Investigation on Efficiency of Repairing and Retrofitting Methods for Chloride induced Corrosion of Reinforced Concrete Structures

B.H.J. Pushpakumara, Sudhira De Silva and G.H.M.J. Subashi De Silva

Abstract: The corrosion of steel reinforcement bars is one of the major deterioration mechanisms of Reinforced Concrete (RC) structures. Once the corrosion signs appear on the concrete surface, it may be too late to prevent further corrosion. As a result, service life of RC structures would be reduced. Use of repairing and retrofitting methods at the appropriate time will contribute enormous saving of country budget, which is required for re-construction. This paper presents an experimental investigation of repairing and retrofitting methods for the RC structures corroded due to chloride attack. As repairing methods for delaminated areas of corroded RC structures, Fly Ash (FA) and Silica Fume (SF) mixed mortars were developed and their performances were evaluated. As retrofitting methods, Cathodic Protection (CP) and Electrochemical Chloride Extraction (ECE) were conducted. ECE method is similar to CP method except the anode was covered by $Ca(OH)_2$ layer. RC beams with concrete of Grade 20 and reinforcement bars of 16 mm diameter were cast. Efficiency of both repairing and retrofitting methods was evaluated by measuring free and total chloride ion concentration and rust production. Efficiency of repairing and retrofitting methods was further evaluated by measuring resistivity and Rapid Chloride Permeability Test (RCPT) and current measurement, respectively. FA mixed mortar reduces the total chloride ion concentration near embedded steel reinforcement bars in concrete by 40% while SF mixed mortar reduces 25% compared to OPC mortar. FA and SF mixed mortars prevent the corrosion process by minimizing the diffusion of chloride ions into concrete. It was found that CP method removed around 49% of total Cl^- while ECE method removed around 69% of total Cl^- near the steel reinforcement of RC beams. Removing of total Cl^- by ECE is grater (in 20%) than that of by CP method. Chloride contaminated concrete that is still sound can be retrofitted by using CP and ECE methods and the spalled and detached concrete can effectively be repaired by using FA mixed mortars.

Keywords: Accelerated Corrosion Test Method (ACTM), chloride attack, corrosion, repairing mortars

1. Introduction

Sri Lanka is an Island surrounded by the Indian Ocean and has large number of Reinforced Concrete (RC) structures near the coastal belt. These structures are suffered by chloride ion induced corrosion; therefore the service life of these RC structures may be reduced. When use of the structures is critical, the authorities have to use reconstruction measures. As a result, considerable portion of country's budget are consumed for reconstruction of corroded RC structures.

The use of effective repairing and retrofitting methods at right time helps to increase the service life of RC structures, as result there will be enormous saving of country's budget. If a RC structure is cracked or spalled or delaminated (Figure 1), repairing of these damaged areas must be done using mortars before applying the retrofitting methods.

Figure 1 - Existing corroded bridge girders

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Most of repairing mortars minimize the diffusion of chloride ions to steel reinforcements by increasing the density of repair mortar, producing chemical reaction with chloride ions, applying water proof materials and applying hydrophobic agents with repair mortars (Jennifer et al. [8]). These repair mortars could normally consist of more than one type of cement (special cement, like ultra-fine alumina cement), additions (silica fume, slag or fly ash), aggregates (normal, light weight and special type fillers), admixtures (such as plasticizers), air-entrainers and accelerators, polymer additives and fine polymer fibers (Saraswathy and Song [11]). The Fly Ash (FA) and Silica Fume (SF) are normally used during concrete batching to increase the density and strength. Therefore, FA and SF would be effective admixtures to increase the density of repairing mortars. According to Detwiler et al. [3], the optimal replacement percentage of cement (by mass) in concrete by using SF is between 6% and 8%. The amount of FA between 25% and 60% of cement weight were normally used to produce sustainable, high performance concrete mixtures (Aggarwal et al. [1]).

Cathodic Protection (CP) is one of most effective retrofitting method for the corroded RC structures. CP works by using current, to shift the potential of reinforcement steel in negative direction. If the potential is shifted far enough so that all of the steel reinforcements behave as cathode, in which corrosion will be terminated. An advantage of using CP method as a retrofitting method for RC structures is that only spalled and detached concrete need to be repaired. Chloride contaminated concrete that is still sound (i.e., no any visible external damages like cracking and spalling) can remain in place, because the CP system prevents further corrosion and in fact, reduces the concentration of chloride ions adjacent to the protected reinforcement bars.

The Electrochemical Chloride ion Extraction (ECE) method, which is another retrofitting method, is similar to the CP method except that the anode in ECE method is covered by a chemical media. This chemical media absorbs Cl^- which approach towards the anode area (i.e., concrete surface). ECE method is a new technology and it accelerates the efficiency of CP method by removing the Cl^- effectively. The chemical media can be any of alkaline solutions which react with Cl^- and produce chloride salt of particular cation (Virmani and Clemena [13]). Further, $Ca(OH)_2$, which is an alkaline

solution, would react with Cl^- and produce $CaCl_2$ salt. Formation of $CaCl_2$ salt will prevent the present of free Cl^- near anode, which helps to continue current path without restriction. Therefore, $Ca(OH)_2$ would be an effective chemical media for ECE method.

Use of repairing and retrofitting methods at right time, helps to increase service life of RC structures which save the financial expenditures of a country for reconstruction. Therefore, it is an urgent need to introduce suitable repairing and retrofitting methods for RC structures in Sri Lanka.

The objectives of this study are;
- To identify the performances of Fly Ash and Silica Fume mixed mortars for corrosion
- To determine and compare the performances of Cathodic Protection and Electrochemical Chloride ion Extraction methods
- To identify the performances of $Ca(OH)_2$ as a new chemical media for Electrochemical Chloride ion Extraction method

2. Methodology

Fly Ash (FA) and Silica Fume (SF) mixed mortars were evaluated as mortars for repairing spalled and detached RC structures. Cathodic Protection (CP) and Electrochemical Chloride ion Extraction (ECE) were evaluated as retrofitting methods for chloride ion contaminated concrete which is still sound.

2.1 Repairing Methods

Five RC beams were cast with concrete of Grade 20 and reinforcement bar diameter of 16 mm. Three steel stirrups with diameter of 6 mm were used in each steel reinforcement bar cage. Size of the RC beams is 380 mm x 80 mm x 130 mm and the clear cover is 10 mm (Figure 2).
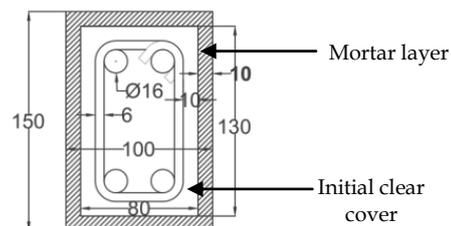

Figure 2 - Schematic diagram of cross section of RC test beam (Dimensions are in mm)

All the RC beams were immersed in water for 28 days of curing. After curing, RC beams were covered by using mortar layers. The mortars were prepared with the cement sand ratio of

1:3. Surfaces of RC beams were chipped and 10 mm thick mortar layers were applied as the final clear cover was to be 20 mm (Figure 2). Cement in the mortar was partially replaced by adding FA and SF on weight basis. Two beams were treated with 50% of FA mixed mortar and other two beams were treated with 10% of SF mixed mortar. The remaining RC beam was used as the control beam with 10 mm thick OPC mortar layer.

After applying mortars, RC beams were again immersed in water for 28 days of curing. After 28 days curing, the RC beams were subjected to Accelerated Corrosion Test Method (ACTM) until 0.2 mm corrosion crack width was attained. Then, free and total chloride ion concentration, rust production and resistivity of the RC beams were determined. In addition, chloride ion permeability through mortars was evaluated by conducting Rapid Chloride Permeability Test (RCPT).

2.2 Retrofitting Methods

Eight RC beams having the sizes of 400 mm x 100 mm x 150 mm were cast using Grade 20 concrete. Four steel reinforcement bars with diameter of 16 mm were tied into a cage by using three steel stirrups, whose diameter is 6 mm. Two wires were set to each beam for the purpose of applying current to the beams during experiments. The cover depth was kept as 20 mm. All RC beams were immersed in a water tank for 28 days of curing.

Corrosion in seven RC beams was accelerated by performing ACTM until 0.2 mm corrosion crack width was attained. The remained RC beam was not subjected to ACTM and it was labelled as "before performing ACTM beam" and used as control beam to identify effect of ACTM on corrosion. This control beam and one beam out of seven corroded beams by using ACTM were tested for free and total chloride ion concentration and rust production measurements in order to identify the effect of ACTM on corrosion of RC beams.

Four RC beams (i.e., two beams for each retrofitting method) were retrofitted by using CP and ECE methods. Other two beams were used as control beams. Three of these beams (i.e., control beam and one beam from each retrofitting method) were tested for free and total chloride ion concentration and rust production measurements in order to determine effectiveness of each retrofitting method. The remaining three beams; (i.e.,

control beam and one beam from each retrofitting method) were again subjected to ACTM. Resistivity of these three RC beams was measured by using Resistivity meter (James – RM8000).
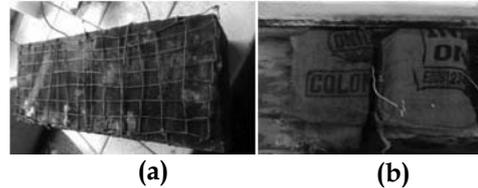
2.2.1 Cathodic Protection (CP) Method

(a)   (b)

Figure 3 - CP method procedure (a) Copper mesh was fixed (b) Wet sags were laid on the beams

Copper meshes were connected to 400 mm x 150 mm surface of each RC beam as shown in Figure 3(a) and the mesh was covered by using wet sags for the purpose of contacting the mesh with concrete surface (Figure 3(b)). The current was supplied by using a Direct Current (DC) power supply unit; the positive terminal was connected to copper mesh (i.e., anode) and the negative terminal was connected to embedded steel reinforcements which would be the cathode. Since the higher current flow cause hydrogen ion generation, current should be maintained below 1 A (Jennifer et al. [8]). Hydrogen ion generation can cause the brittle failure of RC structures. Therefore, a current of 0.3 A was supplied initially. The current of 0.3 A could be supplied with the voltage of 11.5 V. This lead to which the current was supplied to the system with a constant voltage of 11.5 V and was monitored with time until a negligible current reading (current reading < 0.1 A) was observed.

2.2.2 Electrochemical Chloride ion Extraction (ECE) Method

(a)   (b)

Figure 4 - ECE method (a) Ca(OH)$_2$ layer was laid on copper mesh (b) Experimental

In this method, copper meshes were connected to RC beams as similar to that in CP method presented in Section 2.2.1. The meshes were covered by using hydrated lime (Ca(OH)$_2$) layer of 5 mm thickness (Figure 4(a)). Similar to the CP method, electric system was prepared and the current was supplied (Figure 4(b)). In

ECE method also, the current was monitored with time until a negligible reading (i.e., current reading < 0.1 A) was observed.

2.3 Laboratory Experiments
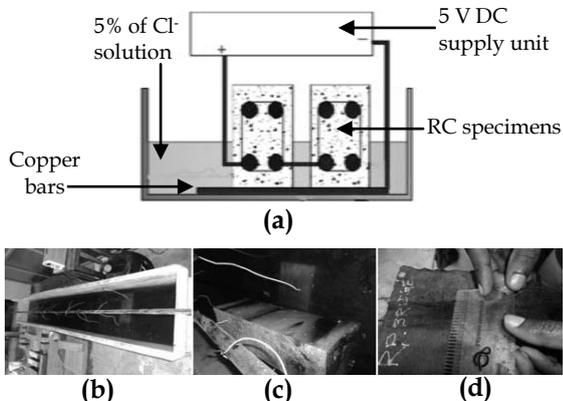
2.3.1 Accelerated Corrosion Test Method

(a)

(b) **(c)** **(d)**

Figure 5 - (a) ACTM procedure (b) DC was supplied (c) Corroded beam (d) Measuring the crack width

ACTM was based on the electrochemical polarization principle. The corrosion of embedded steel reinforcement bars were accelerated as specified in FDOT 2000 [4] and Sahmaran et al. [10]. The beams were immersed in a sea water container where the Cl- concentration of sea water was improved up to 5% by adding NaCl. The NaCl concentration of sea water sample was measured by using titration against $AgNO_3$ and was observed as 34.8 g/l. The current for the system was supplied by using a DC power supply unit (Figure 5(a) and 5(b)). The positive terminal of the unit was connected to the embedded steel reinforcement bars and the negative terminal was connected to the copper bars which were placed under the RC beams. Then, a small current was supplied to the system with the constant voltage (5 V). Finally, the corrosion crack width was monitored with the time as shown in Figure 5(d), until 0.2 mm corrosion crack width was attained.

2.3.2 Free and Total Chloride ion Concentration

Test samples were prepared by collecting the concrete powder at nine locations of each RC beam; three points of 400 mm x 150 mm surface: centre point and two points (100 mm away from the centre, at both sides). At each point, samples were collected at 20 mm, 40 mm and 60 mm depth. For each beam, the concrete powder samples, which were collected at the same depth, were mixed and separately sieved

through 75 μm sieve pan. For each depth, two samples of 5 g were prepared to measure total and free chloride ion concentrations.

One sample (5 g) 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 ions. Free chloride ion concentration was measured using the remaining 5 g sample. The sample was mixed with 50 ml distilled water and stirred for 10 minutes using a magnetic stirrer to extract water-soluble chlorides ions which were mostly equivalent to free chloride ions. Each solvent sample was filtered through a filter paper. Finally, all filtered samples were titrated against silver nitrate ($AgNO_3$) and the free and total chloride ion concentrations were measured.

2.3.3 Rust Production

Rust production of embedded steel reinforcement was measured by using two methods: rust weight and reduction in bar diameter. The steel bars were carefully removed from the beams and the bar surface was scrapped in order to collect rust. The weight of the collected rust was measured. The bar diameter was measured by using a vernier calliper and the reduction in bar diameter was determined. The average values of rust weights and reduction in bar diameter were calculated to determine the rust production of steel bars.

2.3.4 Resistivity
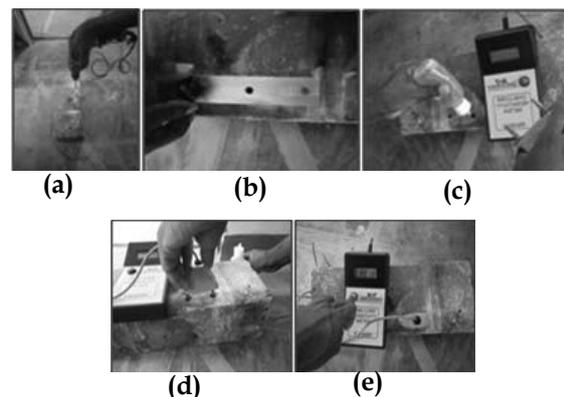

(a) **(b)** **(c)**

(d) **(e)**

Figure 6 - Procedure of measuring resistivity (a) Preparation of 8 mm depth hole (b) Preparation of additional hole at 50 mm apart (c) Use of conductive gel (d) Placing Resistivity meter (e) Measuring resistivity

Resistivity meter (James RM-8000), which is capable in assessing the possible rate of corrosion in reinforcement bars with the electric

resistivity measurement method, was used to measure the internal corrosion level. Two holes with the diameter of 6 mm and the depth of 8 mm, 50 mm apart (along the reinforcement bar), were drilled on the surface of beam (Figure 6(a)). The stainless steel template plate, which was given with the equipment, was used to identify the location of the additional holes (Figure 6(b)). The two holes were filled with dispenser conductive gel (Figure 6(c)). This was necessary to create proper contact between concrete and Resistivity meter probes, which, was connected to the holes as shown in Figure 6(d). Resistivity (in k Ohms cm) was measured and the possible corrosion rate (possible corrosion rate for resistivity: <5 = very high, 5-10 = High, 10-20 = Moderate to low and >20 = Insufficient) of steel reinforcement bars was determined by referencing the resistivity levels provided with the Resistivity meter (Instruction manual [9]).
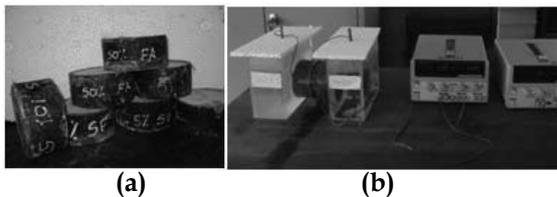
2.3.5 Rapid Chloride Permeability Test

(a)   (b)
Figure 7 - RCPT setup (a) Repair mortar cylinders (b) RCPT experimental setup

Rapid Chloride Permeability Test (RCPT) was performed for FA mixed and SF mixed mortars to evaluate permeability as specified in ASTM C1202 (Ganesan et al. [5]). Twenty one mortar cylinders (i.e., three cylinders for each mortar percentage and three OPC mortar cylinders) (Figure 7 (a)) having a diameter of 100 mm and a thickness of 50 mm were cast by using 1:3 cement sand mortar; cement in the mortar was partially replaced by FA and SF, in weight basis, as summarized in Table 1.

Table1 - Admixture replacement level

Type of mortar	Admixture replacement percentages (%)
Control (OPC)	0
Fly Ash (FA)	25, 50, 75
Silica Fume (SF)	5, 10, 15

After 90 days of curing, all the cylinders were set to the RCPT experimental setup (Figure 7(b)). Two copper electrodes were connected to terminals and the positive terminal was immersed in NaOH solution (with possessed normality of 0.3 N) reservoir while the negative terminal was immersed in 3% of NaCl solution

reservoir. The cylinders were connected between two reservoirs as shown in Figure 7(b). A constant voltage of 60 V, DC was supplied to the system and current across the cylinders were recorded at 30 minute intervals over the period of 6 hours. The total Charge Passed (CP) through the specimen was computed by Simpson's rule (Equation 1) as specified in the ASTM C1202 (Ganesan et al. [5]).

$$CP = 900[I_0 + 2I_{30} + 2I_{60} + 2I_t + \cdots + 2I_{330} + 2I_{360}] ----(1)$$

where CP is total charge passed in coulombs, I_0 is the initial current in Ampere (A) and I_t is current in Ampere (A) at time t, measured in minutes.

3. Results

3.1 Efficiency of Repairing Mortars

Efficiency of the repairing mortars was investigated by free and total chloride ion concentration, rust production, resistivity and permeability and is presented in this section.

3.1.1 Free and Total Chloride ion Concentration

Figures 8 and 9 show free and total Cl⁻ concentration of RC beams, respectively. The Cl⁻ concentration was determined at four different stages: before performing ACTM, after performing ACTM for OPC, FA mixed and SF mixed mortar laid RC beams.
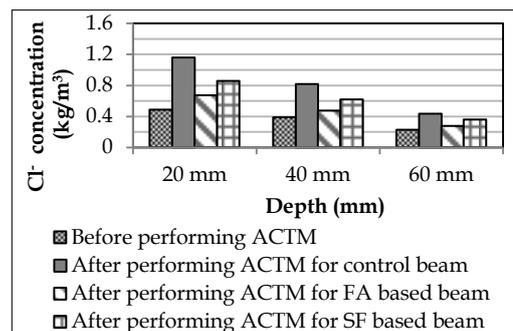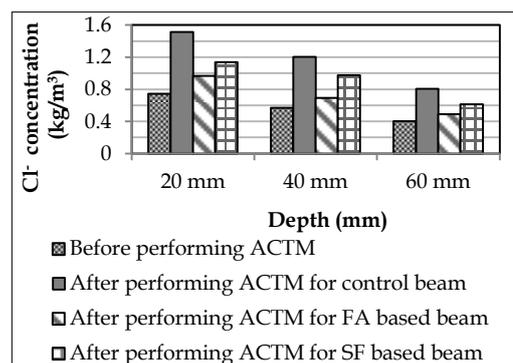

Figure 8 - Free chloride ion concentration

Figure 9- Total chloride ion concentration

It was observed that free and total Cl⁻ concentrations decreased with increasing depth of the beam. This trend was common at all the four stages. For all depth levels (i.e., 20 mm, 40 mm and 60 mm), total Cl⁻ concentration was higher than the free Cl⁻ concentration. Generally, Cl⁻ concentration is greater after performing ACTM compared to the concentration before performing ACTM. After performing ACTM, in repaired beams both free and total Cl⁻ concentrations were less than those for the control beam. At 20 mm depth level, after performing ACTM, the total Cl⁻ concentration is 1.514 kg/m³ for OPC mortar. At the same depth, FA and SF mixed mortar applied beams which were subjected to ACTM simultaneously with the OPC mortar applied beam, have lower Cl⁻ concentrations: 0.97 kg/m³ for FA mixed mortar and 1.14 kg/m³ for SF mixed mortar, respectively.

3.1.2   Rust Production

Rust weights and reduction in bar diameter of repaired RC beams, which were tested after performing ACTM, are shown in Table 2.

Table 2- Rust production

Inspection Stage		Average weight of rust (W) (g)	Average bar diameter (Φ) (mm)	Average reduction in bar diameter (Φ$_r$) (mm)
Initial condition		0	16	0
After performing ACTM	OPC mortar	7.8	13.57	2.43
	FA mixed mortar	1.76	15.81	0.19
	SF mixed mortar	3.64	14.75	1.25

It can be seen from Table 2 that, in the FA and SF mixed mortar applied beams, the average weight of rust and reduction in bar diameter (after performing ACTM) were lesser values compared to that of OPC mortar applied beams. The rust production (rust weight (W) and bar diameter reduction (Φ$_r$)) of beams repaired with FA mixed mortar (W = 1.76 g and Φ$_r$ = 0.19 mm) was lower than that of the beam repaired with SF mixed mortar (W = 3.64 g and Φ$_r$ = 1.25 mm).

3.1.3   Resistivity

Resistivity of RC beams (OPC, and 50% of FA and 10% of SF mixed mortar applied) which were subjected to ACTM is shown in Table 3.

Table 3- Resistivity of mortars

| Mortar condition	Average resistivity (k Ohms cm)
OPC	1.8
50% of FA	12.0
10% of SF	9.05

It has been clearly seen that resistivity in the OPC mortar applied beam was very much lower (i.e., 1.8 k ohms cm) compared to that of FA and SF mixed mortar applied beams (FA = 12.0 k Ohms cm and SF = 9.05 k Ohms cm). The resistivity of beams repaired by FA mixed mortar is slightly larger than beams repaired by SF mixed mortar.

3.1.4   Rapid Chloride Permeability Test

Variation of current with time for the FA mixed and SF mixed mortar cylinders is shown in Figures 10 and 11, respectively.
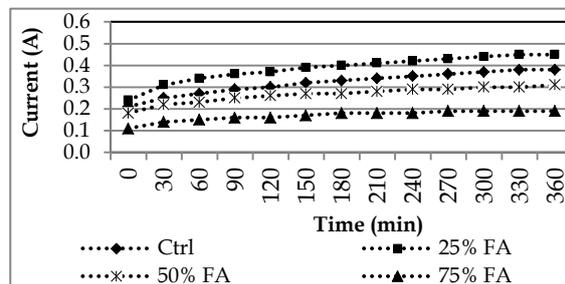
Figure 10- Current measurement of RCPT for FA mixed mortar
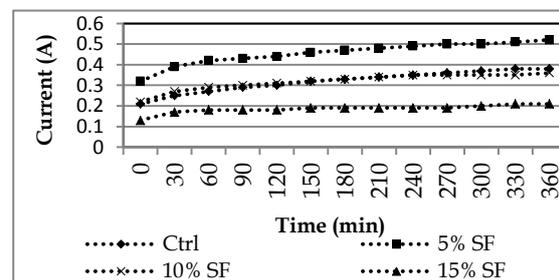
Figure 11- Current measurement of RCPT for SF mixed mortar

The current pass through the specimen decreases with increasing both FA and SF content in the mortars. This trend is clear from 25% to 75% of FA and from 5% to 15% of SF, although the trend is not clear when increasing FA content from 0% to 25% and SF content from 0% to 5% in the specimen. The calculated average charge passed (using Equation 1,

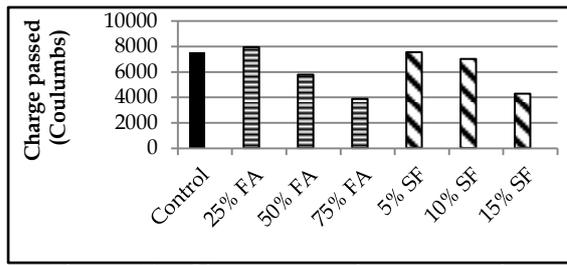Figures 10 and 11) across the mortar cylinders is shown in Figure 12.

Figure 12- Charge passed average value

The charge passed values decrease with increasing of both FA and SF percentages. The average charge passed across the mortar cylinders cast by using mortar of having 75% of FA and 15% of SF are 3873 C and 4278 C, respectively. These values are lower compared to OPC mortar cylinder (7518 C).

3.2 Efficiency of Retrofitting Methods

This section presents the efficiency of retrofitting methods (CP and ECE) that were evaluated by using chloride ion concentration, rust production and resistivity of RC beams and current passed through RC beams.

3.2.1 Free and Total Chloride ion Concentration

Figures 13 and 14 show the free and total Cl⁻ concentration, respectively, for the depth level of 20 mm, 40 mm and 60 mm at the four stages.
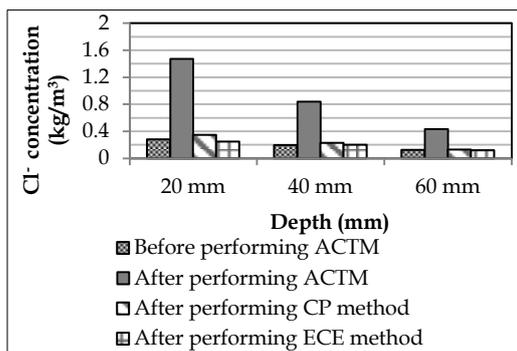
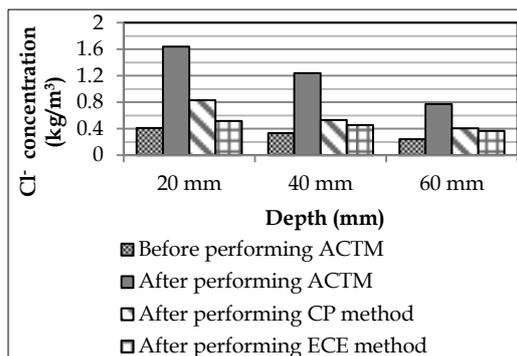

Figure 13- Free chloride ion concentration

Figure 14- Total chloride ion concentration

The free and total Cl⁻ concentrations were greater after performing ACTM. Both free and total Cl⁻ concentrations decreased with increasing depth. Comparing Figures 13 and 14, it can be clearly seen that for all depths, the total Cl⁻ concentration was higher than the free Cl⁻ concentration. For all depths, both Cl⁻ concentrations were reduced after applying retrofitting methods. At 20 mm depth, the total Cl⁻ concentration of control beam (non-retrofitted), after performing ACTM, is 1.64 kg/m³ while it is 0.831 kg/m³ for the beam retrofitted by the CP method and is 0.516 kg/m³ for the beam retrofitted by the ECE method. At the same depth level, the free Cl⁻ concentration of control beam (non-retrofitted), after performing ACTM, is 1.471 kg/m³ while it is 0.346 kg/m³ for the beam retrofitted by the CP method and is 0.25 kg/m³ for the beam retrofitted by the ECE method. The free and total Cl⁻ concentrations of beams with the condition of before performing ACTM are 0.282 kg/m³ and 0.41 kg/m³, respectively, at 20 mm depth level.

3.2.2 Rust Production

Table 4 shows the average weight of the rust production and reduction in bar diameter of embedded steel reinforcements.

Table 4- Rust production

Inspection Stage	Average weight of rust production (W) - (g)	Average bar diameter (Φ) - (mm)	Average reduction in bar diameter (Φ$_r$) - (mm)
Initial condition	0	16	0
After performing ACTM	3.5	15.56	0.44
After retrofitting by CP method	4	15.48	0.52
After retrofitting by ECE method	3.75	15.53	0.47
Control specimen (without retrofitting)	4.28	15.41	0.59

The weight of the rust and the reduction in bar diameter were lower for the beams retrofitted with CP and ECE methods, compared with that of control beams. There was a negligible amount of rust production in retrofitted beams. The rust (rust weight (W) and reduction in bar diameter (Φ$_r$)) produced in beams treated by CP

method (W = 4 g and Φ_r = 0.52 mm) were greater than that in the beams retrofitted by ECE method (W = 3.75 g and Φ_r = 0.47 mm). As mentioned in the methodology, retrofitting methods were applied on the corroded beams (after performing ACTM). Therefore, rust is already produced on the bar surface. Comparing to after performing ACTM stage, the rust production and reduction in bar diameter of CP method (ΔW = 0.5 g and $\Delta\Phi_r$ = 0.8 mm) and ECE method (ΔW = 0.25 g and $\Delta\Phi_r$ = 0.03 mm) are lesser than that of control beam (ΔW = 0.78 g and $\Delta\Phi_r$ = 0.15 mm).

3.2.3   Resistivity

Table 5 shows comparison of resistivity of beams, retrofitted by using CP and ECE methods.

Table 5- Comparison of resistivity

Beam description	Resistivity (k Ohms cm)
Control beam	0.7
Beam retrofitted by CP	3.1
Beam retrofitted by ECE	4.5

From Table 5, it can be seen that the resistivity of the control beam was 0.7 k Ohms cm, which is significantly lower compared with the resistivity of other beams: beam retrofitted by CP method gives 3.1 k Ohms cm while beam retrofitted by ECE gives 4.5 k Ohms. The resistivity ofthe RC beam retrofitted by ECE method was slightly higher than that of the RC beam retrofitted by CP method.

3.2.4   Current

For CP method, the initial current reading was 0.3 A for the first mesh, 0.23 A for the second mesh, and 0.16 A for the third mesh (the system was not continued with replacing third copper mesh after observing negligible current). Therefore the total current reduction was 0.14 A. The total time for the beam retrofitted by CP method was 31 days.

For ECE method, the initial current reading was observed as 0.5 A. The initial current reading for the second mesh was 0.29 A, and for the third mesh it was 0.17 A (the system was not continued with third mesh). The total current reading reduction was determined as 0.33 A. The total time for beam retrofitted by ECE method was 23 days.

4.   Discussion

According to the JSCE (2001), the critical Cl^- concentration is 0.3 ~ 0.6 kg/m³ (Veerachai et al. [12]). Further, according to the JSCE (2001), when the Cl^- concentration exceeds 1.2 ~ 2.4 kg/m³, the corrosion incorporating micro-cracks might be initiated (Veerachai et al. [12]). Simply, when the Cl^- concentration of RC beams is higher than 0.6 kg/m³, the critical Cl^- level was initiated (i.e., corrosion risk initiate) and when it was 1.2 kg/m³, the corrosion is initiated on embedded steel reinforcement. The threshold Cl^- concentration for onset corrosion is considered as 1.2 kg/m³ (Gunesekara et al. [6]).

4.1   Repairing Mortar

Relatively high percentage of SF makes the concrete expensive and causes the difficulties in mixing and finishing. In the current study, 10% of SF and 50% of FA were used in producing mortars with high density and high strength, while reducing the difficulties in mixing and finishing. Further, 5%, 10% and 15% of SF and 25%, 50% and 75% of FA mixed mortars were used to identify optimum level of admixture percentages for reducing the Cl^- diffusion, which was investigated by using RCPT.

The most critical depth region related to corrosion was considered as less than 20 mm depth, because steel reinforcements were embedded to the depth of 20 mm. The total Cl^- concentration, at 20 mm depth level of OPC mortar applied beam (1.514 kg/m³) (Figure 9) is higher than threshold value of 1.2 kg/m³, hence the beam was corroded. The total Cl^- concentrations of FA and SF mixed mortar applied beams (FA = 0.97 kg/m³ and SF = 1.14 kg/m³) were less than the threshold value of 1.2 kg/m³, hence the corrosion risk is minimized. The total Cl^- reduction, at 20 mm depth level, in the beam repaired with FA mixed mortar was 0.544 kg/m³ and in the beam repaired with SF mixed mortar was 0.374 kg/m³ (Figure 9). FA mixed mortar reduces Cl^- concentration near embedded steel reinforcement by 36%, while SF mixed mortar reduces 25% of Cl^- concentration. Therefore, FA mixed mortar prevents the diffusion of Cl^- effectively compared to SF mixed mortar.

After the 30 days period of ACTM, the corrosion cracks (crack width > 0.2 mm) in OPC mortar applied beam were observed. Micro level corrosion cracks (crack width < 0.05 mm) were observed in the beams repaired with SF

mixed mortar and there was no surface corrosion crack in the beam repaired with FA mixed mortar. These results imply that the RC beam repaired by OPC mortar was totally corroded, and the beams repaired with SF mixed mortar was slightly corroded where the beam repaired with the FA mixed mortar seems to be free from the corrosion.

The rust production (both rust weight and reduction in bar diameter) of OPC mortar applied beam is higher value compared to FA and SF mixed mortars applied beams (Table 2). Further, rust production of FA mixed mortar applied beam is negligible value (i.e., W = 1.76 g, Φ_r = 0.19 mm) compared to OPC mortar applied beam (i.e., W = 7.8 g, Φ_r = 2.43 mm). This implies that the OPC mortar applied RC beam was continued corrosion while FA mixed mortar prevents production of rust.

According to Table 3, possible corrosion rate of OPC mortar (i.e., 1.8 k Ohms cm) applied beam is very high (resistivity < 5 k ohms cm) while that is high (resistivity between 5 to 10 k Ohms cm) in the RC beams repaired by using 10% of SF mixed mortar (i.e., 9.05 k Ohms cm) and moderate to lower (resistivity between 10 to 20 k ohms cm) in the RC beams repaired by 50% of FA based mortar (i.e., 12 k Ohms cm). These results imply that the internal corrosion level of the beams repaired by FA based mortar has significantly reduced.

Charge passed through of 15% of SF and 75% of FA mixed mortar are lower values compared to that of OPC mortar (Figure 12). Therefore, chloride ion diffusion through these mortars (75% of FA and 15% of SF mixed mortars) is lower compared to OPC mortar. Compared to OPC mortar, 75% of FA mixed mortar reduces the diffusion of Cl⁻ through mortars by 48.5% and 15% of SF mixed mortar reduces 43.1%. The uses of FA and SF with mortars reduce the diffusion of Cl⁻ into concrete, which prevents the corrosion.

The pozzolanic reaction in FA and SF converts the calcium hydroxide in to more of the calcium silicate hydroxide (CSH), thus increase the strength which leading to reduce permeability. Further, FA and SF have fine particles which might have contributed to minimize the voids in mortars. Therefore, the replacement of both FA and SF admixtures increases the density of mortars. As a result, FA and SF mixed mortars effectively minimize the diffusion of Cl⁻ ions, moisture, oxygen and aggressive chemicals into concrete compared to OPC mortar.

Considering the results of Cl⁻ concentration, rust production, resistivity and charge passed values, the corrosion prevention performances of FA mixed mortar is a high value compared to SF mixed mortar. Jansen and Pratt [7] showed, by using microstructure studies, that the reaction product from the pozzolanic reaction of FA was CSH (calcium silicate hydrates) and CAH (calcium aluminate hydrates), where the latter can give rise to increased chloride binding capacity. With the increase of SF amount, the producing of CAH decreased which cause to decrease the binding capacity. Therefore, FA mixed mortar minimizes the diffusion of Cl⁻ compare to SF mixed mortar. In addition, coal power generation has recently been established in Sri Lanka and one of by-products of the coal power plants is FA. Hence FA can be easily found in Sri Lanka with minimum cost.

4.2 Retrofitting Methods

Before performing ACTM, both free and total Cl⁻ concentrations were less than the threshold value of 1.2 kg/m³ (Figures 13 and 14). After performing the ACTM, free and total Cl⁻ concentrations of all test beams were greater than the threshold value of the Cl⁻ concentration resulting to initiate corrosion. After retrofitting, the total Cl⁻ concentrations in these beams reduced to a value less than the threshold value. This implies that the applying of retrofitting prevents or minimizes further corrosion of RC beams by reducing Cl⁻ concentration near to embedded steel reinforcement bars.

Table 7- Percentages (%) of chloride ion removed by retrofitting methods

Depth (mm)	Cl⁻ concentrations as percentages (%)			
	CP method		ECE method	
	Free	Total	Free	Total
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

In the current experimental investigation, 20 mm depth level is the most critical level as the clear cover thickness provided is 20 mm. In this region, the ECE retrofitting technique removed 68.5% of total and 83% of free Cl⁻ from the corroded beams (i.e., after performing ACTM) while the CP retrofitting technique removed 49.3% of total and 76.5% of free Cl⁻ (Table 7). Clemena and Jackson [2], have carried out ECE method (Ca(OH)₂ with H₂O were used as

chemical media) on a 28-year old bridge deck located in Arlington, Virginia and observed similar results for free Cl$^-$ ion concentration where ECE removes Cl$^-$ in concrete with about 75.8% of Cl$^-$ at the 6 to 19 mm depth, and 72.2% of Cl$^-$ at the 19 to 32 mm depth. In their study, ECE method was conducted using titanium mesh (i.e., as anode) which is better than copper mesh used in the current study. However, use of copper mesh for the anode is cost effective rather than use of titanium mesh. Compared to the current study (Cl$^-$ concentration of corroded RC beam was 1.64 kg/m^3 at 0 to 20 mm depth), the bridge deck was highly chloride contaminated (initial Cl$^-$ concentration was 4.97 kg/m^3 at 6 to 19 mm depth). Therefore, it is easier to remove free Cl$^-$ ions from bridge deck. Further, in the previous study (Clemena and Jackson [2]) ECE was conducted for bridge deck over a long period (58 days) while it was 23 days in the current study. However, removal of Cl$^-$ is less (75.8%) for bridge deck than that of the current study (83%) and final Cl$^-$ concentration (after performing ECE) of bridge deck was 1.2 kg/m^3 (which was equal to threshold value), while it was 0.516 kg/m^3 in the current study. It seems that conducting the ECE for bridge deck in-situ condition and for current study in the laboratory with less Cl$^-$ contamination condition would cause the slight variation in results for bridge deck and test beams.

When the current was supplied to the CP setup, the steel reinforcement became cathode and the chloride ions are redistributed away from the steel bars and reached towards the copper anode (at concrete surface area). This might contribute to the reduction in chloride ion concentration near the steel reinforcements. In ECE retrofitting technique, the copper mesh is covered by using chemical media (calcium hydroxide) and the chloride ions which approached towards the copper mesh are removed by calcium hydroxide by producing CaCl$_2$. This might attribute to increase the efficiency of removing chloride ions by the ECE method compared to that of the CP method.

After retrofitting (CP and ECE methods), the free Cl$^-$ concentration of test beams decreases nearly down to the Cl$^-$ concentration of beams observed at 28 days curing (Figure 13). The retrofitting methods are based on the electrical system and the free Cl$^-$ contributes directly to conduct the current across concrete area. Therefore, admittedly, the free Cl$^-$ are redistributed from steel reinforcements and reached towards the concrete surface area.

These free Cl$^-$ are removed by calcium hydroxide layer by producing CaCl$_2$. On the other hand, free Cl$^-$ causes the corrosion of steel reinforcement. The bonded chloride ions may not contribute to the corrosion process. Possibility of removing free chloride ions by these retrofitting techniques is an advantage.

The weight of rust production and reduction in bar diameter of retrofitted RC beams are lesser compared to control RC beam (Table 4). This implies that retrofitting methods contribute to prevent further corrosion. The resistivity of all RC beams (Control beams and retrofitted beams) is lower than 5 k Ohms cm (Table 5), implying the possible corrosion rate of all beams is very high. Before retrofitting (CP and ECE methods), RC beams were subjected to ACTM in order to make sure the RC beams were already corroded. After retrofitting, the beams were again subjected to ACTM. This allowed the Resistivity meter to measure the resistivity at both corrosion stages: before retrofitting and after retrofitting. The observed corrosion rate was significantly high value, possibly because the corrosion was accelerated by conducting the ACTM. Further, considering the measured values, control beam shows very lower value, means it would be highly corroded than other two beams.

The free Cl$^-$ conduct the current through the concrete area, hence considering the current distribution through retrofitted RC beams, the free Cl$^-$ were redistributed away from the embedded steel reinforcement (cathode) area towards concrete surface area (copper mesh anode). Therefore, the reduction in current of ECE and CP methods implied the reduction in Cl$^-$ concentrations. The efficiency of removing chloride ion (based on the current reduction) for CP method was 46.7%, while it was 66% for ECE method. Time taken to remove Cl$^-$ by CP method is around 31 days while it is around 23 days for the ECE method indicating that the ECE method removes Cl$^-$ within shorter time period compared to the CP method.

In both CP and ECE methods, the potential of embedded steel reinforcement were shifted to negative direction, making the steel reinforcement became cathode with time. When the steel reinforcement bars totally charge with negative ions, further continuation of current might help to produce hydroxyl ions (with the presence of water and oxygen) near the reinforcement bars, resulted in creating of alkaline conditions. This leads to re-passivate the steel reinforcements, produce iron oxide

(Fe_2O_3) film surrounding the steel reinforcement bars, prevent the diffusion of oxygen to steel bar area and hence prevent the further corrosion. In addition, these retrofitting methods help to redistribute the Cl^- from embedded steel reinforcement towards the concrete surface. The Cl^- which approached to concrete surface is removed by calcium hydroxide as producing calcium chloride ($CaCl_2$). The use of calcium hydroxide as chemical media in ECE retrofitting method cause to increase the efficiency of the method, compared to CP method.

5. Conclusions

As repairing methods, Fly Ash (FA) and Silica Fume (SF) mixed mortars were developed and Cathodic Protection (CP) and Electrochemical Chloride ion Extraction (ECE) were conducted as retrofitting methods for corroded RC structures. Efficiency of both repairing and retrofitting methods was evaluated by measuring free and total Cl^- concentrations and rust production. Efficiency of the methods was further evaluated by conducting resistivity measurements and Rapid Chloride Permeability Test (RCPT) relevant to the repairing mortars and current measurement relevant to the retrofitting methods.

The FA and SF mixed mortars minimize the corrosion of RC structures by preventing the diffusion of Cl^- into concrete. It was found that the 50% of FA mixed mortar performs better compared to the 10% of SF mixed mortar. With the use of coal power generation, recently established in Sri Lanka, FA can be easily found with minimum cost, as one of by-product of the coal power plants is FA. The CP and ECE methods remove around 49% and 69% of total Cl^-, respectively. These retrofitting methods prevent further corrosion of RC structures by removing Cl^- near the steel reinforcements and producing alkaline conditions around the steel bars which helps to form iron oxide film around the steel bars. With ECE method, calcium hydroxide helps to increase the efficiency of the CP method process by nearly 20% with removing the Cl^- approached towards copper mesh area.

The spalled and delaminated areas of corroded RC structures can be repaired by using FA mixed mortars and the chloride contaminated concrete that is still sound can remain in place by using ECE method, effectively. The use of calcium hydroxide as chemical media with ECE method accelerates the performances of CP method. Experimental investigation conducted in this study confirmed that the use of both FA based repair mortar and ECE retrofitting more effectively help to prevent the chloride ions diffusion into concrete and enhancing the service life of structures.

Acknowledgments

References

1. Aggarwal V., Gupta S. M. and Sachdeva S.N., "Concrete Durability through High Volume Fly Ash Concrete (HVFC) - A Literature Review", *International Journal of Engineering Science and Technology, Vol. 2(9), 2010,* pp. 4473-4477.

2. Clemena G. G. and Jackson D. R., "Pilot Applications of Electrochemical Chloride Extraction on Concrete Bridge Decks in Virginia", *Transportation Research Record, No. 1597,* 1997, pp. 70-76

3. Detwiler R. J., Whiting D. A. and Lagergen E.S., "Statistical Approach to Ingress of Chloride Ions in Silica Fume Concrete for Bridge Decks", *ACI Materials Journal, Vol. 96, No. 6, Nov.-Dec. 1999,* pp. 670-675.

4. Florida Department of Transportation (FDOT), "An Accelerated Laboratory Method for Corrosion of Reinforced Concrete using Impressed Current", Manual of Florida Sampling and Testing Methods, Tallahassee, FL, September 2000, pp. 6.

5. Ganesan K., Rajagopal K. and Thangavel K., "Chloride Resisting Concrete Containing Rice Husk Ash and Bagasse Ash", *Indian Journal of Engineering & Materials Sciences, Vol.14,* June 2007, pp.257-265.

6. *Gunasekara M. P. C. M., Mutsuyoshi H. and Sumita A., "Renovate RC Structures with Newly Developed Mortar Considering Chloride Binding and Inverse Diffusion*

Phenomenon", *International Conference on Structural Engineering, Construction and Management (ICSECM), Kandy, Sri Lanka,* December 2011.

7. Jansen H. U. and Pratt P. L., "The Binding of Chloride Ions by Pozzolanic Product in Fly Ash Cement Blends", Advances in Cement Research, Vol. 2, No. 7, 1989, pp.121-129.

8. Jennifer L. K., David D. and Carl E. L., "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.*

9. NDT James Instruments Inc., "Instruction Manual - RM-8000 Resistivity Meter", *James Instruments Inc., Chicago, U.S.A.*

10. Sahmaran M., Li V. C. and Andrade C., "Corrosion Resistance Performance of Steel-Reinforced Engineered Cementitious Composite Beams", *ACI Materials Journal, V. 105, No. 3, May-June 2008*, pp. 243-250.

11. Saraswathy V. and Song H., "Evaluation of Cementitious Repair Mortars for Corrosion Resistance", *PortugaliaeElectrochimicaActa, 26/5, June 2008*, pp. 417-432.

12. Veerachai L., Toshimitsu S., Yuichi T. and Masayasu O., "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.

13. Virmani Y. P. and Clemena G. G., "Corrosion Protection-Concrete Bridges," *Report No. FHWA-RD-98-088, Federal Highway Administration, Washington, D.C.,* September 1998.