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Evaluation of the short and long-term efficiencies of electro-chemical chloride extraction

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ABSTRACT

The short and long-term effects of electro-chemical chloride extraction (ECE) treatment on corrosion rate of corroded reinforcement have been studied. The factors controlling ECE treatment were identified, and the alterations which occurred in the chloride profile of the cover zone due to ECE process were followed. Contaminated reinforced OPC and SRC mortar specimens made with 1 or 2% NaCl, by mass of cement, were prepared, cured and then subjected to 3 or 5% NaCl for one year. These specimens were finally treated with ECE using various impressed current densities (1 and 2 A/m^2) and electrolytes (water and calcium hydroxide) for 2, 4 and 8 weeks. The state of corrosion was monitored regularly every 2 weeks from halting ECE process up to 52 weeks using zero-resistance ammeter device for measuring the corrosion current density of reinforcement. Selected samples from the cover zone of the untreated and treated specimens were finally taken to assess their chloride profiles.

1. Introduction

Steel-reinforced concrete is extensively used as a structural material because of its low cost and ease of construction. However, with exposure to chloride ions, the steel embedded in concrete may corrode and form expansive products at the steel/concrete interface, causing cracking and spalling of concrete cover and reducing its service life. Two rehabilitation methods are currently available and capable of stopping corrosion once it has been initiated, the conventional treatment of cathodic protection and electro-chemical chloride extraction method [1]. Both techniques normally use an impressed current that transforms the corroding steel from a collection of anodic and cathodic sites to a cathode with the addition of an external electrode and power supply to the surface of the concrete [2,3]. The resultant electrical field gradient repulses the negative chloride ions and other anions away from the reinforcing steel. In cathodic protection, an impressed current density of 3 to 20 mA/m^2 is applied for the remaining service life of the reinforced concrete structures. Electro-chemical chloride extraction (ECE), however, uses higher impressed current densities over shorter time periods, typically 0.5 to 5 A/m^2 for 2 to 8 weeks [4].

Marcotte et al. [1] studied the effect of ECE treatment on corrosion rate of reinforced OPC mortar made with 0.5 w/c ratio, 1/3 cement/sand ratio, 2% admixed NaCl and exposed to external chloride ingress of 1 mol/L NaCl. After approximately 10 months, linear polarization resistance measurements were performed on those specimens prior to ECE treatment. The extraction treatment was performed using an impressed current density of 1 A/m^2 for 8 weeks with 0.1 mol/L sodium borate as electrolyte and platinized mesh as external anode. Their results indicated that specimens exposed to external ingress chlorides exhibited lower corrosion rate than those made with admixed chlorides and the corrosion rate values remained significantly high even after 31 days of ECE treatment. These findings confirmed the results reported by Green et al. [5], who observed that, prior to the application of the extraction treatment, the corrosion rates were 80 to 350 mA/m^2, whereas immediately after the treatment, the corrosion rate was 3.2 A/m^2 and dropped to 80 mA/m^2 after 21 days of treatment. They concluded that the extraction treatment did not significantly reduce the corrosion rate of reinforcement in the period up to 21 days after the treatment was halted.

Polder [6] studied the efficiency of ECE treatment using different electrolytes, water and sodium borate and various cement types (OPC, slag cement). He reported that no influence on the chloride removal efficiency was found when the electrolyte and cement type were changed. On the contrary, Sharp et al. [4] noted that, in specimens made with OPC, 0%–52% of the chlorides were removed during ECE treatment, whereas 33%–76% of the chloride were removed from the specimens made with type II cement. These observations agrees with those obtained by Orellan et al. [7], where their results showed that about 40% of the initial chloride was removed within 7 weeks after ECE treatment.

The short-term efficiency of ECE, using impressed current densities of 1 and 5 A/m^2 for 10, 20 and 31 days as period of treatment applied on reinforced OPC mortar, was recently investigated by Toumi et al. [8] and Marcotte et al. [9]. They observed that, ECE can significantly reduce the amount of chloride ions and increase the amount of potassium and sodium ions in the region of the reinforcement.

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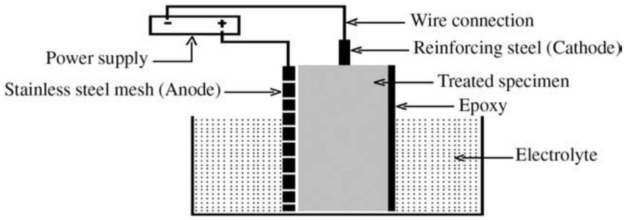

Fig. 1. Schematic drawing of ECE setting-up.

It seems from the available data in literature that most studies were concerned with the short-term effectiveness of ECE on reinforcement corrosion, while, up to the authors' knowledge, there is a lack of information regarding the long-term effect of ECE on corrosion rate after halting ECE process. It is thought that chloride ions can re-diffuse towards reinforcement after halting ECE treatment. If such phenomenon occurs, this means that the passive film created on reinforcement surface due to ECE would be disrupted again. Thus, reinforcement corrosion might take place and a remedial treatment measures has to be considered. However, this belief has to be confirmed by an experimental proof. Moreover, there is still a need to clarify the factors that could affect the long-term efficiency of ECE treatment, where a few data in literature regarding this aspect are available.

Therefore, this study was conducted with the main following objectives: —

1. To assess the long-term effect of ECE after halting the treatment on corrosion rate of re-passivated reinforcement, i.e. to study the possibility of re-starting the steel corrosion due to re-diffusion of chloride ions towards reinforcement after halting ECE treatment.
2. To clarify the factors that would control the short and long-term efficiency of ECE treatment.

2. Experimental program

Mortar mixes were prepared using two local types of cement; ordinary Portland cement (OPC) and sulphate resistance cement (SRC), complying with BS 12 (1978) and ESS 373 (1991). Natural siliceous sand with medium fineness was used. Tap water was used for mixing and curing of mortar specimens. Mild steel (240/350) of 10 mm diameter complying with ESS 262 (2000) were used for corrosion current density measurements. Stainless steel wire meshes with 2 mm and 3 mm diameter spacing were used as an anode during ECE and auxiliary electrode for zero-ammeter device. Sodium chloride (NaCl) was used as a source of chloride ions. In addition to water, calcium hydroxide ($Ca(OH)_2$) was used as an electrolyte in ECE treatment.

Four 0.5 w/c ratio mortar mixes made with either OPC or SRC and admixed with different NaCl contents (1 and 2%, by mass of cement) were prepared. A constant binder/sand ratio of 1:3 was regarded throughout. From each mortar mix, twenty four prismatic specimens ($80 \times 80 \times 300$ mm) were taken. Mild reinforcing steel bar with 320 mm length was centrally embedded in each specimen during its casting such that 280 mm was fixed inside the specimen while the remainder part (40 mm) was kept outside. The mixing and compaction processes of specimens have been carried out according to ASTM C 305-82. After casting, all molded samples were covered with polyethylene sheet for 24 h and stored in water curing tanks at constant laboratory temperature of 21 ± 2 °C and 65% RH for 27 days.

After curing, half of the specimens were submerged in 3% NaCl solution and the other half were submerged in 5% NaCl solution for 3 days and then dried in laboratory air at 21 ± 2 °C and 65% RH for another 11 days. This cycle of wetting and drying was repeated up to one year till the corrosion processes of embedded reinforcement take place. The corrosion process was monitored by zero-resistance ammeter device. This period of immersion of specimens in NaCl solution was considered to be enough for changing the state of reinforcement from passive corrosion to active corrosion, where the corrosion current density measurements of all tested specimens were greater than 0.1 $\mu A/cm^2$, as affirmed by Andrade et al. [10–12].

At end of exposure, five faces of the mortar specimens were sealed with epoxy resin, leaving one face for electrolyte exposure. The ECE was then performed by connecting the positive pole of D.C power supply with stainless steel mesh (grade No. 316), while the reinforcing steel bar of 10 mm diameter (cathode) was connected with the negative pole of D.C power supply which gives constant current density. The stainless steel mesh was attached to the specimen surface by using a glue resin. The ECE setting-up and procedures were carried out as described earlier in literature [1,3,6,8]. A schematic drawing for ECE setting-up is shown in Fig. 1. Current densities of 1 and 2 A/m^2 of mortar surface, and electrolyte types (water and calcium hydroxide) were considered. Each current density was applied for 2, 4 or 8 weeks. Immediately after halting ECE, the treated specimens were kept in a relative humidity chamber (65% RH and 21 ± 2 °C) for 52 weeks.

The corrosion current was recorded immediately after halting ECE and then regularly monitored every 2 weeks up to 52 weeks, using a zero-resistance ammeter device. A schematic drawing for zero-resistance ammeter device is shown in Fig. 2. Two electrodes were used in this adopted device, the first was an auxiliary electrode made from stainless steel mesh, attached to the specimen surface using glue resin, while the other electrode was embedded in the tested specimen (reinforcing steel bar). The full details of this test technique and its procedure were described elsewhere [13].This technique was adopted in this study because it can provide a reliable and useful information about the corrosion current density of reinforcement, as appeared from the results reported in the previous studies [13–17]. It can also be stated that this device is a simple and cheap technique for assessing the corrosion sate of reinforcement. For each case of study, the average mean of tested results for triplicate specimens was regarded.

Immediately after halting ECE process, selected samples from the untreated and treated OPC mortar specimens admixed with 1% NaCl by mass of cement and ingressed with 3% NaCl were taken at consecutive depths from reinforcement (every 7 mm) for measuring the total chloride content along the cover. The samples taken from treated specimens were chosen for those specimens treated with impressed current density of 1 A/m^2 for 4 weeks.

3. Results and discussion

To assess the short-term efficiency of ECE, the corrosion current density measurements taken after 4 weeks from halting ECE were investigated instead of relying on the measurements that were taken immediately after ECE process. This was carried out to get the reliable short-term effect for ECE on corrosion rate of reinforcement, where, earlier study carried out by Green et al. [5] indicated that the ECE did not significantly reduce the corrosion rate of reinforcement in the period up to 21 days after the treatment was halted. Moreover, the

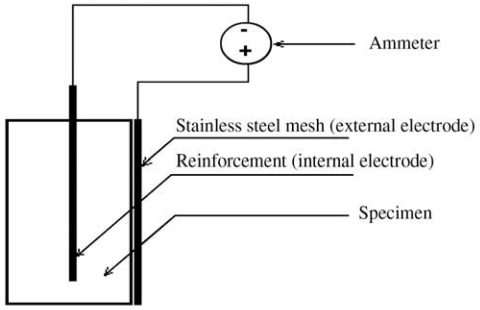

Fig. 2. Schematic drawing of zero-resistance ammeter device.

Table 1
Effect of ECE with various impressed current density (*I*) for different treatment periods (TP) on corrosion current density of reinforcement.

I, A/m^2	TP, week	Corrosion current density, μA/cm^2			Coefficient of variation, %
		Icorr1	Icorr2	Icorr3	
1	2	1.25	5.83	0.02	3.51
	4	1.25	6.25	0.01	3.66
	8	1.25	5.60	0.08	4.25
2	4	1.25	9.00	0.01	3.86

short-term effect of ECE on chloride profile of cover zone around reinforcement was also critically reviewed and signified, aiming to clarify the alterations that would occur in the distribution of chloride ions in the cover zone due to ECE treatment.

Assessment of the long-term efficiency of ECE on the rate of reinforcement corrosion is an essential task for verifying the extent of success of ECE in inhibiting/delaying reinforcement corrosion after long elapsed ages from halting ECE treatment and determining the proper time to re-start a remedial treatment, when the passive film is re-disrupted again. So, an extensive experimental program was conducted for regularly monitoring the corrosion current density (Icorr) of re-passivated reinforcement of all treated test specimens considered in the above section. Regular monitoring of Icorr was continued up to one year from halting ECE.

3.1. Short-term efficiency of ECE

The results listed in Tables 1 to 5 illustrate the effects of amount of impressed current density (*I*) applied for different treatment periods (TP), electrolyte type, content of admixed chloride, amount of external chloride and cement type on the corrosion current density of reinforcement measured immediately after halting ECE (Icorr2) and after 4 weeks from halting ECE (Icorr3), respectively. These tables also summarize the corrosion current density measurements of reinforcement prior to the application of ECE (Icorr1) and the coefficient of variations of Icorr1, Icorr2 and Icorr3 measurements. As noted from the results reported in these tables, the dispersion of the Icorr measurements is not high, where the values of coefficient of variation are lying between 3.50 and 4.50%.

Generally, it can be seen from these results that, for all considered cases of study, the values of Icorr2 are significantly higher than those of Icorr3 and greater than the corrosion rate limit for passive steel stated in literature, (0.1 μA/cm^2) [9–11]. The values of Icorr2 were always greater than those of Icorr1. This means that ECE treatment has no significant effect on diminishing the corrosion current density measurement of reinforcement, if it is monitored immediately after halting ECE. While, a substantial reduction in the corrosion current density measurements was noted when these measurements were recorded after 4 weeks from halting ECE, where all values were dramatically diminished and settled down to a value lower than 0.1 μA/cm^2.

These results also confirm that ECE can be considered as a successful technique for reducing the corrosion rate of reinforcement and inhibiting corrosion, where all corrosion current density measurements were lowered from values range from 1.25–2.5 μA/cm^2 to values of less than 0.1 μA/cm^2 (limit for passive reinforcing steel). However, one should be cautious when considering the time of assessment. So, it is not recommended to assess the corrosion rate immediately after halting ECE process but should be after about 4 weeks from halting ECE. The insignificant effect of ECE on reducing the corrosion current density of reinforcement measured immediately after treatment (Icorr2) agrees with the results obtained by Green et al. [5] who attributed this phenomena to the effects of depletion of local oxygen and increase of pH as a result of reduction of oxygen and water hydrolysis process. These effects can therefore increase the corrosion rate of reinforcement relative to the passive corrosion rate, thus keeping the values of corrosion current density in a quite higher rate of more than the limit of steel passivity (0.1 μA/cm^2). However, these effects can be vanished within a very short elapsed period from halting ECE (≈4 weeks), thus leading to a substantial reduction in the corrosion rate of reinforcement.

Table 2
Effect of electrolyte type on corrosion current density of reinforcement.

Electrolyte type	Corrosion current density, μA/cm^2			Coefficient of variation, %
	Icorr1	Icorr2	Icorr3	
Water	1.25	3.51	0.01	3.68
Calcium hydroxide	1.25	3.66	0.01	4.02

Table 3
Effect of content of admixed chloride on Icorr of reinforcement.

Admixed chloride content, % by mass of cement	Corrosion current density, μA/cm^2			Coefficient of variation, %
	Icorr1	Variation	Icorr3	
1	6.25	9.00	0.01	4.25
2	1.85	6.25	0.02	4.18

Table 1 demonstrates the effect of ECE treatment using various impressed current densities (*I*) for different periods (TP) on the corrosion current density (Icorr) of reinforcement embedded in OPC specimen contaminated with 1% NaCl, by mass of cement. As can be seen, the values of Icorr2 were increased by increasing *I* and fairly unvaried by increasing treatment period (TP). After four weeks from halting ECE, a substantial reduction in the corrosion current density was noted, compared to that measured immediately after ECE. The values of Icorr3 were not varied as a result of increasing *I* and inconsistent with altering TP. Generally all treatments considered was quite enough to return the corroded reinforcement to their passive state, where the values of Icorr were less than 0.1 μA/cm^2.

Similar observations were noted when the ECE treatment was carried out on OPC specimens contaminated with 1% NaCl, by mass of cement, using two different electrolytes (water or calcium hydroxide), as shown in Table 2, where the values of Icorr3 remained unvaried despite of the considered electrolyte. In other words, the short-term efficiency of ECE is not dependent on the nature of the adopted electrolyte. However, this observation disagrees with the findings reported earlier by Orellan et al. [7] and Toumi et al. [8], whom their observation was based on assessing the state of corrosion by taking Icorr measurements immediately after halting ECE processes. However, relying on Icorr measurements that were taken immediately after haling ECE may provide a misleading information about the real state of reinforcement corrosion, due to the effects of depletion of local oxygen and the increase of pH as a result of reduction of oxygen and water hydrolysis process, as mentioned above and in Green et al. [5]. So, the disagreement between the results reported herein and that obtained earlier [7,8] may be due to the difference in the considered time of assessment of Icorr values.

A comparison between the effects of contents of either admixed or ingress chlorides on Icorr of reinforcement embedded on OPC specimens, that were treated with 1 A/m^2 for 4 weeks, were carried out as represented in Tables 3 and 4, respectively. As shown in the table, the

Table 4
Effect of external chloride content on Icorr of reinforcement.

Chloride content, %	Corrosion current density, μA/cm^2			Coefficient of variation, %
	Icorr1	Variation	Icorr3	
3	1.25	6.25	0.01	3.66
5	2.50	6.25	0.08	3.73

Table 5
Icorr of reinforcement embedded in treated OPC and SRC specimens.

Cement type	Corrosion current density, μA/cm^2			Coefficient of variation, %
	Icorr1	variation,	Icorr3	
OPC	1.25	6.25	0.01	3.66
SRC	1.25	10.0	0.03	4.43

source of chloride (admixed or ingressed) and their contents had a slight effect on the values of Icorr3. The values of Icorr3 for specimens exposed to 5% NaCl were higher than those made with admixed chlorides. A similar comparison between corrosion current density measurements (Icorr2 and Icorr3) taken for reinforcement embedded in OPC and SRC specimens treated with 1 A/m^2 for 4 weeks was carried out, see Table 5. It can be seen that the type of cement can affect the short-term efficiency of ECE, where the values of Icorr2 and Icorr3 of reinforcement embedded in OPC specimens are lower than those of SRC specimens. In other words, ECE is more efficient in inhibiting corrosion of reinforcement embedded in OPC matrix than that embedded in SRC matrix.

Generally, ECE has been shown as a successful approach for inhibiting reinforcement corrosion caused by internal (admixed) or/and external (ingress) chloride ions. This beneficial effect of ECE can be mainly attributed to various mechanisms; electrolysis and migration of severe aggressive chloride ions away from reinforcement [12]. Electrolysis process of moisture that existed in the pore solution can lead to increase the amount of hydroxyl ions (OH^-) around reinforcement, thus leading to re-storing the passive film again around reinforcement. Meanwhile the electric field used in ECE process would lead to migration of the negative aggressive ions (Cl^-) away from reinforcement and hence reducing the possibility of occurring corrosion. In other words, the concentration ratio of Cl^-/OH^- would dramatically be decreased due to ECE processes (electrolysis and migration), thus inhibiting reinforcement corrosion process. The electric field used in ECE can also lead to transformation of the corroding steel from a collection of anodic and cathodic sites to cathodic sites [2,3]. This process would lead to changing the state of corrosion of reinforcement from an active state to a passive state.

To confirm such explanation, the chloride content along the cover zone (chloride profile) of untreated and treated OPC specimens with ECE using 1 A/m^2 for 4 weeks was measured, see Fig. 3. It can be seen that, for treated specimens, the total chloride contents of all considered depths measured from reinforcement were lower than that measured for untreated specimens, where, 30% of the initial chloride was removed from the transition zone around reinforcement. This means that ECE treatment had led to migrating and reducing chloride ions from the zone around reinforcement successfully, which agrees with the finding reported earlier by Toumi et al. [8], where their results showed that, at interface between steel and hardened cement paste, 70 to 85% of the initial chloride was removed when an impressed current density of 5 A/m^2 for 6 weeks was applied. However, the amount of chlorides removed from the treated specimens considered herein is fairly lower than that removed from specimens used in literature [6–8]. This may be attributed to the differences in considered amount of impressed current density and ECE treatment period herein and that regarded in literature.

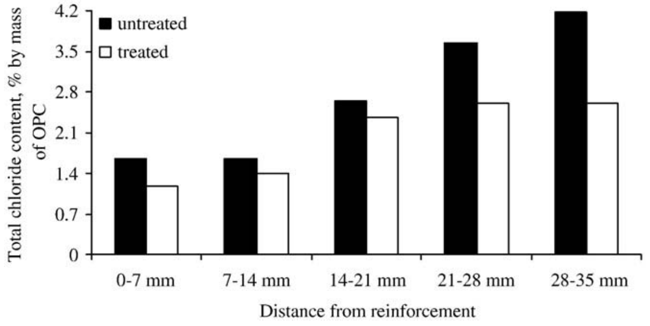

Fig. 3. Total chloride profile of untreated and treated OPC mortar with ECE.

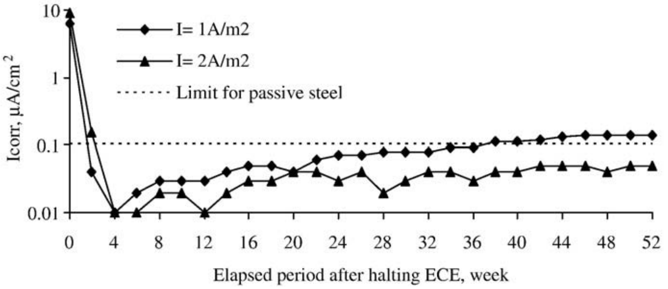

Fig. 4. Effect of impressed current density on Icorr of reinforcement.

It also seems from the results shown in Fig. 3 that not all chloride ions were removed away from reinforcement and a quite enough amount of chloride ions still remained in the cover zone after halting ECE. This amount of remained chloride ions is greater than that specified by standards and enough to disrupt the re-formed passive film around reinforcement due to ECE process. So, the dramatic reductions in corrosion rate of reinforcement (Icorr3) noted in the results tabulated in Tables 1 to 5 may be attributed not only to the reductions that occurred to the amount of chloride ions removed from the cover zone, but also due to the other mechanisms of ECE, such as electrolysis and migration of positive cations (e.g. Na^+ and K^+) towards reinforcement (cathode). These mechanisms of electrolysis and migration can lead to increasing the amount of OH^- ions and alkalinity, thus enhancing the stability of re-formed passive film around reinforcement.

3.2. Long-term efficiency of ECE

Regular monitoring of Icorr was continued up to one year from halting ECE. The results of this assessment are illustrated in Figs. 4 to 8. All recorded corrosion current density measurements were compared with the corrosion rate limit for passive steel of 0.1 μA/cm^2 [10–12], to determine the elapsed time for reinforcement to re-corrode again, i.e. when the state of reinforcement starts to alter from passive to active. This estimated elapsed time was denoted by Ta.

Fig. 4 illustrates the Icorr of reinforcement embedded in OPC specimens treated with ECE, using an impressed current of 1 and 2 A/m^2 for 4 weeks. As seen, a substantial reduction in Icorr within the first four weeks from halting ECE was produced, followed by a slight increase in Icorr with increasing the elapsed period from halting ECE. This pattern was repeatedly produced for all considered cases of study (see Figs. 4 to 8). The results plotted in Fig. 4 also show that the amount of increase in Icorr was reasonably decreased with increasing the amount of impressed electrical charges (I) considered during ECE

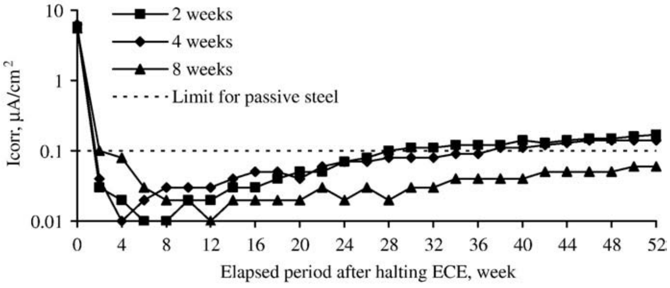

Fig. 5. Effect of ECE treatment period on Icorr of reinforcement, $I = 1$ A/m^2.

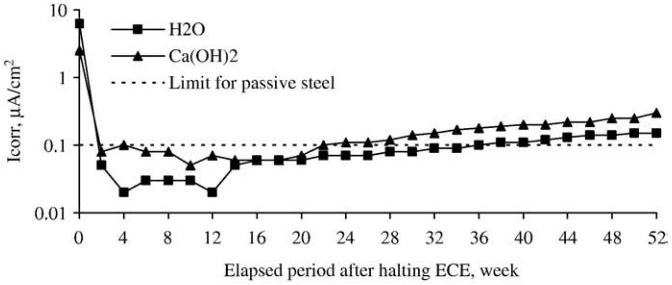

Fig. 6. Effect of electrolyte type on Icorr of reinforcement, $I = 1$ A/m^2.

processes. For specimens treated with 2 A/m^2, the reinforcement remained in a passive state of corrosion during this program of study, where all Icorr measurements were below 0.1 μA/cm^2, while for specimens treated with 1 A/m^2, the reinforcement started to re-corrode after an age (Ta) of 40 weeks, approximately.

Similarly, the Icorr values of reinforcement embedded in OPC specimens treated with ECE using an impressed current of 1 A/m^2 for different treatment periods (2, 4 and 8 weeks) were monitored and the results are shown in Fig. 5. As seen, the reinforcement of specimens treated with ECE for 8 weeks was sustained in a passive state of corrosion, where all Icorr measurements are less than 0.1 μA/cm^2. Also, prolonging the period of ECE treatment has led to a reasonable beneficial effect on reducing Icorr of reinforcement and an increase in Ta, where Icorr was increased with decreasing the period of ECE treatment, while the value of Ta increased with increasing the period of ECE treatment. The estimated values of Ta were 28 and 40 weeks for specimens treated for 2 and 4 weeks, respectively. This means that the long-term efficiency of ECE is significantly enhanced with increasing the amount of current charges that were considered in ECE, which can be achieved by either increasing the density of impressed electrical current or prolonging the period of treatment.

The gradual increase in the corrosion rate of reinforcement after halting the ECE treatment may be attributed to two main reasons; firstly, re-diffusion of Cl^- ions from the bulk of specimens and towards the reinforcement, secondly, diffusion of OH^- ions formed by electrolysis process away from transition zone around reinforcement, due to concentration gradient effect. These can lead to increasing the amount of Cl^- ions and decreasing the concentration of OH^- around the re-passivated reinforcement. As a result, the concentration ratio of Cl^-/OH^- would increase, thus increasing the possibility of disrupting the re-formed passive film that existed around reinforcement due to ECE treatment. Where, increasing Cl^- concentration and decreasing the amounts of OH^- ions can lead to increasing the acidity environment in the transition zone between reinforcement and hardened cement paste, hence, decreasing the stability of the passive film restored around reinforcement [10,18]. In other words, these processes resulted in re-depassivation of the treated reinforcement.

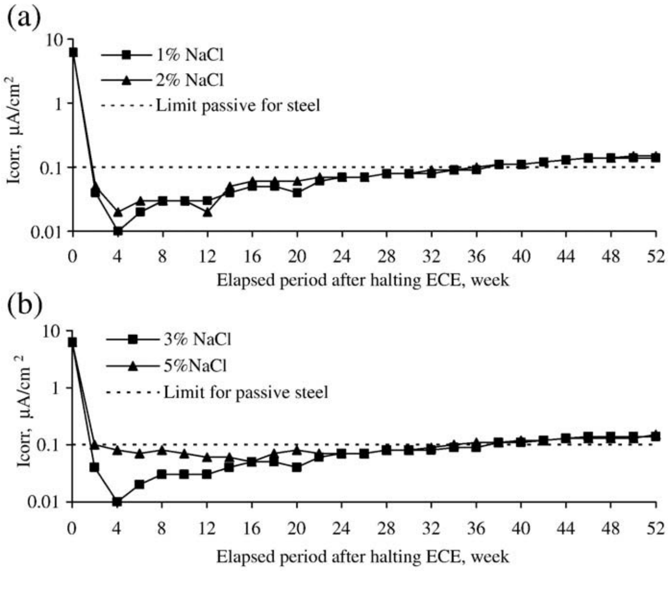

Fig. 7. Icorr of reinforcement embedded in OPC specimens attacked various chloride sources (a) admixed and (b) external and treated with ECE.

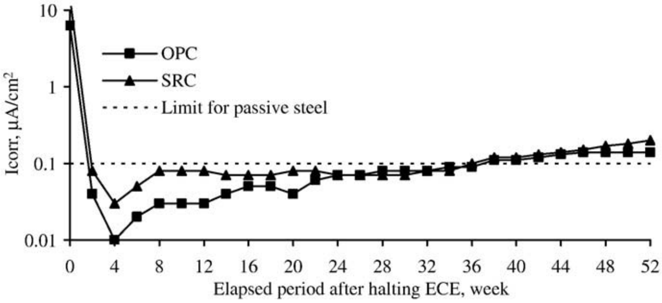

Fig. 8. Icorr of reinforcement embedded in OPC and SRC specimens treated with ECE.

The process of re-depassivation of reinforcement would be augmented with increasing the elapsed time from halting ECE treatment, due to increasing the amount of the re-diffused Cl^- ions and decreasing the concentration of OH^- around the re-passivated reinforcement. This was reflected by the increase in Icorr3 measurements with prolonging the elapsed period from halting ECE treatment. However, the process of re-depassivation can be minimized with increasing the amount of electric charges used during ECE treatment, which can be achieved by either increasing the density of electrical charges (I) or increasing the period of ECE treatment (TP). Where, increase of I or/and TP would lead to minimizing the concentration ratio of Cl^-/OH^-, which, in turn, would lead to keeping the passive state of reinforcing steel for long periods, i.e. prolonging the value of Ta, as noted from the results shown in Figs. 4 and 5.

The gradual increase of Icorr with time after halting ECE can be due to the phenomena of re-diffusion of chloride ions towards reinforcement. Re-diffusion of chloride ions towards reinforcement can lead to the increase of the amount of chloride ions around reinforcement and hence increase the value ratio of Cl^-/OH^-, thus causing re-depassivation of reinforcement again after halting ECE process by a definite period (Ta).

The impact of electrolyte type on Icorr of reinforcement was also studied, as demonstrated in the results plotted in Fig. 6. As it seemed, using calcium hydroxide as an electrolyte instead of water increased the rate of corrosion of reinforcement and reduced Ta from 40 to 22 weeks. This may be attributed the to differences in OH^- concentration gradients formed in both specimens under investigation, which in turn, can affect the rate of OH^- diffusion towards the surface zone and consequently affect the concentration ratio of Cl^-/OH^- around the reinforcement.

The effects of chloride content and cement type on Icorr of reinforcement were finally, investigated, as shown in Figs. 7 and 8. It is clear from Fig. 7 that increasing the content of either admixed (internal) or ingress (external) chloride had insignificant effect on Icorr and Ta values. On the other hand, Fig. 8 shows that, despite the slight increase in Icorr of reinforcement embedded in SRC specimens compared to that embedded in OPC specimens, the reinforcement embedded in both OPC and SRC specimens was re-corroded after about 40 weeks from halting ECE process. This means that the concentration ratios of Cl^-/OH^- around reinforcement for all considered specimens were almost comparable, hence, re-depassivation of all reinforcement embedded in these specimens has occurred with a similar extent. Consequently, the long-term efficiency of ECE is insignificantly controlled by source and content of chloride and considered matrix under treatment.

Generally, it can be noted from the results represented in Figs. 4 to 8 that, after 4 weeks from halting ECE and altering the state of reinforcement corrosion from active to passive, the corrosion current density measurements of reinforcement started to increase gradually again with time until it reached the passivity-limit for reinforcing steel (0.1 $\mu A/cm^2$). This can emphasize the fact that ECE is a temporary approach for delaying reinforcement corrosion and necessary remedial measures have to be considered afterward to stop/delay corrosion process again. So, it is vital to study the long-term performance of reinforced concrete structures after halting ECE and not to satisfy with investigating the short-term efficiency of ECE on reinforcement corrosion.

4. Conclusions

The following conclusions can be drawn from the present study:

1- Electro-chemical chloride extraction (ECE) has been confirmed to be a successful temporary remedial treatment of reinforcement corrosion. It can lead to a reasonable decrease in the chloride profile of the cover zone and a substantial reduction in the corrosion rate of reinforcement, thus transforming the state of reinforcement corrosion from active to passive.

2- Assessment of the short-term efficiency of ECE on the corrosion rate of corroded reinforcement is preferable to be carried out after a short period from halting ECE process (about 4 weeks) and not immediately after halting the treatment.

3- ECE is more efficient in reducing the corrosion rate of reinforcement embedded in OPC matrix than that embedded in SRC matrix.

4- The long-term efficiency of ECE on the corrosion rate of reinforcement after halting ECE treatment was reasonably improved with increasing the amount of impressed current charges and using water as an electrolyte. However, the source and content of chloride ions and the type of cement had insignificant effect on the long-term efficiency of ECE. On the other hand, all the above-mentioned parameters had a slight effect on improving short-term efficiency of ECE, compared to their effects on the long-term efficiency of ECE.

5- Re-diffusion of chloride ions towards reinforcement after halting ECE can be possibly be reduced with increasing the amount of impressed current considered in ECE treatment, prolonging the period of ECE treatment and using water as an electrolyte. Reducing the amount of re-diffused chloride ions can lead to reducing the rate of reinforcement corrosion and hence extending the time for reinforcement to re-corrode again.

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