ELSEVIER

Cement & Concrete Composites 24 (2002) 151–158

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Effect of steel manufacturing process and atmospheric corrosion on the corrosion-resistance of steel bars in concrete

M. Maslehuddin [a,*], M.M. Al-Zahrani [a], S.U. Al-Dulaijan [a], Abdulquddus [a], S. Rehman [a], S.N. Ahsan [b]

[a] *Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
[b] *SABIC Research and Technology Center, Al-Jubail Industrial City, Saudi Arabia*

Abstract

This paper presents results of a study conducted to evaluate the effect of steel manufacturing process and the surface condition of reinforcing steel on their corrosion-resistance when embedded in concrete. Steel bars produced by water quenching and air-cooling were utilized. The corrosion-resistance of fresh bars, i.e., those that were clean and shiny, and those exposed to atmosphere and accelerated salt spray, when embedded in concrete, was evaluated. The corrosion-resistance of the clean and corroded reinforcing steel bars was assessed by measuring corrosion potentials and corrosion current density. Accelerated impressed current technique was also utilized to evaluate the corrosion-resistance of clean and corroded reinforcing steel bars in concrete. A longer time-to-initiation and lower rate of reinforcement corrosion was noted in the concrete specimens prepared with water-quenched steel bars compared to similar bars manufactured by the hot-rolling process. Similarly, the rate of reinforcement corrosion in the concrete specimens prepared with corroded steel bars, exposed to atmosphere for 12 months and salt spray, was less than that on the unexposed bars. The data developed in this study also indicate that the surface layer formed on the water-quenched steel bars, due to the cooling process, provides protection to the metal substrate as against the loose mill scale formed on the steel bars produced by the air-cooling process.

Keywords: Air-cooling; Concrete; Reinforcement corrosion; Water quenching

1. Introduction

Reinforcing steel bars are normally air-cooled after hot rolling. However, there is an increasing trend to cool them by water quenching after hot rolling. This process presumably leads to the formation of a thin protective layer on the steel bars. This protective layer is claimed to enhance the corrosion-resistance of steel bars. However, discoloration is noted on the water-quenched steel bars. This surface layer is uniformly spread all over the length of the steel bars and is well adherent to the surface, unlike the loose mill scale that is formed on the air-cooled steel bars.

The effect of the surface layer that is formed on the steel bars due to the water-quenching or the corrosion product formed due to atmospheric exposure on the corrosion-resistance of steel bars when embedded in concrete is of concern to the construction industry. The apprehension on the effectiveness of the passive layer formed on the rusted bars is overwhelmingly voiced in regions where reinforcement corrosion is the main form of concrete deterioration. Limited studies [1–4] conducted earlier have indicated that atmospheric corrosion of steel bars does not significantly affect their corrosion behavior in concrete. Proverbio and Cigna [1] evaluated the influence of rebar surface condition on the corrosion-resistance of steel in concrete. The corrosion rate of originally rust-covered steel bars was two times higher than that of pickled steel [1]. The authors [1], however, note that the absolute value of corrosion rate obtained by the polarization resistance method has little importance from a practical point of view, especially for new structures. Al-Tayyib et al. [2] reported a slightly better corrosion-resistance of pre-rusted steel bars in concrete compared to unexposed steel bars. The rate of

---

[*] Corresponding author. Tel.: +966-3-860-2853; fax: +966-3-860-3996.

E-mail address: muddin@kfupm.edu.sa (M. Maslehuddin).

0958-9465/02/$ - see front matter
PII: S0958-9465(01)00035-X

corrosion of steel in the concrete specimens prepared with pre-rusted steel bars was 0–17% less than that in the concrete specimens prepared with rust-free steel bars. The improved performance of the pre-rusted steel bars was attributed to the physical barrier effect of the initial atmospheric rust layer that is formed on the steel. John et al. [3] indicated active corrosion of bars in the concrete specimens prepared with pre-rusted steel bars compared to those specimens prepared with bright steel bars. The authors [3] attribute this behavior partly to the concrete quality. Hanson and Sorensen [4] evaluated the effect of chloride ions on reinforcement corrosion in the concrete specimens prepared with as-rolled as well as pre-rusted steel bars. After 100 days of exposure, corrosion activity was noted on two out of six concrete specimens prepared with pre-rusted steel bars as against in five out of six concrete specimens prepared with steel bars in as-received condition. Based on these results, the authors [4] concluded that the presence of rust has a positive effect on reinforcement corrosion in concrete. However, the corrosion-resistance of water-quenched steel bars is yet to be investigated.

This study was conducted to evaluate: (i) the effect of steel cooling process, namely water-quenching or air-cooling, and (ii) the effect of atmospheric corrosion on the corrosion-resistance of steel bars when embedded in concrete. The corrosion-resistance of clean and atmospherically corroded steel bars was evaluated by measuring corrosion potentials and corrosion current density. The accelerated impressed current technique was also utilized to assess the corrosion-resistance of steel bars.

2. Methodology of research

2.1. Selection of steel samples

Samples of reinforcing steel bars 12 and 18 mm in diameter were obtained from four sources. One of the suppliers produced the steel bars by the water-quenching process while the other three produced them by the air-cooling process. For the purpose of this paper steel bars produced by the water-quenching process will be denoted by the acronym WQ, while those cooled by the air-cooling process will be identified as HR. Steel samples measuring 50 cm long were cut and tagged to show the source of steel, size, exposure site, and the intended use. Tables 1 and 2 show the composition of the minor elements in the 12- and 18-mm diameter steel bars, respectively. Steel bars intended for exposure to environmental conditions were weighed and then transported to the exposure sites. The specimens intended for accelerated reinforcement corrosion were placed in a salt spray chamber.

2.2. Exposure of steel samples

To evaluate the effect of atmospheric corrosion of reinforcing steel bars on their corrosion-resistance when embedded in concrete, two exposure sites were selected. One exposure site was located in a coastal area while the other was located in an inland area. The coastal exposure site was about 5 km from the seashore while the inland exposure site was 400 km from the seashore. The samples at these two exposure sites were placed on wooden racks that were 1 m above the ground. Table 3 summarizes the environmental conditions at the expo-

Table 1
Composition of residual elements in the 12-mm diameter steel bars

Source of steel bars	Composition of residual elements (%)											
	C	Si	Mn	P	S	Cu	Cr	Mo	Ni	Sn	V	N
WQ	0.32	0.22	0.69	0.011	0.013	0.038	0.009	0.001	0.019	0.005	0.002	0.012
HR1	0.37	0.30	1.25	0.019	0.013	0.012	0.022	0.001	0.022	0.003	0.039	0.012
HR2	0.40	0.19	1.38	0.019	0.004	0.013	0.029	0.001	0.014	0.003	0.019	0.007
HR3	0.40	0.24	1.30	0.014	0.023	0.50	0.11	0.01	0.09	0.019	0.004	0.014

Table 2
Composition of residual elements in the 18-mm diameter steel bars

Source of steel bars	Composition of residual elements (%)											
	C	Si	Mn	P	S	Cu	Cr	Mo	Ni	Sn	V	N
WQ	0.29	0.21	0.68	0.009	0.015	0.066	0.015	0.001	0.021	0.008	0.003	0.011
HR1	0.40	0.23	1.23	0.014	0.011	0.021	0.014	0.001	0.018	0.004	0.037	0.013
HR2	0.39	0.18	1.26	0.019	0.003	0.007	0.015	0.001	0.014	0.002	0.034	0.010
HR3	0.36	0.21	1.31	0.030	0.039	0.570	0.120	0.010	0.110	0.023	0.002	0.018

Table 3
Environmental conditions at the exposure sites

Variable	Maximum	Mean	Minimum
Coastal exposure site			
Ambient temperature (°C)	49.5	25.7	7.4
Relative humidity (%)	100.0	55.1	14.0
Wind speed (m/s)	12.9	4.4	1.0
Inland exposure site			
Ambient temperature (°C)	48.1	25.8	3.5
Relative humidity (%)	100.0	27.7	5.0
Wind speed (m/s)	9.8	3.3	0.0

sure sites. The steel samples were retrieved from the field sites after three, six and 12 months of exposure.

A second batch of steel specimens was exposed to salt spray for 1000 h, according to the procedures outlined in ASTM B 117, in a salt spray chamber.

2.3. Measurements

The corrosion-resistance of unexposed and exposed steel bars, embedded in concrete, was evaluated by conducting accelerated impressed current measurements and by measuring the corrosion potentials and corrosion current density. For this purpose, reinforced concrete specimens, 75 mm in diameter and 150 mm high, with a centrally placed reinforcing steel bar, were cast using unexposed and exposed steel bars. An effective cover of 25 mm was provided at the bottom of the specimen. In order to avoid crevice corrosion, the steel specimens were coated with cement slurry overlaid by an epoxy resin at the bottom of the bar and at the concrete–air interface.

The concrete specimens were prepared with a cement content of 370 kg/m^3 and an effective water–cement ratio of 0.4. Crushed limestone and dune sand were utilized in the preparation of concrete mixtures. After casting, the concrete specimens were covered with wet burlap for 24 h and then demolded. After demolding, they were cured under water for 28 days and then allowed to dry under laboratory conditions (25 ± 2°C and RH 45 ± 5%) for two to three days, prior to exposing them to 5% sodium chloride solution.

In the impressed current studies, the specimens were partially dipped in 5% sodium chloride solution and the steel bar was connected to the positive terminal of a DC power source, while the negative terminal was connected to a stainless steel plate placed near the specimen. Reinforcement corrosion was accelerated by impressing an anodic potential of 2.5 V. The current required to maintain this potential was noted by measuring the potential drop over the two leads of a precision resistor. The current measurements were recorded every hour through the use of a computerized data acquisition system. The time–current curves were utilized to evaluate the time to initiation of reinforcement corrosion, which was taken as the point at which a significant increase in the current or a change in the slope of the time–current curve occurred.

To evaluate the corrosion-resistance of unexposed and exposed steel bars, under freely corroding conditions, the reinforced concrete specimens were partially exposed to 5% sodium chloride solution. The level of the solution was adjusted such that only half the depth of the specimen was in the solution. The corrosion-resistance of these specimens was evaluated by measuring the corrosion potentials and the corrosion current density. The corrosion potentials were measured at periodic intervals using a high-impedance voltmeter and a saturated calomel reference electrode (SCE).

The corrosion-resistance of unexposed and exposed steel bars embedded in concrete and exposed to 5% sodium chloride solution was also evaluated by measuring the corrosion current density. To determine the corrosion current density, the steel bar and the stainless steel counter electrodes were connected to a potentiostat/galvanostat. The polarization resistance (R_p) was determined by conducting a linear polarization resistance scan in the range of ±10 mV of the corrosion potential. A scan rate of 0.1 mV/s was used. The corrosion current density (I_{corr}) was determined using the Stern and Geary formula [5], as given below:

$$I_{corr} = B/R_p,$$

where I_{corr} is the corrosion current density in μA/cm^2, R_p is the polarization resistance in Ω cm^2, $B = (\beta_a\beta_c)/2.3(\beta_a + \beta_c)$, and β_a and β_c are the anodic and cathodic Tafel constants in mV/decade of current, respectively.

For steel in an aqueous medium, a value of 100 mV is normally 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, values of B equal to 52 mV for steel in the passive condition and 26 mV for steel in the active condition are used. Lambert et al. [6] indicated a good correlation between the corrosion current density determined using the linear polarization resistance method (LPRM) and the gravimetric weight loss technique by adopting a value of 120 mV for both anodic and cathodic Tafel constants. Similar values were adopted in this study.

3. Results and discussion

3.1. Corrosion potentials

The corrosion potentials on the 12-mm diameter unexposed steel bars embedded in concrete and placed

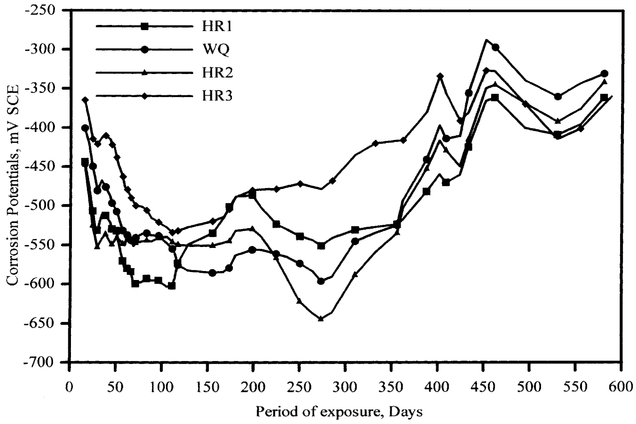

Fig. 1. Corrosion potentials on the 12-mm diameter unexposed steel bars.

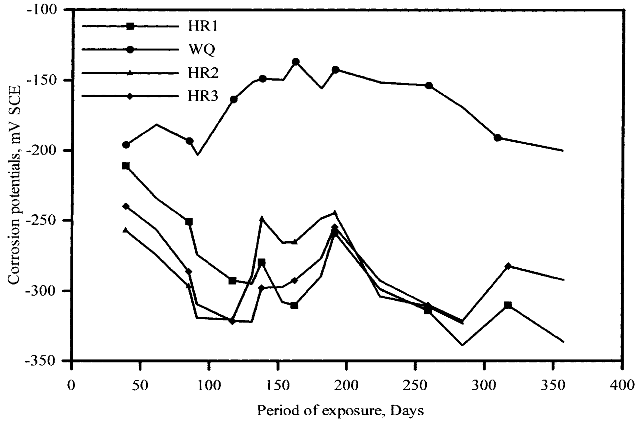

Fig. 2. Corrosion potentials on the 18-mm steel bars exposed for 12 months at an inland exposure site.

in a 5% NaCl solution are plotted against the period of exposure in Fig. 1. An initial decrease in the potential values was noted in all the concrete specimens. Further, the corrosion potentials were less than the ASTM C 876 criterion of −270 mV SCE. According to this criterion there is more than 90% probability of corrosion initiation if the corrosion potentials are more negative than −270 mV SCE. However, the probability of reinforcement corrosion may be as low as 10%, even though the corrosion potentials are more negative than −270 mV SCE. Normally such a situation is noted in the water-saturated concrete, such as the submerged zone in marine environments and foundations. Due to oxygen starvation in the saturated concrete, the γ-Fe_2O_3 layer is not formed resulting in a considerable decrease in the potential value. The rate of reinforcement corrosion in these situations, however, remains low. A shift in the corrosion potential–time curves, indicating reinforcement corrosion, was noted after 283 days in the water-quenched steel bars while it was in the range of 113–271 days in the air-cooled steel bars. A shift in the corrosion potential–time curve signifies the diffusion of chloride ions to the steel surface.

The corrosion potentials on the 18-mm diameter steel bars exposed at the inland exposure site for 12 months are plotted against the time of exposure in Fig. 2. The corrosion potentials decreased with the period of exposure in all the concrete specimens, except in those prepared with the water-quenched steel bars. The corrosion potentials in the concrete specimens prepared with the air-cooled steel bars crossed the ASTM C 876 criterion of −270 mV SCE after 57–91 days, while the corrosion potentials on the water-quenched steel bars were more positive than −270 mV SCE even after 370 days of exposure to 5% NaCl solution.

The corrosion potential–time curves were utilized to evaluate the time-to-initiation of reinforcement corrosion. The time-to-initiation of reinforcement corrosion was reckoned as the point at which a shift in the corrosion potential–time curve was noted, or when it crossed the ASTM C 876 criterion of −270 mV SCE. The data so generated are summarized in Table 4. These data indicate that the time-to-initiation of reinforcement corrosion in the concrete specimens prepared with the unexposed water-quenched steel bars and those exposed to atmosphere for six months was generally more than that in the concrete specimens prepared with the air-cooled steel bars. Further, the corrosion potentials on the water-quenched steel bars exposed to the atmosphere for 12 months was generally more positive than −270 mV SCE indicating no corrosion initiation on these bars. The higher time to initiation of reinforcement corrosion noted in the unexposed water-quenched steel bars and those exposed to the atmosphere for six months compared to air-cooled steel bars indicates the superiority of water-quenched steel bars in resisting reinforcement corrosion. Also, the passive corrosion potentials, i.e., more positive than −270 mV SCE, noted on the water-quenched steel bars exposed to the atmosphere for 12 months indicates that atmospheric corrosion improves the corrosion-resistance of steel. It is possible that the formation of the rust layer delays the diffusion of chloride ions to the metal substrate.

3.2. Corrosion current density

The corrosion current density on the 12-mm diameter unexposed steel bars is plotted against the period of exposure to the chloride solution in Fig. 3. The corrosion current density increased with the period of exposure in all the concrete specimens. However, the rate of increase in the corrosion current density on the water-quenched steel bars was less than that on the air-cooled steel bars. Further, the corrosion current density on the water-quenched steel bars was much less than that on the air-cooled steel bars at all periods of exposure.

Table 4
Time-to-initiation of corrosion of 12- and 18-mm diameter steel bars

Exposure	Exposure duration	Bar diameter (mm)	Time-to-initiation of corrosion (days)			
			WQ	HR1	HR2	HR3
Unexposed	None	12	283	113	271	113
		18	195	113	77	113
Coastal exposure site	3 months	12	227	136	127	73
		18	163	171	113	71
	6 months	12	160	155	155	125
		18	229	164	90	90
	12 months	12	Passive	Active	Passive	Active
		18	Passive	225	225	260
Inland exposure site	3 months	12	139	240	130	145
		18	91	55	91	40
	6 months	12	175	155	155	125
		18	229	193	114	90
	12 months	12	329	130	117	100
		18	Passive	91	57	83

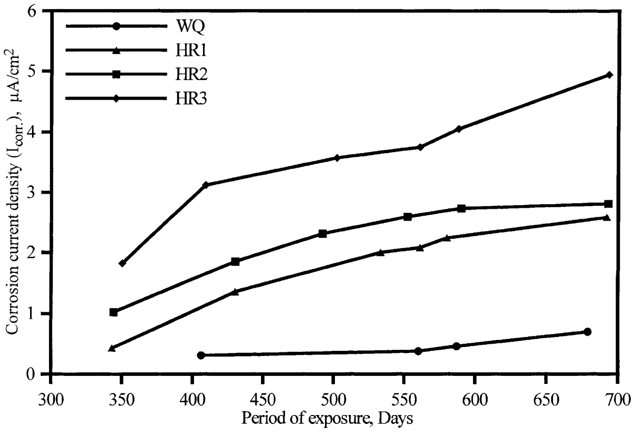

Fig. 3. Corrosion current density on the 12-mm diameter unexposed steel bars.

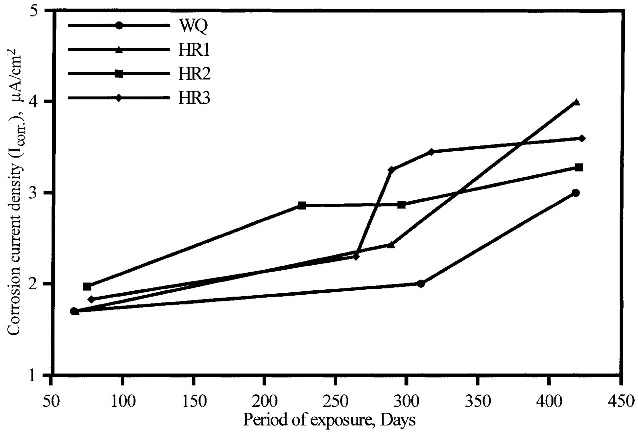

Fig. 4. Corrosion current density on 12-mm diameter steel bars exposed at coastal site for 12 months.

The corrosion current density on the 12-mm diameter steel bars exposed at the coastal site for 12 months are plotted in Fig. 4. The corrosion current density on the water-quenched steel bars and that on one of the air-cooled steel bars were similar up to about 250 days of exposure to the chloride solution. However, these values tended to differ from each other at later periods. After 250 days of exposure, the lowest corrosion current density was noted in the concrete specimens prepared with the water-quenched steel bars.

The corrosion current density on the 18-mm diameter steel bars exposed for 12 months at the inland exposure site is plotted in Fig. 5. The I_{corr} values increased almost linearly with the period of exposure in all the specimens. Further, the I_{corr} values on the water-quenched steel bars were less than those on the air-cooled steel bars. After about 400 days of exposure to the chloride solution the

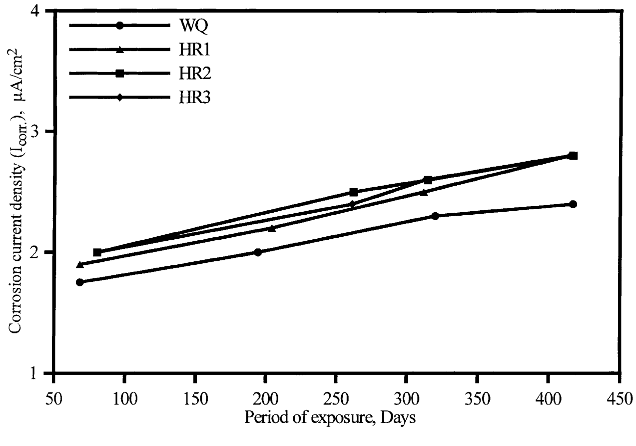

Fig. 5. Corrosion current density on the 18-mm diameter steel bars exposed for 12 months inland.

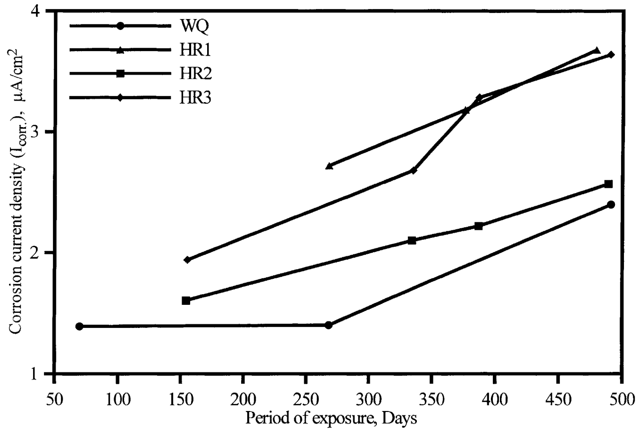

Fig. 6. Corrosion current density on 18-mm diameter steel bars exposed to salt spray for 1000 h.

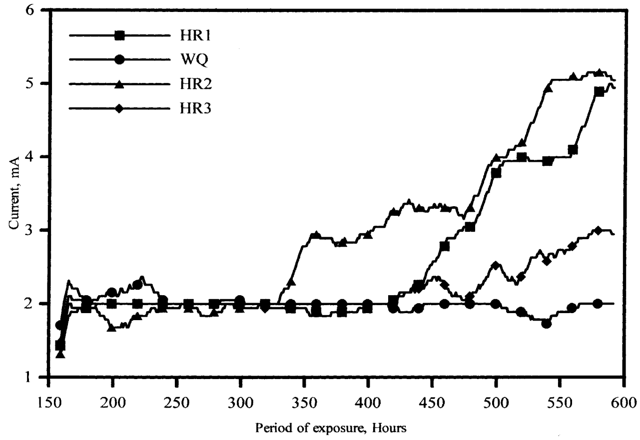

Fig. 7. Time–current curves for the 12-mm diameter unexposed steel bars.

corrosion current density on water-quenched steel bars was 2.40 $\mu A/cm^2$, while it was 2.80 $\mu A/cm^2$ on the air-cooled steel bars.

The corrosion current density on the 18-mm diameter steel bars exposed to the salt spray for 1000 h is plotted in Fig. 6. In this group of specimens also the corrosion current density increased with the period of exposure to the chloride solution. Further, the corrosion current density on the water-quenched steel bars was less than that on the air-cooled steel bars. After about 475 days of exposure, the I_{corr} on the water-quenched steel bars was 2.40 $\mu A/cm^2$ while it was in the range of 2.57–3.68 $\mu A/cm^2$ on the air-cooled steel bars.

In summary, the data in Figs. 3–6 indicate that the corrosion current density on both fresh and exposed steel bars increases with the period of exposure. Further, the I_{corr} values on the water-quenched steel bars were generally less than those on the air-cooled steel bars.

3.3. Accelerated reinforcement corrosion

The corrosion of the fresh and exposed steel bars embedded in concrete was accelerated by impressing an anodic potential of 2.5 V, and the current required to maintain this fixed potential was plotted against time. The current required to maintain the fixed potential depends on the electrical resistivity of concrete. With the initiation of reinforcement corrosion concrete cracks thus decreasing the electrical resistivity. As a result the current required to maintain the anodic potential increases.

The current–time curves were utilized to evaluate the time-to-initiation of reinforcement corrosion. An instantaneous increase in the current requirement indicates a change in the structure of the concrete, for example, the formation of microcracks due to reinforcement corrosion. Fig. 7 shows the time–current curves for concrete specimens prepared with the unexposed 12-mm diameter steel bars. Initially, the current requirement for all the concrete specimens was similar. However, an increase in the current requirement was noted in the concrete specimens prepared with air-cooled steel bars, while the current required to maintain an anodic potential of 2.5 V was more or less stable in the concrete specimens prepared with the water-quenched steel bars. The increase in the current requirement in the concrete specimens prepared with the air-cooled steel bars was noted after 325–460 h.

Fig. 8 shows the time–current curves for the 12-mm diameter steel bars exposed at the inland site for 12 months. The time to initiation of corrosion, as indicated by a sharp increase in the current requirement, in the water-quenched steel bars was more than that in the air-cooled steel bars.

Fig. 9 summarizes the time-to-initiation of reinforcement corrosion in the concrete specimens prepared

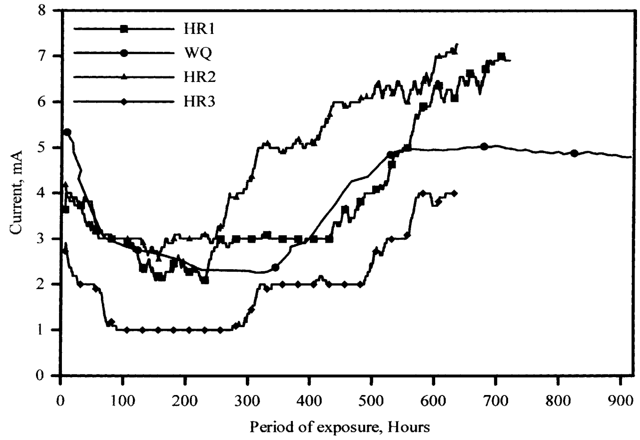

Fig. 8. Time–current curves for 12-mm diameter steel bars exposed at the inland exposure site for 12 months.

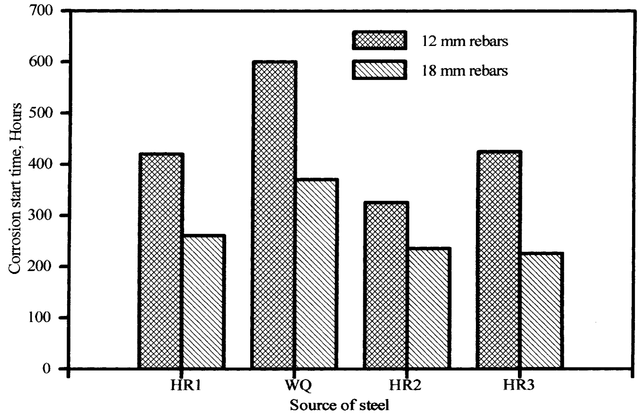

Fig. 9. Time-to-initiation of corrosion of unexposed steel bars.

with the unexposed 12- and 18-mm diameter steel bars. A longer time-to-initiation of reinforcement corrosion was noted in the concrete specimens prepared with the water-quenched steel bars compared to that in the concrete specimens prepared with the air-cooled steel bars. The time-to-initiation of reinforcement corrosion in the concrete specimens prepared with the 12-mm diameter unexposed water-quenched steel bars was 600 h while it was in the range of 300–400 h in the concrete specimens prepared with the unexposed air-cooled steel bars. These values in the concrete specimens prepared with the 18-mm diameter unexposed steel bars were 375 and 190–280 h, respectively.

Fig. 10 shows the time-to-initiation of reinforcement corrosion in the concrete specimens prepared with the steel bars exposed at the coastal exposure site for 12 months, while Fig. 11 shows the time-to-initiation of reinforcement corrosion in the concrete specimens prepared with the steel bars exposed at the inland exposure site for a similar period. The data in Figs. 10 and 11 indicate superior performance by the water-quenched steel bars in resisting corrosion of the metal substrate compared to the air-cooled steel bars evaluated in this study.

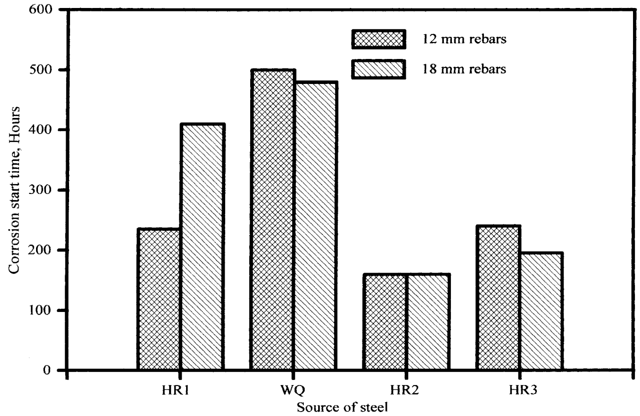

Fig. 10. Time-to-initiation of corrosion of steel bars exposed for 12 months at the coastal exposure site.

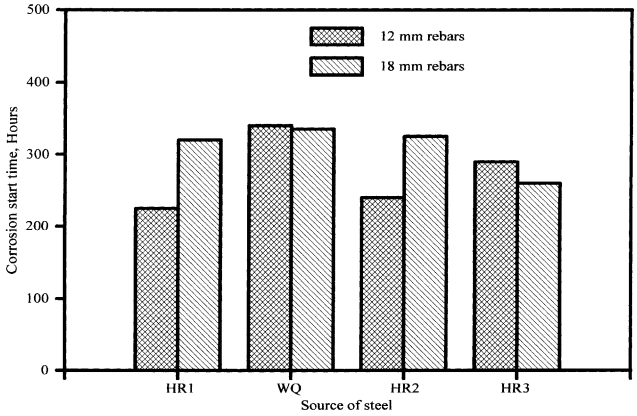

Fig. 11. Time-to-initiation of corrosion of steel bars exposed for 12 months at the inland exposure site.

The data in Figs. 8–11 indicate that the corrosion-resisting characteristics of water-quenched steel bars are better than those of the air-cooled steel bars. The longer time-to-initiation of reinforcement corrosion in the concrete specimens prepared with the water-quenched steel bars, compared to those prepared with the air-cooled steel bars, may be attributed to the protective oxide layer formed on the water-quenched steel bars due to the quenching process. This protective layer perhaps slows down the diffusion of chloride ions to the substrate metal, thereby prolonging the onset of its corrosion. The absence of this protective layer culminates in the early initiation of corrosion of air-cooled steel bars. The improved corrosion-resistance of the water-quenched steel bars may also be attributed to its microstructure. Cooling of steel bars by the water-quenching process creates a composite microstructure, consisting of an outer layer of tempered martensite and an inner core of ferrite and pearlite. The microstructure of the air-cooled bars consists of a uniform inner core of ferrite and pearlite. The tempered martensite layer provides additional protection to the inner core. It is also possible that the volume of corrosion product formed on the water-quenched steel bars is less than that formed on the air-cooled steel bars. This is evident from the fact that the time to cracking of concrete in the specimens prepared with the former group of steel bars was less than that in the specimens prepared with the latter group of steel bars.

4. Conclusions

The data developed in this study have indicated that water-quenching of steel bars, after hot rolling, produces a microstructure that is more corrosion-resistant than the steel bars produced by the air-cooling process. The time-to-corrosion initiation in the concrete specimens prepared with the water-quenched steel bars was longer than in the concrete specimens prepared with the air-cooled steel bars. This trend was noted in the unexposed steel bars and those exposed to the atmosphere for six months. Further, activation of reinforcement corrosion was not noted on the water-quenched steel bars exposed to atmosphere for 12 months. This indicates that the corrosion product formed on the water-quenched steel bars, due to atmospheric exposure, retards the ingress of chloride ions to the metal substrate.

The corrosion current density on the unexposed and exposed steel bars increased with the period of exposure to the chloride solution. However, the corrosion current density on the water-quenched steel bars was less than that on the air-cooled steel bars evaluated in this study.

The time-to-initiation of reinforcement corrosion, evaluated by the accelerated impressed current technique, in the concrete specimens prepared with the water-quenched steel bars was more than that in the concrete specimens prepared with the air-cooled steel bars evaluated in this study.

The longer time-to-initiation of reinforcement corrosion noted in the concrete specimens prepared with the unexposed water-quenched steel bars compared to the air-cooled bars indicates that the surface layer that is formed on the unexposed water-quenched steel bars is more protective than the mill scale on the air-cooled steel bars. It is also possible that the tempered martensite layer that is formed on the surface of the water-quenched steel bars, as a result of water-quenching, offers better corrosion-resistance to these bars compared to the ferrite and pearlite microstructure noted in the air-cooled steel bars.

Acknowledgements

The authors acknowledge the support provided by the Research Institute at King Fahd University of Petroleum and Minerals and Saudi Basic Industries Corporation (SABIC), Saudi Arabia.

References

[1] Proverbio E, Cigna R. Influence of rebar surface condition on polarization resistance measurement in concrete structures. Mater Sci Forum 1995;192–194:877–82.

[2] Al-Tayyib AJ, Khan MS, Allam IM, Al-Mana AI. Corrosion behavior of pre-rusted bars after placement in concrete. Cem Concr Res 1990;20(6):955–60.

[3] John DG, Coote AT, Treadaway KWJ, Dawson JL. Repair of concrete – a laboratory and exposure site investigation. In: Crane AP, editor. Corrosion of reinforcement in concrete construction. London: Ellis Harwood; 1983. p. 263–86.

[4] Hanson CM, Sorensen B. Threshold concentration of chloride in concrete for the initiation of reinforcement corrosion. In: Corrosion rates of steel in concrete, ASTM STP 1065. Philadelphia: American Society for Testing and Materials; 1990.

[5] Stern M, Geary AL. A theoretical analysis of the slope of the polarization curves. J Electrochem Soc 1957;104:56.

[6] Lambert P, Page CL, Vassie PRW. Reinforcement corrosion, 2. Electrochemical monitoring of steel in chloride-contaminated concrete. Mater Struct 1991;24:351–8.