/cm^2$ from the initial period of exposure. The I_{corr} in all the specimens increased with the time of exposure. The I_{corr} on steel in the silica fume cement concrete specimens exposed to a temperature of 35 °C is depicted in Figure 10. The I_{corr} was the least in FBEC steel bars it was the maximum on the uncoated bars. The I_{corr} on FBEC steel bars with 1.5% and 3% damage tended to be between that of the uncoated and FBEC bars. In all the specimens, the I_{corr} value was less than 0.3 $\mu A/cm^2$ indicating better resistance to corrosion.

Figure 11 shows the I_{corr} values on steel in plain cement concrete specimens exposed to a temperature of 48 °C. As expected, the I_{corr} on the uncoated steel bars was more than that on the FBEC steel bars. The corrosion current density was more than 0.3 $\mu A/cm^2$ from initiation of exposure itself. The I_{corr} in the undamaged FBEC steel bars was less than 0.3 $\mu A/cm^2$. The I_{corr} on steel in the silica fume cement concrete specimens exposed to a temperature of 48 °C is shown in Figure 12. The trend of these data was similar to that noted on the specimens exposed to 35 °C. However, the I_{corr} in the specimens exposed to 48 °C was more than that in the specimens exposed to 35 °C.

CONCLUSIONS

The following conclusions could be drawn from the data developed in this study:

1. The time to initiation of corrosion decreased with increasing surface damage, and exposure temperature. Corrosion initiation was noted earlier in the plain cement concrete specimens than in the silica fume cement concrete specimens.

2. The data on the corrosion current density indicated very low corrosion in the concrete specimens prepared with undamaged FBEC steel bars. As expected, the I_{corr} values on the uncoated steel bars were very high. In these bars, the I_{corr} increased with increasing temperature. While the I_{corr} values in the undamaged FBEC bars were very low; they tended to increase with increasing surface damage, and exposure temperature.

3. The I_{corr} values on steel in the silica fume cement concrete specimens were less than in the plain cement concrete specimens, this trend was noted at all the exposure temperatures. This indicates that silica fume cement concrete should be used in the structures that are exposed to high temperature and excessive chloride contamination.

ACKNOWLEDGEMENT

The authors acknowledge the support provided by King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia.

REFERENCES

1. Malasheski, G. J., Maurer, D. A., Mellot, D. P. and Arellano, J. L., Bridge Deck Protective Systems, PENN DOT Research Project 85-17, 1986.

2. Pfeifer, D. W., Landgren, J. R. and Zoob, A., *Protective* Systems for New Prestressed and Substructure *Concrete*, FHWA Report No. RD-86/193, 1987.

3. Al-Gahtani A.S., "Environmental Consideration for the Use of Epoxy-Coated Rebars (FBECR) in the Gulf Region," Proceedings of the Symposium on performance of Concrete Structures in the Arabian Gulf Environment, KFUPM, Nov, 15-17, 1998, pp. 21-36.

4. Swamy RN, Koyama S. Epoxy coated rebars- the panacea for steel corrosion in concrete. Construction and Materials, 1989, pp. 86-91.

5. Satake J, Kawamura M, Shirakawa K, Mekami N, Swamy RN, Long-term corrosion of reinforcement in concrete construction. In: Crane AL, editor. The Society of Chemical Industry, London: Ellis Horwood, Chicchester, England, 1983, pp. 357-377.

6. Hedadahl P, Ramboll H, Manning DG. Field investigation of epoxy-coated reinforcing steel, Report No. MAT-89-02. The Research and Development Branch, Ontario Ministry of Transportation, December 1989.

7. Scanell WT, Clear KC. Long-term exposure evaluation of concrete slabs containing epoxy coated reinforcing steel, Paper No. 890431. Transportation Research Board 69th Annual Meeting, Washington, DC, January 1990.

8. Sohangpurwala AA, Clear KC. Effectiveness of epoxy coating in minimizing corrosion of reinforcing steel in concrete, Paper No. 890432. Transportation Research Board 69th Annual Meeting, Washington, DC, January 1990.

9. Macenzie M. The effect of defects on the durability of epoxy-coated reinforcement, Transportation Research Circular No. 403.National Research Council, Washington, DC, March 1993, pp.17-28.

10. Erdogdu S, Bremmer TW. Field and laboratory testing of epoxy coated reinforcing bars in concrete, Transportation Research Circular No.403. National Research Council, Washington, DC, March 1993, pp. 5-16.

11. American Society for Testing and Materials. Standard Specification for epoxy coated reinforcing bars, ASTM A 775/A 775M-04a, West Conshohocken, Pennsylvania, 2004.

12. American Society for Testing and Materials. Standard method for half-cell potentials of uncoated reinforcing steel in concrete, ASTM C 876, V.4.02, Philadelphia, 1991, pp. 437-442.

13. Al-Amoudi, O. S. B., Maslehuddin, M and Mohammed Ibrahim. Long term performance of Fusion-Bonded Epoxy-Coated Steel Bars in chloride-Contaminated Concrete, ACI Material Journal July-August 2004.

14. Lambert P, Page CL, Vassie PRW. Investigations of reinforcement corrosion, 2. Electrochemical monitoring of steel in chloride contaminated concrete. Mater Struct 1991, pp. 351-358.

15. Rodriguez P, Ramirez E, Gonzalez JA. Methods for studying corrosion in reinforced concrete. Mag Concr Res 1994, pp. 81-90.

Table 1: Time to initiation of reinforcement corrosion in the uncoated and FBEC steel bars in plain and silica fume cement concrete specimens exposed to varying temperature.

Surface damage, %	Plain cement concrete			Silica fume cement concrete		
	25 °C	35 °C	48 °C	25 °C	35 °C	48 °C
0%	-*	150	150	-*	250	240
1.5%	110	15	15	250	200	190
3%	55	15	15	190	140	130
Uncoated	25	Active	Active	140	50	40

* Corrosion activation was not noted.

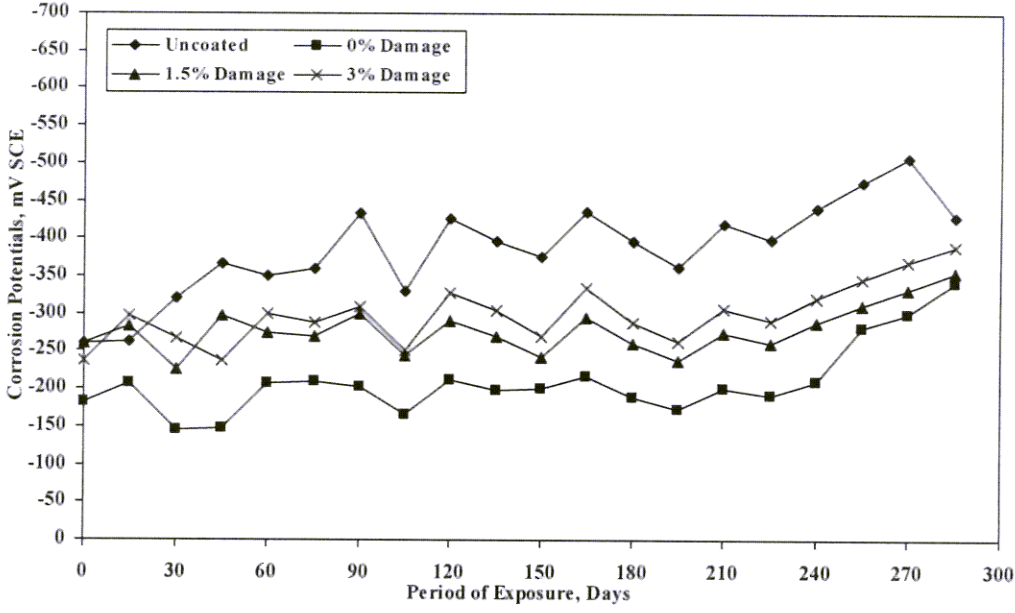

Fig. 1: Corrosion Potentials on uncoated and FBEC steel bars in Plain Cement Concrete Specimens (Exposure Temp: 25 °C).

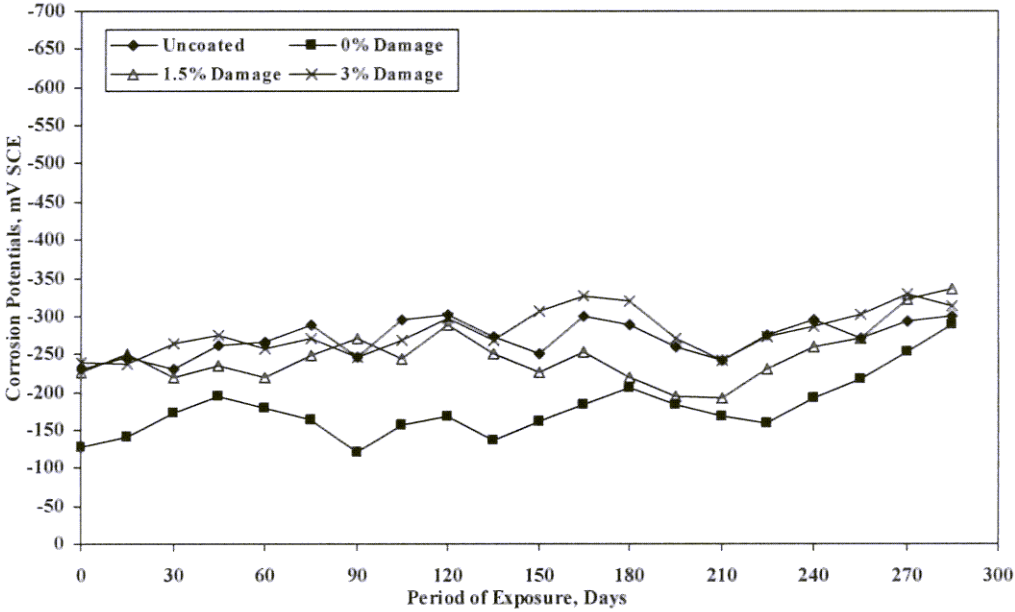

Fig. 2: Corrosion Potentials on uncoated and FBEC steel bars in the Silica Fume Cement Concrete Specimens (Exposure Temp: 25 °C).

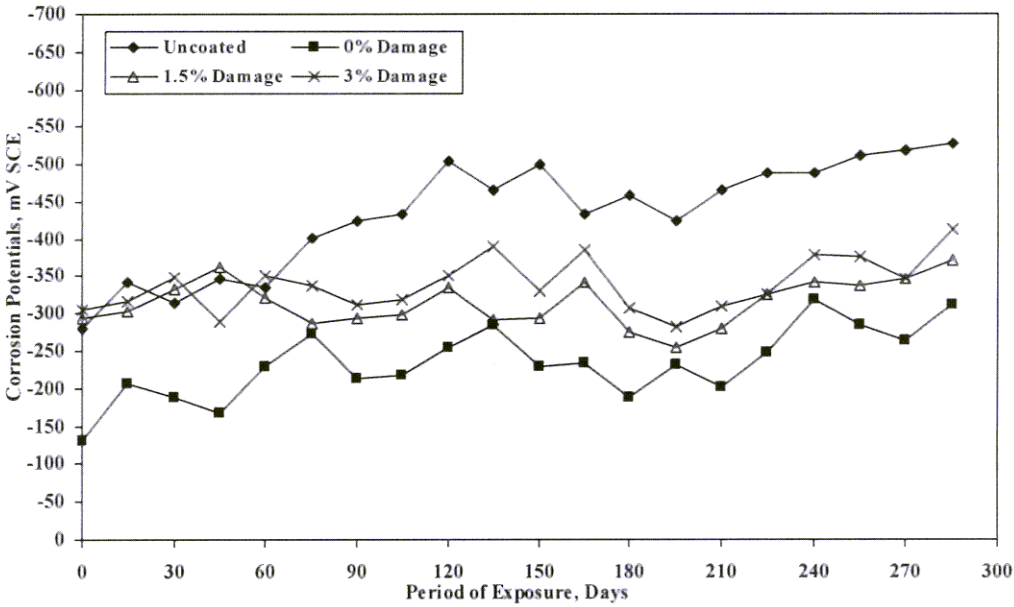

Fig. 3: Corrosion Potentials on uncoated and FBEC steel bars in the Plain Cement Concrete Specimens (Exposure Temp: 35 °C).

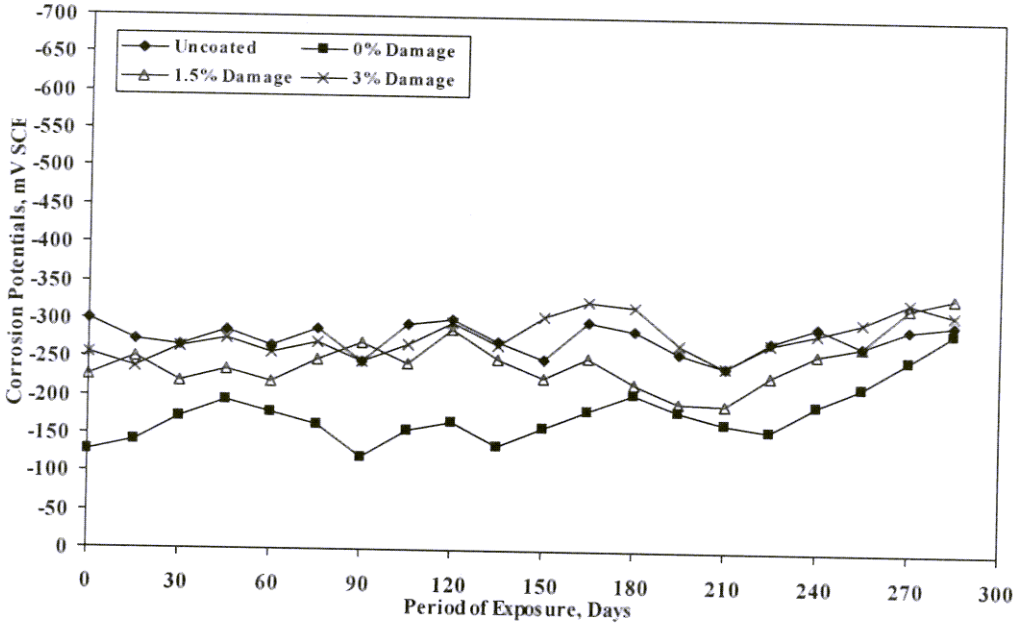

Fig. 4. Corrosion Potentials on Uncoated and FBEC steel bars in the Silica Fume Cement Concrete Specimens (Temp: 35 °C).

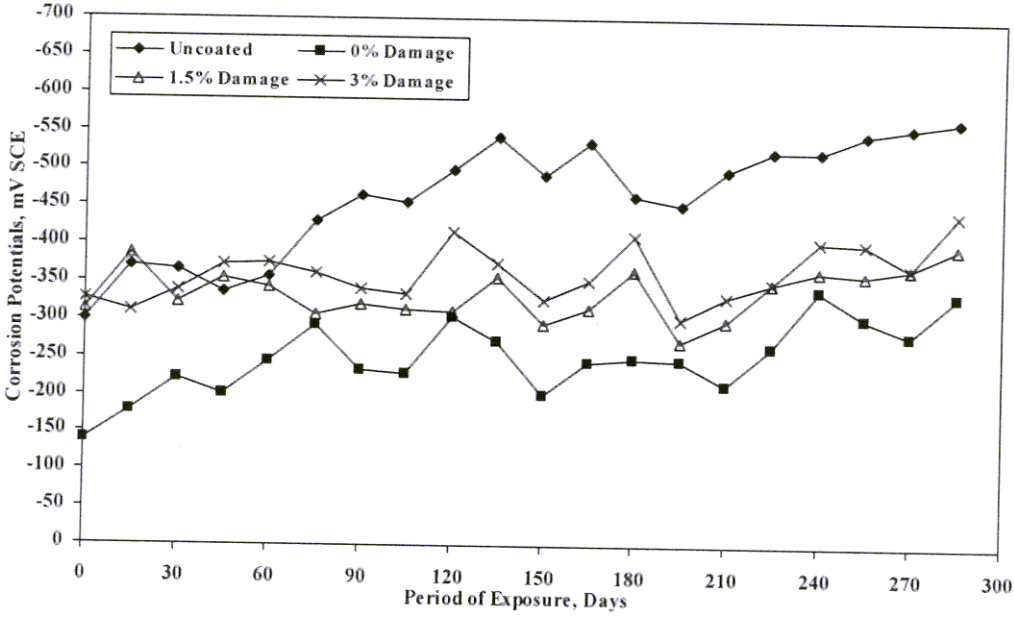

Fig. 5. Corrosion Potentials on Uncoated and FBEC steel bars in the Plain Cement Concrete Specimens (Temp: 48 °C).

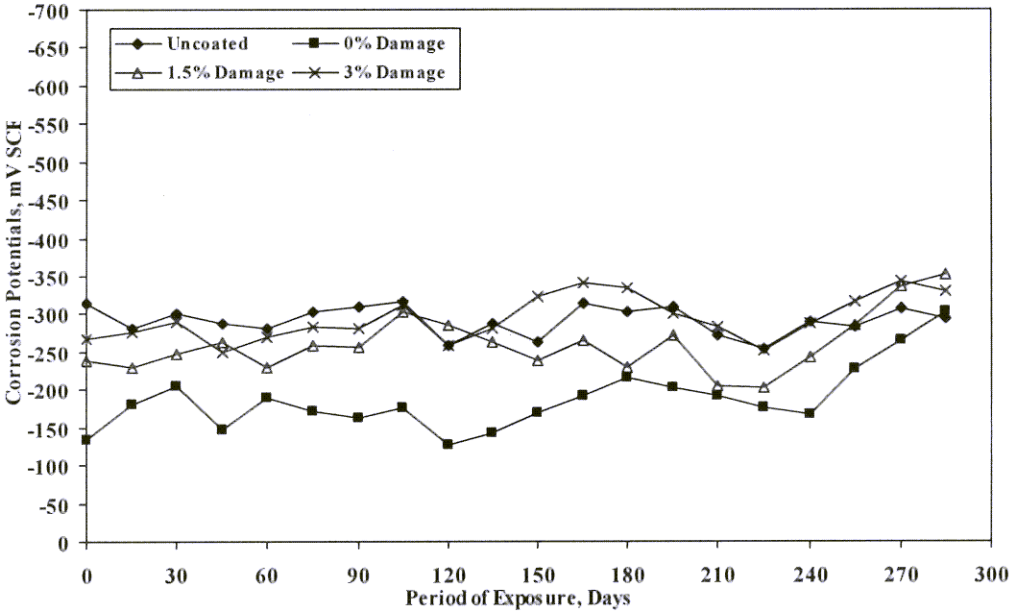

Figure 6: Corrosion Potentials on Uncoated and FBEC steel Bars in the Silica Fume Cement Concrete Specimens (Temp: 48°C).

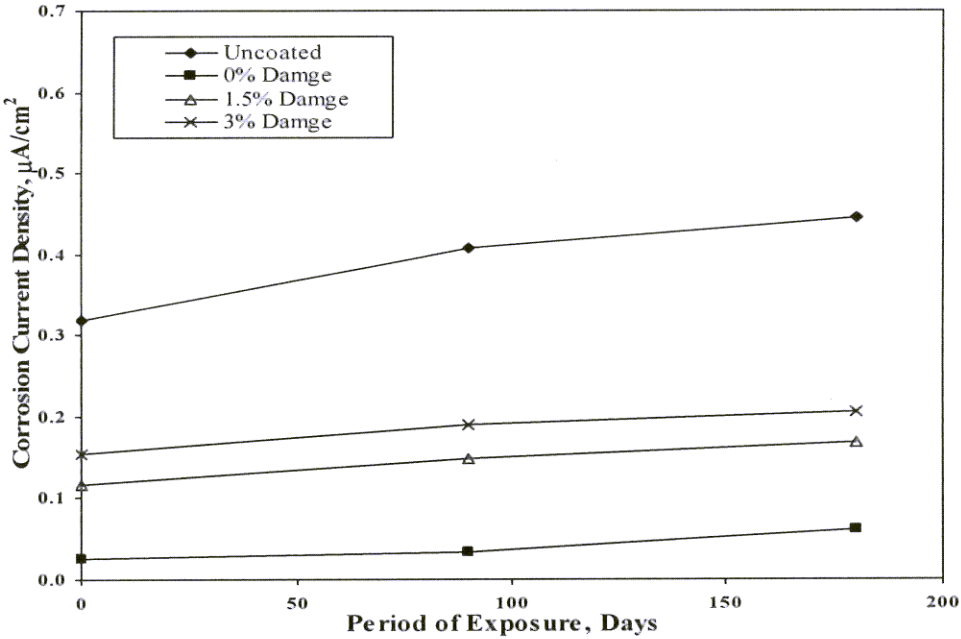

Figure 7: Corrosion Current Density on steel in the Plain Cement Concrete Specimens exposed to 25 °C.

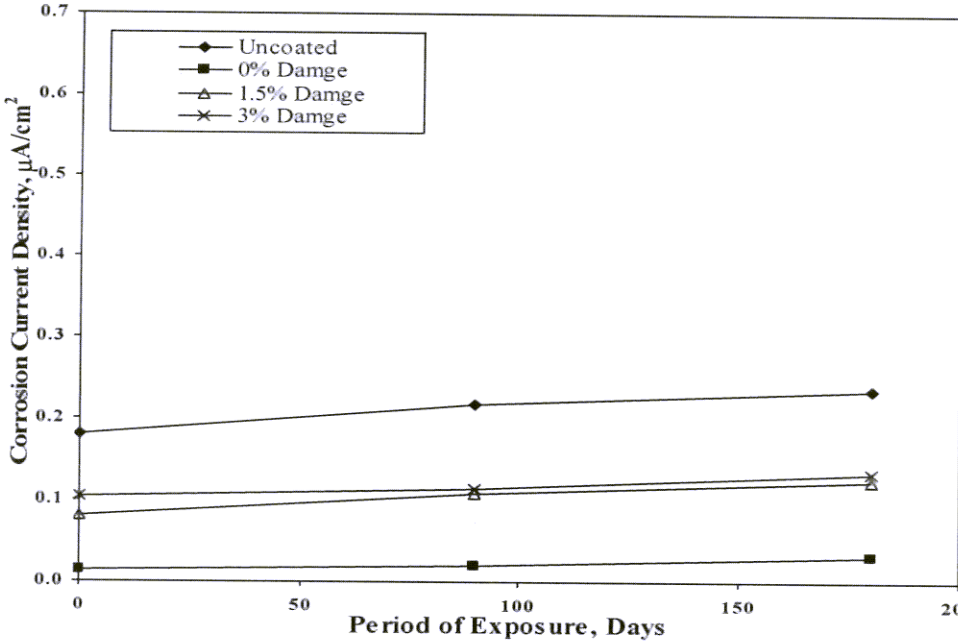

Figure 8: Corrosion Current Density on Steel in the Silica Fume-Cement Concrete Specimens exposed to 25 °C.

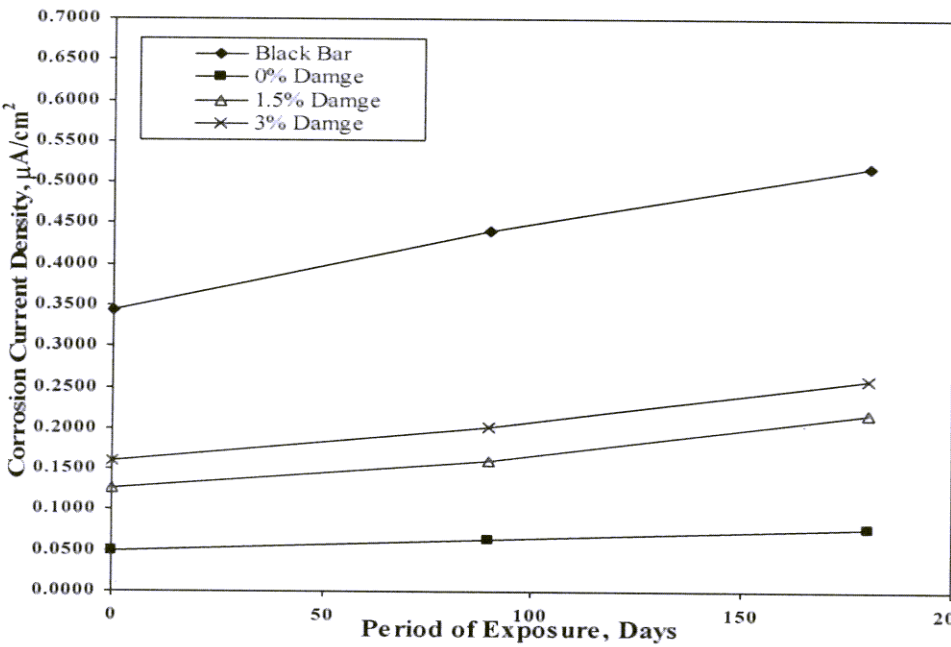

Figure 9: Corrosion Current Density on Steel in the Plain Cement Concrete Specimens exposed to 35 °C.

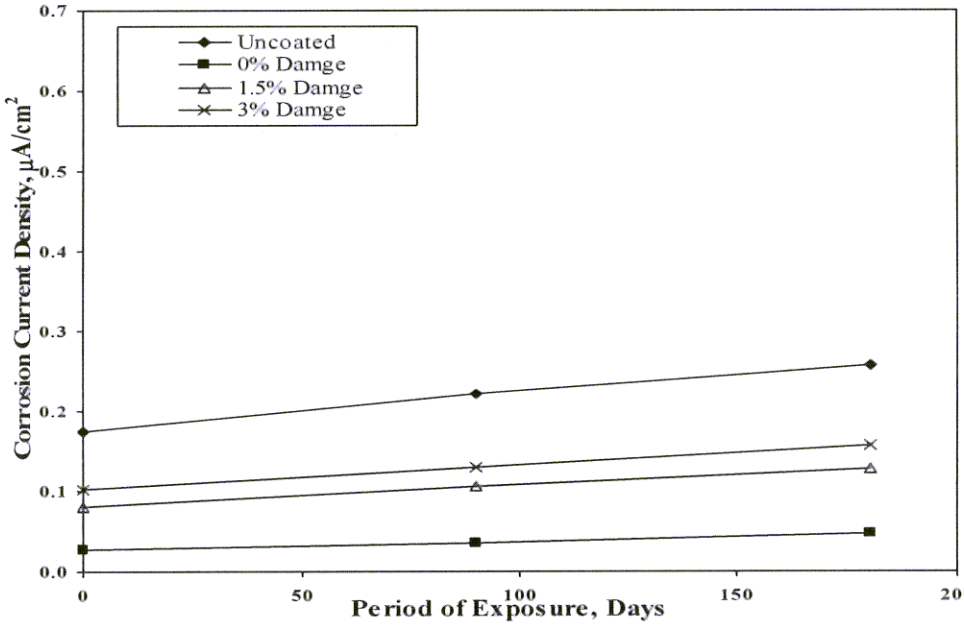

Figure 10: Corrosion Current Density on Steel in the Silica Fume Cement Concrete Specimens exposed to 35°C.

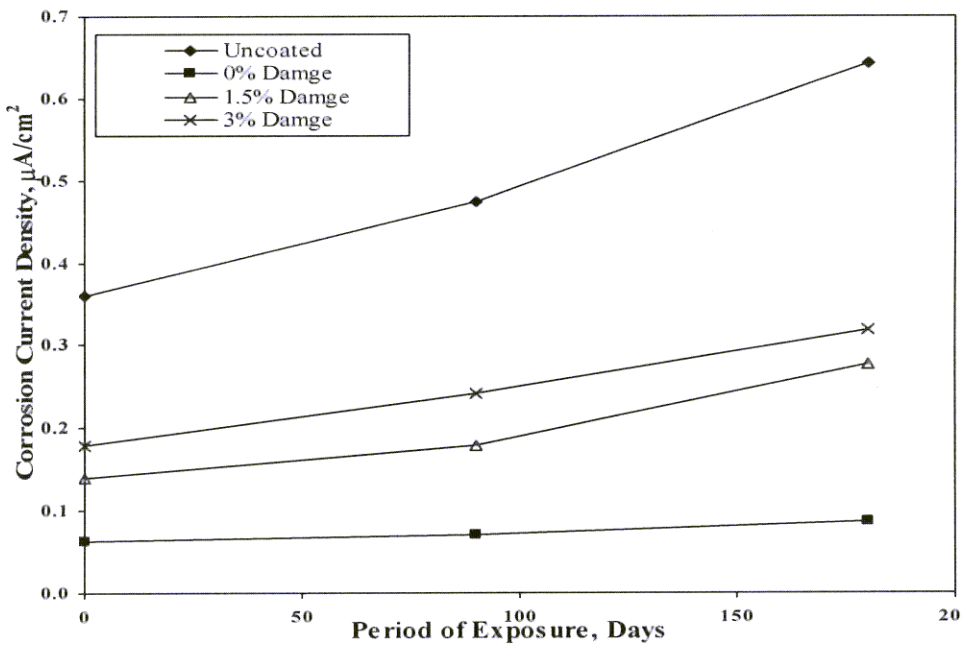

Figure 11: Corrosion Current Density on Steel in the Plain Cement Concrete Specimens exposed to 48 °C.

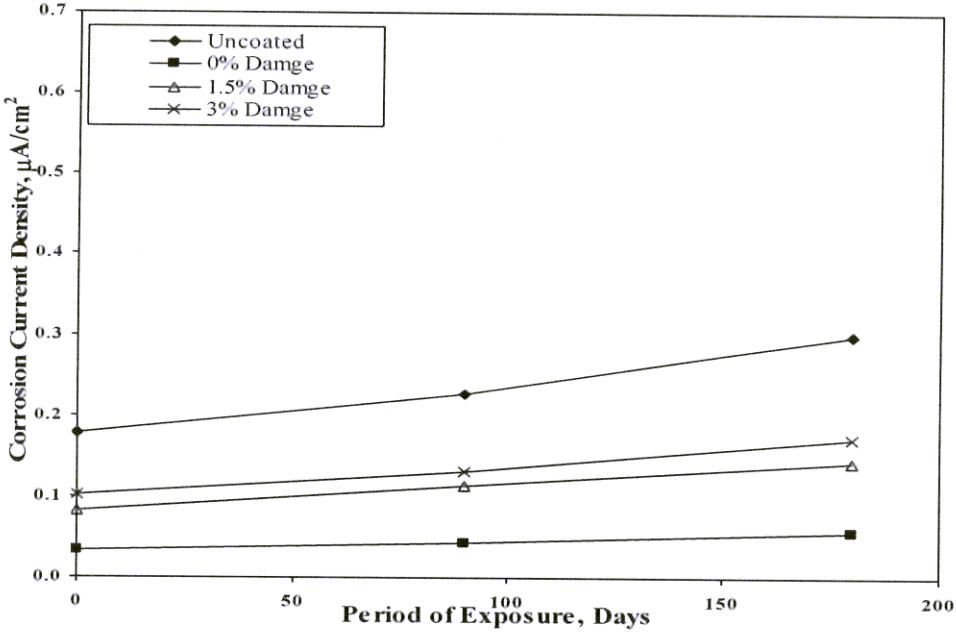

Figure 12: Corrosion Current Density on steel in the Silica Fume Cement Concrete Specimens exposed to 48 °C.