

Corrosion protection provided by chemical inhibitors to damaged FBEC bars

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ABSTRACT

This paper presents the results of a study conducted to evaluate the corrosion protection provided by chemical inhibitors to the fusion bonded epoxy coated (FBEC) steel bars with surface damage. FBEC bars with 0%, 1%, 2%, or 4% damage to the coating were utilized to prepare concrete specimens contaminated with 0%, 0.4%, 1%, and 2% chloride by weight of cement. Three proprietary inhibitors and one generic inhibitor, calcium nitrate, were selected to assess their performance in decreasing the rate of reinforcement corrosion of the FBEC bars with coating damage. The data developed in this study indicate that reinforcement corrosion increases with the extent of chloride contamination and the degree of damage to the coating. Further, the incorporation of chemical inhibitors was generally beneficial in decreasing the corrosion of FBEC bars. However, one of the organic-based proprietary inhibitor performed much better than the other proprietary inhibitors and calcium nitrate.

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1. Introduction

Concrete deterioration, due to corrosion of reinforcing steel, is now very well documented. Such a phenomenon has been noted in several parts of the world. Structures exposed to marine environment, bridge decks, and those serving in hot and arid regions are particularly prone to accelerated deterioration due to reinforcement corrosion. Deterioration of the highway structures in Europe and North America is attributed to the use of deicer salts. Reinforcement corrosion is also observed in marine structures.

One or more of the preventive measures that are generally utilized to minimize reinforcement corrosion are: (i) production of dense and impermeable concrete, (ii) utilization of appropriate design and construction practices, (iii) application of hydrophobic agents or surface coatings on concrete, and (iv) protection of steel through metallic/non-metallic coatings or the use of chemical inhibitors [1]. Two of the protective measures, namely the use of FBEC bars or chemical inhibitors are commonly utilized these days. However, there are concerns regarding the effect of damage to the FBEC on corrosion of coated bars. As such, there is a gradual shift towards the use of FBEC bars in conjunction with chemical inhibitors.

Since the primary purpose of FBEC is to protect the substrate steel from corrosion, its performance is of major concern when it is damaged. Damaged coating may accelerate localized corrosion that may lead to severe pitting. Several studies have been

published reporting the positive or negative aspects of the FBEC bars with damage or pin holes. In view of this controversy, the possibility of utilizing chemical inhibitors with FBEC bars was investigated.

Corrosion inhibitors can be divided into three types, namely anodic, cathodic and mixed, depending on whether they interfere with the corrosion reaction preferentially at the anodic or cathodic sites or whether both are involved [1]. Anodic corrosion inhibitors function due to their ability to accept electrons. The mechanism involves oxidizing the dissolving ferrous oxide to form a protective film of hydrated ferric oxide on the steel surface. The commonly used anodic corrosion inhibitors are calcium and sodium nitrite, sodium benzoate, and sodium chromate. Other chemicals which have shown promise are sodium salts of silicates and phosphates, stannous chloride, and hydrazine hydrate [1]. One of the serious draw backs in the use of anodic inhibitors is that they are effective in maintaining passivity only if they are present in sufficiently high concentrations. If inadequate quantities are used or if the ratio of inhibitor to the chloride ions is small, corrosion becomes intensely localized and the attack is significant. Sodium benzoate behaves differently, in that general corrosion, rather than localized corrosion, occurs if low levels of inhibitor additions are used [1]. On the other hand, sodium nitrite suffers two disadvantages; one pertinent to the reduction in strength [2,3] and the other being the risk of the alkali-aggregate reaction which may be aggravated by the addition of alkaline salts [4].

Cathodic inhibitors act either by slowing the cathodic reaction or by selectively precipitating at the cathodic sites. Materials in this group are strong proton acceptors and their action, in contrast

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to anodic inhibitors, is usually indirect. Some of the commonly used cathodic inhibitors are bases, such as NaOH, Na₂CO₃, or NH₄OH, which increase the pH of concrete and thereby the solubility of the ferrous ions. Cathodic inhibitors consisting mainly of aniline and its chloroalkyl- and nitro-substituted forms, as well as the amino-ethanol group are used at 1–2% dosage levels by cement weight in the presence of 1–2% CaCl₂ [1].

Mixed inhibitors may simultaneously affect both the anodic and cathodic processes. A mixed inhibitor is usually more desirable because its effect covers corrosion resulting from chloride attack as well as that due to microcell on the metal surfaces. Mixed inhibitors contain molecules in which the electron density distribution causes the inhibitor to be attracted to both the anodic and cathodic sites. The molecules may have more than one orienting group attached. These types of inhibitors are typically organic compounds (e.g., amines, AMAs, fatty acids, etc.). Gaidis [5] has reviewed the chemistry of corrosion inhibitors. He has discussed the chemical reactions of the corrosion process in concrete and the role of most commonly used inhibitors in inhibiting corrosion.

Several studies have been conducted to evaluate the effectiveness of chemical inhibitors in minimizing reinforcement corrosion [6–10]. These studies have shown encouraging results regarding the performance of chemical inhibitors in decreasing the rate of corrosion of uncoated bars. However, there has been no study to evaluate their effectiveness in decreasing the rate of reinforcement corrosion in FBEC bars with surface damage.

2. Methodology of research

2.1. Materials

FBEC steel bars of 12 mm diameter with a uniform coating thickness of 160 μm were obtained from a local applicator. The epoxy coating was scratched with an electric scriber to obtain a damage of 1%, 2%, or 4% of the surface area per foot length of the bar.

The following four inhibitors were selected for studying their effectiveness in inhibiting corrosion of FBEC bars with damage:

- i. Proprietary corrosion inhibitor (P1). This is an organic inhibitor designed to be added to the concrete during mixing.
- ii. Proprietary corrosion inhibitor (P2). This is a nitrite-based inhibitor designed to be added to the concrete during mixing.
- iii. Proprietary corrosion inhibitor (P3). This is an amino alcohol-base aqueous liquid. It is designed to be applied to the external surface of concrete.
- iv. Calcium nitrate, a generic corrosion inhibitor.

2.2. Preparation of concrete specimens

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, reinforced with a 12 mm diameter steel bar were prepared using Type I cement plus silica fume, crushed limestone aggregate and dune sand. The concrete mixtures were prepared with cement content of 344 kg/m³, silica fume content of 26 kg/m³ and water to cementitious materials (Type I cement plus silica fume) ratio of 0.40. Suitable dosage of a plasticizer was added to the concrete to obtain a slump of 75–100 mm.

Several batches of concrete specimens were prepared to accommodate the variation in the salt content and corrosion inhibitor. Proprietary inhibitor P1 was added at a dosage of 5 L/m³ of concrete while 10 L of P2 was added to one cubic meter of concrete. Calcium nitrate was added at a dosage of 4% by weight of cement.

Immediately after casting, the concrete specimens were covered with plastic sheet for 24 h. They were then demolded, covered with wet burlap and cured for 21 days. The burlap was kept wet by spraying water from time to time. After this curing, one batch of concrete specimens was thoroughly cleaned of dust and lance and coated externally with two coats of inhibitor (P3).

2.3. Monitoring

The concrete specimens were wetted for 30 min twice a week and allowed to dry. This allowed the corrosion to proceed at a more rapid rate since both oxygen and moisture are available for the electrochemical reactions. The corrosion potentials were measured every month. They were measured using a copper–copper sulfate reference electrode (CSE) and a high impedance Voltmeter. The positive terminal of the Voltmeter was connected to the steel bar and its negative terminal was

connected to the reference electrode. The contact between the reference electrode and the concrete surface was made through a soft absorbent paper wetted with distilled water. The corrosion potentials were measured at three locations each on the two opposite faces of the cylindrical concrete specimen, thus generating six readings on each specimen. Triplicate specimens were used. The 18 corrosion potential readings were averaged to obtain the mean reading.

The corrosion current density (I_{corr}) on steel was evaluated by the linear polarization resistance method (LPRM). A stainless steel plate was used as a counter electrode. The steel bar and stainless steel plate were connected to a potentiostat/galvanostat. The polarization resistance (R_p) was determined by conducting a linear polarization scan in the range of +10 mV of the corrosion potential. A scan rate of 0.1 mV/s was used. The I_{corr} was determined using the Stern and Geary formula [11] given below:

$$I_{\text{corr}} = B/R_p$$

where I_{corr} = Corrosion current density, μA/cm²; R_p = Polarization resistance, Ω cm²; and $B = (\beta_a * \beta_c)/2.3(\beta_a + \beta_c)$, β_a and β_c are the anodic and cathodic Tafel constants, respectively.

For steel in aqueous media, a value of 100 mV is often used for both β_a and β_c . However, in the absence of sufficient data on β_a and β_c for steel in concrete, a value of B equal to 52 mV for steel in a passive condition and equal to 26 mV for steel in an active condition are normally used. Lambert et al. [12] and Al-Amoudi et al. [13] have found a good correlation between the corrosion current density determined using the LPRM and gravimetric weight loss techniques by adopting a value of 120 mV for both anodic and cathodic Tafel constants. Since resistivity is a major concern with concrete and in particular with FBEC bars, AC impedance technique is preferred over LPRM. However, a potentiostat/galvanostat with IR compensation may be used for the LPR measurements. This equipment uses the current interrupt technique to compensate for the IR drop between the steel bar and the reference electrode. Al-Amoudi et al. [13] have reported a good correlation between the corrosion rates measured by the LPRM and gravimetric weight loss technique for FBEC bars.

After more than two years of exposure to the wet-dry cycles, the reinforcing steel bars were retrieved by splitting the concrete specimens and they were examined visually to assess the extent of corrosion of the metal substrate and the condition of the coating.

3. Results

3.1. Visual observations

The extent of corrosion noted on steel bars exposed to alternate wetting and drying is summarized in Table 1. Corrosion was not noted on any of the undamaged FBEC steel bars in specimens with chloride contamination of as much as 2%.

In the concrete specimens prepared with FBEC bars with 1% surface damage and 2% chloride, corrosion could be noted at the damaged area in the concrete specimens prepared without any inhibitors. In the concrete specimens with inhibitors, negligible corrosion was noted in the specimens with inhibitor P1 while it was minor to moderate in the specimens with other inhibitors.

In the concrete specimens prepared with FBEC bars with 2% surface damage and a chloride contamination of 2%, corrosion could be noted on the steel bars in the specimens prepared without inhibitor and those incorporating calcium nitrate inhibitor. Corrosion was not noted on the steel bars in the concrete specimens incorporating P1 and P2 inhibitors while minor rust stains were noted on steel bars in the concrete specimens coated with P3 inhibitor.

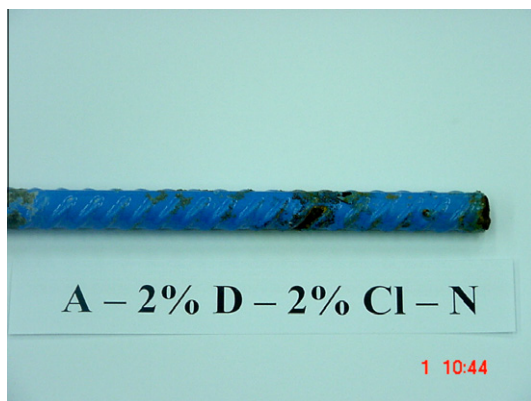
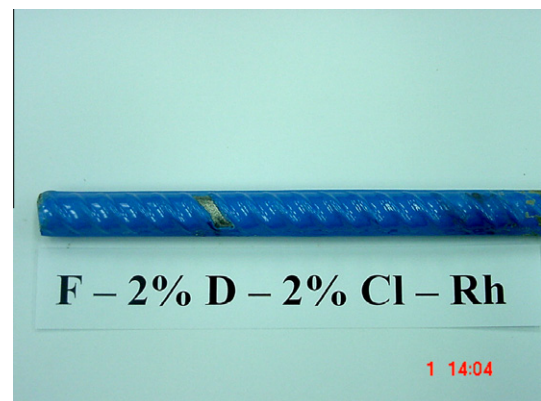
Rust spots were noted on all the steel bars in the concrete specimens prepared with FBEC bars with 4% surface damage and 2% chloride contamination. However, the extent of corrosion in the concrete specimens without inhibitor was more than that in the specimens with inhibitors. Further, the extent of corrosion in the concrete specimens with inhibitor P1 was less than that in the specimens with other inhibitors.

Figs. 1–5 show some of the bars extracted from the specimens with 2% chloride contamination and 2% surface damage to the bar.

Table 1

Condition of steel bars in the concrete specimens contaminated with 2% chloride and exposed to alternate wetting and drying.

Bar type	Inhibitor	Bar condition
Coated 0% damage	No inhibitor	Negligible corrosion at few spots
Coated 0% damage	P1	No corrosion
Coated 0% damage	P2	No corrosion
Coated 0% damage	P3	No corrosion
Coated 0% damage	Calcium nitrate	No corrosion
Coated 1% damage	No inhibitor	Moderate corrosion over all of the damage area; as well as few pop-outs in undamaged area of the bar. Deposit of corrosion product in 80% of the damage area. No damage to the bar
Coated 1% damage	P1	Negligible corrosion in damaged area. Deposit of corrosion product in 10% of the damage area. No damage to the bar
Coated 1% damage	P2	Minor corrosion in damaged area. Deposit of corrosion product seen in 25% of the damage area. No damage to the bar
Coated 1% damage	P3	Moderate corrosion over all of the damage area and pop-outs in 1–2 places in undamaged area of the bar. Deposit of corrosion product in 80% of the damage area. No damage to the bar
Coated 1% damage	Calcium nitrate	Moderate corrosion noticed over all of the damage area. Deposit of corrosion product seen in all of the damage area. No damage to the bar
Coated 2% damage	No inhibitor	Minor corrosion noticed over all of the damage area. Deposit of corrosion product seen in the damage area. No damage to the bar
Coated 2% damage	P1	No corrosion. No sign of corrosion product. No damage to the bar and the bar retains its shiny surface
Coated 2% damage	P2	No corrosion except at 1–2 spots in damaged area. No damage to the bar
Coated 2% damage	P3	Moderate corrosion over all of the damage area and pop-outs in 1–2 places in undamaged area of the bar. Deposit of corrosion product in 80% of the damage area. No damage to the bar
Coated 2% damage	Calcium nitrate	Moderate corrosion over all of the damage area. Deposit of corrosion product in the damage area. No damage to the bar
Coated 4% damage	No inhibitor	Moderate corrosion over all of the damage area. Deposit of corrosion product in the damage area. No damage to the bar
Coated 4% damage	P1	Minor corrosion over all of the damage area. Deposit of corrosion product in the damage area. No damage to the bar
Coated 4% damage	P2	Major corrosion over all of the damage area and at 1–2 spots in undamaged area. Deposit of corrosion product in the damage area. About 40% damage to the bar in damage area
Coated 4% damage	P3	Minor corrosion over all of the damage area. Deposit of corrosion product in the damage area. No damage to the bar
Coated 4% damage	Calcium nitrate	Moderate corrosion over all of the damage area. Deposit of corrosion product in the damage area. No damage to the bar

**Fig. 1.** FBEC steel bar with 2% damage extracted from the concrete specimen contaminated with 2% chloride and no inhibitor.**Fig. 2.** FBEC steel bar with 2% damage extracted from the concrete specimen contaminated with 2% chloride and incorporating P1 inhibitor.

3.2. Corrosion potentials

The corrosion potentials on steel bars in the concrete specimens contaminated with 0.4% chloride and not incorporating any inhibitor are depicted in Fig. 6. The corrosion potentials on FBEC bars (both with and without damage) were in the passive range, except on those with 4% damage. In these specimens, corrosion activation was noted after about 750 days. Fig. 7 shows the corrosion potentials on steel bars with 1% chloride. Active corrosion was noted on

the FBEC steel bars with surface damage while it was passive in the specimens with undamaged FBEC bars. The corrosion potentials on steel bars with 2% chloride contamination in the concrete and without any inhibitor are depicted in Fig. 8. Active corrosion was indicated in all the bars from the beginning, except the undamaged bars. Corrosion activation was noted in these bars after about 550 days.

The corrosion potentials on steel in the concrete specimens with 0.4% chloride contamination and incorporating calcium ni-

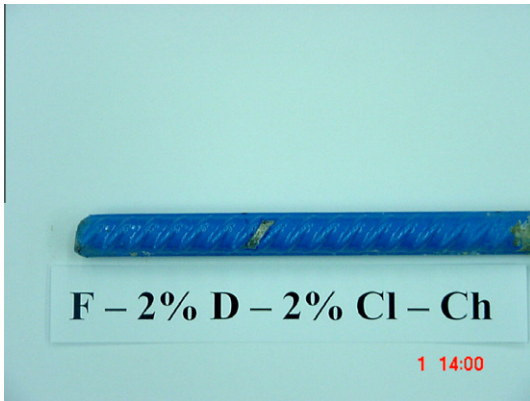


Fig. 3. FBEC steel bar with 2% damage extracted from the concrete specimen contaminated with 2% chloride and incorporating P2 inhibitor.

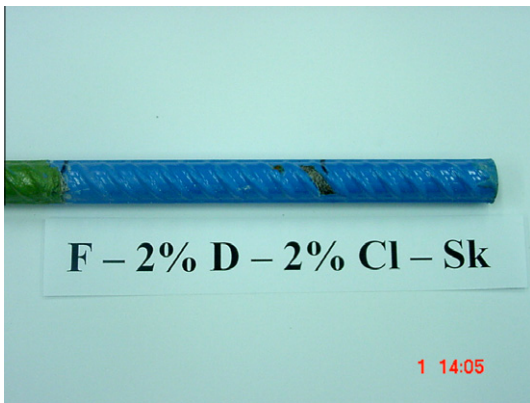


Fig. 4. FBEC steel bar with 2% damage extracted from the concrete specimen contaminated with 2% chloride and coated with P3 inhibitor.

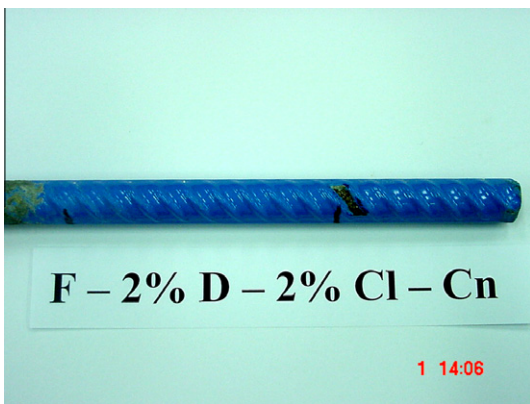


Fig. 5. FBEC steel bar with 2% damage extracted from the concrete specimen contaminated with 2% chloride and incorporating calcium nitrate inhibitor.

trate inhibitor are plotted against time of exposure in Fig. 9. The potentials were in a passive range on the bars with 0% and 1% damage while corrosion activation was noted after about 700 days in the concrete specimens with 3% and 4% damage. Corrosion activation was noted after about 675 days on the damaged steel bars in the concrete specimens with 1% chloride contamination, as shown in Fig. 10. Fig. 11 depicts the corrosion potentials on steel in the concrete specimens with 2% chloride contamination and calcium nitrate inhibitor. Active reinforcement corrosion was noted from the beginning on the steel bars with 2% and 4% damage. Corrosion

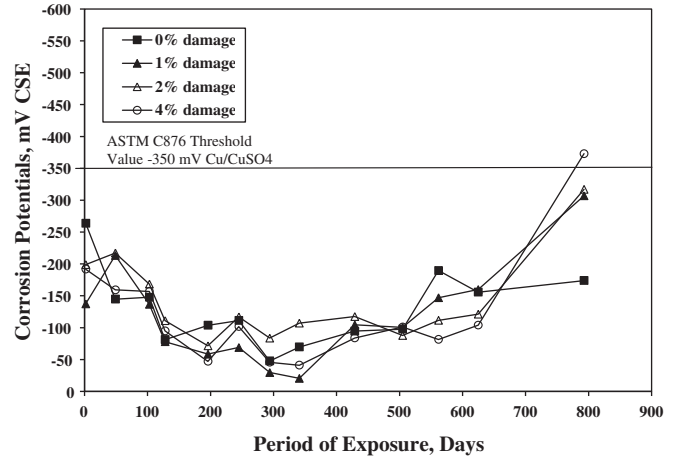


Fig. 6. Corrosion potentials on steel in 0.4% chloride-contaminated concrete without inhibitor.

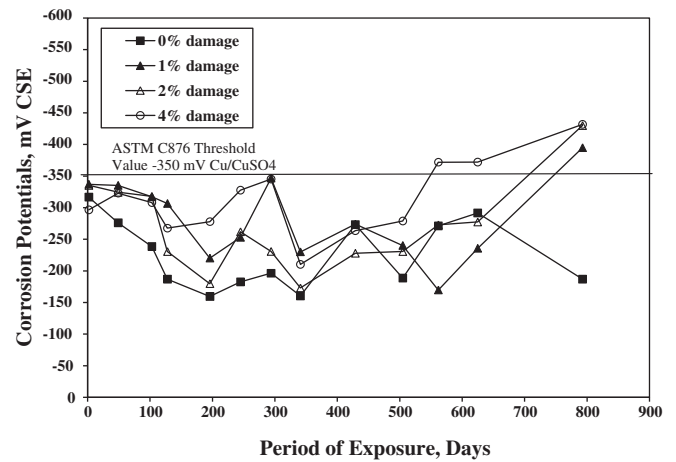


Fig. 7. Corrosion potentials on steel in 1% chloride-contaminated concrete without inhibitor.

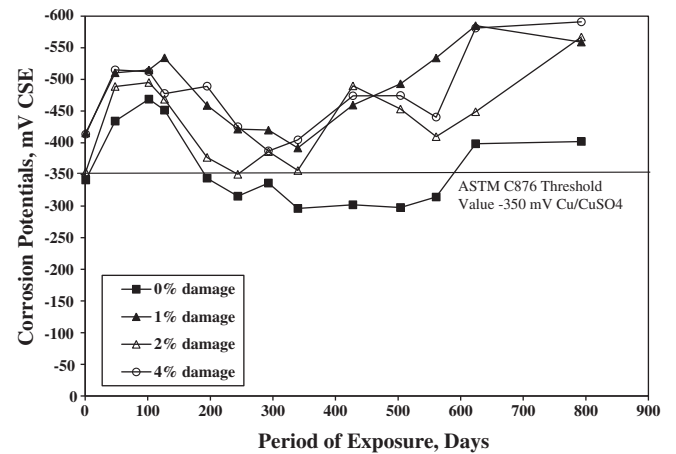


Fig. 8. Corrosion potentials on steel in 2% chloride-contaminated concrete without inhibitor.

initiation was noted after about 650–700 days on the bars with 0% and 1% damage.

The corrosion potentials on the steel bars in the concrete specimens with 0.4% chloride and incorporating inhibitor P1 are de-

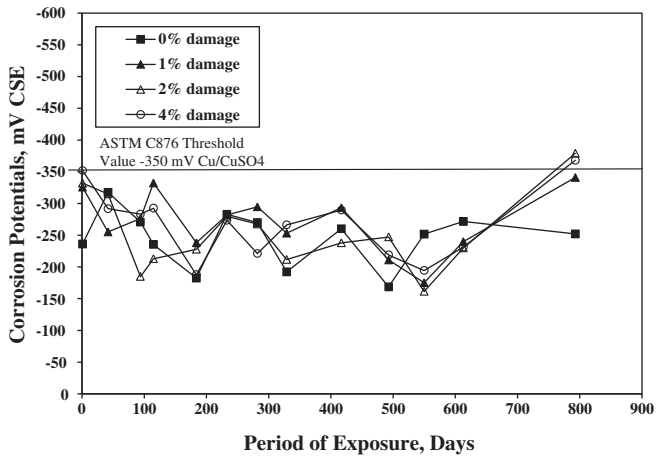


Fig. 9. Corrosion potentials on steel in 0.4% chloride-contaminated concrete with calcium nitrate inhibitor.

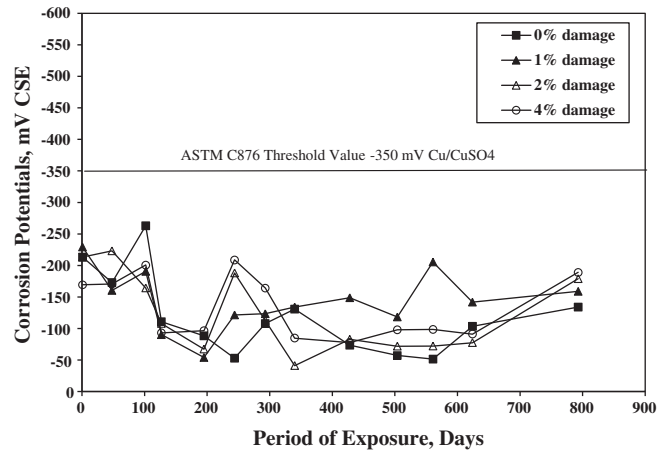


Fig. 12. Corrosion potentials on steel in 0.4% chloride-contaminated concrete with P1 inhibitor.

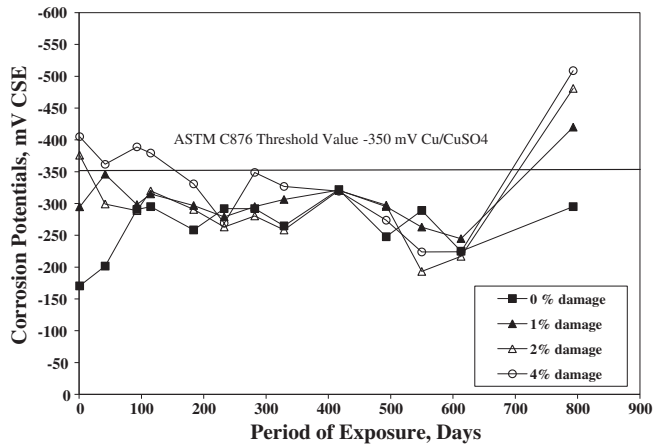


Fig. 10. Corrosion potentials on steel in 1% chloride-contaminated concrete with calcium nitrate inhibitor.

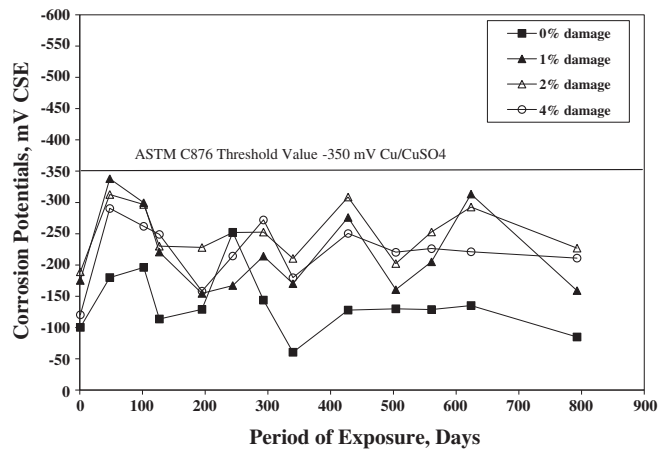


Fig. 13. Corrosion potentials on steel in 1% chloride-contaminated concrete with P1 inhibitor.

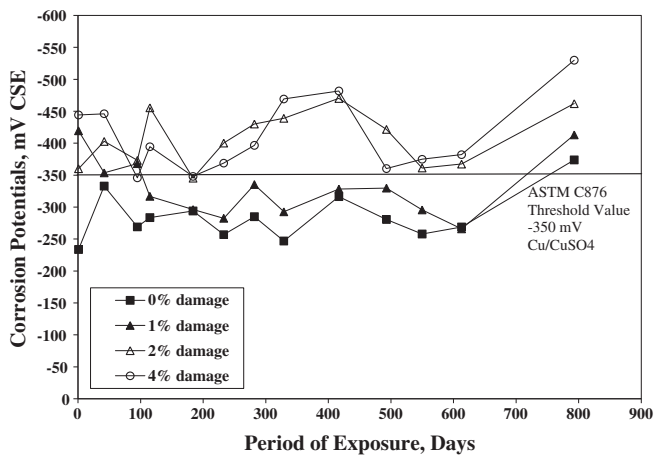


Fig. 11. Corrosion potentials on steel in 2% chloride-contaminated concrete with calcium nitrate inhibitor.

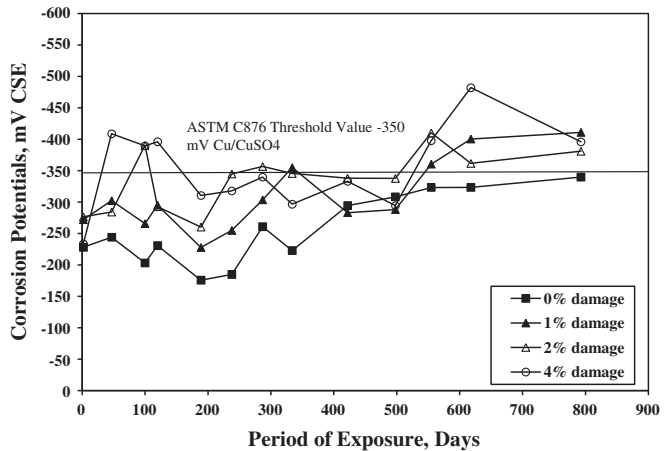


Fig. 14. Corrosion potentials on steel in 2% chloride-contaminated concrete with P1 inhibitor.

pictured in Fig. 12. Passive corrosion was indicated on all the steel bars even after 800 days. A similar trend was noted in the concrete specimens contaminated with 1% chloride, as shown in Fig. 13. Fig. 14 depicts the corrosion potentials on steel bars in the concrete specimens with 2% chloride. Active corrosion was noted only on the FBEC steel bars with surface damage.

The corrosion potentials on steel bars in the concrete specimens incorporating P2 inhibitor and 0.4% chloride are depicted in Fig. 15. Passive corrosion was noted on all the FBEC bars. Active corrosion was noted only on the FBEC steel bars with damage in the concrete

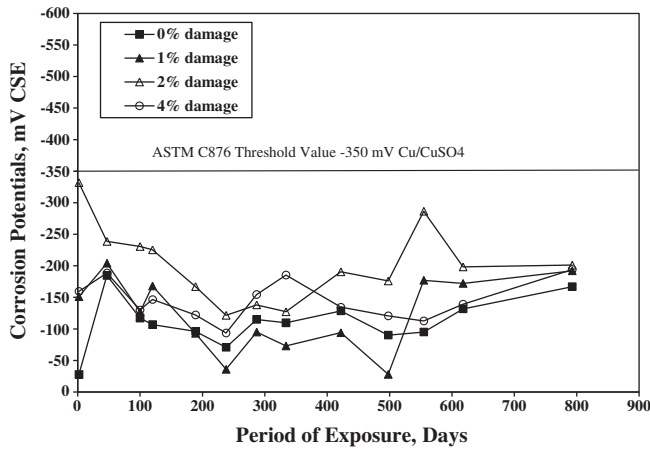


Fig. 15. Corrosion potentials on steel in 0.4% chloride-contaminated concrete with P2 inhibitor.

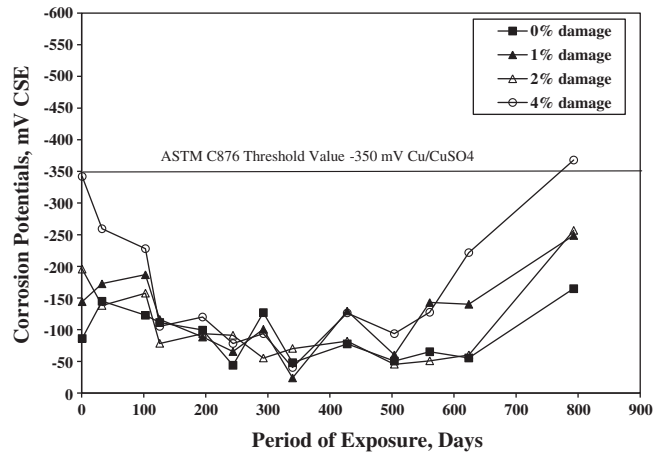


Fig. 18. Corrosion potentials on steel in 0.4% chloride-contaminated concrete with P3 inhibitor.

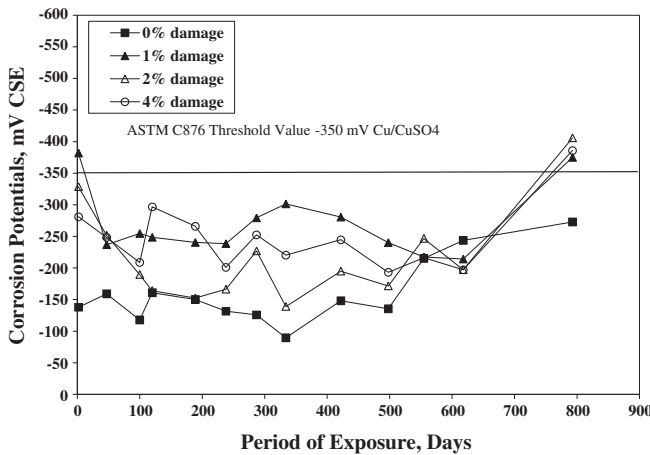


Fig. 16. Corrosion potentials on steel in 1% chloride-contaminated concrete with P2 inhibitor.

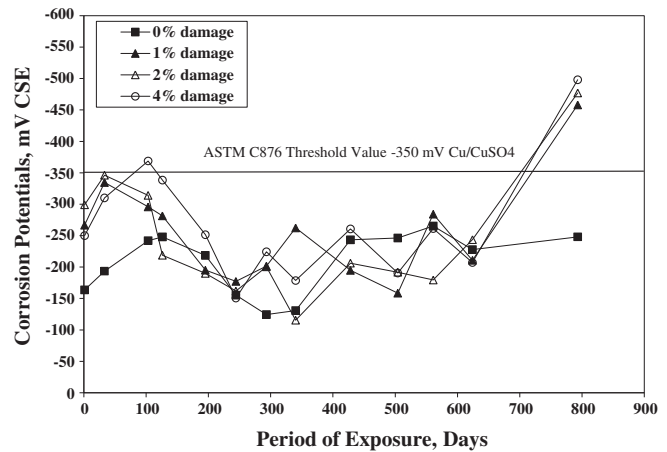


Fig. 19. Corrosion potentials on steel in 1% chloride-contaminated concrete with P3 inhibitor.

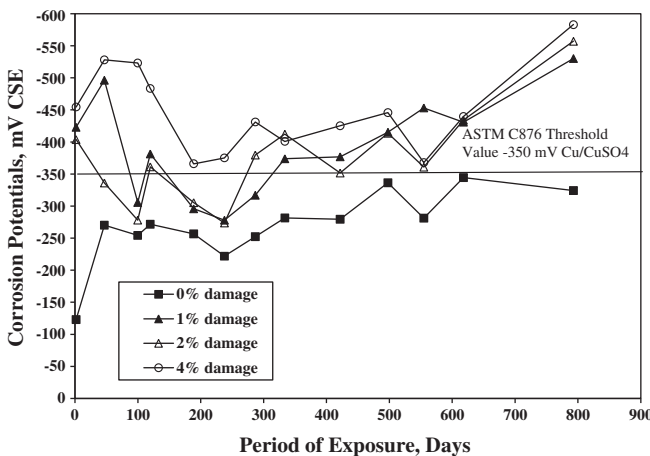


Fig. 17. Corrosion potentials on steel in 2% chloride-contaminated concrete with P2 inhibitor.

specimens with 1% chloride contamination, as shown in Fig. 16. Corrosion initiation was not noted in the undamaged bars. A similar trend was noted in the concrete specimens contaminated with 2% chloride, as depicted in Fig. 17.

The corrosion potentials on steel bars in the concrete specimens with 0.4% chloride and coated with P3 inhibitor are depicted in Fig. 18. Passive corrosion was indicated on the FBEC bars with up to 2% damage even after 800 days. Active corrosion was noted after about 700 days on the steel bars with 4% damage. Active corrosion was noted on all the bars with coating damage in the concrete specimens with 1% chloride, as shown in Fig. 19, while corrosion initiation was not noted on the undamaged bars. An almost similar trend was noted in the concrete specimens incorporating 2% chloride (Fig. 20).

The corrosion potential curves in Figs. 6–20 were utilized to calculate the time to initiation of reinforcement corrosion based on the ASTM C 876 criterion of -350 mV CSE. These data are summarized in Table 2. The time to initiation of reinforcement corrosion generally decreased with the level of chloride contamination and damage to the coating. This trend was noted in the concrete specimens with and without inhibitor. Corrosion activation was not noted in the bars with up to 2% surface damage (Two times the ASTM A705 allowable value) and chloride concentration of 0.4% (BS 8110 limit), except in the specimens with calcium nitrate inhibitor where corrosion activation was noted after 715 days. Corrosion activation was not noted in the concrete specimens with P1 inhibitor with up to 1% chloride and 4% surface damage to FBEC.

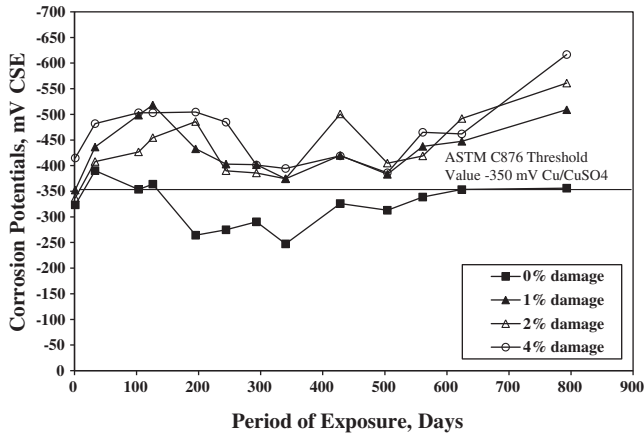


Fig. 20. Corrosion potentials on steel in 2% chloride contaminated concrete with P3 inhibitor.

3.3. Corrosion current density

The corrosion current density (I_{corr}) on steel in the concrete specimens prepared with 0.4% chloride contamination is depicted in Fig. 21. The I_{corr} values were much less than the threshold value of $0.3 \mu A/cm^2$ [13]. The I_{corr} values were less than $0.01 \mu A/cm^2$, the threshold value for long-term service-free life of reinforced concrete structures [14,15], on FBEC bars with 0% and 1% damage. The I_{corr} on steel in the concrete specimens incorporating proprietary inhibitors was less than that on steel bars in the concrete specimens incorporating calcium nitrate. Further, the I_{corr} values in the concrete specimens with calcium nitrate were almost similar to those in the concrete specimens without inhibitor. Least I_{corr} values were measured in the concrete specimens incorporating inhibitor P1.

The I_{corr} on steel in the concrete specimens contaminated with 1% chloride is depicted in Fig. 22. The I_{corr} in these specimens was also less than $0.3 \mu A/cm^2$. Least I_{corr} was noted in the concrete specimens with inhibitor P1.

Fig. 23 depicts the I_{corr} on steel in the concrete specimens contaminated with 2% chloride. The I_{corr} increased with the extent of the surface damage. Also, I_{corr} decreased due to the incorporation of the inhibitors. Minimum I_{corr} was measured on steel bars in the concrete specimens incorporating P1 inhibitor.

In summary, the data developed in this study indicate that incorporation of chemical inhibitors generally decreased the rate of corrosion of FBEC steel bars. The corrosion current density data, summarized in Figs. 21–23, also indicate the beneficial role of inhibitors in decreasing the rate of corrosion of the FBEC steel bars. The decrease in the corrosion rate due to the incorporation of inhibitors, as shown in Table 3, was in the range of 2–98%. The improvement ranged from 2% to 23% in the concrete specimens with calcium nitrate while it was 61–98% in the concrete specimens incorporating P1 inhibitor. The improvement ranged from 10% to 36% and 6% to 49% in the concrete specimens with inhibitor P2 and P3, respectively.

The above results indicate that incorporation of inhibitors has generally decreased the rate of corrosion of FBEC bars. The benefit was more evident in the case of inhibitor P1 than in the other proprietary inhibitors and calcium nitrate. The corrosion resistance (time to initiation of corrosion and I_{corr}) of the concrete specimens with inhibitor P1 was better than that of the specimens with other proprietary inhibitors and calcium nitrate. This inhibitor was useful in delaying the onset of corrosion and decreasing its rate, thereby exhibiting the characteristics of a mixed corrosion inhibitor. A variation in the performance of the selected inhibitors

Table 2 Time to initiation of reinforcement corrosion in the concrete specimens with 2% chloride contaminated with chloride and incorporating corrosion inhibitors.

Condition of bar	Time to initiation of corrosion, days									
	No inhibitor		Calcium nitrate		P1		P2		P3	
	0.4% chloride	1% chloride	0.4% chloride	1% chloride	0.4% chloride	1% chloride	0.4% chloride	1% chloride	0.4% chloride	1% chloride
0% Damage	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion
1% Damage	No corrosion	710	Active corrosion	670	750	675	590	Active corrosion	710	Active corrosion
2% Damage	No corrosion	690	Active corrosion	660	660	Active corrosion	690	Active corrosion	690	Active corrosion
4% Damage	No corrosion	750	Active corrosion	725	725	Active corrosion	750	Active corrosion	725	Active corrosion

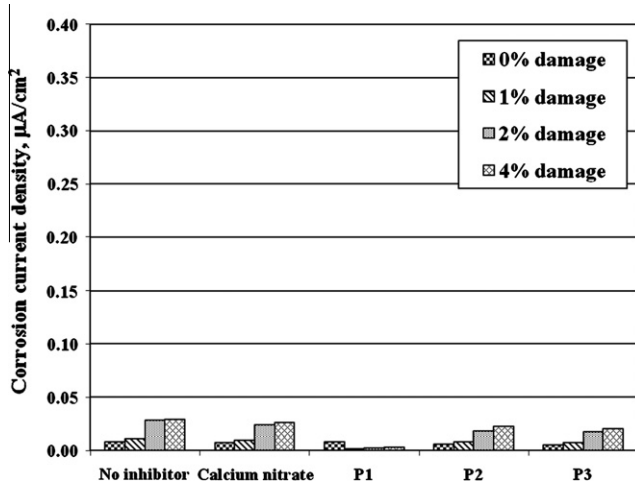


Fig. 21. Corrosion current density on steel in the concrete specimens prepared with 0.4% chloride and different types of inhibitors.

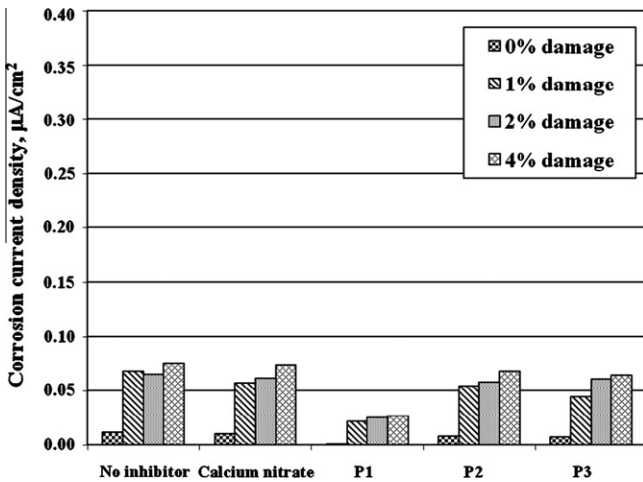


Fig. 22. Corrosion current density on steel in the concrete specimens prepared with 1% chloride and different types of inhibitors.

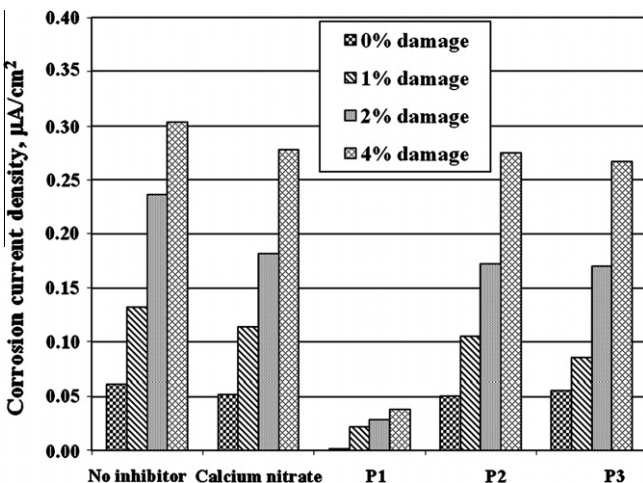


Fig. 23. Corrosion current density on steel in the concrete specimens prepared with 2% chloride and different types of inhibitors.

Table 3

Decrease in corrosion current density on uncoated and FBEC steel bars due to inhibitors.

Inhibitor	Bar type (% damage)	Decrease in I_{corr} due to corrosion inhibitor (%)		
		0.4% Cl 20 Months	1% Cl 20 Months	2% Cl 20 Months
Calcium nitrate	0	6	11	15
	1	10	15	14
	2	15	5	23
	4	9	2	9
P1	0	10	92	98
	1	84	68	84
	2	90	61	88
	4	90	64	87
P2	0	28	29	18
	1	28	19	21
	2	36	11	27
	4	23	10	10
P3	0	35	32	9
	1	32	34	35
	2	40	6	28
	4	30	14	12

indicates the need for a careful selection of these chemicals prior to their use. For this purpose, a screening procedure may be developed. Accelerated impressed current corrosion technique [13] has been found to be very useful for this purpose.

Another point to be discussed is the good correlation noted between the results of electrochemical and gravimetric measurements. The time to initiation of reinforcement corrosion in the concrete specimens incorporating inhibitors was more than that in the specimens without an inhibitor. Similarly, the I_{corr} decreased with the incorporation of inhibitors. Minor to moderate corrosion was noted in the concrete specimens with inhibitors while the corrosion ranged from negligible to moderate in the concrete specimens without inhibitor. The extent of corrosion in the concrete specimens with inhibitor P1 was less than that with concrete specimens with other inhibitors. These results corroborate the findings by the authors [13] regarding a good correlation between the electrochemical and gravimetric weight loss measurements.

4. Conclusions

The following conclusions can be made from the data developed in this study:

1. Reinforcement corrosion was indicated from the initial stages in the concrete specimens with 2% chloride. Corrosion was not noted in the concrete specimens with undamaged FBEC steel bars for a chloride contamination of up to 1%. However, it was noted after about 590 days in the concrete specimens with 2% chloride.
2. The I_{corr} values on FBEC bars in the concrete specimens with 0.4% chloride were less than $0.01 \mu A/cm^2$, the threshold value for long-term maintenance-free service life. However, the I_{corr} was less than $0.01 \mu A/cm^2$ on the FBEC bars without any surface damage in the concrete specimens with 1% and 2% chloride contamination. The I_{corr} on other FBEC bars increased with the extent of surface damage and chloride contamination.
3. FBEC bars without any surface damage can sustain as much as 2% chloride contamination. However, for a surface damage of 1% and above the chloride contamination should not be more than 0.4%.

4. The incorporation of chemical inhibitors decreased the rate of corrosion of FBEC steel bars. In the concrete specimens incorporating calcium nitrate, P2, and P3 inhibitors and contaminated with 2% chloride, the corrosion initiation was noted from the time of exposure. In the concrete specimens with a similar chloride contamination but incorporating P1 inhibitor the corrosion activation was noted after 580 days.
5. The corrosion current density data indicated the beneficial role of inhibitors in decreasing the rate of corrosion of the FBEC steel bars with damaged coating. These data indicated that the use of inhibitors, particularly P1, is beneficial in decreasing the corrosion of FBEC bars with surface damage.
6. A good correlation was noted between the results of electrochemical and gravimetric weight loss measurements.

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