# A Review Study of the Electrochemical Chloride Extraction Treatment Process from Concrete

**Mohamed Menshawy[1],*, Mahmoud Mostafa Elhawary[1], Ahmed Serag Faried[2]**

[1] Construction Engineering Department, Misr University for Science and Technology, Giza, Egypt.
[2] Civil Engineering Department, Faculty of Engineering, Fayoum University, Fayoum, Egypt.

* Corresponding Author: Mohamed Menshawy (mohamedrezk5748@gmail.com)

## Abstract

This paper presents a comprehensive analysis of electrochemical chloride extraction (ECE) as a remediation technique for reinforced concrete structures suffering from chloride-induced corrosion. The study thoroughly examines the principles of ECE, emphasizing its role in reducing corrosion and extending the lifespan of concrete infrastructures. It explores various measurement methodologies to assess ECE's efficacy, focusing on outcomes like effective chloride removal, corrosion prevention, and pH changes in concrete. The review also highlights key factors influencing ECE's performance, including the types of electrodes and electrolytes used, and the impact of different environmental conditions. Particularly, the paper discusses potential disadvantages and risks associated with ECE and recommends using caution in its application. The conclusion of the study stresses the need for continued research to evaluate the long-term effectiveness and durability of ECE treatments, particularly in different environmental settings. This comprehensive analysis aims to contribute to the development of knowledge in the field of civil engineering, especially in the area of concrete durability and corrosion prevention. The article is a significant resource for researchers and professionals seeking to understand and apply ECE in concrete rehabilitation projects.

## Keywords

pH – External anode – Cathode – Electrolyte – Steel Corrosion – compressive strength.

## 1. Introduction

Steel corrosion in concrete structures has been recognized since the latter part of the 20th century, extremely affecting the durability of various infrastructures [1-4]. This corrosion is a significant factor contributing to the deterioration of buildings, bridges, tunnels, dams, and historical sites. The embedded steel rebar in concrete, initially in an alkaline environment with a pH of around 13, steel rebar is subjected to passivation. However, over time, environmental outside factors and chloride ion penetration challenge this passivity, leading to corrosion.

The mechanisms of steel corrosion in concrete are complex, involving both chemical and electrochemical

processes. The penetration of chloride ions, particularly from external sources such as deicing salts or seawater, plays a critical role in accelerating the corrosion process. These ions disturb the protective oxide layer on the steel rebar, leading to its deterioration [5-9].

Various environmental and structural factors participate in the corrosion process. Factors such as moisture content, temperature variations, and concrete quality can influence the rate and severity of corrosion. Additionally, the design and construction practices, such as the depth of the concrete cover and the quality of the concrete mix, significantly affect the sensitivity of steel to corrosion [10-14].

Steel corrosion in concrete has a variety of effects. It compromises the structural integrity and safety of the infrastructure, leading to costly repairs and maintenance. In severe cases, it can result in catastrophic failures, Presenting considerable hazards to public safety and requiring substantial economic resources for rehabilitation [15-19].

The corrosion of steel in concrete also has cultural consequences, particularly when it affects historical structures. Preserving these structures is necessary for cultural heritage, Corrosion presents a substantial risk to the durability and conservation of these objects.

Traditional methods to reduce steel corrosion in concrete include the use of corrosion inhibitors, protective coatings, cathodic protection, and design modifications. However, these methods often have limitations, particularly in complex structures or historical monuments, where preservation of the original material is essential [25-29].

Electrochemical Chloride Extraction (ECE) was developed as a solution to address steel corrosion in concrete. This method involves applying an electric current through the concrete, and migrating chloride ions away from the steel rebar, thus restoring the alkaline environment and re-passivating the steel [30-34].

The evolution of ECE has seen significant advancements since its inception. Initial tests and developments in the United States in the 1970s were followed by further developments in Europe in the 1980s. Recent developments have focused on optimizing the process, understanding its long-term effects, and adapting it to various environmental conditions [35-39].

Metwally[76] concluded that the current intensity was affected by the efficiency of ECE, as increasing the current intensity enhanced the process. In addition to, 1:2 $A/m_2$, was found to be the most efficient current.

Véronique Bouteiller[77] discovered that the effectiveness of ECE should be determined using various criteria, including the removal of chlorides (both free and total), reduction of corrosion (measured by half-cell potentials, corrosion current density, resistivity, etc.), pH levels, and visual inspection.

Thamara Tofeti Lima [78] found that the advancement and effectiveness of ECE in concrete structures can be measured by monitoring not only the rate at which chloride is removed but also by measuring the electrical potential of corrosion (half-cell potential) or the corrosion rate, which is determined using the linear polarization resistance method. It can be deduced that ECE does not ensure the restoration of corroded rebars and is more suitable as a proactive measure to prevent early corrosion, rather than as a method to restore structures that are already significantly deteriorated. Moreover, to attain superior outcomes for post-treatment assessment, it is strongly advised to analyze the collective impact of all factors, including chloride removal rate, Ecorr, and Icorr.

Abd el Rahman[80], and Nourhan[81] examined the efficacy of Electrochemical Chloride Extraction (ECE) by using un-galvanized steel mesh combined with conductive cement paste as an external anode on a reinforced concrete slab. The behavior of the slab was analyzed by assessing its compressive strength, concrete chloride content, and steel corrosion potential both before and after ECE. Also, the study focused on the behavior of the slab, particularly considering the steel arrangement with a spacing of 20 cm between the reinforcement bars.

## 2. Electrochemical Treatment Mechanisms

Electrochemical treatment processes for concrete structures are considered a non-destructive technique to rehabilitate concrete degradation caused by corrosion of steel. There are three electrochemical corrosion protection methods, cathodic protection (CP), Electrochemical realkalisation, and electrochemical chloride extraction (ECE). The main differences between the three methods are related to the magnitude of the applied current density, the duration of the treatment, the used anodes, and the electrolyte.

Cathodic protection (CP) is mainly applied as a rehabilitation technique to structures suffering from chloride which causes corrosion. It has also less commonly been applied to the carbonated structure. CP is a permanent treatment with a proven track record although its main disadvantage is when it is used for protecting pre-stressed concrete structures due to the risks associated with hydrogen embitterment. In this method the sacrificial anode is connected to the positive terminal of a low voltage D.C power supply, while the negative terminal is connected to the reinforcement (cathode), the typical current density is 3 to 20 mA/m2 (concrete surface), the electrolyte is cementitious material [11, 12, 13, 14].

Electrochemical realkalisation is a temporary application and the main purpose of this method is to restore a high PH in the concrete to reinstall corrosion protection in cases where de-passivation has occurred due to carbonation of the concrete. In this method, the anode, and the cathode are connected such as in the CP method but the typical current density is 0.8 to 2, with an upper limit of 5 A/m2 concrete surfaces, the duration of this treatment is 3 to 14 days and the electrolyte is sodium carbonate, water, or lithium hydroxide [12, 15, 16].

Electrochemical chloride extraction (ECE) is a temporary technique that has been shown to remove a lot of chloride from the cover of concrete. In this method, the anode, and the cathode are connected such as in the CP method but the typical current density is 0.5 to 2 mm2 of the concrete surface, the duration of this treatment is 4 to 8 weeks and the electrolyte is water, sodium borate, or calcium Hydroxide [12, 14, 17, 18].

## 3. Principles of ECE

### 3.1 History of ECE

The Federal Highway Administration performed the first electrochemical chloride extraction (ECE) tests in the mid-1970s in the United States, utilizing high voltages of up to 220 V [19, 20, 21]. This approach, however, for the next 20 years, was not used often. In the 1980s, Oystein Vennesland unique invention in Europe, which was a major advance [22]. In the 1990s, research performed as part of the United States Strategic Highways Research Program (SHRP) enhanced our knowledge of ECE [23, 24, 25, 26]. Pocock's 1994 book [27] emphasized the possibility of ECE for recovering chloride-ion-contaminated reinforced concrete. Numerous papers, cutting-edge findings, and chapters on ECE therapy have appeared [28, 29].
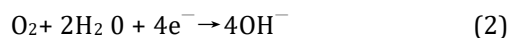
### 3.2 Corrosion Mechanism

Equation (1) illustrates the anodic dissolution of iron, which leads to steel rebar corrosion. Equation (2) describes the related oxygen reduction at the cathode, which employs the electrons produced by the metal dissolution in its reaction.

Iron Anodic dissolution

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad (1)$$

Oxygen reduction

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad (2)$$
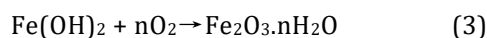
The surface of the steel is the focal point of both of these reactions, which produce corrosion products. Concrete cover cracks may result from the accumulation of these corrosion products at the rebar/concrete contact, as shown by Equation (3).

Corrosion inhibitors

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2$$

$$Fe(OH)_2 + nO_2 \rightarrow Fe_2O_3.nH_2O \qquad (3)$$
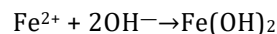
By lowering the thermodynamic potential of the steel, its chloride content to decrease, and the pH levels at the interface between the rebar and concrete to rise, ECE is intended to stop or restore the passivity of steel rebar.

A schematic representation of the ECE arrangement using a direct current source is shown in Figure 1. The anode, which is often found on the concrete surface, acts as the positive pole of the direct current source, while the corroded steel rebar, acting as the cathode, connects to the negative pole. During ECE, it is essential to keep the pH moderated and reduce circuit resistance between the cathode and anode. To do this, electrolyte solutions are often used in combination with tanks, sprayed cellulose fibers, or artificial surfaces.
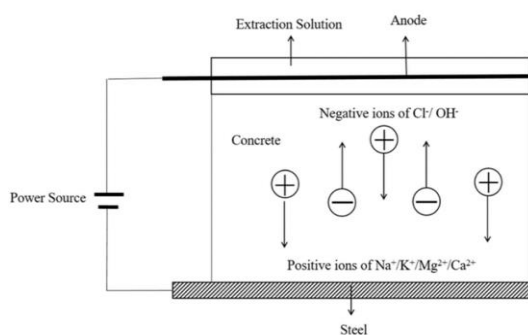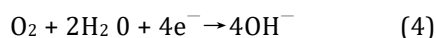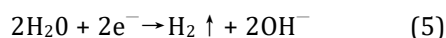


Figure 1: Illustration of the ECE Components.

Alkaline reinforced concrete's cathode and anode have different electrical potentials, which stimulate ion migration in both the electrolyte and the concrete [17, 28, 30]. This might result in the following reactions:

Oxygen reduction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (4)$$

Water reduction

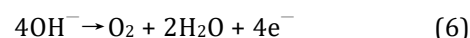$$2H_2O + 2e^- \rightarrow H_2 \uparrow + 2OH^- \qquad (5)$$

The steel rebar is protected from corrosion by the low voltage of the cathode. Equation (4) illustrates how slowly the oxygen reduction reaction proceeds due to the restricted oxygen availability in the concrete. To begin with, the concrete's cathode region has very little
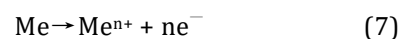
oxygen, and oxygen diffusion from the outside is slow. Equation (5), which describes the water reduction process, now takes center stage [30]. The release of hydrogen gas has the potential to increase local pressure, which may lead to hydrogen embrittlement of steel and the breaking of concrete.

The oxidation of hydroxyl ions at the anode results in the creation of water and oxygen (Equation (6)). If metal is inert, no anode dissolution occurs (Equation (7)). Because of safety and environmental concerns, it is vital to prevent chloride ions oxidation into chlorine gas (Equation (8)) in settings where electrolyte acidification occurs.

Water oxidation

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \qquad (6)$$

Anode dissolution

$$Me \rightarrow Me^{n+} + ne^- \qquad (7)$$

Chlorides

$$2Cl^- Cl_2 + 2e^- \qquad (8)$$

At typical ECE current densities, migration becomes major in addition to the oxidation-reduction processes, speeding up the flow of ions in the electrolyte and concrete. Diffusion, reduction, electrical migration, and concentration gradients are examples of ion transport mechanisms. The electric field produced by the rebar and the anode mainly prevents anions such as free chlorides ($Cl^-$), hydroxyls ($OH^-$), carbonates ($CO_3^{2-}$), and sulfates ($SO_4^{2-}$) from moving away from the cathode area and toward the anode. The same method is used by cations such as calcium ($Ca^{2+}$), potassium ($K^+$), sodium ($Na^+$), and lithium ($Li^+$) ions to enter the cathodic steel region. Despite the irregular distribution of specific ions inside the concrete, electrical neutrality is preserved on a large scale. The alkali-silicate reaction may be greatly influenced by the quantity of alkali ions in concrete if reactive aggregates are present.

The electrical field that was accomplished throughout the treatment is shown in **Figure 2**, which indicates that the anode and rebar have the greatest extraction effectiveness. Moreover, it is challenging to eliminate chloride ions from deeper levels close to the rebar [28].
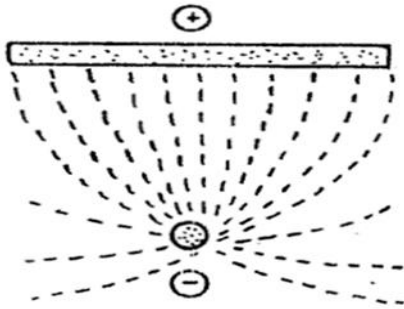


**Figure 2:** Streamlines in an inhomogeneous field at the concrete surface between rebar (cathode) and anode.

### 3.3 Components of the ECE Treatment Process

Components of the ECE treatment process are presented in this section

### 3.3.1 Cathode

The cathode is represented by the rebar which may be plain or deformed. It may combined with stirrups or with structural reinforcement. When a deeper depth of chloride was present than the rebar, Arya[31] inserted a further external cathode. The design of the arrangement had an impact on the extraction of chloride, which rose from 40% (achieved with the normal configuration) to 55% when the external platinized titanium mesh and the rebar were joined as cathodes.

### 3.3.2 External Anode

The external anode in ECE treatment must meet several standards to confirm its optimal functionality [4]. It needs to effectively separate the selected current across the entire protection area for the complete duration of the treatment. Additionally, the anode must exhibit corrosion resistance and should not change the visual appearance of the structural element. Lastly, its fixation must be cost-effective.

In 1976, Slater et al. [19] carried out their first experiment with graphite, titanium, and platinized titanium anodes in a 0.1 N calcium hydroxide solution. The best material to use as an external anode is platinized titanium, as opposed to titanium, which has limited electrocatalytic activity, and graphite, which corrodes at high current densities.

The most reliable and extensively used anode nowadays is titanium which has been coated with another metal or activated with oxides. This anode is adaptable, safe for a variety of concrete constructions, and comes in mesh, wire, or strip form. It works well on both sides of curved surfaces and may be applied to both vertical and horizontal constructions. To increase a ductile fiber (PE or PVA) reinforced cementitious composite's (DFRCC) adhesion to a prepared concrete surface, Ueda et al. [32] included a titanium mesh in the composite. There was an accumulation of chlorides in the DFRCC layer, which may have contributed to their migration back into the concrete cover, even though the efficacy of the chloride extraction at the rebar level was close to 75%. Steel's cheap cost prompted investigation; however, as it is rapidly consumed during the treatment and leaves rust spots on the concrete surface, its use is improper [23].

Several anode technologies have been studied and documented in this literature as titanium anode substitutes. The concept of replacing the Ti-RuO$_2$ mesh anode with a graphite anode and a conductive cement paste (CCP) combination applied rapidly like plaster was examined by P'erez [33]. Although the chloride extraction was the same for both kinds of anodes, the CCP layer experienced an accumulation of chloride ions, which may be extended back into the concrete cover. The use of a sprayed conductive graphite powder cement paste as an external anode was investigated by Canon [34] and Carmona [35]. This method offers flexibility in working on diverse surfaces, shapes, and inclinations, making the application of ECE easier. The effectiveness of the chloride extraction, according to the data, was similar to what was observed when titanium was used as an anode. Moreover, this sprayed layer failed to retain chlorides but kept moisture for up to 10–12 hours, unlike the anode used by P'erez [33]. The durability of this anode layer was examined after anodic reaction damage.

Lastly, Zhu [36] studied the use of a conductive carbon-fiber-reinforced polymer (CFRP) mesh as an electrochemically stable anode with excellent mechanical properties, durability, and conductivity. The results of the chloride extraction were similar to those using an activated titanium mesh anode. It should be noted that the use of a conductive anode layer homogenizes the data and prevents half-cell potential mapping measurements for inspectional reasons.

### 3.3.3 Electrolyte

In the ECE treatment process, the electrolyte fulfills three key functions:

- Electrolyte decreases electrical resistance by saturating the contact between the concrete surface and reinforcing and allowing ions in the concrete to hydrate and dissolve. This reduces the applied voltages and enhances ionic mobility.
- The electrolyte's pH prevents any change in concrete PH.
- Electrolyte collects chlorine gas, which has a hazardous influence on human health.

Typically, the electrolyte demands replacement or circulation. When applied to horizontal or vertical surfaces.

Water [30, 34, 35, 37, 50, 52, 70, 72, 74, 75] and a saturated solution of calcium hydroxide ($Ca(OH)_2$) [19, 23, 36, 37, 38, 39, 47, 50, 51, 52, 53, 55, 58, 69, 71] are the most widely used electrolytes for ECE. To prevent acidification and the generation of chlorine gas, a saturated calcium hydroxide solution with a pH of 12.4 is linked to the requirement for a moderated medium in addition to a sufficiently high pH value.

Sodium hydroxide (NaOH) [31, 37], sodium carbonate ($Na_2CO_3$) [38], and sodium borate solutions ($Na_3BO_3$ [39], $Na_2B_4O_7$ [40], and $Na_2B_4O_7.10H_2O$ [65, 66] were studied as electrolyte solutions containing sodium ions. However, the presence of sodium ions may occasionally be detrimental to the alkali-silica reaction (ASR). In addition, since lithium ions may minimize ASR [26, 32, 41], a lithium borate solution was used as an electrolyte.

Ueda [41] also noted that using a high temperature of $Li_3BO_3$ as an electrolyte solution will increase the efficiency of the treatment process.

### 3.3.4 The Current's Flow

Transmission of current between the cathode and the external anode is critical for guaranteeing steel rebar cathodic protection. Continuous or intermittent current flow may be produced in two types: constant voltage and constant current. The current flow in the first one is indicated in voltage [19, 20, 21, 23, 24, 25, 26, 31, 42, 43, 44, 45]. The current flow in the second type is indicated by the current density in $A/m^2$ of the reinforcement steel or area of concrete, which was selected. In references [14, 17, 35, 36, 37, 38, 40, 46, 47, 50, 53, 54, 55, 56, 58, 66, 67, 68, 69, 70, 71, 74, 75], the current density is indicated in $A/m^2$ of the reinforcement steel, and $A/m^2$ of the concrete surface.

In addition, some authors attempted to increase the effectiveness of the therapy by using either the voltage control mode [21] or the current control mode [30, 46, 55, 64, 73, 74, 75] to achieve intermittent current flow as opposed to continuous current flow.

### 3.3.5 Duration

In contrast to Cathodic Protection, which is often supplied for 2 to 8 weeks [14, 26, 30, 31, 32, 33, 34, 36, 37, 38, 40, 41, 45, 52, 53, 54, 56, 57, 58, 69, 70, 71, 75]. Studies have also been conducted over longer periods [44], especially when evaluating pre-stressed concretes or using lower current densities.

## 4. Efficiency of the ECE
### 4.1 Chloride Removal Rate

The rate of chloride removal during Electrochemical Chloride Extraction (ECE) can be influenced by various conditions, involving voltage, impressed current density, electrolyte solution type, anode materials, concrete mix design, and reinforcement geometry. Many research papers typically focus on studying only a part of these factors under normal conditions, given the unknown relationship and order of importance among

them. In this section, data has been collected from a substantial number of research papers, as presented in **Table 1**. In each specific case, certain factors remain constant, while the relevant one is changed to evaluate the impact of treatment setup on chloride removal.

## 4.2 Effect of Electrolyte Type on Chloride Removal

Using tap water as the electrolyte in ECE enhanced resistance, improving anode polarization, according to studies by Monteiro [46]. On the other hand, Polder found no appreciable difference in saturated calcium hydroxide solutions' and tap water's ability to remove chloride [37]. Further investigation by Polder [47] compared solutions of calcium hydroxide ($Ca(OH)_2$) and sodium carbonate ($Na_2CO_3$), and the results indicated that calcium hydroxide extraction was more effective. In comparison, the percentage of chloride extracted over the same time with $Na_2CO_3$ electrolyte was only 35% and 55%, corresponding to current densities of 1 and 4 $A/m^2$ of steel reinforcement, respectively. The use of $Ca(OH)_2$ as an electrolyte resulted in a 67% extraction of total chlorides (0.7 $A/m^2$ of reinforcement steel, 42 days). Especially when Na was used as an electrolyte, Na+ moved into the pore solution and reduced the passing number of Cl-. Using a sodium tetraborate ($Na_2B_4O_7$) solution, Bouteiller [40] removed chloride from a reinforced concrete beam that had been exposed to a coastal environment in France for forty years. Up to 70% of the free chlorides around the rebar, 50% in the intermediate layer, and This treatment can assist in reducing 5% at the concrete surface. Orellan [48] categorized a variety of electrolytes according to how well they extracted chloride, with tap water (60%) being the most effective, sodium-based electrolytes (54%), and calcium and lithium-based electrolytes (40%) being the least effective.

## 4.3 Effect of Different Durations on Chloride Removal

Electrochemical Chloride Extraction treatments continue for 28 or 56 days, treatments ranging from 3 to 112 days have been observed. According to numerous research [17, 36, 64, 74, 75], the extraction of chlorides is more efficient in the early phases of treatment. This behavior is simply explained because chloride ions predominate as the principal negative ions moving across the current flow during the early phase. As the process advances, the chloride transport number reduces due to extraction, and hydroxyl ions generated At the cathode begin to compete with one another to be the carriers of negative charge. Tang (64) proposed the existence of a limit that makes it difficult to remove more chloride ions.

## 4.4 Measurement of Corrosion

To measure half-cell potentials, a connection must be made between the reinforcement and an external reference electrode, which may be composed of copper, copper sulfate, SCE, or CSE. Following this, potential measurements are obtained from the surface of the concrete. An investigation into the reliability of half-cell potential measurements for evaluating the repair of corroded concrete structures was carried out by Elsener [49]. It is not accurate to rely on a fixed value to determine whether passivation has been accomplished, he emphasized because this condition is influenced by a variety of factors. Additionally, the author noted that extremely negative potentials of rebars are recorded after the ECE procedure as a result of the treatment's intense polarization. Hence, it is advisable to obtain significant potential measurements, especially after a specified amount of time which is generally between one and three months after the end of the current. The presence of this periodic delay ensures that half-cell potential measurements provide accurate indicators of the passive state of rebars. However, it is crucial to exercise caution when explaining the results due to the variety of factors that can affect half-cell potential measurements. Diverse potential values could potentially signify corrosion of rebars in various structures.

In the majority of cases, Electrochemical Chloride Extraction (ECE) tends to transition the structure into a more passive state. With an increase in the charge applied during the treatment, more positive values are generally attained. However, there are situations where these values may still fall short of reaching the passive zone. Stoop and Polder [50] stated that ECE effectively moves potentials towards a more passive range, and

specimens subjected to the treatment maintained their positive values even a year after the procedure's completion.

Regarding measurements of corrosion rate (Icorr), a small amount of research investigated data on this aspect after Electrochemical Chloride Extraction (ECE).

Some authors argue that corrosion rate results may conflict with those obtained from electric potential measurements. $I_{corr}$ values ($\mu A/cm2$) are derived by calculating linear polarization resistance (LPR), half-cell potential ($E_{corr}$), and the electrical resistance of concrete (Re). Studies by Green[51] and Abdelaziz [52] explored the impact of the ECE on decreasing the

**Table 1:** Collected and organized data about the setup of ECE and removal rate.

| Author/Reference | Anode Type | Electrolyte Type | Initial Cl− content | Current density ($A/m^2$) | Duration (weeks) | Removal rate (%) |
|---|---|---|---|---|---|---|
| Arya et al.[31] | TM | NaOH | 2 | 1.0 | 12 | 36 |
|  |  |  | 1.87 | 1.0 | 12 | 50 |
|  |  |  | 1.8 7 | 0.75 | 8 | 45 |
| Ihekwaba [67] | TM | Na$_3$Bo$_3$ | 3 | 3.0 | 8 | 45 |
|  |  | Na$_3$BO | 1.7 | 1.0 | 8 | 55 |
| Buenfeld and Broomfield [17] | TM | Water | 1.5 | 0.75 | 4 | 75 |
| Otero et al. [59] | TM | Ca(OH)$_2$ | 3 | 1.0 | 4 | 54 |
| Sharp et al. [57] | TM | Ca(OH)$_2$ | 3 | 1.0 | 7 | 60 |
| Polder et al. [68] | TM | Water | 3 | 4.0 | 3 | 75 |
| Chang [69] | TM | Ca(OH)$_2$ | 3 | 1.88 | 6 | 83 |
| Siegwart et al. [70] | TM | Water | 2 | 5.0 | 6 days | 79 |
| Orellan et al. [58] | TM | Ca(OH)$_2$ | 3 | 1.0 | 7 | 45 |
| Hosseini and Khaloo [60] | TM | Ca(OH)$_2$ | 2 | 1.0 | 8 | 60 |
|  |  |  | 1.5 |  | 8 | 50 |
| Sanchez et al. [61] | TM | Water | 3 | 5.0 | 8 | 43 |

| Author/Reference | Anode Type | Electrolyte Type | Initial Cl⁻ content | Current density $(A/m^2)$ | Duration (weeks) | Removal rate (%) |
|---|---|---|---|---|---|---|
| Miranda et al. [71] | SS | Ca(OH)$_2$ | 3 | 1.0 | 12 days | 85 |
| Sanchez et al. [72] | TM | Water | 3 | 5.0 | 6 | 76 |
| Climent et al. [73] | TM | Water | 0.5 | 5.0 | 12 days | 40 / 60 |
| Swamy and McHugh [55] | TM | Ca(OH)$_2$ | 2.4 | 1.0 | 12 days | 70 |
| Fajardo et al. [74] | TM | Water | 4.6 | 1.0 | 13 | 75 |
| Miranda et al. [53] | TM | Ca(OH)$_2$ | 3 | 1.2 | 6 | 78 |
| Elsener and Angst [75] | SS | Water | 1.5 | 0.63 | 8 | 69 |
| Abdelaziz et al. [52] | SS | Water / Ca(OH)$_2$ | 3 / 5 | 1.0 | 4 / 2 | 30 / 36 |
| Canon et al. [34] | TM | Water | 1.5 | 5.0 | | 79 |
| Qiao et al. [62] | SS | Ca(OH)$_2$ | 3 | 1.0 | | 83 |
| Yodsujai et al. [63] | SS | NaOH / KOH / Ca(OH)$_2$ | 5 | 1.5 | 4 | 62 / 74 / 76 |

corrosion rate and stated that similar to half-cell potential measurements, evaluating the short-term effectiveness of ECE on the corrosion rate of corroded reinforcement is more reliable after the conclusion of ECE, typically around 3 to 4 weeks later when the corrosion rate experiences a significant reduction.

Miranda et al. (53) emphasized the fact that re-passivation of corroded rebars cannot be verified through complete chloride removal, particularly in cases where partial chloride removal occurs, which is a common occurrence. In conclusion, although ECE can be considered an effective preventive measure against early corrosion, it might not be suitable for restoring structures that have suffered extensive deterioration. Furthermore, the authors claimed that by increasing the charge passing through the ECE treatment and utilizing water as the electrolyte, the long-term effectiveness of ECE on the corrosion rate of reinforcement was enhanced following ECE treatment. This is due to the

pattern identified in the literature review concerning half-cell potential values. The literature suggests that an explanation for the supposed advantages of increasing the transmitted charge is its capacity to reduce the concentration ratio of Cl−/OH−, thereby enabling the reinforcing steel to remain in its passive state for prolonged periods.

## 4.5 PH of Concrete

During the process of electrochemical corrosion (ECE), the pH values at the interface between the rebar and concrete increase as a consequence of hydroxyl ion formation at the cathode, Buenfeld [17] used a phenolphthalein indicator in an Electrochemical Chloride Extraction (ECE) arrangement using water as the electrolyte and found continuous purple discoloration was seen 48 hours post-application, surrounding regions that included the concrete near the rebar. Using calcium hydroxide as an electrolyte, Zhu et al. [36] observed an increase in pH around the rebar. In a different study, Yeih et al. [54] found that using a sodium hydroxide (NaOH 0.1 M) solution increased pH values up to 12.4.

## 4.6 Effect of ECE on Compressive Strength of Concrete

The researchers focused on the compressive strengths as examined in references [55, 56]. Bond stress variations were determined through pull-out tests conducted in references [36, 69, 67]. In the case of larger specimens such as beams, flexural strength tests were carried out as described in reference [55].

## 5. Beneficial Effects of the ECE

Cathodic protection (CP) functions by inducing a more negative electrochemical potential in the steel, therefore decelerating or eliminating corrosion, which is its primary purpose. Under the influence of the electric field, chloride ions migrate towards the anode, moving away from the reinforcement, where chlorides are identified as the primary causes of corrosion. After immersing the anode in an electrolyte, the chlorides and the electrolyte are removed after treatment. This process significantly removes chlorides from the concrete,

typically ranging from 50-90%. This removal is particularly noticeable near the steel, leading to a considerable enhancement of repassivation of the steel [12, 57, 58].

## 6. Side Effects of the ECE

The discussed electrochemical chloride extraction (ECE) treatment carries potential adverse effects, including reducing the bond between steel and concrete, hydrogen evolution, Reinforcing steel's tendency to become brittle, and the initiation of an alkali-silica reaction. The application of direct current has the potential to weaken the bond between steel and concrete. The decrease in bond strength results from changes in the composition of the hardened cement matrix, particularly the significant accumulation of alkali hydroxides around the cathode. This accumulation may cause a weakening of the binder, thereby reducing the bond [12, 13, 57, 58].

The work by Bennett et al. [23] focused on the variations in bond strength between reinforcing steel and concrete following electrochemical chloride extraction (ECE) of contaminated concrete. They discovered that after ECE treatment, bond strength dropped by 11% compared to its pre-treatment level. The application of the high current associated with electrochemical chloride extraction seems to result in a decrease in binding strength.

In a study by Buenfeld and Broomfield [17], specimens that cured a 3-month curing period before ECE treatment were subjected to a current density of 0.75 A/m² of reinforcement for up to 31 weeks. The results showed that 24 hours after concluding the ECE treatment, chloride-free specimens showed a gradual, slight increase in bond strength throughout the 32-week ECE duration. Before ECE, specimens containing chloride (1.5% chloride by weight of cement) showed an average bond strength 57% higher than that of chloride-free specimens, attributed to corrosion-enhancing bonds likely resulting from a combination of prestressing and mechanical interlock. However, this increased bond strength was significantly reduced after just 2 weeks of ECE treatment.

The potential risks of hydrogen evolution and

embrittlement in reinforcing steel are major considerations when applying cathodic protection for prestressing steels. Numerous studies have been conducted to evaluate whether these effects could lead to structural failure in such situations. Bennet et al. [23] concluded that the recommended current densities and charge quantities for electrochemical chloride extraction (ECE) do not provide a risk to ordinary reinforcement in terms of hydrogen evolution.

In cases where concrete contains reactive siliceous aggregates, an alkali-silica reaction may occur due to an increase in the alkalinity of the pore solution around the reinforcement. Bennet et al. [23] investigated the occurrence of alkali-silica reaction in reinforced concrete subjected to ECE. They conducted tests on two-month-old concretes with the same cement but different aggregates namely, inert quartz, reactive chert, or reactive opal. The study showed that concrete containing opal exhibited more damage than the other aggregates due to ECE treatment.

## 7. Conclusion

Electrochemical chloride extraction (ECE) is considered an effective method for preventing chloride-induced corrosion in reinforced concrete structures. However, its effective utilization requires accurate application. The major conclusions discussed in this research are summarized as follows:

1. The study confirmed that ECE's effectiveness in reducing chloride content in concrete, particularly in inaccessible areas, is crucial for restoring alkaline environments and re-passivating steel rebar.
2. The research emphasized the importance of optimizing factors like current density, treatment duration, electrode types, and electrolytes to enhance ECE efficiency.
3. ECE presents challenges including potential risks like hydrogen evolution and the initiation of alkali-silica reactions, which emphasizes the need to use it with caution.
4. The paper discussed recent advancements in Electrochemical Engineering (ECE), focusing on innovations in electrode materials, electrolyte compositions, and control systems.
5. The study presents case studies showing the practical applications of ECE in various environmental conditions.
6. This study emphasized the need for continuous monitoring and maintenance of ECE to fully comprehend its lasting impact.
7. The environmental and economic benefits of ECE are noted, particularly its contribution to sustainable infrastructure development and reduced maintenance costs.
8. Post-treatment monitoring strategies are necessary for evaluating ECE's ongoing effectiveness and identifying possible problems over time.
9. The need for adapting ECE to various global environmental conditions and construction practices is highlighted, considering unique challenges in different regions.

Future research must focus on optimizing ECE parameters, exploring its long-term effects, and developing integrated approaches for concrete rehabilitation.

## 8. References

[1] J.P. Broomfield, Corrosion of steel in concrete - Understanding, investigation and repair, E&FN SPN, London, 1997.

[2] A. Bentur, S. Diamond, N.S. Berke, Steel corrosion in concrete - Fundamentals and civil engineering practice, E&FN SPON, London, United Kingdom, 1997.

[3] Woodward R, Cullington DW, Daly AF, Vassie PRW, Haardt P, Kashner R, Astudillo R, Velando C, Godart B, G. B, C. C, Mahut B, B. Mahut, A. Raharinaivo, M.I. Lau, Bevc L et Perus I, C. C, Bridge management in Europe (BRIME)- Deliverable D14- Final Report, 2001, pp. 228.

[4] L. Bertolini, B. Elsener, P. Pedeferri, R.B. Polder, Corrosion of steel in concrete: prevention, diagnosis, repair, Wiley Vch Verlagsgesellschaft Mbh, Weinheim, 2004.

[5] U. Angst, B. Elsener, C.K. Larsen, O. Vennesland, Critical chloride content in reinforced concrete - A review, Cem. Concr. Res. 39 (2009) 1122–1138.

[6] J.Y. Hu, S.S. Zhang, E. Chen, W.G. Li, A review on corrosion detection and protection of existing reinforced concrete (RC) structures, Constr. Build. Mater. 325 (2022), 126718.

[7] R.N. Cox, R. Cigna, O. Vennesland, T. Valente, COST 509 - Corrosion and protection of metals in contact with concrete - Final Report, European Commission, Directorate General Science, Research and Development, Brussels, EUR 17608 EN 1997.

[8] R. Cigna, C. Andrade, U. Nürnberger, R. Polder, R. Weydert, E. Seitz, COST 521 - Corrosion of steel in reinforced concrete structures - Final Report, European Commission, Directorate-General for Research, Brussels, EUR 20599 2003.

[9] S. Matthews, M. Sarkkinen, J.R. Morlidge, Achieving Durable Repaired Concrete Structures: Adopting a Performance-based Intervention Strategy, CONREPNET Project Report IHS BRE Press, Watford, UK, 2007.

[10] G.P. Tilly, J. Jacobs, CONREPNET - Concrete repairs - Performance in service and current practice, HIS BRE Press, Watford, UK, 2007.

[11] AFNOR, NF EN ISO 12696 - Cathodic protection of steel in concrete 2017.

[12] RILEM Draft Recommendation, Repair strategies for concrete structures damaged by reinforcement corrosion Material Structure, Vol. 27. 4.1.5 pp, 1994.

[13] J.P. Broomfield, Corrosion of steel in concrete, second Edition, Winston, R., John Wiley, Vol. 6, pp. 581-600.

[14] T.D. Marcotte, C.M. Hansson, B.B. Hope, The effect of the electrochemical chloride extraction treatment on steel-reinforced mortar - Part I:

Electrochemical measurements, Cem. Concr. Res. 29 (1999) 1555–1560.

[15] ABDELAZIZ, G.E., Microstructural analysis of surface and interface zones in concrete, Ph.D. thesis, Aston University, UK. 250 pp, 1998.

[16] ABDELAZIZ, G.E., Factors controlling the mechanism of electro-chemical realkalisation, Engineering Research Journal, Shoubra Faculty of Engineering, Zagazig University, Egypt, NO.1, pp. 16-30, 2004.

[17] N.R. Buenfeld, J.P. Broomfield, Influence of electrochemical chloride extraction on the bond between steel and concrete, Mag. Concr. Res. 52 (2000) 79–91.

[18] AFNOR, PR NF EN 14038-2, Electrochemical realkalization and chloride extraction treatments for reinforced concrete - Part 2: Chloride extraction 2019.

[19] J.E. Slater, D.R. Lankard, P.J. Moreland, Electrochemical removal of chlorides from concrete bridge decks, Mater. Perform. 15 (1976) 21–26.

[20] G.L. Morrison, Y.P. Virmani, S.F. Wayne, W.J. Gilliland, Chloride removal and monomer impregnation of bridge deck concrete by electro-osmosis, Report FHWA-KS-RD-74-1 (1976).

[21] D.R. Lankard, J.E. Slater, W.A. Hedden, D.E. Niesz, Neutralization of chloride in concrete - Final report FHWA-RD-78-60, Federal Highway Administration, Washington DC, 1975, p. 136.

[22] O. Vennesland, O. Opsahl, Removal of chlorides from concrete, European Patent Application N∘ 86302888.2 Norwegian Concrete Technologies AS (1986).

[23] J. Bennett, Evaluation of NORCURE Process for electrochemical chloride removal from steel reinforced concrete bridge components, SHRP-C-620, Strategic Highway, Research Program (1993).

[24] J. Bennett, Chloride removal implementation, SHRP-S-347, Strategic Highway, Research Program (1993).

[25] J. Bennett, Electrochemical chloride removal and protection of concrete bridge components: laboratory studies, SHRP-S-657 Strategic Highway, Research Program (1993).

[26] J. Bennett, Electrochemical chloride removal and protection of concrete bridge components: field trials, SHRP-S-669, Strategic Highway, Research Program (1993).

[27] D. Pocock, Chloride extraction and realkalisation - six years on Corrosion and protection of reinforced concrete Dubai, 1994.

[28] J. Mietz, Electrochemical rehabilitation methods for reinforced concrete structures – a state of the art report. European Federation of Corrosion Publications EFC N∘ 24, IOM Communications Ltd, London, 1998.

[29] B. Elsener, L. Zimmermann, D. Bürchler, H. B¨ohni, Repair of reinforced concrete structures by electrochemical techniques - Field experience, European Federation of Corrosion Publication EFC N∘ 25, J. Mietz, B. Elsener and R. Polder, European Federation of Corrosion Publications ed., IOM n∘ 25 Communications Ltd, London, 1998.

[30] J. Tritthart, Electrochemical chloride removal - a case study and laboratory tests Fourth International Symposium on corrosion of reinforcement in concrete construction The Royal Society of Chemistry, Cambridge (1996) 433–447.

[31] C. Arya, Q. SaidShawqi, P.R.W. Vassie, Factors influencing electrochemical removal of chloride from concrete, Cem. Concr. Res. 26 (1996) 851–860.

[32] T. Ueda, T. Kameda, A. Nanasawa, A new electrochemical rehabilitation method for reinforced concrete employing the DFRCC anode system, Sep. Purif. Technol. 79 (2011) 204–207.

[33] A. P´erez, M.A. Climent, P. Garc´es, Electrochemical extraction of chlorides from reinforced concrete using a conductive cement paste as the anode, Corros. Sci. 52 (2010) 1576–1581.

[34] A. Ca˜n´on, P. Garc´es, M.A. Climent, J. Carmona, E. Zornoza, Feasibility of electrochemical chloride extraction from structural reinforced concrete using a sprayed conductive graphite powder–cement paste as anode, Corros. Sci. 77 (2013) 128–134.

[35] J. Carmona, P. Garces, M.A. Climent, Efficiency of a conductive cement-based anodic system for the application of cathodic protection, cathodic prevention and electrochemical chloride extraction to control corrosion in reinforced concrete structures, Corros. Sci. 96 (2015) 102–111.

[36] J.H. Zhu, L.L. Wei, Z.H. Wang, L.C. Ke, Y. Fang, F. Xing, Application of carbon fiber- reinforced polymer anode in electrochemical chloride extraction of steel reinforced concrete, Constr. Build. Mater. 120 (2016) 275–283.

[37] R.B. Polder, Electrochemical chloride removal from concrete prisms containing chloride penetrated from seawater, Constr. Build. Mater. 10 (1996) 83–88.

[38] R.B. Polder, R. Walker, P.C. L., Electrochemical chloride tests of concrete cores from a coastal structure, in: R.N. Swamy (Ed.) Proceedings of International Conference on Corrosion and corrosion protection of steel in concrete Sheffield Academic Press, University of Sheffield, 1994, pp. 1463-1472.

[39] N.M. Ihekwaba, B.B. Hope, C.M. Hansson, Carbonation and electrochemical chloride extraction from concrete, Cem. Concr. Res. 26 (1996) 1095–1107.

[40] V. Bouteiller, A. Laplaud, A. Maloular, R.S. Morelle, B. Duchesne, M. Morin, Electrochemical chloride extraction of a beam polluted by chlorides after 40 years in the sea, J. Phys. IV 136 (2006) 331–340.

[41] T. Ueda, K. Wakitani, A. Nanasawa, Influence of electrolyte temperature on efficiency of electrochemical chloride removal from concrete, Electrochim. Acta 86 (2012) 23–27.

[42] G.G. Clemena, D.R. Jackson, Pilot applications of electrochemical chloride extraction on concrete piers in Virginia - Interim report VTRC-96-IR4, US Department of Transportation Federal Highway Administration, 1996.

[43] C.C. Chang, W. Yeih, J.J. Chang, R. Huang, Effects of stirrups on electrochemical chloride removal efficiency, Constr. Build. Mater. 68 (2014) 692–700.

[44] I. Martinez, F. Rozas, S. Ramos-Cillan, M. Gonzalez, M. Castellote, Chloride Electroremediation in reinforced structures: preliminary electrochemical tests to detect the steel repassivation during the treatment, Electrochim. Acta 181 (2015) 288–300.

[45] W. Yeih, J.J. Chang, C.C. Chang, K.L. Chen, M.C. Chi, Electrochemical chloride removal for reinforced concrete with steel rebar cage using auxiliary electrodes, Cem. Concr. Compos. 74 (2016) 136–146.

[46] P.J.M. Monteiro, P. Helene, I. Aoki, P. Barbosa, E. Monteiro, Influence of water cement ratio and cover thickness on chloride extraction of reinforced concrete, ACI Mater. J. 102 (2005) 9–14.

[47] R.B. Polder, J.R. Walker, C.L. Page, Electrochemical desalination of cores from a reinforced concrete coastal structure, Mag. Concr. Res. 47 (1995) 321–327.

[48] J.C. Orellan Herrera, Efficacit´e et effets secondaires des techniques electrochimiques de maintenance des structures en b´eton arm´e, Th`ese, Universite de Toulouse, 2002.

[49] Elsener, B. (2001) Half-Cell Potential Mapping to Assess Repair Work on RC Structures. Construction and Building Materials, 15, 133-139.

[50] B.T.J. Stoop, R. Polder, Redistribution of chloride after electrochemical chloride removal from reinforced concrete prisms, in HERON (Ed.)1999, pp. 31-44.

[51] W.K. Green, S.B. Lyon, J.D. Scantlebury, Electrochemical Changes in Chloride- Contaminated Reinforced-Concrete Following Cathodic Polarization, Corros. Sci.35 (1993) 1627–1631.

[52] G.E. Abdelaziz, A.M.K. Abdelalim, Y.A. Fawzy, Evaluation of the short and long term efficiencies of electro-chemical chloride extraction, Cem. Concr. Res. 39 (2009) 727–732.

[53] J.M. Miranda, A. Cobo, E. Otero, J.A. Gonzalez, Limitations and advantages of electrochemical chloride removal in corroded reinforced concrete structures, Cem. Concr. Res. 37 (2007) 596–603.

[54] W.C. Yeih, J.J. Chang, C.C. Hung, Selecting an adequate procedure for the electrochemical chloride removal, Cem. Concr. Res. 36 (2006) 562–570.

[55] R.N. Swamy, S. McHugh, Effectiveness and structural implications of electrochemical chloride extraction from reinforced concrete beams, Cem. Concr. Compos. 28 (2006) 722–733.

[56] T.D. Marcotte, C.M. Hansson, B.B. Hope, The effect of the electrochemical chloride extraction treatment on steel-reinforced mortar - Part II: Microstructural characterization, Cem. Concr. Res. 29 (1999) 1561–1568.

[57] S.R. Sharp, G.G. Clemena, Y.P. Virmani, G.E. Stoner, R.G. Kelly, Electrochemical chloride extraction: influence of concrete surface on treatment - Report FHWARD-02-107, Federal Highway Administration (2002) 43.

[58] J.C. Orellan, G. Escadeillas, G. Arliguie, Electrochemical chloride extraction efficiency and side effects, Cem. Concr. Res. 34 (2004) 227–234.

[59] Otero, E., Gonzalez, J.A., Cobo, A. and Gonzalez, M.N. (2001) Electrochemical Chloride Removal from Reinforced Concrete Structures and Its Ability to Repassivate Prerusted Steel Surfaces. Materials and Corrosion, 52, 581-589.

[60] Hosseini, A. and Khalou, A.R. (2005) Study of Electrochemical Chloride Extraction as a Non-Destructive Repair Method: Part I. Discrete Test Samples. Asian Journal of Civil Engineering (Building and Housing ), 6, 167-182.

[61] Sánchez, M.J., Garcés, P. and Climent, M.A. (2006) Electrochemical Extraction of Chlorides from Reinforced Concrete: Variables Affecting Treatment Efficiency. Materiales de Construcció , 56, 17-26.

[62] Qiao, G., Hong, Y., Liu, T. and Ou, J. (2013) Passive Corrosion Control and Active Corrosion Prevention of the Reinforced Concrete Structures by Electrochemical Chloride Removal and Inhibitors. Anti-Corrosion Methods and Materials, 61, 32-37.

[63] Yodsudjai, W. and Saelim, W. (2014) Influences of Electric Potential and Electrolyte on Electrochemical Chloride Removal in Reinforced Concrete. Journal of Materials in Civil Engineering, 26, 83-89.

[64] L. Tang, L. Bertsson, J. Aavik, L.O. Nilsson, Effect of an electrical field on the removal of chloride ions from concrete slabs, in: V.M. Malhorta (Ed.), 3rd CANMET/ACI International Conference on Durability of Concrete Nice, France, 1994, pp. 597–608.

[65] Y. Tissier, Etude des processus de corrosion et de la r´eparation par traitement electrochimique d'extraction des ions chlorure dans les b´etons arm´es doublement contamin´es carbonatation et chlorures) Th`ese, Universit´e Paris-Est, 2017, p. 313.

[66] Y. Tissier, V. Bouteiller, E. Marie-Victoire, S. Joiret, T. Chaussadent, Y.Y. Tong, Electrochemical chloride extraction to repair combined carbonated and chloride contaminated reinforced concrete, Electrochim. Acta 317 (2019) 486–493.

[67] N.M. Ihekwaba, B.B. Hope, C.M. Hansson, Pull-out and bond degradation of steel rebars in ECE concrete, Cem. Concr. Res. 26 (1996) 267–282.

[68] R. Polder, A.W.M. Van Den Hondel, Laboratory investigation of electro-chemical chloride extraction from concrete with penetrated chloride, HERON 47 (2002) 211–220.

[69] J.J. Chang, Bond degradation due to the desalination process, Construction and Building Materials, 17 (2003) 281-287 DOI: Pii S0950-0618(02)00113-7.

[70] M. Siegwart, J.F. Lyness, 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. 33 (2003) 1211–1221.

[71] J.M. Miranda, J.A. Gonzalez, A. Cobo, E. Otero, Several questions about electrochemical rehabilitation methods for reinforced concrete structures, Corros. Sci. 48 (2006) 2172–2188.

[72] M. S´anchez, M.C. Alonso, Electrochemical chloride removal in reinforced concrete structures: Improvement of effectiveness by simultaneous migration of calcium nitrite, Constr. Build. Mater. 25 (2011) 873–878.

[73] M.A. Climent Llorca, M.J. Sanchez de Rojas, G. de Vera, P. Garc´es, Effect of type of anodic arrangements on efficiency of electrochemical chloride removal from concrete ACI, Mat J (2006) 243–250.

[74] G. Fajardo, G. Escadeillas, G. Arliguie, Electrochemical chloride extraction (ECE) from steel-reinforced concrete specimens contaminated by "artificial" sea-water, Corros. Sci. 48 (2006) 110–125.

[75] B. Elsener, U. Angst, Mechanism of electrochemical chloride removal, Corros. Sci. 49 (2007) 4504–4522.

[76] Metwally abd elaty, Mohamed Taman, Asmaa Mohamed, Chloride Extraction from Portland Cement

Concrete: A Review, International Journal of Advances in Structural and Geotechnical Engineering, ASGE Vol. 03 (0 2), pp. 26-37, 2022

[77] V´eronique Bouteiller, Yolaine Tissier, Elisabeth Marie-Victoire, Thierry Chaussadent, Suzanne Joiret, The application of electrochemical chloride extraction to reinforced concrete – A review, Construction and Building Materials 351 (2022) 128931.

[78] Thamara Tofeti Lima, A State-of-the-Art Review of Electrochemical Chloride Extraction for Concrete Structures, Open Journal of Civil Engineering, 2023, 13, 1-24.

[79] Zofia Szweda, Evaluating the Impact of Concrete Design on the Effectiveness of the Electrochemical Chloride Extraction Process, Materials 2023, 16, 666. https://doi.org/10.3390/ma16020666.

[80] Abdelrahman Osama, Effect of important parameters on efficiency of Electrochemical Chloride Extraction, Extraction, Master thesis, Faculty of Engineering, Ain Shams University.

[81] Nourhan EL-sayed, Mohamed Kohail, Mohamed A. Khalaf, Efficiency of ECE Applied on RC Slab using Locally Available Un-Galvanized Steel with Conductive Cement Paste Anode,   International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958 (Online), Volume-9 Issue-4, April 2020