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Effect of rebar cleanliness and repair materials on reinforcement corrosion and flexural strength of repaired concrete beams

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Abstract

This paper presents result of a study conducted to evaluate the effect of two rebar cleaning procedures and repair materials on reinforcement corrosion and flexural strength of repaired concrete beams. The steel bars in the reinforced concrete beams were corroded to varying degrees to simulate field situations and then repaired utilizing two different cleaning techniques and two repair materials. The repaired beams were then tested in flexure to evaluate the effect of cleaning method and repair materials on the corrosion-resistance and flexural capacity of repaired beams. The electrochemical behavior of cleaned and corroded steel bars was evaluated by conducting a DC potentiodynamic scan. The data indicated an insignificant change in the flexural strength of repaired beams regardless of the cleaning techniques or the repair materials. The accelerated corrosion data indicated lowest corrosion rate in the concrete specimens repaired with polymer-modified cement mortar after cleaning the bars by sand blasting (SB). The DC polarization data indicated the formation of a stable passive film on the steel bars cleaned by SB compared to uncleaned bars and those cleaned by wire brush.

Keywords: Accelerated corrosion; Flexural strength; Polarization of steel; Repair material; Sand blasting; Steel bar cleaning techniques

1. Introduction

Deterioration of reinforced concrete structures, due to reinforcement corrosion, and the subsequent reduction in their useful service-life has been reported from many parts of the world. Corrosion of reinforcing steel due to the use of deicer salts is noted in the highway structures in the temperate climatic conditions while this phenomenon is noted in marine environments in almost all parts of the world. In the Arabian Gulf, reinforcement corrosion is caused by the combined effect of aggressive service conditions and poor quality of the construction materials, particularly the aggregates [1].

Repair and rehabilitation of deteriorated concrete structures are essential not only to use them for their intended service life but also to assure the safety and serviceability of the associated components [2]. A good repair improves the function and performance of a structure, restores and increases its strength and stiffness, enhances the appearance of the concrete surface, provides water tightness, prevents ingress of the aggressive species to the steel surface, and improves durability.

Almusallam et al. [3] investigated the effectiveness of repair materials in improving the functional performance of beams and slabs with corroded reinforcement. In that study [3] reinforcement corrosion in the beams and slabs was accelerated by the application of a direct current for various periods of time. The deteriorated specimens were repaired and tested for flexural strength. The results indicate that not all the repair materials were able to restore the original strength of the components. One of the epoxy resin mortars investigated, as well as silica fume cement concrete, to some extent, were able to restore the original strength of the component. Furthermore, the improvement in the functional performance of the repaired structure due to the application of epoxy resin mortar was noted to be dependent on the degree of reinforcement corrosion [3].

Before repairing a deteriorated concrete structure, reinforcing steel bars are cleaned to remove the rust. This is accomplished by sand blasting (SB) to achieve a near white surface. Hand tools are also sometimes utilized to clean them prior to the application of the steel

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primer. These two cleaning procedures produce different steel surfaces, and this difference may affect the corrosion resistance of the repaired structure.

The effect of degree of rusting of deformed steel bars on the bond with concrete was reported by Johnson and Cox [4]. Their results indicated that deformed bars usually show higher bond strength at low values of slip in the rusted condition than in the unrusted condition [4]. The ultimate pullout strength of the deformed bars was not markedly affected by their rust condition. The effect on bond pullout strength produced by brushing rusted reinforcing steel bars was inconclusive: increased strength at low values of slip was produced in some cases, but little effect was produced in other cases. The total amount of slip before reaching maximum load was usually greater for bars in the unrusted or slightly rusted condition than for those that were heavily rusted [4].

A series of tests on rusty deformed bars by the Bureau of Reclamation in 1956 [5] concluded that rust was not harmful to the bond between concrete and steel and that there was no apparent advantage in removing any of the rust from the reinforcement. It was also noted that rust increases the roughness of the steel surface and tends to augment the holding capacity of the bar [5].

Almusallam et al. [6] evaluated the effect of degree of reinforcement corrosion on the bond strength between steel and concrete. The bond behavior of reinforced concrete elements, including the ultimate bond strength, free-end slip, and the modes of failure in pre-cracking, cracking, and post-cracking stages, was studied. The results indicated that in the pre-cracking stage (0–4% corrosion) the ultimate bond strength increased about 17% [6]. The initial increase in the bond strength was attributed to an increase in the roughness of the rebars and its confinement by concrete. When reinforcement corrosion was in the range of 4–6%, bond failure occurred suddenly at a very low free-end slip. At this level of reinforcement corrosion, a large slip was noted as the ultimate failure of the bond occurred due to splitting of the specimens. Beyond 6% rebar corrosion, the bond failure resulted from a continuous slippage of the rebars [6]. The ultimate bond strength initially increased with an increase in the degree of corrosion, until it attained a maximum value of 4% weight loss after which there was a sharp reduction in the ultimate bond strength for up to 6% rebar corrosion [6].

Vassie [7] investigated the effectiveness of three steel cleaning procedures on corrosion resistance of repaired concrete beams. Three steel conditions were examined namely, generally corroded, locally corroded with coarse pits, and locally corroded with clusters of fine pits. Four procedures were used to prepare the steel bars: no cleaning, manual wire brushing, powered wire brushing, and grit blasting. These treatments have been suggested as methods of removing rust from the steel before repairing. The specimens, after preparation, were exposed outside at ground level on a soil surface. They were soaked with water at two-week intervals. Corrosion potential measurement technique was chosen because it is the simplest non-destructive method of obtaining an indication of whether steel in concrete is corroding. The results show that manual and powered wire brushing are not effective for cleaning locally corroded steel and do not prevent corrosion from continuing in a repair. Grit blasting is usually effective for steel with coarse pits. Also, the results show that durability of the repair is sensitive to the steel cleaning procedure and that for steel with clusters of fine pits none was effective in preventing further corrosion [7].

Proverbio and Cigna [8] evaluated the influence of rebar surface condition on polarization resistance measurement in concrete structures. Working electrodes were made both of rust covered steel, mechanically polished steel, and pickled steel [8]. Corrosion rates were measured by means of a commercial corrosion meter. The results obtained over a period of one year showed that surface condition has a strong effect on the measurements [8]. The corrosion rate of originally rust covered steel was two times higher than that of pickled steel [8].

Al-Tayyib et al. [9] reported a slightly better corrosion-resistance of pre-rusted bars in concrete compared to clean steel bars. The rate of corrosion of steel in the concrete specimens perpared with pre-rusted bars was 0–17% less than that in the concrete specimens made with rust-free steel bars. The improved performance of the pre-rusted steel bars was attributed to the physical barrier effect of initial atmospheric rust layer that is formed on the steel. On the other hand, John et al. [10] indicated active corrosion of bars in the concrete specimens prepared with pre-rusted bars compared to those prepared with bright steel bars.

From the above literature review, it is apparent that the effect of the two rebar cleaning procedures, SB and manual hand brushing, on the quality of the repair, particularly flexural strength and the corrosion-resistance of the steel bar, is not very well investigated. Also, since cleaning the rebars using SB is very costly, there is an interest in using other methods that may result in a reduction of cost. Accordingly, the objective of this study was to evaluate the effect of rebar cleanliness and the type of repair material on the flexural strength and corrosion-resistance of repaired reinforced concrete beams.

2. Experimental program

2.1. Specimen preparation

Two sets of specimens were prepared. The first set of specimens was utilized for accelerated reinforcement

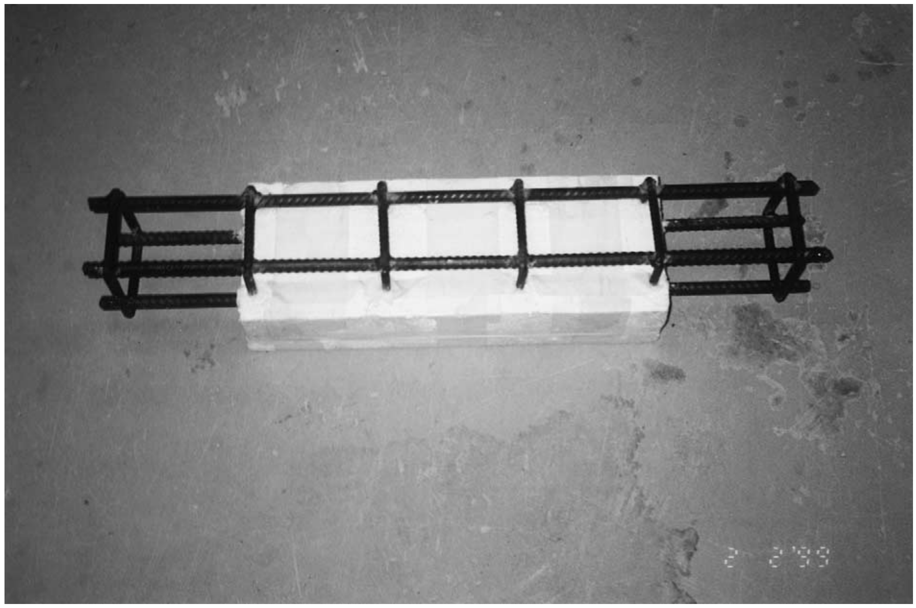

Fig. 1. Steel cage with Styrofoam before concrete casting.

corrosion studies and flexural strength determination. The second set of specimens was utilized for determining the rate of reinforcement corrosion by linear polarization resistance (LPR) measurements.

Reinforced concrete beam specimens measuring 15 cm × 15 cm in cross-section and 75-cm long were utilized for accelerated reinforcement corrosion studies and flexural strength determination. Steel cages consisting of four 12-mm diameter bars, 70 cm in length and held together with six stirrups of 9-mm diameter were fabricated. Only the top reinforcement with stirrups was exposed and the other portion was temporarily covered with Styrofoam. Fig. 1 shows the steel cage with the styrofoam before concrete casting. After casting, the specimens were cured by covering with wet burlap for 14 days. After curing, the styrofoam was removed and the exposed rebars were corroded by spraying saline water (5% NaCl) for about six months until a significant degree of reinforcement corrosion was evident. The rebars were then cleaned by the two methods, namely SB and with a wire brush (HT). After cleaning, a zinc-rich epoxy primer was applied on the rebars, and a bond coat was applied on the concrete before placing the repair mortar. Two types of repair mortars, namely polymer-based cementitious grout (PCG) and cementitious grout (CG), were utilized to repair the reinforced concrete specimens. PCG is based on Portland cement, graded aggregates, special fillers and chemical additives and is polymer-modified to provide a mortar with good handling characteristics, while minimizing water demand. CG is based on Portland cement, graded aggregates and fillers, and additives that impart controlled expansion characteristics in both the plastic and hardened states, while minimizing water demand. Moreover, two beams were cast with corroded rebars (without cleaning), and three control beams were cast with uncorroded steel bars. A total of 21 beams, as detailed in Table 1, was cast.

2.2. Test procedure

The flexural strength of the repaired and control specimens was assessed according to ASTM C 293 test

Table 1
Specimens for flexural strength and accelerated corrosion evaluation

Materials	Beams repaired by polymer-based cementitious grout (PCG)		Beams repaired by cementitious grout (CG)		Control beams	Corroded beams
Rebar cleaning technique	Hand tool (HT)	Sand blasting (SB)	Hand tool (HT)	Sand blasting (SB)	Original	Corroded rebars
Flexural strength	4[a]	4[a]	4[a]	4[a]	3	2
Accelerated corrosion	4[a]	4[a]	4[a]	4[a]	–	–
Total specimens	4	4	4	4	3	2/21

[a] Same beams were subjected to varying levels of accelerated corrosion and then tested for flexure.

procedure [11]. The specimens were placed on the testing machine with the repaired portion of the beam facing down and with a span length 65 cm. The beam supports were 5 cm away from the edge of the beam, as shown in Fig. 2. The load was applied at a rate of 0.5 kN/s. The specimens were loaded until failure, and the maximum load was recorded.

Fig. 3 shows the assembly utilized for the accelerated corrosion specimens. An open base plexiglass frame was glued on the repaired area of the specimen. A steel plate with perforations was placed on the top of the specimen so that this could be used as a counter electrode. During testing each container was filled with 5% NaCl solution. Reinforcement corrosion in the repaired beams was accelerated by impressing an anodic potential. Fig. 4 shows the experimental setup utilized to accelerate reinforcement corrosion in the repaired beams. The beams were divided into four groups. Each group consisted of four beams representing two repair materials and two steel rebar cleanliness methods. Two repair materials, namely PCG and CG were utilized to repair reinforced concrete beams. Accelerated reinforcement corrosion was induced at four levels in order to induce sufficient corrosion as detailed below:

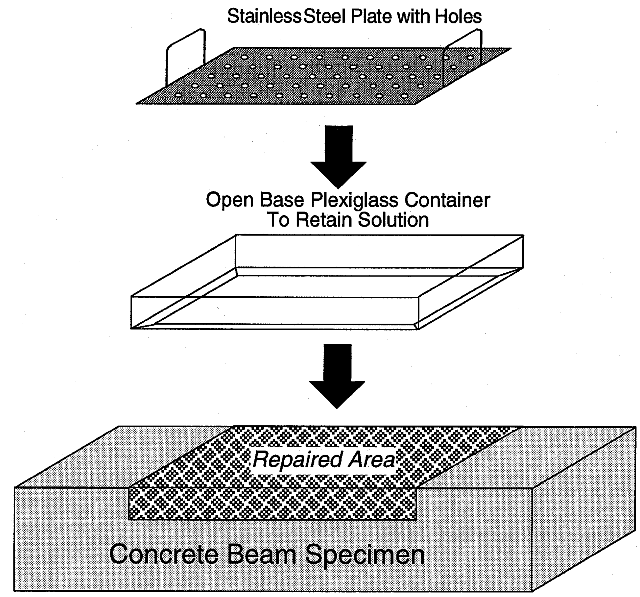

Fig. 3. Details of accelerated corrosion specimen.

Fig. 2. Setup for determination of flexural strength.

In the first group of specimens, an anodic potential of 2 V was impressed for 600 h.

The second group of specimens was initially exposed to an anodic potential of 2 V for 600 h and then to an anodic potential of 4 V for another 600 h.

The third group of specimens was exposed to an anodic potential of 2 V for 600 h, followed by 4 V for 1000 h and finally to 8 V for 600 h.

The fourth group of specimens was exposed to an anodic potential of 2 V for 600 h, followed by 4 V for 1000 h and finally to 8 V for 1800 h.

The corrosion-resisting characteristics of the corroded and cleaned bars were also assessed by conducting a potentiodynamic polarization scan. For this purpose, steel bars 12-mm in diameter and 25-mm long were prepared. The ends of the specimens were sealed with a silicon sealant so that only the curved surface was exposed to the electrolyte.

The electrochemical behavior of cleaned and corroded steel bars was evaluated in a standard corrosion cell, with saturated calcium hydroxide solution as the electrolyte to simulate concrete pore solution [12,13]. The corroded and cleaned steel specimens were connected to the cell as working electrode and two graphite rods were used as counter electrodes. A saturated calomel electrode (SCE) was used as a reference electrode. The steel specimens were polarized to ±20 mV of the open circuit potential (E_{corr}). A microprocessor-based EG&G Model 350A potentiostat/galvanostat was uti-

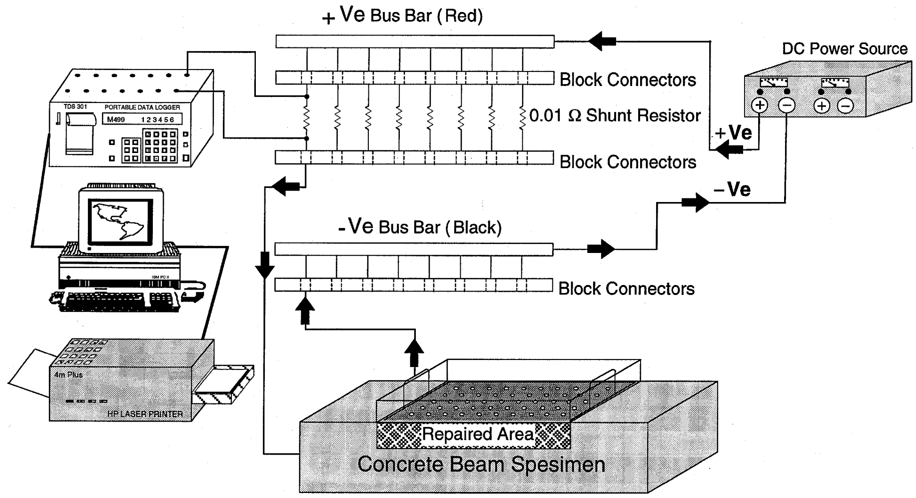

Fig. 4. Accelerated corrosion test setup.

lized for the potentiodynamic studies. The test was run at 0.1 mV/s sweep rate.

3. Results and discussion

3.1. Flexural strength

The flexural strength values of the repaired and unrepaired beams are summarized in Table 2. The average modulus of rupture for the control beams was 24.3 MPa, while for the beams with corroded (uncleaned) bars it was 18.8 MPa. A reduction of 22.6% in flexural strength was noted when corroded bars were used instead of clean bars. This reduction in the modulus of rupture could be attributed to the weaker bond between the rusted steel bars and concrete due to the presence of corrosion product [4,6]. Similar findings were reported by Almusallam et al. [14] who investigated the effect of reinforcement corrosion on flexural behavior of concrete slabs. Results of their study [14] indicated a sharp reduction in the ultimate flexural strength of slabs with up to 29% reinforcement corrosion; thereafter, the flexural strength decreased at a somewhat reduced rate with further increase in reinforcement corrosion [14].

Table 2
Flexural strength of repaired and control beams

Specimen code	Maximum load (kN)	Modulus of rupture (MPa)
Control-1	84.25	24.34
Control-2	87.35	25.23
Control-3	80.8	23.34
Corroded-1	64.31	18.58
Corroded-2	65.65	18.96
CG–SB-1	81.9	23.66
CG–HT-1	85.91	24.82
PCG–SB-1	76.76	22.17
PCG–HT-1	86.81	25.08
CG–SB-2	71.6	20.68
CG–HT-2	83.25	24.05
PCG–SB-2	78.2	22.59
PCG–HT-2	67.6	19.53
CG–SB-3	82.3	23.77
CG–HT-3	88.42	25.54
PCG–SB-3	79.95	23.09
PCG–HT-3	86.25	24.92
CG–SB-4	77.02	22.25
CG–HT-4	77.43	22.37
PCG–SB-4	72.81	21.03
PCG–HT-4	83.65	24.16

Table 3 compares the modulus of rupture for beams repaired with PCG and rebars cleaned by SB or HT techniques, while Table 4 summarizes the modulus of rupture for beams repaired with CG and rebars cleaned by SB or HT.

The data in Tables 3 and 4 provide an indication of the influence of rebar cleaning techniques, namely SB or HT, on the flexural strength of repaired concrete beams. A closer examination of these results indicates that the rebar cleaning techniques do not significantly influence the modulus of rupture of the repaired reinforced concrete beams.

Table 5 compares the modulus of rupture of beams repaired with CG or PCG and rebars cleaned by SB,

Table 3
Modulus of rupture of beams repaired with PCG and rebars cleaned by SB or HT techniques

Group number	Modulus of rupture (MPa)	
	HT	SB
1	25.08	22.17
2	19.53	22.59
3	24.92	23.09
4	24.16	21.03

Table 4
Modulus of rupture of beams repaired with CG and rebars cleaned by SB or HT

Group number	Modulus of rupture (MPa)	
	HT	SB
1	24.82	23.66
2	24.05	20.68
3	25.54	23.77
4	22.37	22.25

Table 5
Modulus of rupture of beams repaired with PCG or CG and rebars cleaned by SB

Group number	Modulus of rupture (MPa)	
	CG	PCG
1	23.66	22.17
2	20.68	22.59
3	23.77	23.09
4	22.25	21.03

Table 6
Modulus of rupture of beams repaired with PCG or CG and rebars cleaned by HT

Group number	Modulus of rupture (MPa)	
	CG	PCG
1	24.82	25.08
2	24.05	19.53
3	25.54	24.92
4	22.37	24.16

while Table 6 compares the modulus of rupture of beams repaired with CG or PCG and rebars cleaned by wire brushing. These results indicate that regardless of the repair material and the cleaning technique there was an insignificant change in the modulus of rupture of the repaired reinforced concrete beams.

3.2. Accelerated corrosion

Table 7 shows the initial current required to maintain an anodic potential of 2 V for the specimens repaired with the selected repair materials and rebar cleaning techniques. The initial current required to maintain an anodic potential of 2 V was the lowest (2.80 mA) in the PCG–SB beam specimens and the highest (7.15 mA) in the CG–HT specimens. The average initial current requirement for beam specimens CG–HT and PCG–HT, was 7.17 and 3.57 mA, respectively. A decrease of about 50% in the initial current requirement was noted for the specimens repaired with PCG over those repaired with CG when rebars used were cleaned by the HT technique. The initial current required for specimens repaired with rebars cleaned by the SB technique, but repaired with CG, and PCG was 7.40 and 2.80 mA, respectively. The data show a decrease of 62% in initial current requirement for specimens repaired with PCG over those repaired with CG.

The average initial current required to maintain an anodic potential of 2 V for the beam specimens repaired using PCG, but with the rebars cleaned by HT and SB techniques was 3.57 and 2.80 mA, respectively. A decrease of about 22% in the current requirement for switching from HT to SB cleaning of rebars prior to repair is observed. Similarly, a decrease of about 4% in the initial current is noted in the beams repaired with CG but cleaned with HT and SB techniques.

The decrease in the initial current requirement of the beams repaired with PCG, over those repaired with CG, could be attributed to the increased efficiency of the former in retarding the flow of electrons from the anode to the cathode and the flow of OH^- ions in the reverse direction. The results also indicate that the SB of rebars prior to repair gives better results in terms of lower initial current as compared to the hand tool cleaning technique, as up to 22% reduction was observed, which could be due to more thorough cleaning of rebar achieved in the SB technique.

A typical time–current curve for the repaired beams subjected to an anodic potential of 2 V is shown in Fig. 5. These curves were analyzed to evaluate the time of cracking of the repaired beams due to reinforcement corrosion. Cracking of the specimens was noted between 1000 and 1300 h of the impressed potential. Table 8 summarizes the time of cracking and the corresponding current at the time of cracking for the concrete specimens repaired using the selected repair materials and the rebar cleaning techniques.

Table 7
Initial current required to maintain an anodic potential of 2V

Sample #	Initial current (mA)				Average current (mA)
	Group 1	Group 2	Group 3	Group 4	
PCG–HT	–	3.00	3.80	3.90	3.57
CG–HT	7.60	7.70	6.60	6.70	7.15
PCG–SB	2.40	1.70	3.40	3.70	2.80
CG–SB	7.30	6.40	5.90	7.40	7.40

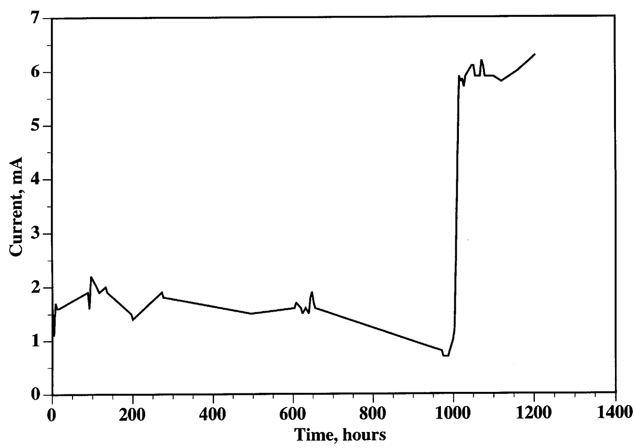

Fig. 5. Time vs. current plot for PCG–SB-2 beam.

The average time required for cracking of beam specimens CG–HT, PCG–HT, CG–SB and PCG–SB was 1010, 1007, 1129, and 1074 h, respectively. For a similar repair mortar, the time of cracking of concrete specimens in which rebars were cleaned by SB was more than that in which the bars were cleaned by HT. However, for a similar rebar cleaning process, the time of initiation of corrosion in the specimens repaired with CG or PCG did not vary very significantly. This is due to the fact that the corrosion product was noticed either at the interface of the repair material and the parent concrete or on the parent concrete portion indicating that the initial cracks must have occurred in the concrete portion. Therefore, it is reasonable to find essentially the same time of crack initiation for all the beam specimens irrespective of the type of repair mortar.

The average current at the time of crack initiation in the beam specimens CG–HT, PCG–HT, CG–SB, and PCG–SB was 10.4, 6.43, 8.3, 5.06 mA, respectively. A decrease of 38% in the current at the time of crack initiation was noted for specimens repaired with PCG over those prepared with CG when the bars were cleaned with HT technique. The average current, as seen from Table 8,

Table 8
Time to cracking of repaired concrete beams due to accelerated reinforcement corrosion

Sample #	Cracking time and current						Average time (h)	Average current (mA)
	Group 2		Group 3		Group 4			
	Time (h)	Current (mA)	Time (h)	Current (mA)	Time (h)	Current (mA)		
PCG–HT	999	7.5	1023	6.8	1000	5	1007	6.43
CG–HT	1003	16.8	1027	7.2	1000	7.1	1010	10.4
PCG–SB	1010	5.7	1043	6.5	1170	3.0	1074	5.06
CG–SB	1019	13.9	1300	3.0	1070	8.1	1129	8.3

Fig. 6. PCG–SB-4 beam after accelerated reinforcement corrosion.

Fig. 7. CG–SB-4 beam after accelerated reinforcement corrosion.

Fig. 8. PCG–HT-4 beam after accelerated reinforcement corrosion.

for the specimens in which the rebars were cleaned by the SB technique, but repaired with CG and PCG repair mortars at the time of crack initiation, was 8.3 and 5.06 mA, respectively. These data show a decrease of 39% in the initial current requirement for specimens repaired with PCG over those repaired with CG.

This decrease in current of up to 39% in the specimens repaired with PCG over CG is due to the better performance of PCG as compared to CG in terms of decreasing the electrical resistivity of the repaired beam.

The average current for beam specimens repaired with PCG, but with the rebars cleaned by the HT and SB techniques, was 6.03 and 5.06 mA, respectively. A decrease of about 16% in the current is noticed at the time of crack initiation by switching from HT to SB. Similarly, a decrease of about 20% in the current requirement is noticed for beams repaired with CG, but cleaned using the different rebar cleaning techniques. Therefore, a reduction of 16% and 20% in the current at the time of crack initiation indicates the superiority of

Fig. 9. CG–HT-4 beam after accelerated reinforcement corrosion.

cleaning of rebars using SB technique over that of hand tool cleaning [7,8].

Figs. 6 and 7 show the PCG–SB-4 and CG–SB-4 beams, respectively, after accelerated corrosion exposure. The superiority of PCG over CG in the corrosion protection is clearly visible in these two plates. A similar conclusion can be derived from comparing Figs. 8 and 9, for PCG–HT-4 and CG–HT-4 beams, respectively. Moreover, by comparing Figs. 6 and 8, it can be noted that the corrosion product formed at the interface between the concrete and the repair mortar is more in the specimens repaired with CG than those repaired with PCG. This indicates that sand-blasted steel bar corroded at a lower rate than the hand tool cleaned steel bar. A similar argument can be put forward by comparing Fig. 7 with Fig. 9.

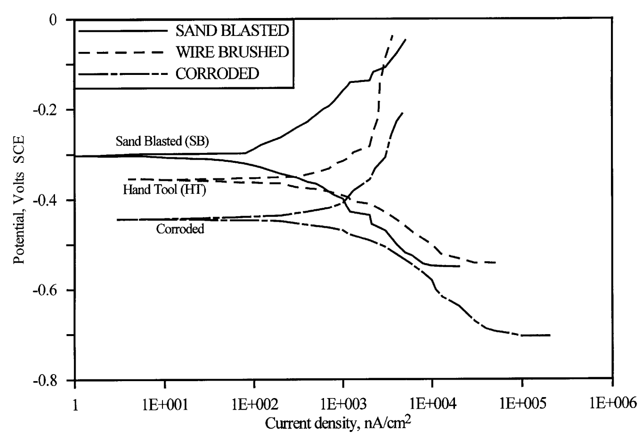

Fig. 10. Potentiodynamic curves for steel with varying surface conditions.

3.3. Electrochemical behavior of corroded and cleaned bars

Fig. 10 shows the potentiodynamic curves for the corroded steel bars and those cleaned by SB and wire brushing. The corroded steel bars exhibited a more cathodic behavior compared to the bars cleaned by wire brushing and SB. Further, the sand-blasted steel bars exhibited a more anodic behavior than those cleaned by wire brushing. The current required for the transition from the cathodic to the anodic region was almost similar in the corroded steel bars and those cleaned by wire brushing, while it was marginally lower in the steel bars cleaned by SB. Fig. 11 shows the LPR curves for SB, HT, and corroded steel specimens. From these curves, the values of E_{corr}, R_p, I_{corr}, and corrosion rate were evaluated and summarized in Table 9. The polarization resistance (R_p) of steel bars cleaned by SB was the highest followed by steel bars cleaned by hand tool. The R_p of the corroded bars was the lowest. Consequently, the average corrosion rate of sand-blasted steel was the lowest being 0.154 mils per year (mpy). The corrosion rate of wire brushed and corroded steels was 1.334 and 2.187 mpy, respectively.

The sand-blasted steel surface has the lowest corrosion rate and accordingly the best performance against corrosion. On the other hand, the uncleaned steel surface has the highest corrosion rate and accordingly the worst performance against corrosion [8]. This may be attributed to the fact that corrosion creates numerous

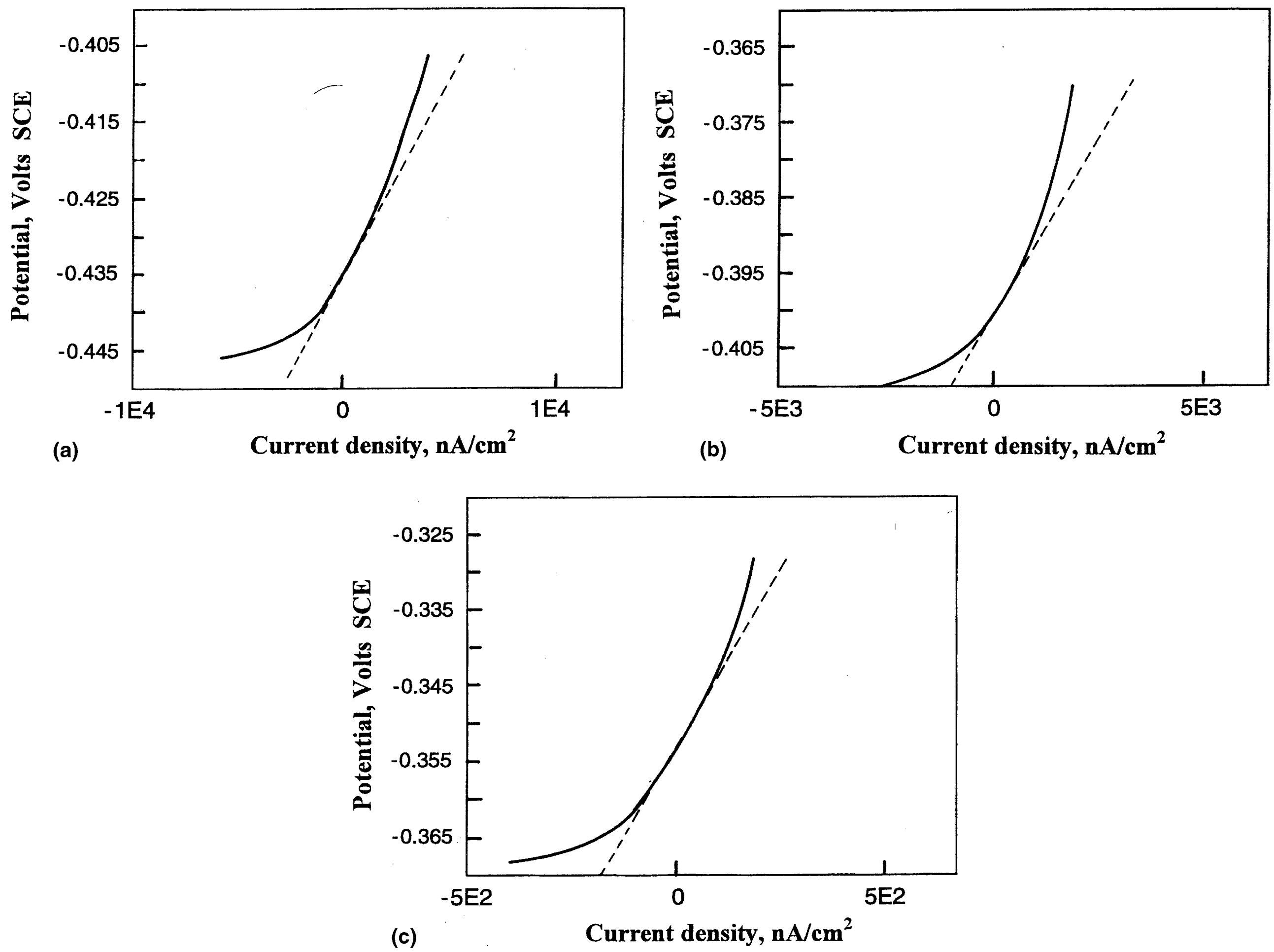

Fig. 11. Linear polarization resistance curves for steel with varying surface conditions (a) SB, (b) HT and (c) corroded.

Table 9
Results of linear polarization measurements

Sample #	Surface condition of steel	E_{corr} (mV)	R_p (Ω cm^2)	I_{corr} (μA/cm^2)	Corrosion rate (mpy)	Average corrosion rate (mpy)
1	SB	−348	9.506×10^4	0.274	0.126	0.154
2	SB	−308	6.632×10^4	0.393	0.181	
1	HT	−390	9.470×10^3	2.752	1.269	1.334
2	HT	−398	8.594×10^3	3.032	1.398	
1	Corroded	−402	5.806×10^3	4.487	2.07	2.187
2	Corroded	−426	5.218×10^3	4.994	2.303	

corrosion cells as well as cavities and pockets in the rust layers where contaminants and harmful chemicals, such as salts can collect. As soon as the surface is exposed to humid or wet condition, which induces formation of an electrolyte, the corrosion of the surface is resumed at a high rate. Moreover, the γ-Fe_2O_3 passive film does not form on the uncleaned steel surface to protect the rebar from further corrosion. The cleaning operation removes the rust layer and thus corrosion cells form on the surface of the steel. The efficiency of the rust removal depends on the extent and quality of the cleaning operation. The cleaner the surface, the fewer will be the number of remnants of corrosion product or corrosion cells. Besides, cleaning exposes the bare metal and a passive film layer can be formed in the exposed surface, which will protect the rebar from corrosion. Therefore, the cleaner the surface, the lower will be its corrosion rate at the initial stages [7,8]. However, as the corrosion of the steel is continued and corrosion products build up on an initially cleaner surface, the initial difference in the corrosion rate, due to the effect of original surface cleanliness, is expected to diminish and disappear.

4. Conclusions

1. The data on flexure strength indicate that regardless of the technique used to clean the rusted rebars, there was an insignificant change in the modulus of rupture of the repaired beams.
2. No significant change in the flexural strength of repaired concrete beams was noted regardless of the repaired mortar used.
3. The LPR data indicate that the sand-blasted steel surface has the lowest corrosion rate and accordingly the best performance against corrosion followed by the steel bars that were cleaned with wire brush. The uncleaned or rusted steel surface had the highest corrosion rate.
4. The accelerated corrosion data indicated a substantial decrease in the initial current requirement in the specimens repaired with PCG over those repaired with CG when the rebars were cleaned by hand tool or SB techniques.
5. Cleaning of bars by SB prior to repair provides better results in terms of corrosion-resistance as compared to cleaning by wire brushing. This could be due to the thorough cleaning of rebars achieved by the SB technique.
6. A decrease of up to 39% in the current at the time of crack initiation was noted for specimens repaired with PCG over those repaired with CG when rebars used were cleaned by wire brushing or SB technique. This decrease in the current requirement by the specimens repaired with the PCG over those repaired with the CG, may be attributed to the higher electrical resistivity of the former than the later.

Acknowledgements

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