

Chloride Removal from Polluted Reinforced Self-Compacting Concrete Using Electrochemical Chloride Extraction

Mounir M. Kamal¹, Mohamed A. Saafan¹, Zeinab A. Etman^{1,2}, Mohamed A. Altobgy^{3*}

¹ Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt.

² Higher Institute of Engineering and Technology, Menoufia, Egypt.

³ Department of Civil Engineering, Faculty of Engineering, Kafrelsheikh University, EEgypt.

*(Corresponding Author: mohammed_tbge2011@eng.kfs.edu.eg)

ABSTRACT

One of the primary causes of concrete deterioration is chloride-induced corrosion, which represents a threat to sustainability. The damaged regions are typically removed in traditional repair methods to restore corroded structures. Another technique involving electrochemical chloride extraction (ECE) has a growing popularity with regard to its effectiveness as a non-destructive treatment. This research aimed to investigate various ECE variables including electrolyte solutions, concrete cover, reinforcement ratio, and charging intervals to optimize ECE. Chloride extraction was investigated in the mid-span and at the two edges of the tested beams. This study was based on the experimental results of 12 reinforced concrete beams. The extraction process was performed for beams cast with self-compacting concrete (SCC). Self-compacting concrete has low pores, which may affect the extraction process. The experimental results show that the ECE efficiency ranged from 44% to 73% based on the examined variables.

Keywords: *electrochemical chloride extraction (ECE); self-compacting concrete; electrolyte; concrete cover.*

1. Introduction

Nowadays, it is thought that the Electrochemical Chloride Extraction (ECE) process is a suitable technology for increasing the durability of reinforced concrete structures. This technique enables a control on the process of corrosion in reinforced concrete (RC) elements due to chloride ions, as they move outward from around the reinforcement to the structure's surface. RC elements are treated by running a direct current (DC) between an anode in an electrolyte on the outside while the reinforcements act as the cathode, and chloride ions are removed. Since the 1970s [1-3], this approach has been refined and a thorough and rigorous series of studies have proved the effectiveness of ECE [4-6]. The publication of an invention entitled "Norcure" by Vennesland and Opsahl, where the anode system was constructed on a Ti-RuO₂ mesh, was a critical step in the development of this application [7]. Moreover, studies were carried out to improve specific application circumstances in order to accelerate operations and save money, mainly in the anode system. For this goal, versatile materials, especially cement-based conductive materials, were considered. Concrete, mortars, and pastes are cement-based materials with low electrical conductivity can be considerably increased by incorporating conductive elements such as carbon fibers or graphite powder. This technique has recently been utilized to impart unique physical and

chemical characteristics to cement-based materials [8-14]. To assess the treatment's efficiency and the possibility of new phases forming in both concrete and steel-concrete interfaces, electrochemical chloride elimination was performed on concrete specimens. 40-45% was decreasing in the chloride level however; alkali ions accumulated surrounding the steel. Moreover, for the specimens held at accelerated conditions; alkali-silica gel was formed. Due to the increased hydroxyl ion content caused by electrochemical treatment, there is no reactive aggregate was happened [15]. Therefore, the success of ECE applications depends on the selection of an appropriate anode system [16, 17]. Different anode systems, which are currently accessible for ECE treatment, were demonstrated in numerous investigations. These anode systems include thermal sprayed zinc [18,19], titanium anodes [20], titanium mesh anodes [21,22], conductive paint [13], and coated overlay anodes [23,24]. Due to its low cost, resistance to corrosion, good electrical conductivity, and fine plasticity, stainless steel mesh has proven a useful anode material in ECE systems [25, 26]. Additionally, earlier studies showed that higher-intensity electrochemical treatment can cause concrete cracks and steel bar hydrogen embrittlement, which results in structural instability [25-27]. Different electrolyte solutions affect the characteristics of concrete after ECE and influence the rate of migration of the chloride ions [28]. In particular, for corrosion-resistant steels, optimal

ECE treatment parameters are crucial for effectiveness and structural safety. J. Bennet and T. J. Schue cover the fundamental knowledge required to carry out the chloride removal procedure on field constructions [29]. The most common American guideline indicates the usage of a borate-buffered electrolyte to avoid alkali silica reaction during the process, while the European Standard does not specify any solution, just mention that it should be alkaline, and the Norcure [30 - 32] patent suggests fresh water. Due to the lack of standard recommendations outlining the most efficient ECE administration, two distinct electrolytes, tap water and calcium hydroxide were considered. To simulate an actual on-site application, tap water is common utilized as an electrolyte in ECE. This approach requires constant humidity, which may be produced in a variety of ways: fully merged anode, drip irrigation system and daily dampening. When

the anode and the concrete specimen are combined in the electrolyte, the result is known as a fully merged anode, [33]. When a pump and multiple pipes with throwers are connected around the specimen perimeter to provide regular watering around the clock, this is referred to as a drip irrigation system. This technique is utilized in both standard anode systems such as titanium mesh anodes and stainless steel anodes and conductive cement paste anode systems [34, 35]. Another technology can be employed if the specimen is wet once a day using a hosepipe titled with daily dampening. This technique was employed with a conductive cement paste anode in order to test the paste's ability to retain moisture without the usage of absorbent layers [36, 37]. A schematic illustration of the mechanics and chemical processes at work in ECE is shown in Figure (1).

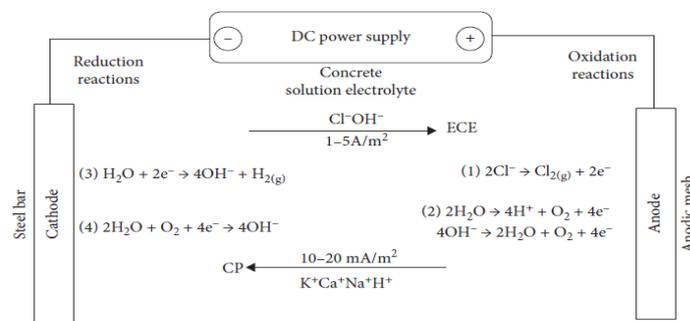


Figure 1- The Fundamental Chemical and Electrochemical Mechanisms Involved in the Processes [28].

After 90 days of treatment, Fajardo et al. [38, 39] reported a chloride extraction effectiveness of 75% and 30% for specimens with a 20 mm and 50 mm concrete cover, respectively. Orellan [40] employed comparable experimental techniques and evaluated several electrolytes in terms of chloride extraction effectiveness from most to least effective, specifically tap water (60%), sodium-based electrolytes (54%), and calcium and lithium-based electrolytes (40%). According to the previous review, ECE has a significant influence on salt extraction from reinforced concrete. This research investigated the extraction process efficiency of self-compacting concrete due to its dense and low porosity, which may have an influence on the extractions processes compared to conventional concrete.

2. Research Significance

This paper's primary goal is to investigate the effects of several electrolyte solutions, including calcium hydroxide and water, electrical connection position, and charging times on the ECE. The effectiveness of chlorine removal from remote locations relative to the electrical connection position and the impact of concrete cover and reinforcement ratio are considered. Also, the extraction process efficiency

of self-compacting concrete due to its dense and low porosity is evaluated.

3. Materials and Testing Parameters

3.1. Materials and concrete mix

Well-graded siliceous sand was used as a fine aggregate with a specific gravity of 2.60, absorption of 0.78%, and a fineness modulus of 2.61. A coarse aggregate of crushed dolomite with maximum nominal sizes of 10 mm was used, with a specific gravity of 2.64 and absorption of 0.76%. Locally produced Portland cement (CEMI: 42.5 N) conforming to the requirements of Egyptian Standard Specifications (E.S. 4756-1/2013) [41] was used. Imported class (F) fly ash meeting the requirements of ASTM C618 [42] with a specific gravity of 2.1 was used. A high-range water reducer (HRWR) with a trading name; Addicrete BVF was used as a superplasticizer meeting the requirements of ASTM C494 (types A and F) [43]. The admixture is a brown liquid having a density of 1.18 kg/L at room temperature. The amount of HRWR ranged from (2.0 to 3%) of the cement weight used. High tensile deformed steel bars and normal mild steel bars comply with the requirements of E.S.S. 262/2015 [44]. Steel bars of 10 mm diameter were utilized as tension steel, with yield strength, tensile strength, and elongation percent of 480 N/mm², 595

N/mm², and 12%, respectively. In addition to mild steel bars of 8 mm diameter with yield strength, tensile strength, and elongation percentage were 292.7 N/mm², 407.27 N/mm², and 24%, respectively.

3.2. Mix design

The laboratory concrete specimens were manufactured as self-compacting concrete (SCC). Mix design's primary goal was to ascertain material quantities of SCC. SCC can be largely affected by the characteristics of materials and the mix proportion [45]. Four mixes were made with mixing ratios shown in Table (1), all based on the same control mixture, for achieving the best possible

concrete mix workability and appropriate compressive strength. Some laboratory tests were carried out according to the technical specifications of SCC [46] to evaluate the fresh properties of self-compacting concrete mixes as shown in Table (2). According to the results in Table (2), M3 achieved the requirements of SCC due to the homogeneity, flow diameter and the time of flowing, as well as the compressive strength of the mix after 28 days, which is 40 MPa. Sodium chloride was added to the mixing water (1%, 2%) by weight of cement to promote the corrosion onset from the beginning before applying the repair treatment.

Table 1- Mix Proportion of SCC (kg / m³)

Mix NO.	Cement	Sand	Dolomite	Fly ash	Water	Admixture
M1	400	1004	823	40	150	6
M2		1001	820			8
M3		998	818			10
M4		995	816			12

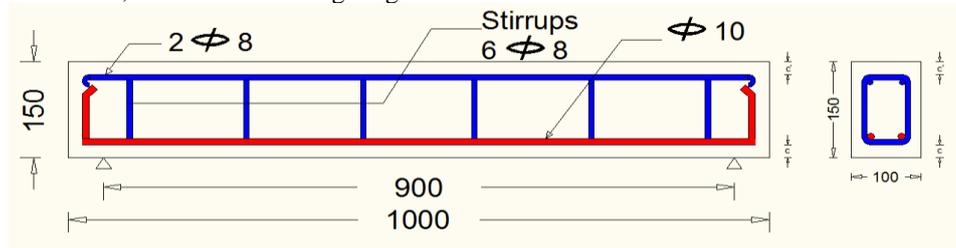
Table 2- Properties of Trail Self-Compacting Concrete Mixes and Recommended Limits for Different Properties of SCC

Mix No.	Slump Flow Diameter (mm)	T _{50cm} (sec)	V-funnel (sec)	Requirements of self-compacting concrete [46]
M1	450	-	31	Slump Flow Diameter = (600: 800) mm
M2	620	5	11	
M3	710	3	9	T50cm = (2: 5) sec.
M4	830	2	6	V-Funnel = (6: 12) sec.

3.3. Testing parameters

The experimental program consists of four groups (G1 – G4), each group has three reinforced concrete beams as shown in Table (3). The primary purpose is to measure the proportion of chloride salts present before and after ECE, while also investigating the

influence of all factors on removal findings. Figure (2) illustrates the reinforcing details. Figure (3) demonstrates the reinforced beams before and after casting. The electric source was connected to the beam in the middle to attempt to transport the electrically current to both ends of the beam.



(a) Elevation of Beam

(b) Cross Section

Figure 2- General Model of Tested Beams, (All Dimensions in mm).



(a): Steel Arrangement before Casting

(b): Casted Beams

Figure 3- Image of Casted Beams.

Table 3- Testing Parameters of Casted Beams.

Group No.	Beam No.	Tension Steel (A_s)	Concrete Cover (mm)	Electrolyte	Chloride Content
G ₁	B ₁	2 Φ 10	20	Water	1%
	B ₂		30		
	B ₃		40		
G ₂	B ₄	2 Φ 10	20	Calcium Hydroxide	
	B ₅		30		
	B ₆		40		
G ₃	B ₇	2 Φ 10	20	Water	2%
	B ₈	3 Φ 10			
	B ₉	4 Φ 10			
G ₄	B ₁₀	2 Φ 10	20	Calcium Hydroxide	
	B ₁₁	3 Φ 10			
	B ₁₂	4 Φ 10			

4. Test Setup

The following are the sequential stages for testing beam preparation: for casting beams, a rectangular mold constructed of contras wood with dimensions 100 mm x 150 mm x1000 mm was prepared. Following the installation of reinforcing steel in wooden forms with electrical connections, a

concrete mix was cast to fill the forms, resulting in the used beams. Finally, the beams were covered in wet burlap for four weeks. The specimens were kept for six months after curing to allow sodium chloride salts to react with concrete components. As indicated in Table (4), the initial chloride concentration was calculated as an average from casted cubes prior to the start of the ECE procedure.

Table 4- Average Concentration of Chloride Salts before Extraction.

Group No.	Chloride Concentration (% of Cement Weight)
G 1 & G 2	0.973
G3 & G4	2.034

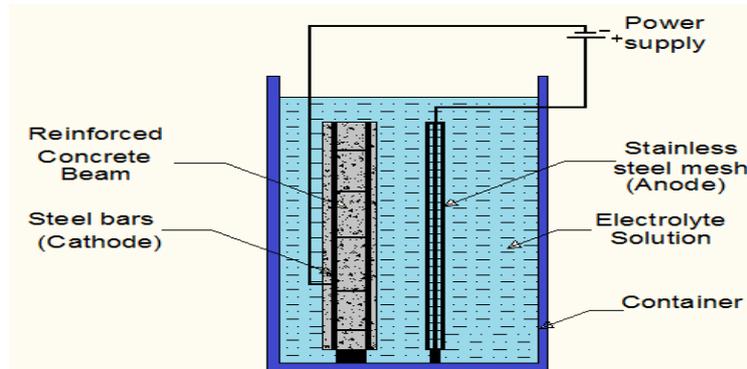
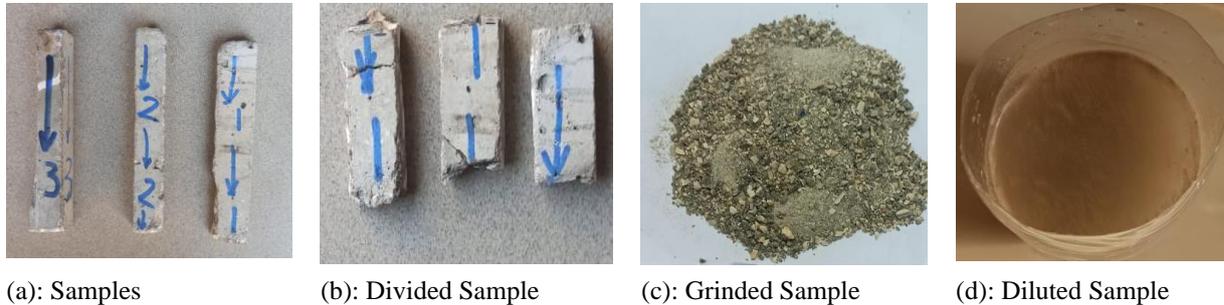


Figure 4- Schematic Diagram for ECE.

The initial stage of ECE involved immersing the reinforced concrete beams in a container filled with the electrolyte, water, or calcium hydroxide, and

then connecting the external anode to the electrolyte. Finally, as indicated in Figure (4), connect the electric supply to the anode and the primary steel to

the cathode. After four weeks, samples were collected from the two ends of each beam. The second stage takes four weeks as well. As Climent Miguelngel et al., 2016 [34] and Carmona Calero et al., 2015 [35] describe a drip irrigation system offer regular watering throughout the clock.



(a): Samples (b): Divided Sample (c): Grinded Sample (d): Diluted Sample
Figure 5- Steps of Determining Chloride Concentration.

To determine the effectiveness of the EEC experiments in reducing the chloride content of the tested beams. Figure (5-a) shows samples obtained from the concrete surface with the entire depth of beams exposed to EEC. Figure (5-b) shows how each sample was split into equal pieces 5 cm deep. To assess chloride content, materials were ground and dissolved in water, as shown in Figure (5-c and 5-d). The chloride content (P) in the specimens was calculated according to Baoguo Ma, 2018 [47]. The following steps were carried out.

1. 20 g of concrete's sample was dried for 2 hours at 65°C.
2. 10 gm (G) powder is extracted from it and mixed with 100 gm distilled water (V1) for half an hour before filtering it.
3. A 20 gram (V2) filter is prepared, then 2 drops of phenolphthalein are added until a pink hue appears, followed by drops of dilute sulphate acid until the pink color disappears. Adding 10 drops of potassium chromate indicator, then a drop at a time from silver nitrate with a concentration of 0.02 mole/L (C) and calculating its volume (V3).
4. Equation (1) is used to calculate the free chloride content according to Baoguo Ma [47].

$$p = \frac{C * V3 * 0.03545}{G * \frac{V2}{V1}} * 100 \% \quad (1)$$

The samples were collected at various stages of the treatment procedure. The first group of samples was collected after 4 weeks, while the second group was collected at the completion of the extraction procedure after 8 weeks. The specimens were collected from various locations along beam spans. The first collection of samples was gathered from the beam's two edges at 4 weeks of age. The second batch of samples was collected at 8 weeks of age from the beam's two edges and the beam's mid-span.

5. Experimental Results

The result of the four test groups (G1: G4) are compared to study the influence of variables on the ECE responses of the tested beams. Figure (5) illustrates the sequential processes taken to calculate chloride concentration.

5.1. Chloride extraction results

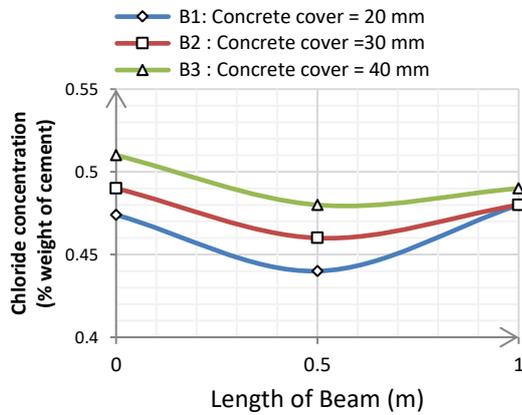
Treated reinforced concrete beams were prepared in the same environment; for all specimens, the initial concentration is comparable before treatment, indicating a significant danger of corrosion. As expected, there is a higher chloride concentration at the upper face of the samples. The therapy was successful in removing chloride ions in all cases but to varying degrees. Taking into account the total chlorides in each position, the concentration at shallow depths, the upper 5 cm of the beam thickness, was not as significantly reduced as expected, which could be attributed to the chlorides carried to the surface of the concrete during treatment taking longer to dissolve into the electrolytic solution. Because of the difference in the ionic medium between the concrete surface and the electrolyte, chloride ions may occasionally be present on the closer surface. Furthermore, because the chloride measurements were performed on dry concrete, the greater chloride concentration towards the surface might be attributed to the concentration of chloride ions owing to migration.

5.1.1. Effect of concrete cover

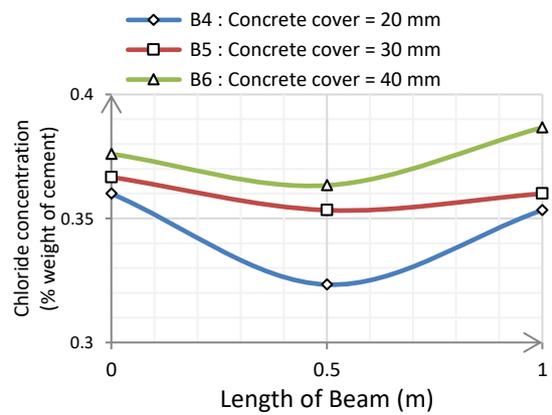
Figure (6) shows the total chloride content at the end of the extraction process after 8 weeks of extraction, for G₁ (using water as electrolyte), and G₂ (using Calcium Hydroxide as electrolyte), at three positions along the beam span at the two edges and the mid-span of the beams. The total chloride content of B1 was lowered to 0.46% on average, 0.475% for B2, and 0.545% for B3, as shown in Figure (6-a). Depending on the cover depth, the average removal effectiveness for B1 was 52.7%, 51.2% for B2, and 44% for B3. According to Figure (6-b), the total chloride content of B4, B5, and B6 was lowered to 0.345%, 0.36%, and 0.375%, respectively. Depending on the cover depth, the average percentage of removal effectiveness for B4 was 64.5%, 63% for B5, and 61.5% for B6. The concentration of salts is reduced in the intermediate

span of either G1 or G2 beams. As the electrical connections were in the midpoint of the beams, this suggests that the extraction process was more efficient in the electrical conduction zones than in

the distant parts. It can be shown that the extraction efficiency improves as the concrete cover decreases, as demonstrated in [38, 40].



(a): G₁: Using Water as Electrolyte.



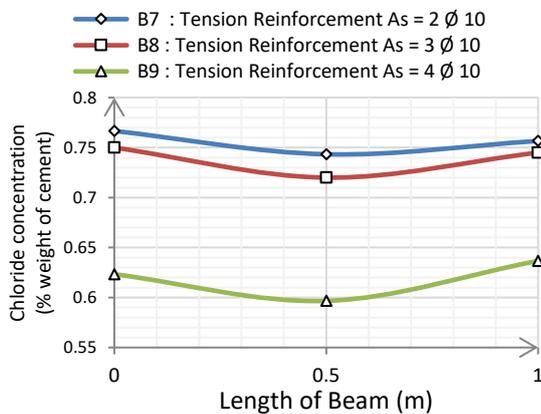
(b): G₂: Using Calcium Hydroxide as Electrolyte.

Figure 6- Chloride Concentration after 8 Weeks of Extraction (Constant Tension Reinforcement $A_s = 2 \text{ } \varnothing 10$).

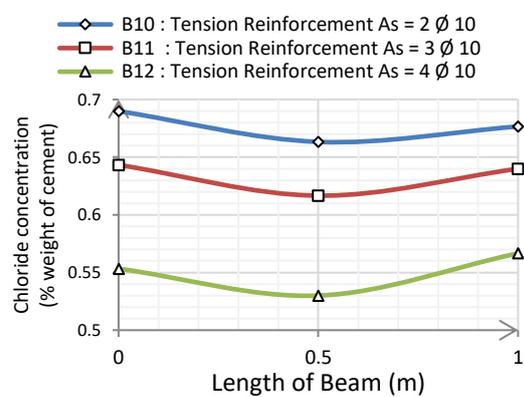
5.1.2. Effect of reinforcement ratio

Figure (7) illustrates the total chloride concentration of G3 (using water as an electrolyte) and G4 (using Calcium Hydroxide as electrolyte) after 8 weeks of extraction. Figure (7-a) shows that the total chloride concentration was decreased to 0.756%, 0.738%, and 0.619% on average for beams B7, B8, and B9. Depending on the reinforcement ratio, the average percentage of removal efficiency for B7 was 62.8%, 63.7% for B8, and 69.6% for B9. According to Figure (7-b), the total chloride content of B10, B11, and B12 was lowered to 0.677%, 0.633%, and

0.55%, respectively. Depending on the reinforcement ratio, the average percentage of removal efficiency for B10 was 66.7%, 68.9% for B11, and 72.96% for B12. Increasing the reinforcement ratio in the concrete segment improves chloride extraction efficiency. The electric current is better spread and the area exposed to extraction from the concrete section grows as the reinforcement ratio increases. As demonstrated in [48], the extraction efficiency rises with increasing reinforcement ratio and uniform distribution in concrete section.



(a): G₃: Using Water as Electrolyte.



(b): G₄: using Calcium Hydroxide as Electrolyte.

Figure 7- Chloride Concentration after 8 Weeks of Extraction (Constant Concrete Cover = 20 mm).

5.1.3. Effect of electrolyte type

Figure 8 (a), (b), and (c) illustrate the total chloride content of G1 beams versus G2 beams, with each beam corresponding to its corresponding one in all parameters except the electrolyte type. B4, treated in Calcium Hydroxide electrolyte, had 22.7% higher removal efficiency than B1, treated in water-electrolyte. B5, treated in Calcium Hydroxide electrolyte, had 23.05% higher removal efficiency

than B2, treated in water-electrolyte. B6, treated in Calcium Hydroxide electrolyte, had 39.77% higher removal efficiency than B3, treated in water-electrolyte.

Figure 9 (a), (b), and (c) illustrate the total chloride content of G3 beams versus G4 beams, with each beam compared to its corresponding one, which agreed in all parameters except the electrolyte type. The percentage of elimination efficiency for B10 in

Calcium Hydroxide electrolyte was 6.21% higher than for B7 in water-electrolyte. The percentage of removal efficiency for B11 in Calcium Hydroxide electrolyte was 8.16% higher than for B8 in water-electrolyte. The percentage of elimination efficiency for B12 in Calcium Hydroxide electrolyte was 4.61% higher than for B9 in water-electrolyte.

Under the same conditions, the impact of calcium hydroxide as an electrolyte is preferred to that of water. However, the findings converge as the chloride concentration increases, as the average extraction when the chloride content was equivalent to 1% was 28.51%, while it was 6.33% with a chloride content of 2%.

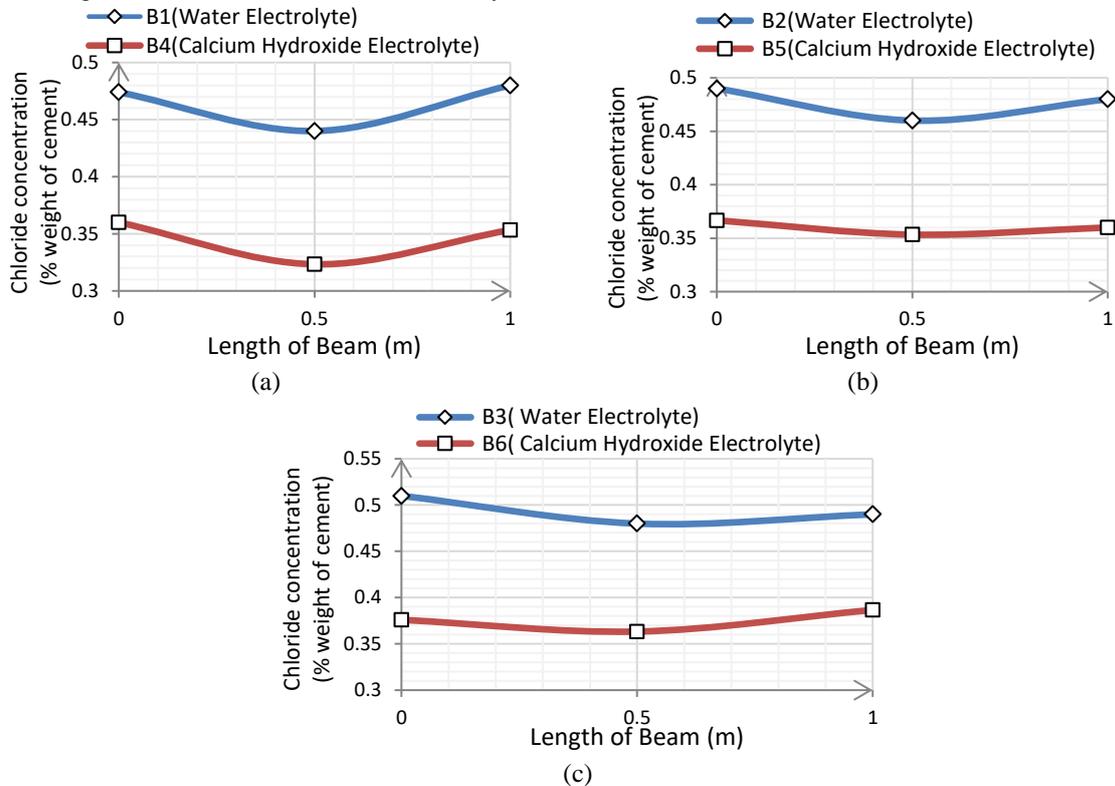


Figure 8- Chloride Concentration after 8 Weeks of Extraction (Chloride Content 1% weight of cement).

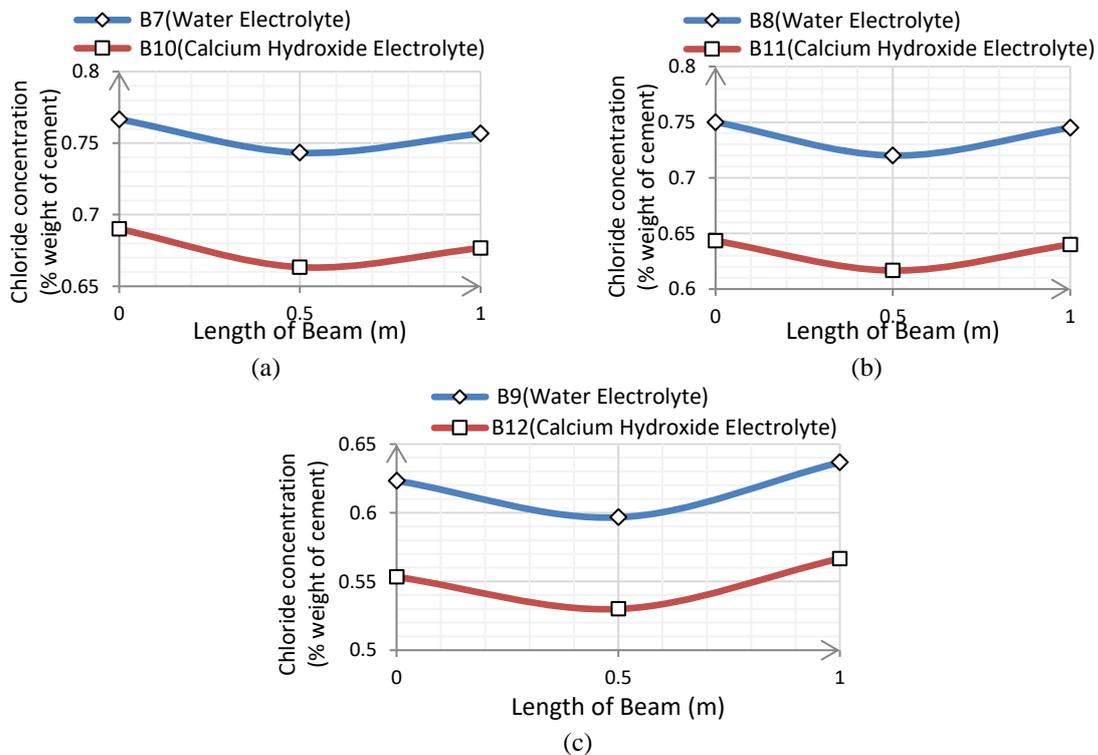
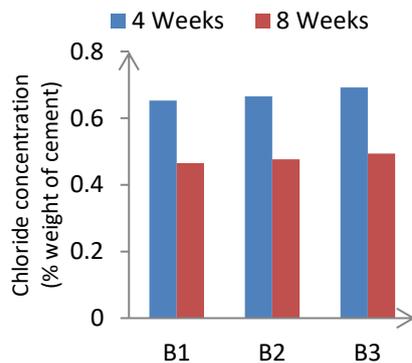


Figure 9- Chloride Concentration after 8 Weeks of Extraction (Chloride Content 2% weight of cement).

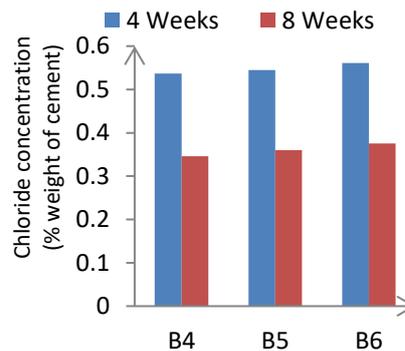
5.1.4. Effect of time

Figure (10) depicts the total chloride concentration after 4 and 8 weeks of extraction for all G1 and G2 beams. The total chloride concentration was lower after 8 weeks than it was after 4 weeks, as seen in the figure. In general, the average extraction efficiency for G1 was 31.45% after 4 weeks and 49.30% after 8 weeks. After 4 weeks, the average extraction efficiency for G2 was 43.71%, whereas it was 63% after 8 weeks.



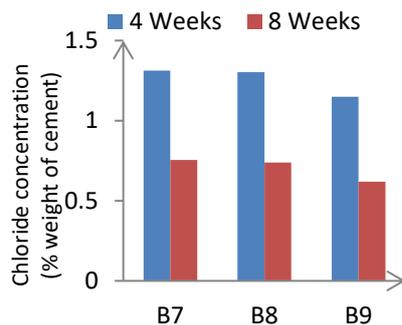
(a) G₁: Using Water as Electrolyte.

Figure (11) depicts the total chloride concentration after 4 and 8 weeks of extraction for all G3 and G4 beams. After 4 weeks, the average extraction efficiency for G3 was 38.32%, whereas it was 65.37% after 8 weeks. After 4 weeks, the average extraction efficiency for G4 was 45.26%, whereas it was 69.52% after 8 weeks. The effectiveness of removing chloride salts rises with time, as demonstrated by the data. On average, extraction efficiency after 8 weeks exceeds that after 4 weeks by 55.7%.

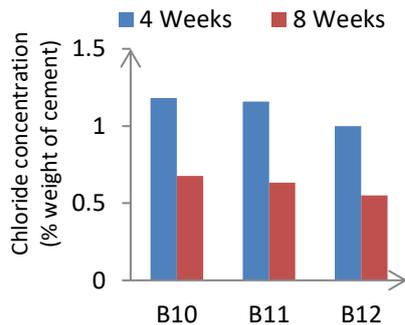


(b): G₂: Using Calcium Hydroxide as Electrolyte.

Figure 10- Chloride Concentration after 4 and 8 Weeks of Extraction (Initial Chloride Concentration 1% Weight of Cement).



(a) G₃: Using Water as Electrolyte.



(b) G₄: Using Calcium Hydroxide as Electrolyte.

Figure 11- Chloride Concentration after 4 and 8 Weeks of Extraction (Initial Chloride Concentration 2% Weight of Cement).

6. Conclusions

In this study, sodium chloride-infused mixing water was subjected to ECE on reinforced concrete beams (1, 2% Cl⁻ as a weight of cement) to stimulate corrosion from the start. After casting the beams for 6 months, the extraction procedure lasted 8 weeks. The chloride content of the tested beams was measured, and the change in chloride content was evaluated after the treatment. The following conclusions were drawn based on the obtained experimental results.

1. Calcium hydroxide electrolyte performs slightly better than water electrolyte. Using water-electrolyte, the total chloride elimination efficacy ranged between 44 and 52.7% depending on the concrete cover beneath tension steel, whereas Ca(OH)₂ elimination effectiveness varied between 61.5 and 64.5% based on the same variable.

2. Increasing the area of tension steel leads to higher extraction under the same cover depth and electrolyte type circumstances. Using water-electrolyte, the elimination efficacy of total chlorides ranged from 62.8 to 69.6% based on the area of tension steel, whereas Ca(OH)₂ removal ranged from 66.7 to 72.96% depending on the area of tension steel.
3. Increasing the time, the concrete beams are exposed to the extraction process increases the extraction process's efficiency. On average, extraction efficiency after 8 weeks exceeds that after 4 weeks by 55.7%.

7. References

- [1] Lankard, David R., et al. Neutralization of chloride in concrete. No. FHWA-RD-76-60 Final Rpt.. 1975.
- [2] J. E. Slater, D. R. Lankard, and P. J. Moreland,

- "Electrochemical removal of chlorides from concrete bridge decks," *Transp. Res. Rec.*, no. 604, 1976.
- [3] G. L. Morrison, Y. P. Virmani, F. W. Stratton, and W. J. Gilliland, "Chloride removal and monomer impregnation of bridge deck concrete by electro-osmosis. Interim report," No. FHWA/KS/RD-74/1. 1976.
- [4] J. Tritthart, "Electrochemical chloride removal: an overview and scientific aspects," *Mater. Sci. Concr. V*, Publ. by Am. Ceram. Soc. Westerville, Ohio, USA, pp. 401–441, 1998.
- [5] J. Meitz, *Electrochemical rehabilitation methods for reinforced concrete structures: a state of the art report*. The Institute of Materials Minerals and Mining, 1998.
- [6] C. Andrade, "An overview of electrochemical realkalization and chloride extraction," in *Proc. of the 2nd RILEM/CSIRO/ACRA International Conference on Rehabilitation of Structures*, 1998, pp. 1–12.
- [7] O. Vennesland and O. A. Opsahl, "Removal of chlorides from concrete." Google Patents, May 23, 1989.
- [8] D. D. L. Chung, "Electrically conductive cement-based materials," *Adv. Cem. Res.*, vol. 16, no. 4, pp. 167–176, 2004.
- [9] M. A. Climent, M. J. S. de Rojas, G. de Vera, and P. Garcés, "Effect of type of anodic arrangements on efficiency of electrochemical chloride removal from concrete," *ACI Mater. J.*, vol. 103, no. 4, p. 243, 2006.
- [10] M. J. Sánchez, P. Garcés, and M. A. Climent, "Electrochemical extraction of chlorides from reinforced concrete: variables affecting treatment efficiency," *Mater. Construcción*, vol. 56, no. 284, pp. 17–26, 2006.
- [11] P. Garcés, L. G. Andión, I. De la Varga, G. Catalá, and E. Zornoza, "Corrosion of steel reinforcement in structural concrete with carbon material addition," *Corros. Sci.*, vol. 49, no. 6, pp. 2557–2566, 2007.
- [12] S. Ivorra, P. Garcés, G. Catalá, L. G. Andión, and E. Zornoza, "Effect of silica fume particle size on mechanical properties of short carbon fiber reinforced concrete," *Mater. Des.*, vol. 31, no. 3, pp. 1553–1558, 2010.
- [13] P. Garcés, E. Zornoza, E. G. Alcocel, O. Galao, and L. G. Andión, "Mechanical properties and corrosion of CAC mortars with carbon fibers," *Constr. Build. Mater.*, vol. 34, pp. 91–96, 2012.
- [14] P. Garcés, J. Fraile, E. Vilaplana-Ortego, D. Cazorla-Amorós, E. G. Alcocel, and L. G. Andión, "Effect of carbon fibres on the mechanical properties and corrosion levels of reinforced portland cement mortars," *Cem. Concr. Res.*, vol. 35, no. 2, pp. 324–331, 2005.
- [15] J. C. Orellan, G. Escadeillas, and G. Arliguie, "Electrochemical chloride extraction: efficiency and side effects," *Cem. Concr. Res.*, vol. 34, no. 2, pp. 227–234, 2004.
- [16] V. Saraswathy, H.-S. Lee, S. Karthick, and S.-J. Kwon, "Extraction of chloride from chloride contaminated concrete through electrochemical method using different anodes," *Constr. Build. Mater.*, vol. 158, pp. 549–562, 2018.
- [17] X. Shi et al., "Replacing thermal sprayed zinc anodes on cathodically protected steel reinforced concrete bridges: experimental and modeling studies," No. 13-4543. 2013.
- [18] S. D. Cramer et al., "Thermal sprayed titanium anode for cathodic protection of reinforced concrete bridges," *J. Therm. spray Technol.*, vol. 8, no. 1, pp. 133–145, 1999.
- [19] S. D. Cramer et al., "Corrosion prevention and remediation strategies for reinforced concrete coastal bridges," *Cem. Concr. Compos.*, vol. 24, no. 1, pp. 101–117, 2002.
- [20] R. Brousseau, B. Arsenault, S. Dallaire, D. Rogers, T. Mumby, and D. Dong, "Sprayed titanium coatings for the cathodic protection of reinforced concrete," *J. Therm. spray Technol.*, vol. 7, no. 2, pp. 193–196, 1998.
- [21] Z.-G. Shao, F. Zhu, W.-F. Lin, P. A. Christensen, H. Zhang, and B. Yi, "Preparation and characterization of new anodes based on Ti mesh for direct methanol fuel cells," *J. Electrochem. Soc.*, vol. 153, no. 8, p. A1575, 2006.
- [22] M. A. Petersen, T. C. Sale, and K. F. Reardon, "Electrolytic trichloroethene degradation using mixed metal oxide coated titanium mesh electrodes," *Chemosphere*, vol. 67, no. 8, pp. 1573–1581, 2007.
- [23] L. Bertolini, F. Bolzoni, T. Pastore, and P. Pedferri, "Effectiveness of a conductive cementitious mortar anode for cathodic protection of steel in concrete," *Cem. Concr. Res.*, vol. 34, no. 4, pp. 681–694, 2004.
- [24] J. Orlikowski, S. Cebulski, and K. Darowicki, "Electrochemical investigations of conductive coatings applied as anodes in cathodic protection of reinforced concrete," *Cem. Concr. Compos.*, vol. 26, no. 6, pp. 721–728, 2004.
- [25] M. Siegwart, J. F. Lyness, and B. J. McFarland, "Change of pore size in concrete due to electrochemical chloride extraction and possible implications for the migration of ions," *Cem. Concr. Res.*, vol. 33, no. 8, pp. 1211–1221, 2003.
- [26] B. Elsener and U. Angst, "Mechanism of electrochemical chloride removal," *Corros. Sci.*, vol. 49, no. 12, pp. 4504–4522, 2007.
- [27] M. Sánchez and M. C. Alonso, "Electrochemical chloride removal in reinforced concrete structures: Improvement of effectiveness by simultaneous migration of calcium nitrite," *Constr. Build. Mater.*, vol. 25, no. 2, pp. 873–878, 2011.
- [28] T. D. Marcotte, C. M. Hansson, and B. B. Hope,

- "The effect of the electrochemical chloride extraction treatment on steel-reinforced mortar Part II: Microstructural characterization," *Cem. Concr. Res.*, vol. 29, no. 10, pp. 1561–1568, 1999.
- [29] J. Bennet and T. J. Schue, Chloride removal implementation guide, no. SHRP-S-347. 1993.
- [30] N. SP0107, "Electrochemical realkalization and chloride extraction for reinforced concrete," *Natl. Assoc. Corros. Eng.*, 2007.
- [31] J. Bennett and T. J. Schue, "Evaluation of norcure process for electrochemical chloride removal from steel-reinforced concrete bridge components," No. SHRP-C-620. 1993.
- [32] T. Tofeti Lima and K. Y. Ann, "Efficiency of Different Electrolytes on Electrochemical Chloride Extraction to Recover Concrete Structures under Chloride-Induced Corrosion," *Adv. Mater. Sci. Eng.*, vol. 2020, 2020.
- [33] Du Fengyin, Jin Zuquan, Zhao Tiejun, and Dai Xueyan. "Electrochemical chloride extraction from corrosion-resistant steel bar-reinforced concrete." *Int. J. Electrochem. Sci* 13 (2018): 7076-7094
- [34] Climent, Miguel-Ángel, Jesús Carmona, and Pedro Garcés. "Graphite–Cement Paste: A new coating of reinforced concrete structural elements for the application of electrochemical anti-corrosion treatments." *Coatings* 6.3 (2016): 32.
- [35] Carmona Calero, Jesús, et al. "Shape Effect of Electrochemical Chloride Extraction in Structural Reinforced Concrete Elements Using a New Cement-Based Anodic System." *Materials* 8.6 (2015): 2901-2917.
- [36] Zhao, L., and Shi-Shuenn Chen. "Preparation of graphene-cement paste anode for chloride extraction from marine reinforced concrete structures." *Int. J. Electrochem. Sci* 11 (2016): 9245- 9253.
- [37] Cañón, A., et al. "Feasibility of electrochemical chloride extraction from structural reinforced concrete using a sprayed conductive graphite powder–cement paste as anode." *Corrosion Science* 77 (2013): 128- 134.
- [38] G. Fajardo, G. Escadeillas, and G. Arliguie, "Electrochemical chloride extraction (ECE) from steel-reinforced concrete specimens contaminated by 'artificial' sea-water," *Corros. Sci.*, vol. 48, no. 1, pp. 110–125, 2006.
- [39] G.d.J. Fajardo San Miguel, *Limites d'utilisation des techniques électrochimiques de maintenance non permanentes pour les ouvrages en béton armé*, Thèse, Université de Toulouse, 2004.
- [40] J.-C. Orellan Herrera, "Efficacité et effets secondaires des techniques électrochimiques de maintenance des structures en béton armé." Toulouse, 2002.
- [41] Egyptian Standard Specifications, 2013. Composition, specifications and conformity criteria for common cements, Part 1. ES: 4756-1.
- [42] ASTM C618, Specification for Fly Ash and Raw Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete. Annual Book for ASTM Stand, 2002, p. 4
- [43] ASTM C 494/C 494M: Standard Specification for Chemical Admixtures for Concrete, Annual Book of ASTM Standards, 2001; 04.02, p. 9.
- [44] E.S.S.262/2015. "Egyptian Standard Specification for Steel Bars. Ministry of Industry", Cairo, Egypt, 2015.
- [45] M. T. El-Nimr, A. M. Basha, M. M. Abo-Raya, and M. H. Zakaria, "Structural behavior of small-scale reinforced concrete secant pile wall," *World J. Eng.*, 2022.
- [46] Technical specification of self-compacted concrete, National Buliding research center, cairo, Egypt, 2007
- [47] B. Ma et al., "Effect of TIPA on chloride immobilization in cement-fly ash paste," *Adv. Mater. Sci. Eng.*, vol. 2018, 2018.
- [48] P. Garcés, M. J. S. De Rojas, and M. A. Climent, "Effect of the reinforcement bar arrangement on the efficiency of electrochemical chloride removal technique applied to reinforced concrete structures," *Corros. Sci.*, vol. 48, no. 3, pp. 531–545, 2006.