EVALUATING MITIGATION METHODS FOR CHLORIDE INDUCED CORROSION OF REINFORCED CONCRETE STRUCTURES

B.H.J. Pushpakumara
Research Student
Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: janaka201@gmail.com
G. Sudeera De Silva
Senior Lecturer
Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: sudhira@cee.ruh.ac.lk
G.H.M.J. Subashi De Silva
Senior Lecturer, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: subashi@cee.ruh.ac.lk

Abstract

Corrosion of steel reinforcement in concrete causes the deterioration of concrete structures. As a result, the corrosion loss consumes considerable portion of the budget of a country by ways of either restoration measures or reconstruction. Once the corrosion signs appear, it may be too late to prevent further deterioration and no proper method to re-passivate the corroded reinforcement steel. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could contribute enormous saving.

Objective of this study is to evaluate the repairing methods for Reinforced Concrete (RC) structures, which were corroded due to chloride attack. Laboratory experiments were conducted with RC beams. The beams were cast by using Grade 20 concrete and steel bars of 16 mm diameter. Cathodic protection and electrochemical chloride ion extraction were used as treatment methods. For both methods, current was supplied by using DC power supply. The positive and negative terminals were connected to the copper mesh laid on concrete surface and steel reinforcement bars of beams, respectively. For electrochemical method, calcium hydroxide was used as an electrolyte media. Cathodic protection and electrochemical chloride ion extraction treatment remove 49.33% and 68.53% of total chloride ions from the embedded steel reinforcement bar area, respectively. Catholic protection method prevented the further corrosion possibly by removing the chloride ions, producing alkaline condition, which helps to form iron oxide film surrounding the steel bars. With the electrochemical chloride ion extraction method, calcium hydroxide helps to increase the efficiency of cathodic protection by removing the chloride ions, which approached to the copper mesh, and by reducing the time duration of cathodic protection.

Keywords: reinforced concrete, chloride attack, corrosion, repair methods, cathodic protection

1. Introduction

Corrosion of embedded steel reinforcement bars has been established as the predominant factor causing deterioration of reinforced concrete structures in worldwide, especially of the structures located at coastal marine environment. In Sri Lanka, most of reinforced concrete structures, including Reinforced Concrete (RC) and Pre-stressed Concrete (PC) bridges are situated near coastal belt. Figure 1 shows a few examples of current conditions of Sri Lankan RC structures, which were deteriorated due to chloride attack. The concrete clear cover of these structures is cracking and delaminating. In addition, the embedded steel reinforcements are exposed to the severe environmental condition, prevailing in coastal region.

Figure 1: Existing corroded structures

After initiating corrosion, the corrosion products (iron oxides and hydroxides) are usually deposited in concrete around steel reinforcements. These corrosion products are more than six times as voluminous as the steel (Hansson et al., 2007). Their formation within this restricted space sets up expansive stresses, which cause signs of deteriorations (i.e., rusting, cracking, spalling and delaminating) usually appear on the concrete surface (Veerachai et al., 2005). This in turn results in progressive deterioration of the concrete. Presence of chloride ion is probably responsible for most of the structural deteriorations caused by the corrosion of steel reinforcement.

Concrete is alkaline due to the presence of $Ca(OH)_2$, KOH, NaOH and the pH value is usually above 12 (Jerzy, 1998). Because of the alkalinity of concrete, the embedded steel reinforcements are passivated and formed iron oxide (Fe_2O_3) film surrounding the steel reinforcement bars (Hansson et al., 2007). Due to the formation of this iron oxide film, the diffusion of oxygen to surface of steel reinforcement bars is reduced. As a result, rate of corrosion also reduced. This iron oxide film is thermodynamically stable as long as the pH value of concrete remains above 11.5 (Jerzy, 1998). However, small amount of chloride ion (Cl^-) can weaken this film and initiate the corrosion (Jerzy, 1998). Corrosion of steel reinforcement bars is an electrochemical process, which needs an anode, a cathode, a metallic path and electrolytes. Oxidation occurs at the anode area of the surface of steel bar while reduction occurs at the cathode area of the surface of steel bar (Hansson et al., 2007).

The service life of RC structures can be increased by applying necessary treatments periodically. The application of treatment methods depends on several factors including current condition of RC structures, required level of treatment, cost and availability of the treatment and environmental conditions. Cathodic protection, electrochemical chloride ion extraction, repair mortars, hydrophobic treatments, anti corrosion paints, corrosion inhibitors and water proof membranes can be used as treatment methods for corrosion.

Among, the above mentioned treatment methods, cathodic protection is the most effective method for the corroded reinforced concrete structures. Cathodic protection works by using current, to shift the potential of reinforcing steel in negative direction. If the potential is shifted far enough so that all of the steel reinforcement becomes cathodic, corrosion will be stopped. An advantage of using cathodic protection as a repair method for reinforced concrete structures is that only spalls and detached concrete need to be repaired. Chloride contaminated concrete that is still sound can remain in place because the cathodic protection system prevents further corrosion and in fact, reduces the concentration of chloride ions adjacent to the protected reinforcing bars. A cathodic protection system for reinforced concrete consists of a number of basic components, including the reinforcement to be protected, an anode, a power source, a monitoring system, cabling to carry the system power and monitoring signals (Jennifer et al., 2000). The positive terminal of the power source is connected to the anode, and the negative terminal is connected to the steel reinforcement bars, which becomes the cathode. A small amount of direct current (DC) is then applied, causing current to flow through the electrolyte from the anode to the reinforcement, making the reinforcement as cathodic in relation to the anode.

The electrochemical chloride ion extraction method is similar to the cathodic protection method except the anode is placed in the electrolyte media for the purpose of absorbing and removing of chloride ions, which approached to the anode (i.e., concrete surface). The electrochemical chloride ion extraction method is a new technology and it accelerates the cathodic protection by removing the chloride ions effectively. The electrolyte media can be any of a number of different solutions such as saturated calcium hydroxide, sodium borate, sodium hydroxide or tap water. If the electrolyte is an alkaline solution, the hydroxyl ions are converted to oxygen gas and water at the anode. If the electrolyte is a relatively neutral solution, such as water, the water is converted into oxygen gas and hydrogen ions at the anode. These hydrogen ions combine with the hydroxide ions to form water, and with the chloride ions to form hydrochloric acid. Excess chloride ions are released in the form of chlorine gas at the anode. The reactions in natural solutions are not desirable because hydrochloric acid attacks the concrete and chlorine gas constitutes a health hazard. As a result, an alkaline electrolyte is usually used. These treatments remove around 20-50% of the chloride ions from the concrete, and also redistribute the remains away from the reinforcement (Clemena and Jackson, 1996).

However, in Sri Lanka, the application of treatment methods to prevent and minimize the corrosion of existing RC structures is not often done. As a result, authorities have to pay more funds for repairing the structures, which are under critical conditions. The introduction of repairing and retrofitting methods for existing corroded reinforced concrete structures are highly required for Sri Lanka. In this study, the effectiveness of the cathodic protection method and the electrochemical chloride ion extraction method are evaluated based on laboratory experiments. The comparisons of above treatment methods are also studied. The use of calcium hydroxide (hydrated lime) as electrolyte media is a new concept of electrochemical chloride ion extraction method.

2. Methodology

The corrosion process of RC beams was accelerated by using Accelerated Corrosion Test Method (ACTM). Eight reinforced concrete beams having the sizes of 400 mm x 100 mm x 150 mm were cast using Grade 20 concrete. Four steel reinforcement bars with the diameter of 16 mm were embedded into each beam as shown in Figure 2(a). A reinforcement cage was prepared by using three stirrups with the diameter of 6 mm. The cover depth was kept as 20 mm. Two wires were set to each beam for the purpose of applying current to the beams during experiments as shown in Figure 2(b). All beams were cast using continuous moulds as shown in Figure 2(c).
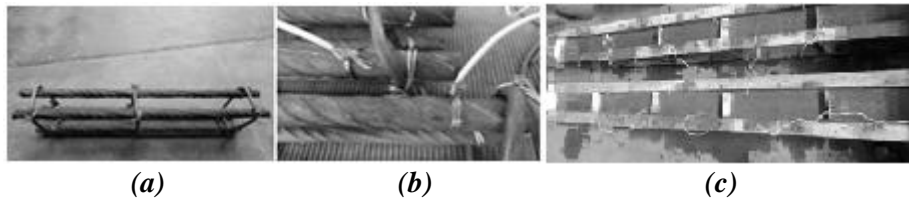

(a)   *(b)*   *(c)*

Figure 2: (a) Steel r/f cage (b) Wires were set to beams (c) Concreting beams

Stage 1: All eight RC beams were immersed in a tank for 28 days curing. After curing, one beam was tested to determine total and free chloride concentration and rust production.

Stage 2: The other seven beams were subjected to accelerated corrosion test method (ACTM) and the ACTM was carried out with monitoring the current, until the 0.2 mm wide corrosion crack was appeared in the concrete surface. After the crack was attained, one of seven beams was again tested to determine total and free chloride concentration and rust production.

Stage 3: Then, protection methods were applied to four of the remained six beams: two beams for cathodic protection and two beams for electrochemical chloride ion extraction. Other two beams were used as control beams. After completion of both treatments, one beam from each treatment method and one of control beams were tested for total and free chloride concentration measurements and rust production measurements. The other remaining treated two beams and the remaining control beam were again subjected to ACTM and the time duration for propagation of the corrosion crack of beams (crack width of 0.2 mm) was measured.

2.1 Accelerated corrosion test method (ACTM)

This test was based on electrochemical polarization principle. The experimental setup (Figure 3(a)) essentially consisted of a non-metallic container. Sea water with higher Cl⁻ concentration (i.e., concentration of Cl⁻ was improved up to 5% of sea water), was filled up to the required level of the container.
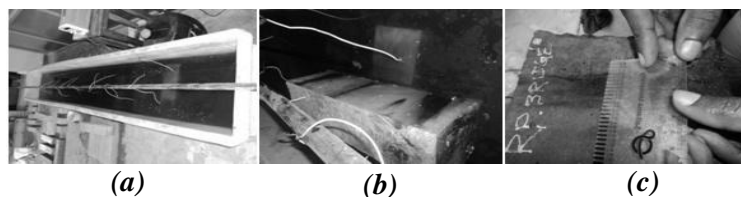

(a)   *(b)*   *(c)*

Figure 3: Accelerated corrosion test procedure
(a) Direct current was supplied (b) Corroded beam (c) Measuring the crack width

The RC specimens were immersed in this container. The reinforcement bars of the concrete specimen were connected to the positive (+) terminal and the copper electrode was connected to the negative (-) terminal of the DC power supply. This set up formed an electrochemical cell (one RC test beam) with reinforcement bar acting as anode and copper electrode acting as cathode. Similar units (RC test beams) were made and connected to a DC power supply of multi-channel system as shown in Figure 3(b). A constant voltage of 5.0 V was applied from the DC power supply. Width of the corrosion crack was monitored with time as shown in Figure 3(c), until the crack width of 0.2 mm was attained.

2.2 Cathodic protection method

As described in the methodology section (Stage 3), two beams were subjected to cathodic protection method. Copper meshes were connected to 400 mm x 150 mm surface of the test beams as shown in Figure 4(a). This surface of beam was covered by using wet sags as shown in Figure 4(b), for the purpose of touching the meshes to concrete surface well and conducting current throughout the surface. The positive terminal of the DC power supply was connected to the copper mesh and the negative terminal was connected to the steel reinforcement. Initially, 0.5 A current was supplied to the system and 11.5 V voltage difference was observed.

(a)   *(b)*

Figure 4: Cathodic protection treatment procedure
(a) *Copper mesh was fixed*   *(b) Wet sags were laid on the beams*

A constant voltage difference (i.e., 11.5 V) was applied to the system and the current was monitored (from the initial reading of 0.5 A) with time until a negligible current reading (up to 0.05 A) was obtained. Because the copper mesh acted as sacrificial anode, with time it was dissolved. After dissolving first mesh, the cathodic protection treatment was continued with another identical copper mesh. Then, one of the treated beams and a control beam were tested for total and free chloride ion concentration measurements and rust production measurement. The other treated beam was subjected to ACTM and the time taken to initiate the corrosion crack (i.e., 0.2 mm wide crack) was measured.

2.3 Electrochemical chloride ion extraction method

(a)   *(b)*

Figure 5: Electrochemical chloride ion extraction treatment
(a) Ca(OH)$_2$ layer was laid on copper mesh (b) experiment set up

The electrochemical chloride ion extraction method is similar to cathodic protection method except the copper mesh laid on concrete surface was covered by using a 5 mm thick layer of hydrated lime ($Ca(OH)_2$). With a constant voltage difference (i.e., 11.5 V), current was monitored with time until a negligible current reading was attained. After dissolving first mesh, the electrochemical treatment was also continued with another identical copper mesh and with new layer of $Ca(OH)_2$. After the negligible current reading was obtained, one of the treated beams and a control beam (same beam which used in cathodic protection) was tested for total and free chloride ion concentration measurements and rust production measurement. The other treated beam was subjected to ACTM and the time taken to initiate the corrosion crack (i.e., 0.2 mm wide crack) was measured.

2.4 Total and free chloride ion test

(a)   *(b)*   *(c)*

Figure 6: Total and free chloride ion concentration measurement procedure
(a) Concrete powder collecting (b) Sieved concrete powder (c) Titration against AgNO₃

Powder form of concrete at nine locations of the beam was collected and chloride concentration was determined by titrating against silver nitrate ($AgNO_3$). In order to collect the concrete powder, the concrete specimens were drilled at three locations (centre point and another place at both sides with 100 mm away from the centre) of one surface of beams to the depths (measured from the surface) of 20 mm, 40 mm and 60 mm. The powder was sieved through 75 μm sieve pan and two samples of 5 g for each depth level were prepared.

For titration, one sample (5 g) from each depth was mixed with 50 ml of 0.05 mol/l nitric acid (HNO_3) and stirred for 10 minutes using a magnetic stirrer to extract acid-soluble chlorides, which were mostly equivalent to total chloride. The remaining sample (5 g) from each depth was mixed with 50 ml distilled water and stirred for 10 minutes using a magnetic stirrer to extract acid-soluble chlorides which were mostly equivalent to free chloride. Each solvent sample was filtered through a filter paper. The above procedure was repeated for samples at three stages (i.e., before conducting ACTM, after conducting ACTM and after applying treatments) as mentioned in Section 2. At Stage 2, 10 ml (from 50 ml) of each solution were titrated while at Stages 1 and 3, 25 ml (from 50 ml) of each solution were titrated against silver nitrate.

2.5 Rust production measurements

(a)   *(b)*

Figure 7: Rust production measurement procedure
(a) Bars were removed from beams, (b) Scraped rust

Rust production was measured for the case of after performing of which accelerated corrosion test, electrochemical chloride extraction test and chathodic protection test, separately. Measurement was also performed by using two methods. In first method, the diameter of bars, at situations which before scraping and after scraping, was measured by using a vernier caliper. For each bar, diameters of the bar at three locations were measured and averaged. In second method, the rust production was quantified by measuring weight of the scraped rust as shown in Figure 7(b). The measurements from both methods were compared and the weight losses were determined.

3. Results

3.1 Free and total chloride ion concentrations

Tables 1 and 2 show the free and total chloride ion concentrations, respectively, for the beam depths of 20 mm, 40 mm and 60 mm at four conditions.

Table 1: Free chloride ion concentration

Depth (mm)	Chloride ion concentration (kg/m^3)			
	Before performing ACTM	*After performing ACTM*	*After performing cathodic protection*	*After performing electrochemical treatment*
20	0.282	1.471	0.346	0.25
40	0.198	0.841	0.23	0.202
60	0.124	0.431	0.13	0.122

Table 2: Total chloride ion concentration

Depth (mm)	Chloride ion concentration (kg/m^3)			
	Before Performing ACTM	*After performing ACTM*	*After performing cathodic protection*	*After performing electrochemical treatment*
20	0.41	1.64	0.831	0.516
40	0.335	1.24	0.533	0.456
60	0.24	0.771	0.407	0.368

Both free chloride ion and total chloride ion concentrations were highest after performing the accelerated corrosion test method (ACTM), compared with all other stages (Table 1 and 2). It can be seen from Tables 1 and 2 that both free chloride ion and total chloride ion concentrations decrease with depth. The highest chloride ion concentration was found at the 20 mm depth level. Comparing Tables 1 and 2, it can be clearly seen that for all depths, the total chloride ion concentration was higher than the free chloride ion concentration. For all depths, both chloride ion concentrations were lower after performing electrochemical chloride ion extraction treatment than that of after performing cathodic protection treatment.

3.2 Rust production measurements

Table 3: Weight of the rust with bar diameter

Inspection Stage	Bar (#)	Bar diameter (mm)					Weight of bars (g)		Rust production (g)	Average rust production (g)
		Reading 1	Reading 2	Reading 3	Average (each bar)	Average	Before removing rust	After removing rust		
After performing ACTM	1	15.4	15.5	15.5	15.47	15.56	526	523	3	3.5
	2	15.9	15.4	15.9	15.73		548	544	4	
	3	14.9	15.5	15.7	15.37		539	535	4	
	4	15.5	15.8	15.8	15.7		499	496	3	
After performing cathodic protection treatment	1	15.7	15.3	15.4	15.47	15.48	553	549	4	4
	2	15.7	15.3	15.6	15.53		532	528	4	
	3	15.4	15.5	15.2	15.37		557	552	5	
	4	15.7	15.4	15.6	15.57		556	553	3	
After performing electrochemical treatment	1	16.1	15.6	15.4	15.7	15.53	518	515	3	3.75
	2	15.4	15.6	15.2	15.4		537	532	5	
	3	15.3	15.5	15.6	15.47		527	524	3	
	4	15.4	15.7	15.5	15.53		519	515	4	

Table 3 shows the rust production of steel reinforcement bars for the stages of after conducting ACTM, after performing cathodic protection and electrochemical treatment. After applying the treatments, the amount of the rust was slightly increasing while the diameter of the bar was slightly decreasing compared to after performing ACTM conditions. The rust amount increment was 0.5 g for cathodic protection treatment and 0.25 g for electrochemical treatment. The amount of rust production of electrochemical treatment was lower than that of cathodic protection. The reduction in the bar diameter for cathodic protection was 0.08 mm while it was 0.03 mm for electrochemical treatment. The reduction in the bar diameter after applying the electrochemical treatment was also lower than that of after applying the cathodic protection.

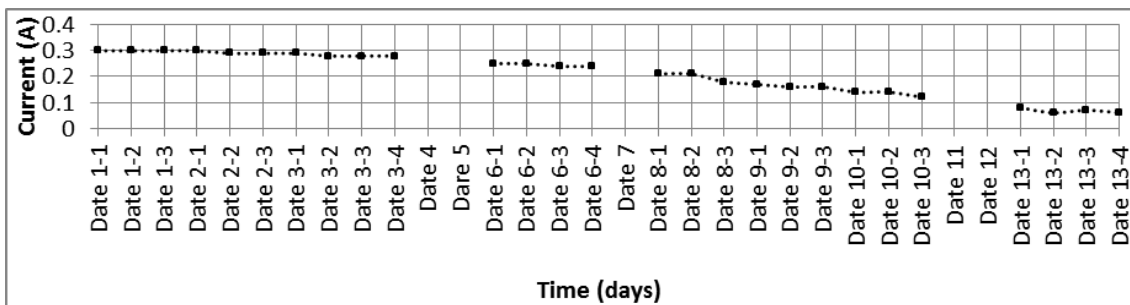## 3.3 Current measured for cathodic protection method

Figure 8: Current measurement for cathodic protection method (first mesh)
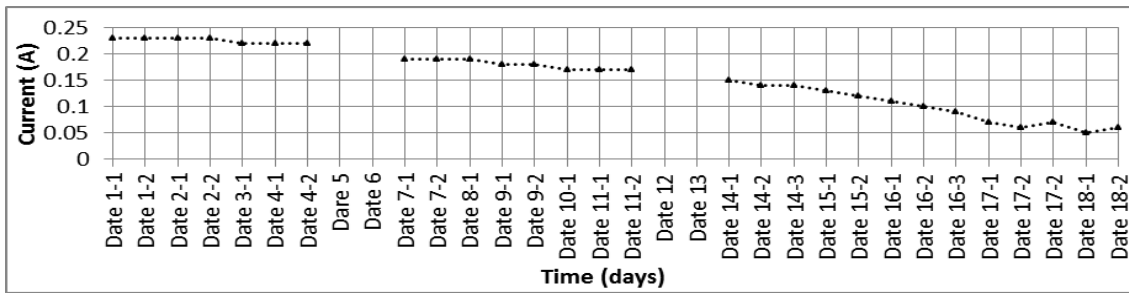
Figure 9: Current measurement for cathodic protection method (second mesh)

Figures 8 and 9 show the current reading (versus time) of cathodic protection treatment. The treatment was conducted over 31 days. Initial current reading for first mesh was observed as 0.3 A (Figure 8). Initial current reading for second mesh was observed as 0.23 A (Figure 9) and for the third mesh initial current reading was observed as 0.16 A. Therefore the total current reduction was 0.14 A.
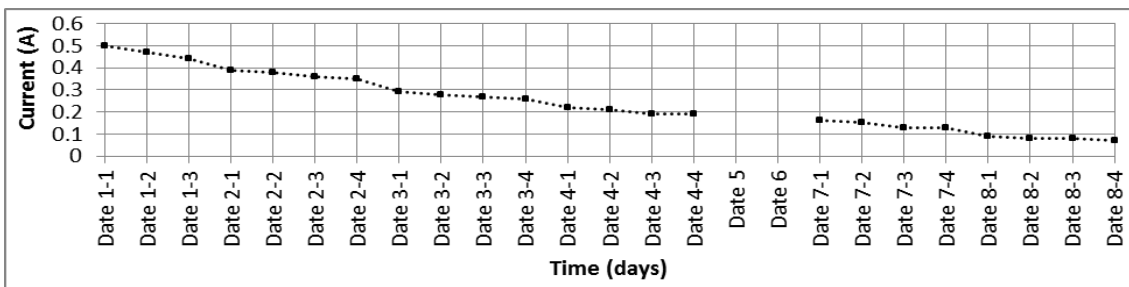

Figure 10: Current measurement for electrochemical treatment method (first mesh)
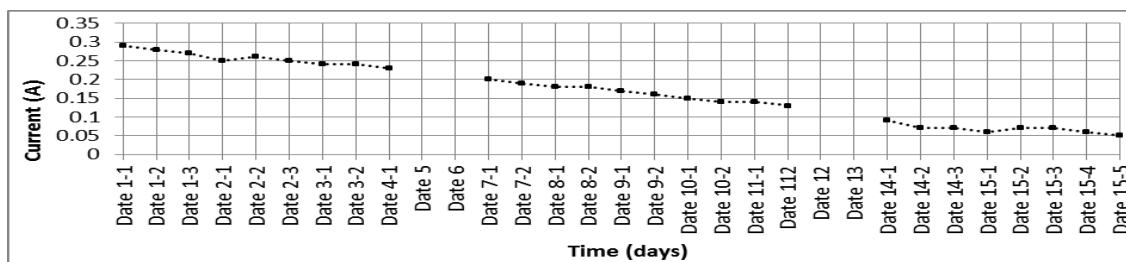
Figure 11: Current measurement for electrochemical treatment method (second mesh)

Figures 10 and 11 show the current with time for the electrochemical treatment method. The electrochemical chloride ion extraction treatment was conducted over 23 days. For the constant voltage of 11.5 V, the initial current was observed as 0.5 A (Figure 10). From the monitoring process of the current, the negligible current reading for first copper mesh was observed after 8 days. After fixing the second mesh the initial current was found as 0.29 A (Figure 11). The treatment was continued for another 15 days with the second mesh. With fixing of the third mesh at the right time (i.e., after the negligible current reading for the second mesh was obtained) the initial current reading was observed as 0.17 A. The total current reduction was found as 0.33 A.
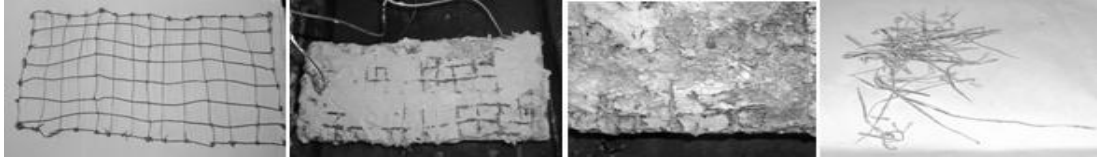
3.4 Copper mesh as anode

Figure 12: Copper mesh was dissolving with time

The copper meshes, which laid on concrete surface during treatments, were acting as sacrificial anodes. As expected, the copper mesh was dissolving with time (Figure 12). The weight of initial and remaining parts (after dissolving) of the copper meshes were measured and presented in Table 4.

Table 4: Weight losses of copper mesh

Treatment method	Mesh (#)	Initial weight (g)	Remaining weight (g)	Weight reduction (g)
Cathodic protection	1	52.6	13.1	39.5
	2	51	16.7	34.3
Electrochemical treatment	1	49.5	4.6	44.9
	2	47.4	6.3	41.1

The amount of copper dissolved by the cathodic protection method was less compared to that of the electrochemical chloride ion extraction treatment. For both treatment methods, the amount of copper dissolved from the first mesh was higher than that from the second mesh.

4. Discussion

The total chloride ion concentrations of test beams, after the 28 day curing (Table 2), were below the critical chloride ion concentration, $0.3 \sim 0.6$ kg/m^3, specified in JSCE (2001) (Veerachai et al., 2005). Therefore, it is appropriate to assume that, the beams were totally free from corrosion risk after the 28 day curing. According to the JSCE (2001), when the chloride concentration exceeds $1.2 \sim 2.4$ kg/m^3, the corrosion incorporating micro-cracks might be initiated (Veerachai et al., 2005). After performing the ACTM, the total chloride ion concentrations of test beams (Table 2) were greater than the threshold value (1.2 kg/m^3) of the chloride ion concentration. In the current study, the test beams were corroded after performing the ACTM and cracks were initiated because of the corrosion. After performing the treatments, the total chloride ion concentrations were below the threshold value (1.2 kg/m^3). This implies that the further corrosion of test beams was prevented or minimized.

Table 5: Percentages (%) of Chloride ion removed by treatment methods

Depth (mm)	Cathodic protection treatment		Electrochemical chloride ion extraction method	
	Free Cl$^-$ (%)	Total Cl$^-$ (%)	Free Cl$^-$ (%)	Total Cl$^-$ (%)
20	76.48	49.33	83	68.53
40	72.65	57.01	75.98	63.2
60	69.84	47.2	71.69	52.27

The most critical depth region related to corrosion was found as less than 20 mm, because steel reinforcements were embedded to the depth of 20 mm. In this region, the electrochemical treatment removed 68.53% of total and 83% of free chloride ions from the corroded beams (i.e., after performing ACTM) while the cathodic protection treatment removed 49.33% of total and 76.48% of free chloride ions (Table 5). When the current was supplied to the cathodic protection setup, the steel reinforcement became cathode and the chloride ions were redistributed away from the steel bars and reached towards the copper anode (at concrete surface area). This might contribute to the reduction in the chloride ion concentration near to the steel reinforcements. In electrochemical chloride ion extraction treatment, the copper mesh was covered by using electrolyte media (calcium hydroxide) and the chloride ions which approached to the copper mesh were removed by calcium hydroxide producing $CaCl_2$. It implies the efficiency of removing the chloride ion by electrochemical chloride ion extraction treatment was higher than the cathodic protection treatment.

After performing the treatments, the free chloride ion concentration of test beams decreases similar to the concentration observed at 28 day curing (Figure 13a). The treatment methods were based on the electrical system and the free chloride ions were directly contribute to the current. Therefore, admittedly, the free chloride ions were redistributed from steel reinforcements and reached towards the concrete surface area. These free chloride ions were removed by calcium hydroxide layer. On the other hand, free chloride ions caused the corrosion of steel reinforcement. The bonded chloride ions did not contribute to the corrosion process. Therefore, removing free chloride ions by these treatments is an advantage than removing bonded chloride ions.
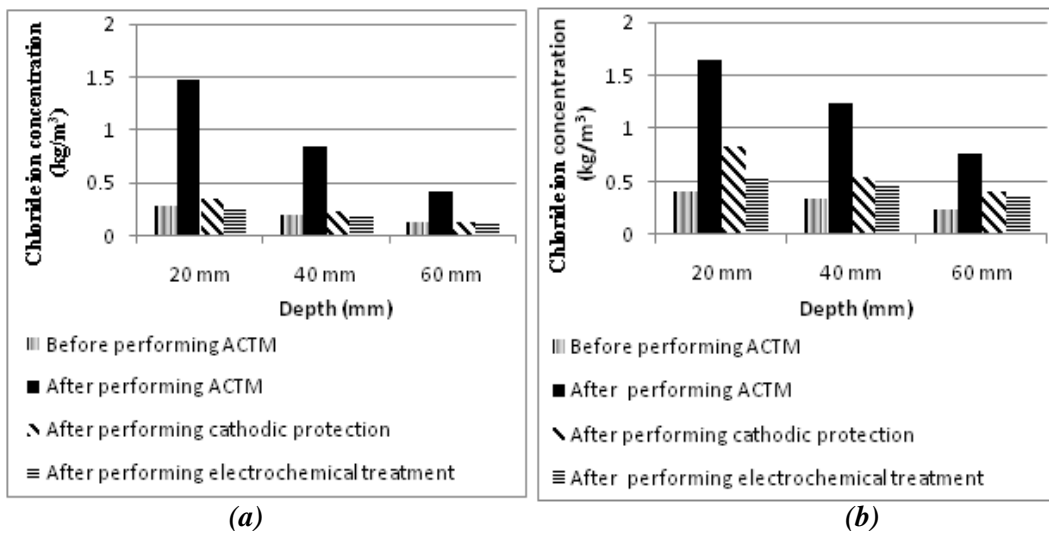

(a) *(b)*

Figure 13: a) Free chloride ion concentration (b) Total chloride ion concentrations

After performing the ACTM, 3.5 g of rust was produced. After applying the treatments, there was little or no rust production. After electrochemical treatment 0.25 g of rust amount and after cathodic protection 0.5 g of rust amount were additionally produced, compared to the rust amount produced by ACTM. These increments of rust amounts (after treatments) were lower compared to rust amount produced in corroded beam (Table 3). The reduction in the bar

diameter was reduced after performing the treatments (Table 3) implying the treatment methods minimized further corrosion.

The reduction in current of electrochemical and cathodic protection treatments also implied the reduction in chloride ion concentration of test beams (Figures 8 to 11). The efficiency of removing chloride ion for cathodic protection was 46.67% with respect to the reduction in current (Figures 8 and 9). The efficiency of removing chloride ion for electrochemical treatment was 66% with respect to the reduction in current (Figures 10 and 11). The cathodic protection was conducted over 31 days while the electrochemical treatment was conducted over 23 days. This indicates the electrochemical treatment required lesser time compared to the cathodic protection. The amount of copper mesh dissolved was higher and dissolving rate was fast for both methods (Table 4). This implies at the beginning, the rate of removing chloride from both methods was higher. The dissolved amount of copper was higher for electrochemical treatment than that of cathodic protection (Table 4). It can be concluded that, the dissolved amounts of copper mesh were directly involved in to efficiency of treatments. However, it is necessary to prevent the breakage of scattered places of mesh, in order to continue uniform current over the treated area.

In the present study, calcium hydroxide was used as an electrolyte media. The calcium hydroxide usually reacts with chloride ions and produce $CaCl_2$. The use of calcium hydroxide as an electrolyte media prevented the entering of chloride ions to RC beams by producing calcium chloride. It also helped to prevent the further corrosion, as observed in the present study. In the cathodic protection and the electrochemical treatment methods, the steel reinforcement bar became cathode with time. When the steel reinforcement bars totally charged with negative ions, further continuation of current might help to produce hydroxyl ions near to reinforcement bars, caused to create alkaline conditions. Because of this alkalinity near reinforcements, the steel reinforcements might have been repassivated and produced iron oxide (Fe_2O_3) film surrounding the steel reinforcement bars, preventing the diffusion of oxygen to steel bar area and hence preventing the further corrosion.

5. Conclusions

Introduction of treatment methods for corroded structures is highly needed to Sri Lanka, because reconstruction of corroded structures consume large amount of annual budget. In this study, effectiveness and efficiency of the electrochemical chloride ion extraction method and cathodic protection treatment method for reinforced concrete (RC) beams, which were corroded due to chloride attack, were evaluated. At the most critical depth interval, where steel reinforcements were embedded, the electrochemical treatment removed 68.53% of total and 83% of free chloride ion from the corroded beams while the cathodic protection treatment removed 49.33% of total and 76.48% of free chloride ions. The use of calcium hydroxide to cover the copper mesh in electrochemical treatment enhances the efficiency of cathodic protection by nearly 20% with respected to total chloride removal. With the calcium hydroxide layer, the time duration for completion of treatment was reduced.

The use of cathodic protection prevents the further corrosion by removing chloride ions, producing alkaline conditions around the steel bars, and helps to form iron oxide film around steel bars. With electrochemical treatment method, the calcium hydroxide helps to increase the efficiency of cathodic protection by removing the chloride ions, which are approached to copper mesh area and reducing the time duration of cathodic protection.

Acknowledgement

References

Clemena G G and Jackson D R (1996) "Pilot Applications of Electrochemical Chloride Extraction on Concrete piers in Virginia", *Interim Report, Transportation Research Council, VTRC 96-IR 4,* Charlottesville, Virginia, May 1996

Hansson C M, Poursaee A and Jaffer S J (2007) "Corrosion of Reinforcing Bars in Concrete", *R & D Serial No. 3013, Portland Cement Association,* Skokie, Illinois, USA

Jerzy Z (1998) "Modelling the Time to Corrosion Initiation for Concretes with Mineral Admixtures and/or Corrosion Inhibitors in Chloride- Laden Environments", *Virginia Polytechnic Institute and State University,* Blacksburg, Virginia, January 1998

Jennifer L k, David D and Carl E L (2000), "Evaluation of corrosion protection methods for reinforced concrete highway structures", *Structural Engineering and Engineering Materials, SM Report No.58, University of Kansas Center for Research, Inc., Lawrence, Kansas*, May 2000

Veerachai L, Toshimitsu S, Yuichi T and Masayasu O (2005), "Estimation of Corrosion in Reinforced Concrete by Electrochemical Techniques and Acoustic Emission", *Journal of* Advanced *Concrete Technology, Vol.3, No.1*, February 2005, pp.137-147