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Accelerated testing of plain and epoxy-coated reinforcement in simulated seawater and chloride solutions

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Abstract

To simulate marine and bridge deck environments, plain and epoxy-coated reinforcing steel bars were cast in concrete slabs and exposed in the laboratory to synthetic seawater and 3% sodium chloride solution. They were monitored on a regular basis using the linear polarization and open-circuit potential techniques. The concrete slabs had a water to cement ratio of 0.60 and the steel reinforcement had 20 mm concrete cover. The epoxy-coated bars were with no damage, and 1% and 2% damage to the coating. A 2-year monitoring program indicated that the corrosion current density was negligible for epoxy-coated bars with no damage to the coating regardless of the exposure conditions and that undamaged epoxy-coated bars provided excellent performance in preventing corrosion activity in reinforced concrete structures subjected to a chloride environment. Similarly, rebar with damaged epoxy coating gave no evidence that sufficient rust had accumulated at the steel/concrete interface to cause the concrete cover to crack. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Chloride; Reinforced concrete; Corrosion rate; Epoxy-coated reinforcement; Time-to-cracking

1. Introduction

A large number of reinforced concrete structures such as harbors, docks, bridge decks, piers, floating offshore platforms, power plants, and waste disposal facilities are generally subjected to chloride ions that come from deicing salts used to melt snow and ice or from seawater and salt spray. Reinforced concrete structures exposed to marine environments are subjected to the simultaneous action of a number of physical, chemical, and electrochemical deterioration processes [1,2]. In view of the immense cost involved in initial construction and in repair and rehabilitation, it is quite important that these structures have a long service life and be able to resist the ravages of time and deleterious effects of the harsh environmental conditions with minimum maintenance cost.

Reinforcing steel in concrete normally is in a passive state due to the highly alkaline environment allowing formation of a thin adherent oxide film on the surface of steel [3]. This oxide layer generally provides reliable protection against corrosion as long as it is intact. However, any disruption of this film, such as a significant concentration of chloride ion on the steel surface in the presence of oxygen and moisture, will initiate the corrosion process [4]. Accumulation of corrosion products at the steel/concrete interface induces tensile stresses in the concrete, causing cracking and spalling of cover over the reinforcing steel.

The basic approaches that have so far been taken to prevent corrosion of reinforcing steel embedded in concrete are as follows:

- improving the quality of concrete and increasing cover depth,
- protection at the concrete surface,
- implementing cathodic protection, and
- protecting the reinforcement at the steel/concrete interface.

The last mentioned protection method was investigated for the case of fusion-bonded epoxy coatings as question as to its effectiveness had been raised.

A literature review indicated that epoxy-coated rebar used in the substructure of bridges in the Florida Keys

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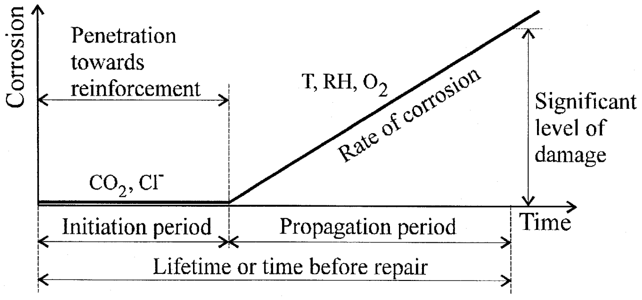

Fig. 1. Schematic sketch of reinforcement corrosion sequence in concrete.

indicated severe corrosion damage after only 6 years in service [5,6]. Recent studies have, nevertheless, revealed that epoxy-coated rebar, when properly coated and handled, can give good long-term performance even under severe exposure conditions [7,8].

In this particular investigation, the major focus has been given to the corrosion initiation and propagation periods for epoxy-coated rebar embedded in concrete slabs subjected to simulated marine and bridge deck conditions relative to bare reinforcing steel.

2. Design against corrosion

As time goes on, aggressive agents such as chloride ions reach the surface of steel reinforcement and accumulate to a sufficient level for corrosion to commence in the presence of moisture and oxygen. The formation of expansive corrosion products at the steel/concrete interface induces tensile stresses in the concrete resulting in spalling or delamination of concrete cover. This briefly outlines the deterioration process which is related to the service life of the reinforced concrete structures. As illustrated in Fig. 1, corrosion may therefore be considered to be a two-phase process as proposed by Tuutti [9]. The initiation period t_i is the time for chloride ions to reach rebar and activate the corrosion process. The propagation period t_p refers to the time taken for the corrosion once initiated to reach a level that causes significant damage. If the length of the initiation period is t_i and that of the propagation period t_p, then $t = t_i + t_p \geq$ design life of structure.

Accurate prediction of the service life of a reinforced concrete structure for a given exposure condition is dependent upon how well t_i and t_p are assessed. In a marine condition, time t_i is directly related to the rate of chloride ingress, which is a function of chloride concentration, diffusivity of concrete, and concrete cover. Time t_p depends on the rate of corrosion which is a function of the temperature and the degree of saturation of the concrete, the availability of oxygen at the rebar surface, and on the acceptable amount of corrosion during the design life.

The typical signs of corrosion in reinforced concrete structures are wide cracks along the reinforcement, delaminations, or substantial spalled areas on the concrete surface. In most practical circumstances spalling occurs well before the reinforcement has become significantly corroded and weakened. Once the concrete cover has been spalled off, rapid corrosion of the exposed steel takes place. The primary objective of design against corrosion should thus be design against spalling rather than design against unacceptable loss in the cross-section of the reinforcement.

3. Experimental details

3.1. Concrete mixture

A concrete mixture with a maximum aggregate size of 12 mm and a slump of 80 mm was used. A relatively high water to cement ratio of 0.60 and a concrete cover of 20 mm over the rebar in the concrete slabs were adopted to accelerate corrosion activity. To have a mixture that could be easily consolidated with external vibration, approximately equal volumes of sand and coarse aggregate were used in the program. ASTM Type I cement with a content of 300 kg/m^3 was used.

3.2. Concrete slabs

The nominal dimensions of the concrete slabs were 55 × 200 × 300 mm (see Fig. 2). Each slab contained a U-shaped reinforcing steel rebar. Concrete slab thickness and width was adjusted so as to have a cover of 20 ± 2 mm between the reinforcing steel, and the sides and face of the slabs. Twenty-four concrete slabs were prepared for the testing program. The slabs were moist-cured for 14 days at 20 ± 2°C at a relative humidity of not less than 95% before subjection to the pertinent exposure conditions.

The U-shaped rebar was 15 mm nominal diameter deformed type and was bent around a 127-mm diameter mandrel. For the corrosion rate measurements, a 100-mm stainless steel rod (303 SS) was centrally located in the concrete slab as a counter electrode. Wires were connected to the stainless steel rod and to the rebar to provide the necessary connections to the measuring devices. The connections were coated with an epoxy compound.

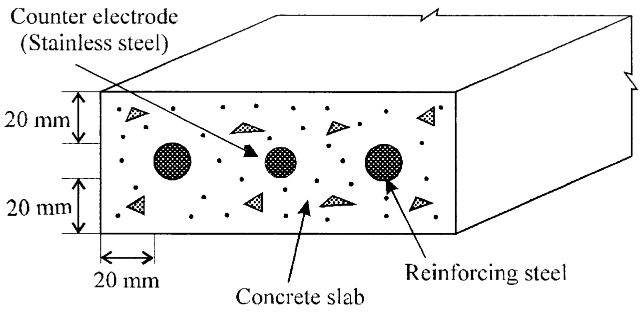

Fig. 2. Sketch of the concrete slab containing U-shaped rebar.

Table 1
Composition of seawater used in the MESS

Ion	ASTM seawater concentration (mg/l)	Synthetic seawater concentration (mg/l)
Cl^-	19500	17500
Mg^{2+}	1329	1020
SO_4^{2-}	7634	4020

3.3. Exposure conditions

The tidal zone of marine structures and bridge decks are subjected to frequent applications of corrosion-inducing solutions which were simulated in an accelerated manner in the laboratory. To simulate marine environment a synthetic seawater, a modified version of ASTM D-1141 [10], was used, the composition of which is given in Table 1. To simulate deicing salts application, a 3% sodium chloride solution was used. The marine environment simulated setup (MESS) consisted of two chambers as sketched in Fig. 3. Each chamber has two fiberglass–wooden tanks, a pump, heaters, and blowers. The tanks were connected so that the upper tank was a container for the concrete slabs while the bottom one was a reservoir for water during the dry cycle. The wet–dry cycling was electronically controlled by a computer. A 2-h wet cycle followed by a 4-h dry cycle was chosen to give four complete cycles within a 24-h period as opposed to two tidal cycles in a natural marine environment. This was done to accelerate the corrosion activity. The wet portion of the cycle was operated at 32 ± 2°C and the dry portion of the cycle was at a temperature of 68 ± 2°C.

Following the curing period, 12 concrete slabs were exposed in the synthetic seawater and the remaining 12 slabs in the 3% sodium chloride solution. Concrete slabs were placed vertically in the upper tanks of the MESS and the water level was adjusted so that in the dry cycle one-third of each slab was immersed and two-thirds was submerged in the wet cycle.

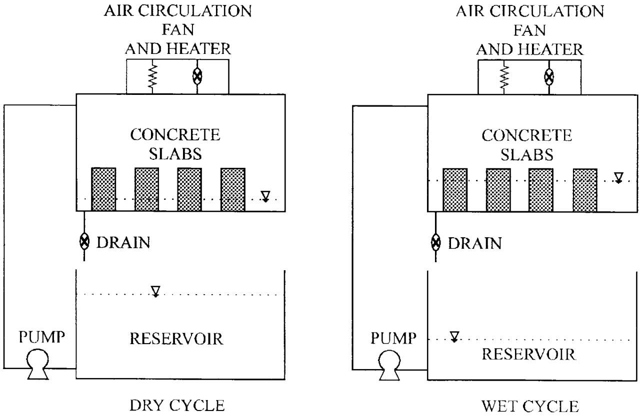

Fig. 3. Schematic illustration of the MESS.

Table 2
Layout of the experimental program

		Epoxy-coated rebar		
Exposure condition	Bare rebar	No damage	1% damage	2% damage
Synthetic seawater (MESS)	SW1, SW2, SW3, SW4	SW5, SW6, SW7, SW8	SW9, SW10	SW11, SW12
3% sodium chloride (MESS)	NC1, NC2, NC3, NC4	NC5, NC6, NC7, NC8	NC9, NC10	NC11, NC12

3.4. Program layout

The layout of the experimental program is given in Table 2. Four slabs for each exposure were cast with the bare rebar and another eight slabs were cast with epoxy-coated rebar. The coated bars were initially tested with an electric holiday detector in accordance with ASTM G-62 [11] and patched with an epoxy compound if a bare spot was noticed. Four coated rebars were cast in the concrete slabs without damage to the coating. On a construction site, some damage to epoxy coating is inevitable through normal concrete compaction procedures, even if the coating is 100% undamaged before concrete placement. To simulate this situation, for two rebars 1% and for the remaining two rebars 2% of the total coated surface was purposely damaged by removing the coating as 6 × 6 mm square areas using a hand grinder. The damaged areas were evenly distributed over the surface of the U-shaped rebar.

4. Results

4.1. Potential measurements

Potential monitoring is related to the thermodynamics of the corrosion process and determines the probability of corrosion occurring in a particular environment, but cannot evaluate the kinetics of the reaction. Potential measurements for each rebar cast in the concrete slabs subjected to synthetic seawater and 3% sodium chloride in the MESS were conducted in accordance with ASTM C-876 using a saturated calomel electrode [12]. It has been shown both in the laboratory and in the field that this method can be misleading in judging the state of corrosion activity of epoxy-coated rebar in concrete [13]. The potential variation of the rebars was monitored continuously with respect to time over a period of 2 years. Once active corrosion took place for the bare rebars subjected to both synthetic seawater and 3% sodium chloride, the potential remained steady afterwards. However, the case for epoxy-coated rebars with no damage was completely different as the potential went from a passive to active state by a series of intermediate steps. This may be associated with either passivity breakdown or the progressive restriction in the supply of oxygen to the surface of the reinforcing steel embedded in concrete

Table 3
Time to active corrosion initiation for the bare rebars in the concrete slabs

Exposure condition	Synthetic seawater				3% sodium chloride			
Bar identification	SW1	SW2	SW3	SW4	NC1	NC2	NC3	NC4
Time to active corrosion initiation (days)	169	119	181	156	42	46	46	42

Table 4
Criteria for corrosion state relative to corrosion current density

Corrosion current density	Corrosion state
$i_{corr} < 0.1$ μA/cm^2 (1.2 μm/year)	passive condition
$0.1 < i_{corr} < 1$ μA/cm^2 (11.7 μm/year)	moderate corrosion rate
$1 < i_{corr} < 10$ μA/cm^2 (116.8 μm/year)	high corrosion rate
$10 < i_{corr} < 100$ μA/cm^2 (1167.5 μm/year)	very high corrosion rate

[14]. Considering this thermodynamic behavior, the state of corrosion observed for rebars in the prevailing exposure conditions is evaluated in accordance with the criteria described elsewhere [15].

According to ASTM C-876, a potential drop to -270 mV$_{SCE}$ or lower indicates that there is a greater than 90% probability of corrosion risk for reinforcing steel embedded in concrete. Based on this criterion, time to active corrosion initiation observed for the bare reinforcing bars exposed to the synthetic seawater and 3% sodium chloride is given in Table 3.

4.2. Corrosion rate measurements

Corrosion rate of reinforcing steel in concrete slabs subjected to synthetic seawater and a 3% sodium chloride in the MESS was monitored on a regular basis using the linear polarization technique for over a period of 2 years. Fig. 4 is a sketch of the linear polarization resistance measurement set-up in which a saturated calomel electrode was used as a reference electrode. Corrosion current density and the corresponding corrosion rate calculations were conducted according to the procedures and equations given elsewhere [16]. The proportionality constant, B, was assumed to be 26 mV in calculating corrosion rate for actively corroding systems and 52 mV for other cases [17]. A scan rate of 4 mV/min was applied during corrosion current measurements. The corresponding graphs for the synthetic seawater and for the 3% sodium chloride exposure are given in Figs. 5 and 6, respectively. In calculating current densities, the total area of the reinforcing bar was used for the bare rebar while only the bare area in the damaged spots was considered for the damaged epoxy-coated ones. For undamaged rebars, the same procedure used for bare rebars was followed to make comparisons. The corrosion current densities obtained for undamaged rebars were not stable. The readings illustrated in the associated graphs are the highest values of sequential measurements. This was done to demonstrate the worst corrosion case of undamaged rebar that would take place. Based on the corrosion current densities measured, an assessment of the state of corrosion activity of rebar in concrete may be carried out as given in Table 4.

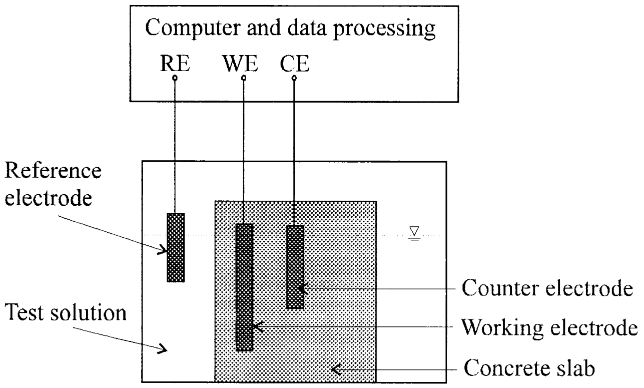

Fig. 4. Sketch of the linear polarization set-up.

4.3. Visual survey

In addition to electrochemical monitoring of corrosion activity, the condition of the concrete slabs has continuously been surveyed during the course of exposure period to record the time to corrosion initiation, evidence of visible rust staining and faint cracking on the surface of the concrete slabs. Based on the visual survey conducted on the concrete slabs containing bare reinforcing steel bars exposed to the synthetic seawater and 3% sodium chloride, the time required for visible rusting and faint cracking is given in Table 5.

At the end of 1 and 2 years of exposure to given conditions, concrete slabs from each category were cut open to expose the rebar for visual and microscopic examination of the corrosion products that might have formed on the rebar surface. Regardless of the exposure conditions, the rusted spots were about 10% to 15% of the total surface of the bare rebars at the end of 1 year of exposure. This means that 10% to 15% of the rebar surface became anode to the rest of the rebar. After an exposure period of 2 years, however, the rebars were heavily corroded. No corrosion products on the surface of the epoxy-coated rebars with no damage to the coating was observed. Some rusted spots were observed as localized pits at purposely damaged areas with no visual evidence of rust accumulation at the steel/concrete interface sufficient to cause cracking of the concrete cover.

Table 5
Time to visible corrosion occurrence on the concrete slabs containing bare rebars

Exposure condition	Synthetic seawater				3% sodium chloride			
Bar identification	SW1	SW2	SW3	SW4	NC1	NC2	NC3	NC4
Time to visible rusting and faint cracking (days)	375	325	400	350	75	100	100	150

5. Discussion of results

Based on the potential measurements, the time to active corrosion for the bare rebars in the concrete slabs with a water to cement ratio of 0.60 and a concrete cover of 20 mm is about 1.5 months in the case of exposure in 3% sodium chloride and is about 5 months for the synthetic seawater exposure.

Fig. 5 indicates that essentially no corrosion is taking place on the undamaged epoxy-coated rebar with a magnitude of current density only 0.0001 μA/cm^2 after an exposure period of 2 years due to the good dielectric characteristics and high resistance to ionic diffusion of the epoxy coating. The epoxy-coated reinforcing bars with 1% and 2% damage to the coating have exhibited some propensity to corrode with an average current density of 0.1 μA/cm^2 at the end of the same exposure period. This clearly indicates that there is a moderate level of corrosion activity in progress.

Fig. 6 illustrates the trend of corrosion current density obtained from the rebars in concrete slabs subjected to 3% sodium chloride over a period of 2 years. Undamaged epoxy-coated bars exhibited a current density of about 0.01 μA/cm^2, which indicates passivity and is negligible in terms of the expected service life of reinforced concrete structures [18]. An average current density of 0.5 μA/cm^2 for 1% damaged epoxy-coated reinforcing steel bars and 1.0 μA/cm^2 for 2% damaged ones was obtained during the exposure period. This is an indication that there is a moderate level of corrosion activity in progress.

Visual inspection of the concrete slabs containing bare reinforcing steel bars subjected to the synthetic seawater and 3% sodium chloride for over a period of 2 years indicated that rust and faint cracking extended to the surface due to the accumulation of corrosion products at the steel/concrete interface. The time required for crack occurrence on the surface of the concrete slabs containing bare rebars was about 3.5 months for the 3% sodium chloride exposure and 12 months for the synthetic seawater exposure. Regardless of the exposure conditions, no visible indication of corrosion was observed on the surface of the concrete slabs other than for those containing bare reinforcement.

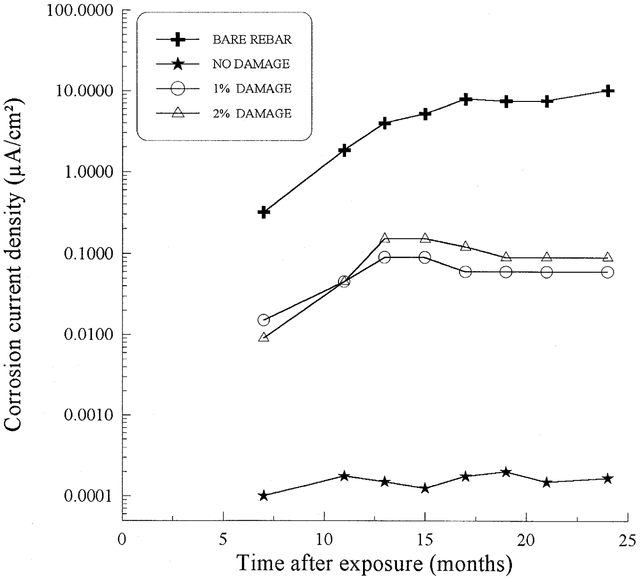

Fig. 5. Current density of rebars in concrete slabs exposed to synthetic seawater.

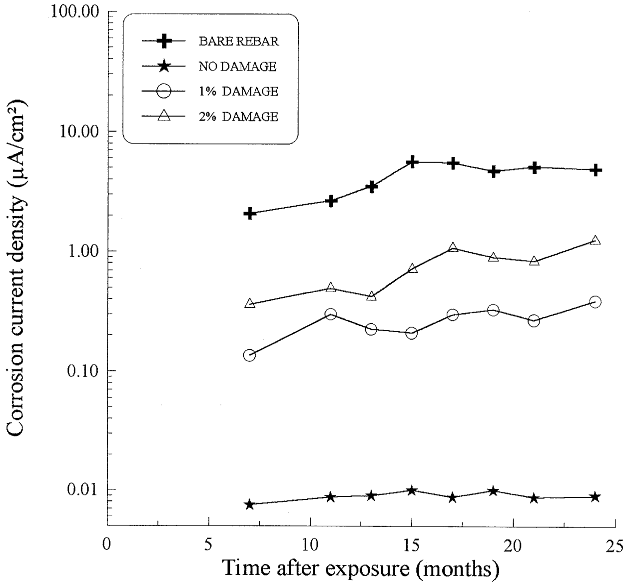

Fig. 6. Current density of rebars in slabs exposed to 3% sodium chloride.

At the end of 2 years of exposure to the synthetic seawater, the bare rebars were heavily corroded. The corrosion products were black–green–brown in color and were formed almost all over the rebar surface. No visible signs of corrosion could be found on the surface of the undamaged epoxy-coated bars while 1% and 2% damaged bars have shown rusting at some damaged areas as tiny deep black rust pits. As some of the damaged areas were quite bright, they might have functioned as cathodes. The rust spots formed in the damaged areas were black in color apparently due to a shortage of oxygen at the reaction front. Shortage of oxygen can be attributed to the 4-h drying period of the cycle not being sufficient to allow a realistic oxygenation of the steel in concrete. There was no sign of cracking of the concrete cover due to the rust products at the steel/concrete interface, and epoxy coating was still firmly adherent to the rebars.

After the exposure in the 3% sodium chloride for 2 years, the bare reinforcing steel bars were totally corroded. No evidence of corrosion products on the surface of the epoxy-coated bars with no damage to the coating was observed. However, the 1% and 2% damaged rebars exhibited some degree of corrosion at the purposely damaged areas. The rust products were mainly black and formed localized pits at the damaged areas. A few damaged spots did not have corrosion products since they have functioned as cathodes for the corroded ones. No visual evidence of rust accumula-

Table 6
Time required for design life of reinforced concrete structures

Exposure condition		Initiation period, t_i (months)	Propagation period, t_p (months)	Lifetime, t (months) $[t=t_i+t_p]$
Simulated conditions	synthetic seawater	5	12	17
	3% sodium chloride	1.5	4	5.5
Actual conditions	marine environment	40	96	136
	bridge deck	12	32	44

tion at the steel surface sufficient to cause cracks in the concrete cover was observed. As in the case of synthetic seawater exposure, the coating was still tightly bonded, and could hardly be lifted with a knife blade.

Based on the forgoing discussion, the following overall picture can be drawn in terms of lifetime or time before repair for reinforced concrete structures subjected to chloride-bearing environments. The values of the parameters defined in Fig. 1, together with the estimated values for the field conditions are as given in Table 6. The values are given for the bare rebar in the concrete slabs low in strength (W/C = 0.60) and with only 20 mm cover. The estimation for field conditions is based on the work previously carried out in which 1 year of accelerated testing in the MESS corresponded to about 8 years of exposure in a tidal zone of an actual exposure condition [13]. Acceleration in corrosion activity can be attributed to a relatively high chloride ingress. Service life can considerably be increased by using high quality concrete with thicker concrete cover, which will reduce the effective chloride diffusion [19].

Estimating the service life of concrete structures containing epoxy-coated rebar is rather difficult as rust staining or cracking was not observed on the surface of concrete slabs after a period of 2 years of exposure. However, assuming no degradation of the epoxy due to long-term exposure to the concrete pore solution, lifetime approximation may roughly be done considering the corrosion current measurements. Figs. 5 and 6 indicate that epoxy-coated rebar with no damage to the coating performed superior with respect to the bare reinforcing steel subjected to both synthetic seawater and a 3% sodium chloride. However, due to handling and concrete compaction procedures, some damage to the coating is inevitable. This is assumed to be about 1% to 2% of the rebar surface. Considering Figs. 5 and 6, damaged epoxy-coated bars exposed to synthetic seawater exhibited an average current density of 10 times lower than those exposed to 3% sodium chloride while the bare rebars indicated almost the same corrosion densities in the two environments. This might be attributed to the clogging effect of the products deposited in the pores near the surface of concrete as $Mg(OH)_2$ that occurs due to the reactions taking place between seawater and cement constituents [20].

6. Conclusions

Based on the findings obtained from the foregoing investigation, the following conclusions are drawn.

(i) The time to active corrosion initiation (90% probability) for bare reinforcing steel in concrete slabs is about 1.5 months for the 3% sodium chloride exposure and about 5 months in case of synthetic seawater exposure.

(ii) The time required for crack occurrence on the surface of the concrete slabs containing bare reinforcing steel is about 3.5 months for the 3% sodium chloride exposure and more than 12 months for the synthetic seawater exposure.

(iii) Regardless of the exposure conditions, slabs containing epoxy-coated rebars with no damage to the coating indicated essentially no corrosion activation during the course of exposure and no visible corrosion signs were observed on the surface of the concrete slabs.

(iv) Microscopic examination of slabs containing damaged epoxy-coated rebars done after exposure testing had been completed showed no evidence of rust accumulation at the rebar surface to cause cracking to the concrete.

(v) Regardless of the degree of damage to the coating, damaged epoxy-coated rebar exposed to both synthetic seawater and 3% sodium chloride indicated only a moderate level of corrosion activity after 2 years of accelerated testing.

(vi) Epoxy-coated rebar even with damaged coating up to 2% of the rebar surface shows significant reduction in corrosion activity compared to bare rebar; however, it does not provide total protection and shows the importance of preventing damage to the coating.

(vii) In terms of long-term performance, accelerated testing indicates that when an epoxy coating is properly applied to the reinforcing steel and the bars are handled carefully, the epoxy coating provides excellent protection and should extend the service life of reinforced concrete significantly as compared to when uncoated reinforcement is used.

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