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The application of electrochemical chloride extraction to reinforced concrete – a review

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Abstract

In a context of ageing reinforced concrete structures, electrochemical chloride extraction (ECE) is an interesting treatment for structures damaged by chloride-induced corrosion. This paper summarises the state of the art by presenting the concept of ECE, assessing available measurement techniques and discussing influencing factors. The determination of ECE efficacy requires the consideration of different results, and particularly those pertaining to chloride extraction, corrosion mitigation and evolution of pH. This literature review also highlights the potential side effects and risks to the concrete structure. Further work is needed to ascertain the long-term performance of ECE.

Keywords

Reinforced Concrete, Electrochemical chloride extraction, Corrosion mitigation, pH, Long-term performance

Highlights

- This paper presents a state of the art of electrochemical chloride extraction.
- ECE is an interesting treatment for RC structures suffering from chloride induced corrosion.
- Efficiency of ECE is studied based on chloride extraction, steel corrosion mitigation and pH.
- ECE potential side effects are described.
- Long-term efficiency of ECE needs to be validated.

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Table 1: Abbreviations used in this paper.

-	not determined
Add	addition of chlorides in the mix
AFNOR	Association Française de Normalisation
ASR	alkali-silica reaction
ASTM	The American Society for Testing and Materials
aSW	artificial sea water
aTi	activated Ti
Av	average (efficacy of chloride extraction)
be	beam
BFSC	blast furnace slag cement
bl	block
bwce	by weight of cement
bwco	by weight of concrete
bwmo	by weight of mortar
C	concrete
CCP	conductive cement paste
CFRP	carbon fibre reinforced polymer
co	column
COST	Cooperation in Science and Technology
CP	cathodic protection
CS	concrete surface
CSE	Copper-copper sulfate electrode
CSH	Calcium-silicate hydrate
cu	cube

cy	cylinder
DC	direct current
De	depth (efficacy of chloride extraction)
DFRCC	ductile fibre reinforced cementitious composites
DS	De-icing salt
DW	distilled water
ECE	electrochemical chloride extraction
<i>f</i>	depends on parameters
f	Free chloride ions
FA	fly ash
G	current control mode
GCP	graphite cement paste
GGBS	ground granulated blast furnace
Gi	intermittent current control mode
GR	graphite rod
Ing	ingressed chlorides
iTi	inert Ti
M	mortar
Mix	chloride added to the mix
OPC	ordinary Portland cement
P	voltage control mode
Pi	intermittent voltage control mode
pr	prism
Re≠	multiple rebar arrangement
Re	rebar
Re#	multiple rebar

RILEM	The International Union of Laboratories and Experts in Construction Materials, Systems and Structures
R _p	polarization resistance
RS	steel rebar surface
SCE	saturated calomel electrode
SF	silica fume
sl	slab
SRC	sulfate resistant cement
SS	stainless steel
SW	sea water
SWI	sea water immersion
SWT	sea water tide
t	Total chloride ions
TW	tap water
W/D	wetting/drying

1 INTRODUCTION

Since the second half of the last century, steel corrosion has been identified as the main cause of deterioration in reinforced concrete structures of civil engineering structures (bridges, tunnels, dams, etc.), buildings (houses, car parks, etc.), and historical monuments (churches, sculptures, etc.) [1-6]. From the moment the concrete is cast, the steel rebar it contains is passivated by the high alkaline pH levels (close to 13). During the service life of reinforced concrete structures, the presence of oxygen and water can lead steel rebar to corrode through the contamination of the rebar/concrete interface by chloride ions and/or the complete carbonation of the concrete cover. The anodic reaction occurring in the steel rebar generates corrosion products in a larger volume than that of the initial iron element, resulting in the formation of cracks in the concrete when stress exceeds its tensile strength. In terms of structural effects, the reduced diameter of the rebar and the debonding of the rebar/concrete interface can lead to decreased loading capacity. The spalling or delamination of the concrete can be a source of danger for the users. Finally, the structure may collapse.

This paper focuses in chloride-induced corrosion [1, 2, 4, 7-9], which is particularly common when the reinforced concrete structure is exposed to marine environment or de-icing salts. In these cases, chlorides penetrate the concrete cover from the outer surface and reach the inner steel rebar/concrete interface. Chloride ions may also have been added to the mix and therefore be more homogeneously distributed within the concrete cover; for example, chloride-based admixtures were sometimes used as setting accelerators (a method that is now prohibited), or marine sand was used for coastal structures.

A number of approaches to avoid steel rebar corrosion have been explored in the literature [10, 11]. Preventive solutions include (i) the use of a protective coating to insulate the steel rebar (epoxy, electroplating or galvanisation) and the use of stainless steel rebar, (ii) the use of anti-corrosion cement, the adapting of the concrete formulation or an increase in the

thickness of the concrete cover in order to delay contamination by chlorides or carbonation, and (iii) the use of corrosion inhibitors or the application of concrete cover coatings.

Maintenance and/or rehabilitation repairs must also be provided for reinforced concrete structures affected by corrosion induced by chloride ions [4, 10-13].

The extensively used conventional “patch repair” consists of replacing all the contaminated concrete and also the rebar when necessary. However, performance of patching through the European CONREPNET project [5] was poor, with a 50% failure rate that was attributed to cracking (30%), debonding (25%), continued corrosion (25%) and other causes (20%). Patch repair becomes impractical for the maintenance of infrastructures such as bridges when contamination reaches beyond the rebar depth. Moreover, the replacement of original materials is not in accordance with restoration principles for historical monuments, as defined by the Venice Charter.

When electrochemical treatments such as cathodic protection or electrochemical chloride extraction are applied to chloride-contaminated reinforced structures, it is only necessary to remove and reconstruct the concrete that no longer bonds with the rebar as polarization ensures the protection of steel rebar, and chloride ions migrate from the steel to the outside of the concrete due to the electrical field.

- Cathodic Protection (CP) of steel in concrete has been demonstrated to be successful in appropriate conditions [14]. CP is designed to decrease the corrosion rate of the steel from significant to negligible values. For this purpose, the steel/concrete potential should be lowered (made more negative) to values in the range of the protection potential. Typical levels of applied current density (with respect to the steel surface) range from 0.2 to 2 mA/m² for prevention and from 2 to 20 mA/m² for protection. CP is a lifelong treatment and requires specific monitoring to assess its efficacy according to several criteria.
- Electrochemical Chloride Extraction (ECE) is also known as desalination, electrochemical chloride removal or electrochemical chloride mitigation. A current

is applied between the steel rebar and an external anode in order to remove chloride ions from the concrete cover, and particularly from the rebar/concrete interface. The current density is usually 1 A/m² of steel rebar surface (approximately 100 times higher than the density used in CP) and is applied for a limited time (4 to 8 weeks) [15].

The aim of this literature review is to gather all available data about the application of electrochemical chloride extraction (ECE) to reinforced concrete. The following section of this paper describes ECE parameters. We then move on to presenting the different ways in which the efficacy of the treatment can be defined. The results of studies based on different parameters pertaining to specificities such as chloride extraction efficacy, corrosion mitigation and pH evolution are discussed in the fourth part of this paper. The fifth section focuses on the potential side-effects and risks of the ECE treatment. The long-term efficacy of ECE is then discussed, followed by ECE specifications and modelling. Finally, this review ends with our conclusions, recommendations for laboratory studies and practical cases, and suggestions of future research avenues.

2 ECE PRINCIPLE

2.1 History

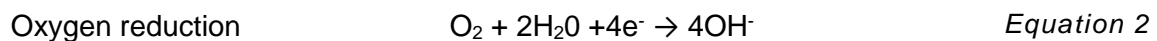
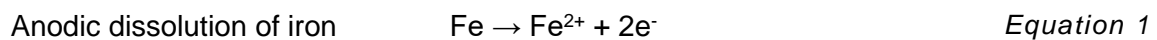
The first trials of electrochemical chloride extraction (ECE) treatment with high DC voltages of up to 220 V were led in the United States of America by the Federal Highway Administration in the mid-70s [16-18], but this procedure was rarely used over the next 20 years. An invention was patented in Europe during the 80s by Oystein Vennesland, a researcher at Norwegian Concrete Technologies [19]. Knowledge of ECE was developed further in the 90s through research carried out in the United States of America Strategic Highways Research Program (SHRP) [20-23]. Pocock's 1994 publication [24] recognized the interest of this treatment for

the repairing of reinforced concrete contaminated by chloride ions. Different publications, state-of-the-art report, chapters on ECE treatment were published [25-27]. ECE treatment was also part of three European Cooperation in Science and Technology (COST) actions (COST 509 in 1997 [10], COST 521 in 2003 [11] and COST 534 (2007) [28]). In 2022, task group 8.1 from the federation Internationale du Béton published fib Bulletin 102 "Guide for protection and repair of concrete structures" [29] and devoted a chapter on chloride extraction/desalination [30].

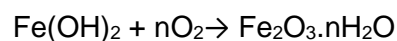
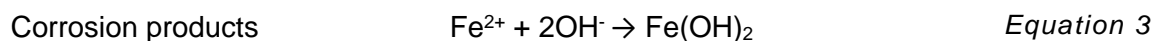
The present literature review seeks to gather the different results from the 1970s until 2022.

2.2 Mechanisms

Corrosion of the steel rebar occurs by two electrochemical reactions: the anodic dissolution of iron, as shown in Equation 1, and the corresponding oxygen reduction at the cathode that uses the electrons generated by the metal dissolution in its reaction, as shown in Equation 2.



Both of these reactions occur on the steel surface, resulting in the formation of corrosion products. The accumulation of corrosion products at the rebar/concrete interface (Equation 3) may induce cracks in the concrete cover.



ECE is designed to arrest the corrosion of steel rebar, or even recover the passivity thereof, through the following phenomena: a lowering of the thermodynamic potential of the steel, a reduction of the chloride content and an increase in the pH levels at the rebar/concrete interface.

Figure 1 shows a schematic representation of the ECE set-up when a direct current source is used¹⁾. The rebar requiring protection acts as a cathode and is connected to the negative pole of the direct current source, while the anode (usually located on the surface of the concrete) is connected to the positive pole. During ECE, it is important to minimize circuit resistance between the cathode and the anode and to maintain a buffered pH. This is usually achieved with the joint use of a solution called electrolyte and one of three different methods: tanks, sprayed cellulose fibres, or synthetic felt mats.

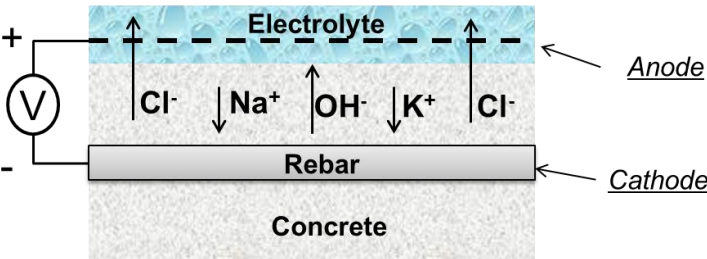
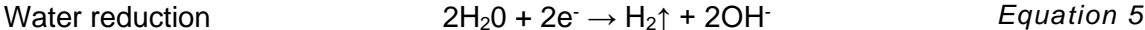
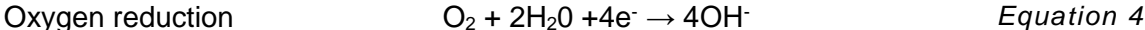


Figure 1: Schematic representation of ECE set-up.

In alkaline reinforced concrete²⁾, the difference in electrical potential between the cathode and anode triggers the transport of the ions present in the electrolyte and in the concrete [25, 31-35], and may cause the following reactions:

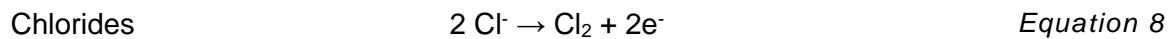
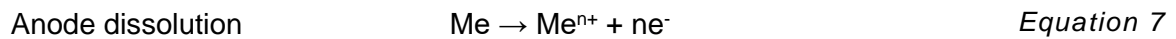
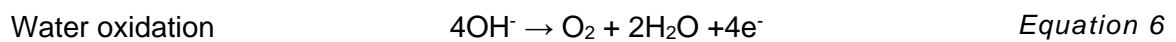


The low potential of the steel at the cathode protects the rebar from corrosion. The oxygen reduction reaction (Equation 4) takes place slowly due to the limited availability of oxygen in concrete: at the outset, there is very little oxygen available around the cathode within the concrete, and oxygen diffusion from the outside is slow. Thus the water reduction reaction

¹⁾ Sacrificial anodes are not considered in this paper.
²⁾ Because concrete is an alkaline medium (sound concrete pH~13 and carbonated concrete pH~9), hydroxyl ions (OH⁻) >>> protons (H⁺).

(Equation 5) predominates [34]. The production of hydrogen gas can increase local pressure, eventually leading to concrete cracking and hydrogen embrittlement of steel (§5.2.2).

At the anode, the oxidation of hydroxyl ions forms oxygen and water (Equation 6). No dissolution of the anode occurs if the metal is inert (Equation 7). In the case of electrolyte acidification, the oxidation of chloride ions in chlorine gas (Equation 8) should be avoided for safety and environmental concerns.



In addition to these oxidation-reduction reactions, at typical current densities for ECE, migration dominates with the transport of ions contained in the concrete and in the electrolyte. The transport of ions involves different processes based on concentration gradients, electrical migration, lixiviation and diffusion. Due to the electrical field of the rebar and the anode, anions such as free chlorides (Cl^-), hydroxyls (OH^-), carbonates (CO_3^{2-}), and sulfates (SO_4^{2-}), are mostly repelled from the vicinity of the rebar and migrate away from the cathode region towards the anode. Similarly, cations such as calcium (Ca^{2+}), potassium (K^+), sodium (Na^+) and lithium (Li^+) ions migrate towards the cathodic steel region. Electrical neutrality is maintained on a macroscale despite the modified distribution of specific ions within the concrete. It is important to note that the accumulation of alkali ions can cause an alkali-silicate reaction if the concrete contains reactive aggregates (§5.2.4).

Figure 2 provides a schematic representation of the electrical field obtained during the treatment, and shows that the maximal extraction efficacy is obtained in the area in between the rebar and the anode. Moreover, chloride ions present at the deepest levels close to the rebar cannot be easily extracted [25].

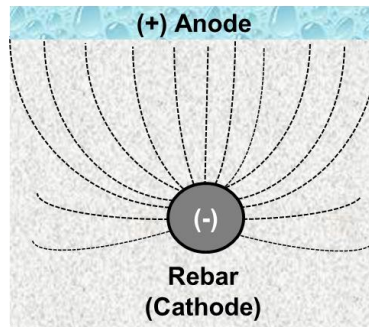


Figure 2: Schematic representation of streamlines in an inhomogeneous field between rebar (cathode) and anode at the concrete surface.

2.3 Process parameters

In this section, each component of the ECE treatment (Figure 1) is presented and some important features are explained.

2.3.1 Cathode

In almost all cases, the cathode is the rebar (simple or deformed rebar, mild steel plate, rebar plus stirrups or structural reinforcement).

Arya et al. [36] used an additional external cathode for cases in which chloride was present at a deeper level than the rebar. Setup design affected chloride extraction, which increased from 40% (obtained with the conventional setup) to 55% when both the rebar and external platinised titanium mesh were connected as cathodes.

2.3.2 Anode

In the context of ECE treatment, the anode has to satisfy various criteria to be fully functional [4]. It must distribute the chosen current throughout the area requiring protection for the entire duration of the treatment. This element must also be corrosion resistant and should not affect the appearance of the concrete surface. Finally, its installation should be inexpensive.

During their preliminary study in 1976, Slater et al. [16] tested platinized titanium, titanium and graphite anodes in a 0.1 N calcium hydroxide solution. Platinized titanium was found to be the most appropriate anode material; it satisfied the test criteria, unlike graphite (which disintegrated at high current densities) and titanium (which had poor electro catalytic activity). The most reliable and widely used anode today is composed of titanium that has been activated with oxides or coated with different metals. This anode can take the form of mesh, wire or strip. It is suitable for the protection of different concrete structures, and can be used to treat vertical and horizontal structures and both sides of curved surfaces. Ueda et al. [37] used a titanium mesh cast in a ductile fibre (PE or PVA)-reinforced, cementitious composite (DFRCC), which improved its adhesion to a prepared concrete surface. Although chloride extraction efficacy at the rebar level was close to 75%, chlorides were accumulating in the DFRCC layer and could therefore spread back into the concrete cover.

Steel was tested given its low price, however its use is not recommended because it is rapidly consumed during the treatment (Equation 9) and causes rust spots on the concrete surface [20].

Different anode systems to replace titanium anodes have been studied and referenced in the literature. Pérez et al. [38] worked on the viability of replacing the classical Ti-RuO₂ mesh anode with a graphite anode and a conductive cement paste (CCP) combination, applied superficially as a plaster. Results showed that although the chloride extraction was similar for both types of anodes, an accumulation of chloride ions appeared in the CCP layer that could eventually spread back into the concrete cover. Canon et al. [39] and Carmona et al. [40] studied the feasibility of using a sprayed conductive graphite powder cement paste as an anode, which would make it possible to work on various surface shapes and inclinations and therefore facilitate the application of ECE. The results showed that the chloride extraction efficacy was similar to that observed in the titanium-based anode. Moreover, unlike the anode suggested by Pérez et al. [38] this sprayed layer retained moisture for up to 10-12 h but failed to retain chlorides. The durability of this anode layer has been questioned following damage by anodic reactions. Finally, Zhu et al. [41] studied the application of a conductive carbon-fibre-

reinforced polymer (CFRP) anode in the form of a mesh with good mechanical properties, durability, conductivity and electrochemical stability. The results for chloride extraction were similar to those obtained with an activated titanium mesh anode. It should be noted that values are homogenized when a conductive anode layer is used meaning that half-cell potential mapping measurements cannot be carried out for inspection.

2.3.3 Electrolyte

The electrolyte plays three main roles in ECE treatment:

- First, it decreases the electrical resistance by wetting between concrete and reinforcement (hydration and dissolution of the ions in the concrete), thus lowering the voltages used and improving ionic migration,
- Second, the pH of the electrolyte should prevent any modification of the concrete pH,
- Lastly, it should trap chlorine gas, which is hazardous to health.

Usually, renewal or circulation of the electrolyte is needed. Tanks or sprayed cellulose fibre can be used for the treatment when applied on horizontal or vertical surfaces.

The two most widespread electrolytes for ECE are water [34, 39, 40, 42-52] and saturated calcium hydroxide ($\text{Ca}(\text{OH})_2$) solution [16, 20, 41, 43, 44, 51-66]. Saturated calcium hydroxide solution with a pH equal to 12.4 is consistent with the requirement for a buffered medium and the need for a relatively high pH value to prevent acidification and chlorine gas.

Other electrolyte solutions containing sodium ions were studied, namely sodium hydroxide (NaOH) [36, 43], sodium carbonate (Na_2CO_3) [65] and sodium borate solutions (Na_3BO_3 [56], $\text{Na}_2\text{B}_4\text{O}_7$ [67] and $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ [68, 69]). Sodium ions can sometimes be detrimental in terms of Alkali-Silica Reaction (ASR) (§5.2.4). Finally, lithium borate solution was also used as an electrolyte, as lithium ions have already demonstrated their ability to limit ASR [23, 37, 70, 71]. Moreover, Ueda [70] demonstrated that increasing the temperature of Li_3BO_3 electrolyte solution resulted in a higher percentage of chloride extraction.

2.3.4 Current flow

The current flow between the rebar and the anode must ensure the cathodic protection of the steel rebar. Current flow can be obtained in two modes: constant voltage (voltage control) and constant current (current control) in a continuous or intermittent ways. In the voltage control mode, the current flow is expressed in voltage [16-18, 20-23, 36, 49, 58, 72-75]. In the current control mode, the current flow is expressed in current density in A/m² of steel surface or concrete surface that must be indicated. Current density is expressed in A/m² of steel rebar surface in references [35, 40, 41, 43, 45, 47, 48, 51, 54, 55, 57-60, 63, 65, 67, 69, 76-85], and in A/m² of concrete surface in references [21, 34, 37-39, 44, 46, 53, 62, 70, 71, 86, 87]. No surface information is clearly indicated in references [61, 88, 89].

Moreover, some authors attempted to increase the efficacy of the treatment through the use of intermittent rather than continuous current flow, via voltage control mode [18] or current control mode [34, 45, 46, 48, 55, 81, 86, 90, 91].

It is important to note that it is very difficult if not impossible to compare the results if the ECE modes are not the same or if the current density units are different.

2.3.5 Duration

ECE is a short-term treatment (vs Cathodic Protection). It is often applied for periods ranging from 2 to 8 weeks [23, 32, 34, 36-39, 41-44, 46-48, 51-55, 57-61, 65-67, 70, 71, 75, 79, 80, 82, 84, 87, 88, 92-95]. Larger duration than 15 weeks [42, 74, 76, 88, 96] has also been considered particularly when using lower current density or for testing prestressed concretes.

3 TECHNIQUES TO ASSESS ECE EFFICACY AND POTENTIAL SIDE EFFECTS

This third section describes the different non-destructive and destructive techniques used by researchers to characterize the efficacy of ECE, and seeks to verify whether the ECE treatment

induces chemical, microstructural and/or mechanical changes that could be detrimental to the reinforced structure.

3.1 Visual inspections

A visual inspection of the appearance of the rebar and its surrounding concrete can provide general information such as corrosion product colours, layer of deposits, cracks, etc. [45, 49, 57, 59, 71, 76-79, 83, 87, 96].

3.2 Chloride analyses

The efficacy of the treatment varies according to the chloride content before, during, after and long after ECE (in case of re-diffusion). In concrete, chlorides are either freely dissolved in the pore solution or exist in a bound form with cement hydration products such as hydrated C3A or C4AF phases and CHS gel. Moreover, penetrated chloride content varies according to the depth at which it is located in the concrete. Usually specimens (from the laboratory or from cores obtained on the field) are sliced, crushed, sieved and dissolved in water where the chloride content profile is determined as water soluble (free chlorides) or acid soluble (total chlorides) based on potentiometric titration using silver nitrate or spectrophotometric analysis or chemical analysis [43, 48, 49, 53-55, 59, 70, 97-99].

It is important to note that the measurement of free chloride ions in the interstitial solution is only possible for pastes [32, 34] where pressure needed for extraction can be achieved. Finally, Elsener et al. [48] developed a chloride ion-selective electrode as an embedded sensor in concrete.

The concentration of removed chloride ions can also be determined from electrolyte analysis [43, 45, 51, 55, 70, 83]. Polder et al. [43] found a good general correlation between the amount of chloride calculated from electrolyte analysis and concrete analysis, respectively.

3.3 Electrochemical characterizations

Non-destructive electrochemical measurements such as half-cell potential, linear polarization resistance and corrosion rate can be used to characterise the corrosion state of the rebar when the latter is in a steady state (no polarization) [16, 20, 23, 37, 42-46, 48, 49, 51-54, 59, 60, 67, 70, 73-75, 79, 82, 84, 100]. According to the literature, the efficacy of the treatment that will eventually lead to a passive state can be assessed by performing electrochemical measurements before ECE and after ECE once the polarization of the rebar is over. It is important to note that the time at which depolarization of the steel occurs cannot be known in advance. During or immediately after the treatment, these electrochemical measurements should confirm that the rebar is polarized (i.e. high electronegative half-cell potential and high current densities values are observed). This is an interesting means to verify that different treated specimens are reacting in the same way, or to prove that no area has been forgotten when the treatment is applied on-site, for example.

Half-cell potential measurements are the most commonly used method because they are very easy to conduct [20, 37, 43, 45, 46, 48, 49, 51-54, 59, 60, 67, 70, 73-75, 79, 82, 84, 100]. However, it should be noted that the results are strongly dependent on parameters such as concrete resistivity (moisture content), chloride content, pH, temperature or climatic conditions. Half-cell potential measurements aim to evaluate the probability of rebar corrosion (when all the other parameters remain constant) and/or to locate corroding zones in larger specimens and in on-site structures, where climatic conditions are not controlled. For reinforced concretes in atmospheric conditions, test procedures and guidelines are described in the ASTM C-876 standard (1991 and 2009) [101, 102] and in the RILEM TC 154 recommendation (2003) [103]. After ECE, more positive potentials and smaller gradients are expected (versus before ECE). Despite the availability of these tools, result analysis for reinforced concrete structures in a marine environment can still be difficult because of the tide that modifies humidity and oxygen content.

The measurement of polarization resistance (R_p) before, during and after treatment with a potentiostat [54, 57, 60] permits the evaluation of the corrosion rate at a given time. Corrosion rate can also be measured on site using a GECOR 6 [32, 55] or a GPM-5000 [73]. The results obtained can be compared to the established corrosion rate classification [104]. The RILEM TC 154-EMC document provides important recommendations for on-site corrosion rate measurements [103]. It is important to note that corrosion rate measurements using R_p do not give realistic values at short timescales after current interruption. This is likely to be due to the chemical changes induced close to the rebar (i.e. high alkalinity and low O_2 activity) [53].

Miranda et al. [59] and Marcotte et al. [79] used a non-stationary method by performing full polarization curves to assess the corrosion rate of reinforced concrete slabs before and after ECE (with ECE performed on both sides of the slabs).

3.4 pH determinations

During the ECE process, pH evolution at the rebar/concrete interface, in the concrete and in the electrolyte can be analysed. This analysis can involve the use of phenolphthalein, a colour acid/base indicator that will turn purple when sprayed on concrete with a pH level of 9-10 or above [35]. Other authors titrated the pH of concrete from concrete samples dissolved in water [58, 73, 75, 82]. Finally, pH values for the electrolyte were reported in [43, 45, 55].

3.5 Concrete characterizations

3.5.1 Ion migration

The performance of atomic absorption spectrophotometry on solutions obtained from dissolved concrete provides quantitative information on the presence of ions such as potassium, sodium, calcium and lithium and their migration through the electrical field during ECE, and thus provides information about the evolution of the concrete composition [45, 52, 57, 71].

3.5.2 Microstructure transformation

Petrographic examination can be performed [23, 43] to study the microstructural evolution of the concrete (i.e. micro cracks, pores, etc.).

Scanning electron microscopy can be used to observe the microstructure of concrete and identify any new phases (petrographic) formed during ECE by comparing treated or untreated specimens [35, 41, 47, 57, 60, 69, 80, 83, 88].

X-ray diffraction is also used to analyse additional crystalline materials present in the concrete or in concrete surface deposits [60, 87, 100].

The Mercury Intrusion Porosimetry technique can be used to determine the pore size distribution within the concrete cover [83] and evaluate ECE impact.

3.6 Steel characterizations

Microstructural observations of the rebar/concrete interface by scanning electron microscopy coupled with dispersive X-ray spectroscopy are used to identify the corrosion products and their location at the rebar/concrete interface after the corrosion process and after the ECE treatment. X-ray diffraction was used by Miranda [59] to determine the nature of the corrosion products.

Raman microspectroscopy can identify the iron corrosion products during and after treatment and help to ascertain the corrosion state of the rebar. Tissier et al [69] developed a specific electrochemical cell set-up without any oxygen contact to perform in-situ observations in the laboratory.

3.7 Mechanical tests

Compressive strengths were studied in [55, 80]. Pull-out tests were performed [41, 50, 58, 76, 78, 96] to determine bond stress changes. For bigger specimens like beams, flexural strength tests were conducted [55].

4 LABORATORY RESULTS

All the published studies considered in the present evaluation are presented in three tables (Table 2, Table 3 and Table 4) according to the electrochemical chloride extraction mode used.

All the abbreviations can be found in Table 1.

Table 2 summarises all the published studies regarding voltage control mode. The voltages are in the range of 5 to 100 V. High voltage (100 V) led the temperature of the concrete to increase drastically (from 25 °C to 50-84° C) and resulted in concrete cracks in some cases.

The major disadvantage when using a voltage control mode is that the current received by the rebar will decrease over time as the resistance of the medium increases (due to the extraction of chloride).

Using current control mode allows a better repeatability of the experiment. Table 3 summarises all the published studies where the current density is based on the area of the concrete surface (A/m^2 CS), whereas Table 4 concerns studies where the current density is based on the area of the steel rebar surface (A/m^2 RS). The type of surface was not clearly indicated in papers [61, 88].

Current densities based on the area of the concrete surface (Table 3), are calculated on the assumption that the ratio of the rebar area to concrete area in the treated structure is equal to one [88]. However, this is not always correct. For example, 1 A/m^2 of CS can be equal to 5 A/m^2 RS [88] or to 9.5 A/m^2 RS [78]. Unnecessarily high current densities can lead to detrimental side effects including increased temperature and concrete cracking. The aim of ECE is to protect the steel from corrosion in concrete; the current density must therefore be based on the area of the steel rebar surface.

Elsener et al. [48] proposed to use an intermittent current control mode in which bound chlorides were released as free chlorides during the OFF period. This led to increased efficacy of chloride extraction during the next ON period. The authors even reached 100% efficacy in this experimental program.

Several papers studied the use of an intermittent voltage control to increase the efficacy of ECE [45, 48, 55, 81, 90]. An interruption of current [48] may have the following advantages:

- Bound chlorides may become free chlorides.
- A redistribution of ions (Cl^- , OH^-) may occur within the concrete. The current interruption period should be long enough to achieve the depolarization of the rebar and therefore permit the expected re-distribution of ions.
- Risks of undesirable side effects arising from the application of electrochemical techniques can be reduced.

Table 4 describes the current control mode and applied current density based on the steel rebar surface. Here, 1 A/m^2 RS is the most frequently used value [41, 43, 45, 47, 51, 54, 55, 57, 61, 63, 65, 67, 69, 81, 82, 85, 90]. Lower densities of applied current ($0.25\text{--}0.75\text{ /m}^2$ RS) were chosen to study the influence of cementitious binder on chloride extraction under electrochemical treatment in concrete [63, 65, 76, 84, 90]. The application of higher current densities was also reported in ranges of $>1\text{--}4\text{ A/m}^2$ RS [40, 41, 43, 48, 51, 59-61, 63, 65, 77, 82, 83, 85] and $\geq 5\text{--}28.6\text{ A/m}^2$ RS [59, 60, 77-80, 82]. The highest densities of applied current were mainly used to study the influence of the ECE treatment on the mechanical properties of reinforced concretes and particularly the loss of bond between the rebar and the concrete. Treatment most often lasts 28 or 56 days, but other periods in the range (3-112 days) were also reported.

From here on, our discussion will solely concern the ECE results obtained with a current control mode and a current density expressed in A/m^2 of steel rebar surface (RS), described in Table 4. Since these data were obtained from a variety of experimental setups, the corresponding details must be considered when comparing them.

The determination of ECE treatment efficacy requires the simultaneous consideration of different results, particularly those pertaining to chloride extraction (§4.1), corrosion mitigation

(§4.2), evolution of pH (4.3) and visual aspects (§4.4). Miranda et al. [59] argued that the determination of chloride profiles, the use of the phenolphthalein test, or the simple measurement of potentials before and after the application of ECE cannot guarantee its efficacy, and underlined the importance of using techniques that provide quantitative determinations of corrosion kinetics. Orellan et al.[54] added that a polarization resistance technique is needed to confirm that the steel has re-passivated after treatment.

1 Table 2: Published laboratory studies on ECE treatment performed using a voltage control mode (continuous P or intermittent Pi).

2

First author [Reference]	Binder	Sample	w/c ratio	Cement (kg/m ³)	Dimensions (mm) [shape]	Steel rebar (diameter mm)	Cover (mm)	Initial chloride content [mode] / [content Cl]	Cathode	Anode	Electrolyte	Voltage control mode	Duration (days)
Lankard [18]	OPC	C	0.44	360	76dx150 [cy]	10	50	[Mix, NaCl] / [(De) (t) 0.019-0.144%bwco]	Re	Ti-Pt	[Ca(OH) ₂ +IER] / [top pond]	[P] / [V 50, 100]	1-3
Lankard [18]	OPC	C	0.45	360	1170x2280x230 [sl]	20	50	[Mix, NaCl] + [ponding 3%NaCl 5 months]	Re	Ti/Pt	[Ca(OH) ₂ +IER] / [top pond]	[P, Pi] / [V 100]	1-2
Chang [73]	OPC	C	0.5	393	150x150x300 [pr]	Re# 9.52, 12.30	20	[Mix, NaCl] / [(Add), 1.28%bwce]	Re#, External cathode	TiPt	[NaOH] / [tank]	[P] / [V 20]	14, 28, 42, 56
Yeih [75]	OPC	C	0.5	393	150x150x300 [pr]	R# 9.52, 12.30	20	[Mix, NaCl] / [(Add), 1.82% bwce], [(Av), (f), 1.79%bwce]	Re	Ti mesh	[NaOH anode cell, TW cathode cell] / [acrylic cell]	[P] / [V 20]	56
Arya [36]	OPC	C	0.65	400	200x200x120 [pr]	10	30, 50, 80	[Mix, NaCl] / [(Add) 2, 3, 4%bwce] / [2 layers: bottom 0%bwce and top layer 75mm: 1.87%bwce]	Re#, External cathode	iTi	[NaOH] / [tank]	[P] / [V 10, 20, 30]	33, 83
Chang * [58]	OPC	C	0.66	307	100dx200 [cy]	12.3	40	[Mix, NaCl] / [(Add), 1.28 %bwce; (Re), 3800ppm bwco]	Re	Ti	[Ca(OH) ₂] / [tank] [NaOH] /	[P] / [V 5, 10, 20, 30]	7, 14, 21, 28, 35, 42

											[tank]		
Sanchez [49]	OPC	M	0.5	-	20x55x80 [pr]	6	24.5	[Mix, NaCl] / [(Add), 1%bwce]	Re, External cathode	-	[DW] / [tank]	[P] / [V 12]	5
Martinez [74]	OPC	M	0.55	450	70x70x70 [cu]	6	30	[Mix, NaCl or CaCl ₂] / [(Add), 1.52 or 2.35%bwce]	Re	MMO aTi	[W] / [sponge]	[P] / [V 8, 12 ,16, 20]	0-93, 115, 133, 143

3 *) Authors said that a voltage control of 5 V corresponds to a 18.8A/m² CS current control

4
5
6

Table 3: Published laboratory studies on ECE treatment performed using a current control mode (continuous G or intermittent Gi) with current densities expressed as A/m² of concrete surface (CS).

First author [Reference]	Binder	Sample	w/c ratio	Cement (kg/m ³)	Dimensions (mm) [shape]	Steel rebar (diameter mm)	Cover (mm)	Initial chloride content [mode] / [content Cl ⁻]	Cathode	Anode	Electrolyte	Current control mode	Duration (days)
Tritthart [34]	-	C	-	-	50d, 200d [cores]	2 rebar layers	45-55 and 60-70	[Ingress, DS] / [(t), (De) 0-170mm: 15-0.5%bwce; (De) 0-10mm: 12-15%bwce, 40- 60mm (overlapping bar depth): 7.8- 9%bwce; 90-100mm: 3-4.5%bwce; 150-160mm:0.5%bwce]	Re	Ti	[W] / [paper pulp]	[G, Gi] / [A/m ² CS 1]	40, 83, 96, interruption 98d, 139d
Canon [39]	-	C	0.6	350	200dx1000 [co]	Re# d8 Stirrups d6	40	[Mix, NaCl] / [(Add), 2%bwce] / [(t) 1.5%bwce]	Re	Ti- RuO ₂ , CCP	[TW] / [irrigation or dampening]	[G] / [A/m ² CS 5]	6, 8, 13.5, 14.6
Ihekwa [86]	OPC	C	0.3	432	300dx1200 [co]	16	50	[Mix, NaCl] / [(Add), (De) 1.7%bwce inner 15cm, 3%bwce outer 15cm] / [(Add), (Av), 5000 (#1), 6000 (#2) ppm bwco]	Re#	iTi	[Ca(OH) ₂] / [cellulose fiber]	[G, Gi] / [A/m ² CS 1]	56, 70 8w ON then 2w OFF, then a second ECE on 1 of the specimens for 2w ON
Ihekwa [86]	OPC	C	0.3	432	300x300x1200 [co]	16	50	[Mix, NaCl] /	Re#	iTi	[Ca(OH) ₂] / [cellulose fiber]	[G, Gi] / [A/m ² CS 1]	56, 70 8w ON then 2w OFF,

								[(Add), (De) 1.7%bwce inner 15cm, 3%bwce outer 15cm] / [(Add), (Av), 5000 (#3), 6000 (#4) ppm bwco]					then a second ECE on 1 of the specimens for 2w ON
Ueda [70]	OPC	C	0.45 0.55	384 340	100x100x200 [pr]	d13 deformed	43,5	[Mix, NaCl] / [(Add), 8% bwce] / [(t) 2.35, 2.08%bwce]	Re	Ti	[Li ₃ BO ₃] / [tank]	[G] / [A/m ² CS 1]	56
Sharp [87]	OPC	C	0.4 0.45 0.5 0.55	377	(92, 105, 118)x127x305 [bl]	16	44, 57, 70	[Mix + Ponding] / [(Add), 0.25%bwco]	Re	aTi	[Ca(OH) ₂ or CaO] / [felt]	[G] / [A/m ² CS 1]	50
Sharp [87]	OPC	C	0.45 0.5 0.55 0.6	377	(177, 190, 203)x610x608 [bl]	16	38, 51, 64	[Mix] / [(Add), 0.25%bwco]	Re	aTi	[Ca(OH) ₂ or CaO] / [felt]	[G] / [A/m ² CS 1]	50
Bennett [20]	OPC	C	0.5	363	600x600x200 [sl]		50	[Mix, NaCl] / [(Add), (De), bottom 8cm: 0.0%bwco, median 8cm: 0.16%bwco, top 4cm: 0.39%bwco] / [(t), (Tit), (De), 0.015- 0.410%bwco]	Re	Steel	[Ca(OH) ₂] / [cellulose fiber]	[G] / [A/m ² CS 1]	91
Ihekwa [56]	OPC	C	0.5	370	500x500x300 [bl]	2 steel mats (uniform or displaced) d19	60	[Pond, NaCl, 18m] / [carbonated blocks, (Av), (t) 1500- 3000 ppm bwco ; non-carbonated blocks, (Av), (t) 3500-8000 ppm bwco]	2 steel mats	iTi	[Na ₃ BO ₃] / [top pond]	[G] / [A/m ² CS 1]	-

Buenfeld [35]	OPC	C	0.5	400	102dx254 [cy]	32	35	[Mix, NaCl] / [(Add), 1.5%bwce] / [(Add), (De 0-30mm), (t) 0.48-0.32%bwce]	Re	aTi	[wet cellulose fibre] / [tank]	[G] / [A/m ² CS 1]	28, 56
Ueda [71]	OPC	C	0.55	338	100x100x300 [pr]	13	43	[Mix, NaCl] / [(Add) 8%bwce] / [(Av), (t) 2.37%bwce]	Re	Ti	[LiOH, Li ₂ CO ₃ , Li ₂ SiO ₄ , LiNO ₃ , Ca(OH) ₂] / [tank] / [30, 40°C]	[G] / [A/m ² CS 1]	56
Ueda [37]	OPC	C	0.55	318	100x80x400 [be]	d10 deformed	15	[Mix, NaCl] / [(Add), 8%bwce] / [(t) 2.52%bwce]	Re	Ti in DFRC C	[Li ₃ BO ₃] / [DFRCC]	[G] / [A/m ² CS 1]	56
Green [53]	OPC	C	0.66	288	130x100x100 [b]	16	42	[Mix, NaCl] / [(Av), (t) 0.26% bwco = 2.17%bwce]	Re	Ti-Pt	[Ca(OH) ₂] / [tank]	[G] / [A/m ² CS 1, 3]	18
Chang * [58]	OPC	C	0.66	307	100dx200 [cy]	12.3	40	[Mix, NaCl,] / [(Add), 1.28%bwce (Re), 3800ppm bwco]	Re	Ti	[Ca(OH) ₂] / [tank] / [NaOH] / [tank]	[G] / [A/m ² CS 1.88, 18.8]	7, 14, 21, 28, 35, 42
Abdelaziz [44]	OPC SRC	M	0.5	-	80x80x300 [pr]	10	35	[Mix, NaCl 1.2%bwce + W/D NaCl 1 year] / [(De 0-35mm) (t) 4.2-1.7%bwce]	Re	SS mesh	[Ca(OH) ₂] / [tank] / [TW] / [tank]	[G] / [A/m ² MS 1, 2]	14, 28, 56

Climent [91]	CEM II/A-L	C	0.5	342	100dx100 [cy]	Re d10 deformed	45	[Mix, NaCl] / [(Add) 1%bwce] / (Add) (t) 0.55%bwce]	Re	aTi- RuO ₂ , Graphi te	[DW] / [immersion or sandwich]	[Gi] / [A/m ² CS 3]	?
Climent [91]	CEM II/A-L	C	0.5	342	200dx1000 [co]	6 Re d12 deformed	30	[Mix, NaCl] / [(Add), 1%bwce] / [(De) (t) 1.3- 1%bwce]	Re#	aTi- RuO ₂ , Graphi te	[TW] / [immersion or sandwich]	[Gi] / [A/m ² CS 5]	280
Perez [38]	CEM II/B-L	C	1(?) 0.5	195 342	180x180x120 [b]	2	60	[Mix, NaCl] / [(Add), 1.2%bwce (Av), (t) 0.24, 0.31%bwco]	Re steel mesh	Ti- RuO ₂ or CCP	[DW] / [top pond]	[G] / [A/m ² CS 2]	139h 556h

* 5 V corresponds to 18.8A/m² CS

7
8

Table 4: Published laboratory studies on ECE treatment performed using a current control mode (continuous G or intermittent Gi) with current densities expressed as A/m² of steel rebar surface (RS).

First author [Reference]	Binder	Sample	w/c ratio	Cement (kg/m ³)	Dimensions (mm) [shape]	Steel rebar (diameter mm)	Cover (mm)	chloride content before ECE [mode] / [content Cl]	Cathode	Anode	Electrolyte	Current control mode (G or Gi) / [A/m ² RS]	Duration (days)
Monteiro [81]	-	C	0.45 0.65	500 380	1180x560x1200 [pr] 1220x960x1200 [pr]	6.3	20, 40	[SS, 4m] / [(De 0-40mm), (t), 1.5, 0.5%bwce]		SS mesh	[TW] / [tank]	[Gi] / [RS 1]	2w ON, 1w OFF, 2w ON, 1w OFF, for a total cycle of 6w
Elsener [48]	-	C	0.5 0.6	340 303	320x245x70 [bl]	8	40, 50	[Cycles+I, NaCl] / [(De 0-50mm), (t) 0.45-1.45%bwce, (f) 0.02-0.15%bwce]	SSR#	SS plate	[TW] / [foam plastic]	[Gi] / [RS 2]	18 (7d ON, 12d OFF, 4d ON, 3d OFF, 7d ON)
Miranda [59, 60]	-	M	0.5	-	1330x1330x70 [sl]	8	31	[Mix, CaCl ₂ 3% bwce] / [(Add), (De 0-60mm), 1000-3500 ppm]	R	Ti	[Ca(OH) ₂] / [cloth soaked]	[G] / [RS 5]	42 (per side) 1 or 2 sides
Zhu [41]	OPC	C	0.32 0.4 0.5	480	100dx100 [cy]	10	45	[Mix, NaCl] / [(Add), 1.82%bwce]	R	CFRP	[Ca(OH) ₂] / [tank]	[G] / [RS 0, 1, 2, 3]	28
Sieglwart [47]	OPC	C	0.4	460	1000x100x100 [pr]	22	39	[Mix, NaCl] / [(Add), 1.5%bwce]	R+PSC	Ir	[W] / [bath]	[G] / [RS 1]	42

Kim [84]	OPC	C	0.40	-	70x70x150	10	30	[Mix, NaCl] / [(Add), 1.82%bwce]	R	Ti	none	[G] / [RS 0.25, 0.50, 0.75]	28
Orellan [57]	OPC	C	0.45	400	110dx100	10	50	[W/D, NaCl, 10m] / [(De 0-50mm), (t) 4.5-6.7%bwce, (f) 3.75-5.7%bwce] / [(Re), (t) 5 %bwce, (f) 4.5 %bwce]	R	Ti	[Ca(OH) ₂] / [tank]	[G] / [RS 1]	50
Polder [43]	OPC	C	0.4 0.54	420 300	500x100x100	5	15, 30, 46	[SWI, 16y] / OPC 0.54 [(Av), (t), 2.7-4.4%bwce] / OPC 0.4 [(Av), (t), 2.5-4.1%bwce]	R	aTi	[Ca(OH) ₂] / [tank] [TW] / [tank]	[G] / [RS 1, 4]	39
Stoop [51]	OPC	C	0.4 0.54	420 300	200x100x100	5	15, 30, 46	[SWI, 16y] / OPC 0.54 [(Av), (t), 2.7-4.4%bwce] / OPC 0.4 [(Av), (t), 2.5-4.1%bwce]	R	aTi	[Ca(OH) ₂] / [bath] [TW] / [bath]	[G] / [RS 1, 4]	39
Buenfeld [35]	OPC	C	0.5	400	102dx254	32	35	[Mix, NaCl] / [(Add), 1.5%bwce]	R	cTi	[W] / [cellulose fibre] / [tank]	[G] / [RS 0.75]	up to 112
Ihekwa [78]	OPC	C	0.5	370	150x150x150	20	65	[Mix, NaCl] / [(Add), 1.7, 3%bwce]	R	aTi	[Na ₃ BO ₃] / [tank]	[G] / [RS 9.5, 28.6]	56
Tang [90]	OPC	C	0.57 0.60 0.70 0.72	285	200x200x25	16	50	[Mix, NaCl] / [(Add), 0, 0.2, 0.7 and 2%bwco]	R	Ti	[TW] / [running]	Gi RS - 0.7; 1.0 and 1.3	56 2w ON then 2w OFF for a total of 8w
Vennesland [77]	OPC	C	0.7	-	-	-	-	[Mix, NaCl] / [(Add), 2%bwce]	R	Ti	[W] / [tank]	[G] / [RS 1.6, 4, 8]	7, 14, 26, 56

Polder	OPC	C	0.45	380	500x400x140	8	15	[W/D, NaCl, 20 to 77w] / [(Av 0-	Re#	aTi	[Ca(OH) ₂] / [tank]	[G] /	21-42
[85]			0.55	345	[pr]	16	30	45mm), (t) 0.3-1.6%bwce]			[TW] / [tank]	[RS 1, 4]	
			0.65	310									
Orellan	OPC	C	0.7	300	50dx100	10	20	[W/D, NaCl, 10m] /	R	Ti	[Ca(OH) ₂] / [tank]	[G] /	10, 20, 30,
[54]					[cy]			[(De 0-20mm), (t) 4.4-6.5%bwce, (f)				[RS 1]	40, 50
								2.2-3.8%bwce]					
Fajardo	OPC	C	0.6	310	50dx110	10	20,	[W/D, aSW, 10m] /	R	Ti	[DW] / [tank]	[G, Gi] /	90 (G), 5d
[45]					[cy],		50	[(Av) 4.6%bwce]				[RS 1]	ON 2d OFF
					110dx110								until 90d (Gi)
					[cy]								
Swamy	OPC	C	0.6	350	100x 165x2300	6mm ²	20	[Mix, NaCl] /	R	TiPt (2	[Ca(OH) ₂] / [tank]	[Gi] /	45
[55]			0.75	383	[be]	(sq)		[(Add), 2.4, 6%bwce] / [(De), (t) 1.5-		sides)		[RS 1]	
								8.2%bwce]					
Yeih	OPC	C	0.66	295	100dx200	9.5	25	[Mix, NaCl] /	R	Ti	[NaOH] / [tank]	[G] /	7, 14, 21, 28,
[82]			0.4	488	[cy]		50	[(Add), 1.8%bwce] / [(Re), (f),				[RS 1, 2, 4, 8]	35, 42
								1.7%bwce]					
Carmona	OPC	C	0.65	250	180x180x80	15.8	20	[Mix, NaCl] /	R#	GCP	[DW] / [top pond]	[G] /	8.8
[40]					[sl]			[(Add) 2%bwce] / [(Av), (t)				[RS 3.4]	
								1.97%bwce]					
Tissier	OPC	μC	0.65	387	100dx40	5	17.5	[Mix, NaCl 5% bwce + Carbonation]	R	TiPt	[Na ₂ B ₄ O ₇ ·10H ₂ O] /	[G] /	3, 7,14, 28,
[69]					[cy]			[Carbonation + W/D NaCl]			[tank]	[RS 1]	56
Marcotte	OPC	M	0.5	-	51dx141	9.5	20,	- [Mix, NaCl] /	R	TiPt	[Na ₃ BO ₃] / [tank]	[G] /	56
[79, 80]					[cy]		65	[(Add), 2%bwce] = [(Add), (-),				[RS 8.37]	
								0.25%bwmo]					
								- [Ing, NaCl] /					

								[(Add), (-), 0.38%bwmo]						
								- [Mix, NaCl + Ing, NaCl] /						
								[(Add), (-), 0.36%bwmo]						
Shan	OPC	M	0.45	M	40x40x160	10	15	[Mix, NaCl] /	R+Ti	Ti	[Ca(OH) ₂] / [tank]	[G] /	28	
[83]			0.55		[pr]			[(Add), 2%bwce]				[RS 2]		
Bouteiller	CEM II/A-S	C	0.53	400	2500x200x200	6	16,	[SWT, 40y] /	R#	TiPt	[Na ₂ B ₄ O ₇] / [top	[G] /	56	
[67]	(6-20%slag)				[be]		41	[(De 0-41mm), (t) 6.6-3.8 %bwce, (f)			pond]	[RS 1]		
								3.9-1.3%bwce]						
Kim	GGBS	C	0.40	-	70x70x150	10	30	[Mix, NaCl] /	R	Ti	none	[G] /	28	
[84]	(40%OPC+ 60%GGBS)				[pr]			[(Add), 1.82%bwce]				[RS 0.25, 0.50, 0.75]		
Tissier	CEM III/A	μC	0.65	387	100dx40	5	17.5	[Mix, NaCl 5% bwce + Carbonation]	R	TiPt	[Na ₂ B ₄ O ₇ ·10H ₂ O] /	[G] /	3, 7,14, 28,	
[69]	(65%slag)				[cy]			[Carbonation + W/D NaCl]			[tank]	[RS 1]	56	
Stoop	BFSC	C	0.4	420	200x100x100	5	15,	[SWI, 16y] /	R	aTi	[Ca(OH) ₂] / [bath]	[G] /	39	
[51]	(70%slag)				[pr]		30,	BFSC 0.4 [(Av), (t), 1.0-2.8%bwce]			[TW] / [bath]	[RS 1, 4]		
							46							
Polder	BFSC	C	0.4	420	500x100x100	5	15,	[SWI, 16y] /	R	aTi	[Ca(OH) ₂] / [tank]	[G] /	39	
[43]	(70%slag)				[pr]		30,	BFSC 0.4 [(Av), (t), 1.0-2.8%bwce]			[TW] / [tank]	[RS 1, 4]		
							46							
Bertolini	BFSC	C	0.4	420	500x100x100	5	15,	[SWI, 16y] /	R	aTi	[Ca(OH) ₂] / [tank]	[G] /	39	
[61]	(70%slag)				[pr]		30,	BFSC 0.4 [(Av), (t), 1.0-2.8%bwce]			[TW] / [tank]	[RS 1, 4]		
							46							
Polder	BFSC	C	0.45	380	500x400x140	8	15	[W/D, NaCl, 20 to 77w] / [(Av 0-	Re#	aTi	[Ca(OH) ₂] / [tank]	[G] /	21-42	
[85]	(70%slag)		0.55	345	[pr]	16	30	45mm), (t) 0.3-1.6%bwce]			[TW] / [tank]	[RS 1, 4]		
			0.65	310										

Polder [63, 65]	BFSC (70%slag)	C	0.55	-	150d [cores]	16	30, 45	[Splash, 8y] / [(De 0-58mm), (t), 1.45-0.02% bwce]	R	aTi	[Ca(OH) ₂] / [bath] [Na ₂ CO ₃] / [bath]	[G] / [RS 0.7, 1, 4]	19, 21, 42
Kim [84]	Ternary (40%OPC+ 40%GGBS+ 20%FA)	C	0.40	-	70x70x150 [pr]	10	30	[Mix, NaCl] / [(Add), 1.82%bwce]	R	Ti	none	[G] / [RS 0.25, 0.50, 0.75]	28

14 4.1 Chloride extraction

15 4.1.1 Ion migration

16 The current flowing from the rebar to the anode allows the migration of ions (anions Cl^- , OH^-
17 migrate from the rebar to the external anode and cations Na^+ and K^+ migrate towards the
18 rebar). The extraction of chloride ions from the vicinity of the rebar and from the concrete cover
19 is expected to decrease corrosion. The efficacy of chloride extraction depends on the chloride
20 transport number t_{Cl} that depends on the chloride concentration and on the amount of other
21 ions present in the medium. The transport numbers of the different ions [26] are indicated in
22 Table 5.

23

24 *Table 5: Transport numbers t of ions (from [26]).*

Ion	OH^-	Cl^-	Na^+	K^+	Ca^{2+}
C (mol/L)	0.5	0.2	0.035	0.58	10^{-4}
t	0.62	0.1	0.01	0.27	0

25

26 The quantity of chloride ions extracted (Cl_{ext}) per m^2 per second is obtained using Equation 9.

27

$$\text{Cl}_{\text{ext}} = i \cdot t_{\text{Cl}} \cdot G / F \quad \text{Equation 9}$$

28 Where i is the current density, t_{Cl} is the transport number of chlorides, G is a geometrical
29 constant (f (rebar-concrete interface)) and F is the Faraday constant.

30 Assuming that the current remains constant, the quantity of chloride ions extracted will vary
31 according to the transport number of the different ions present in the concrete pore solution
32 [63, 86].

33

34 4.1.2 Efficacy of ECE

35 The authors calculated the efficacy of chloride extraction (Cl_{eff}) according to Equation 10 based
36 on the available published results using current control mode.

37

$$Cl\ Efficacy = 100 \times \frac{Chloride\ content\ before\ ECE - Chloride\ content\ after\ ECE}{Chloride\ content\ before\ ECE} \quad \text{Equation 10}$$

38

39 Figure 3 presents the efficacy of ECE using a current control mode and current densities
40 expressed in surface of steel rebar (RS) applied to reinforced concretes or mortars
41 contaminated by chloride ions from different sources (studies from Table 4). The authors
42 calculated the chloride extraction efficacy close to the rebar (Re) based on free (f) or total (t)
43 chloride ions. In some papers, it was not clear if the chloride concentration after ECE was
44 determined close to the rebar or averaged from the concrete cover. We therefore considered
45 the data as the average chloride extraction in the concrete (Av). Figure 3 plots chloride efficacy
46 versus total charge in the range of 168 to 39 782 A.h/m² RS. The total charge is indicated on
47 the abscissa axis, as well as duration and applied current density, which are noted in brackets.
48 The authors highlight the need to include these three types of information (applied current
49 density, duration and total charge) as part of the design. When the efficacy is related to a
50 parameter of the ECE set-up, it is indicated in Figure 3 as f (parameter). Finally, results
51 pertaining to OPC binder are presented on the right-hand side of the graph, whereas the results
52 for the other binders are presented on the left.

53 For OPC binder, which is the main cement studied in literature, chloride extraction efficacy in
54 areas located close to the rebar increases from 25 to 97% as the applied total charge increases
55 from 168 to 1344 A.h/m² RS. The application of higher total charges ranging from 2016-39 782
56 A.h/m² RS with current densities above 2A/m² RS can cause detrimental mechanical
57 degradations [59].

58

59 Kim et al. [84] found that an increase in the total charge resulted in a decrease in the chloride
60 concentration around the steel rebar (i.e., at a depth of 27-30 mm) for current densities that
61 varied from 0.25 to 0.75 A/m² RS and were applied for 28 days, whatever the binder concerned.
62 Yeih et al. [82] studied the efficacy of chloride extraction using different current densities
63 varying between 1 to 8 A/m² RS and different durations (7, 14, 21, 28, 35, 42 days) applied on
64 different reinforced concretes (w/c ratio (0.4 or 0.66)) and concrete covers (25 or 50 mm). They
65 proposed a unified regression curve describing the evolution of the chloride content near the
66 rebar versus the total charge [82]. Looking at the overview of many data (Figure 3), the authors
67 can recommend for ordinary Portland cement a total charge of 1 000 – 2 000 A.h/m² RS for
68 achieving a 80% efficacy.

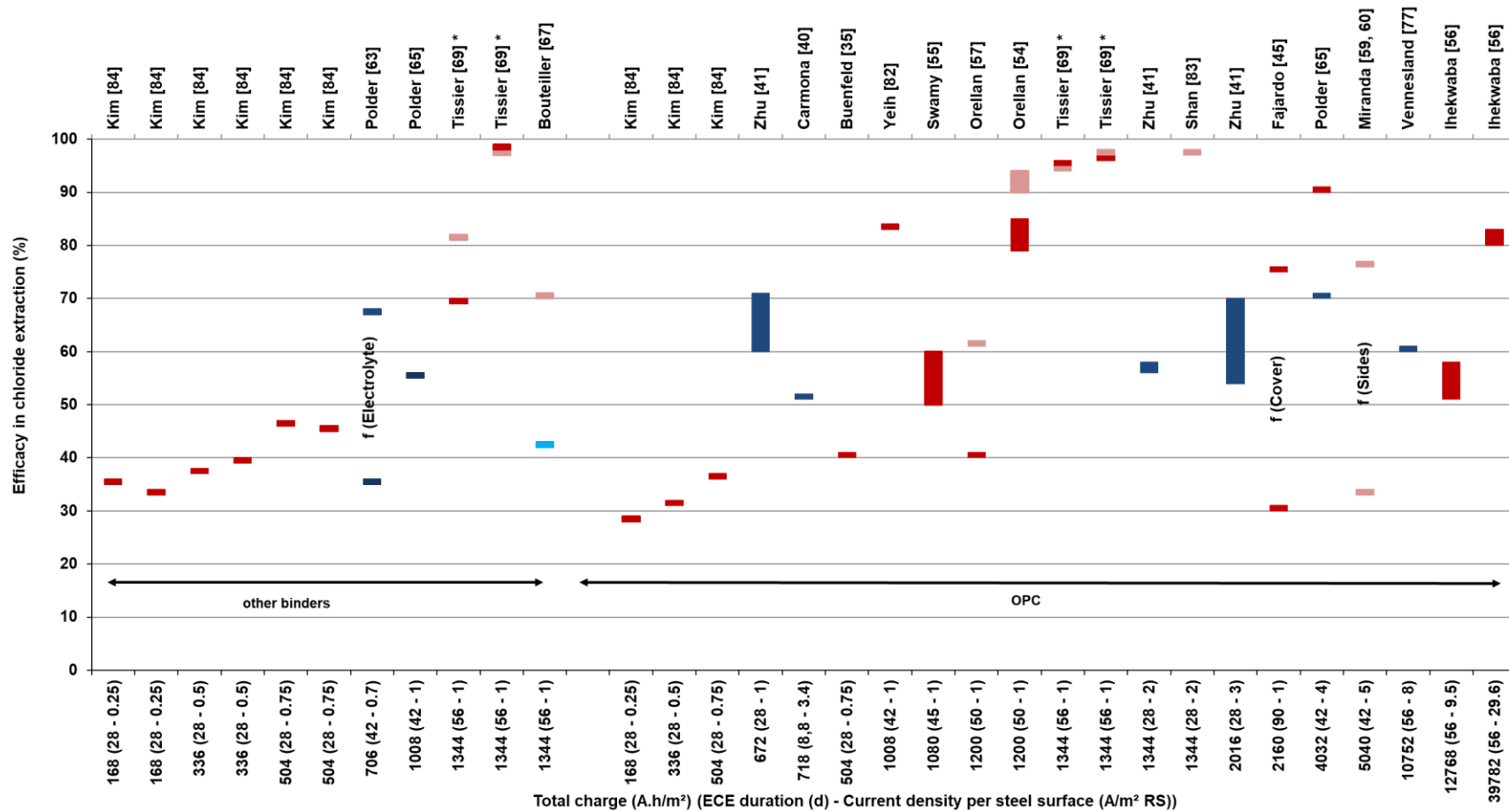
69 On the left-hand side of Figure 3, chloride extraction is also shown to increase with total charge
70 for non-OPC binders such as BFSC [43, 51], binary (40%OPC+60%GGBS) or ternary binders
71 (40%OPC+40%GGBS+20%FA) [84] and CEM II/A-S (6-20% slag) [67].

72 Finally, the results of Tissier et al [68, 69, 105, 106] are original because the reinforced
73 concretes made with OPC or CEM III/B binders were contaminated by both chloride ions and
74 carbonation prior to ECE. The excellent extraction efficacy reported was due to the free form
75 of most chloride ions after carbonation and the thinness of the concrete cover (17 mm).

76

77 From a practical perspective, clear criteria are required to ensure that a satisfactory chloride
78 extraction has been achieved. The literature proposes the following criteria: (i) attaining a
79 certain percentage of extracted chlorides and/or (ii) obtaining chloride content values in the
80 vicinity of the rebar that are below a threshold content, such as 0.4% bwce.

81



82

83 *Figure 3: Efficacy of chloride extraction applied to reinforced concrete specimens (chloride concentration close to the rebar (Re for*
 84 *rebar (red)) or chloride concentration of concrete cover (Av for Average, (blue)). Efficacy was calculated based on total or free chloride*
 85 *ions (shown in dark or pale colours, respectively). A star following the reference (top axis) indicates that the reinforced specimens were*
 86 *contaminated by both chlorides and carbonation prior to ECE.*

87 4.1.3 Influencing factors on chloride extraction

88 The authors used the published results to analyse the factors influencing chloride extraction
89 efficacy, i.e. concrete properties, chloride characteristics, electrolyte type and duration of
90 treatment.

91 4.1.3.1 Concrete properties

92 Concrete properties such as w/c ratio, concrete cover, binder type and contamination can have
93 an impact on ECE efficacy.

94 4.1.3.1.1 *Water/cement ratio*

95 Polder et al. [43, 85] found no impact on the extraction efficacy when ECE was applied to
96 concretes with different w/c ratios (0.4 up to 0.65). Zhu et al. [41] did not find a clear trend
97 between w/c ratios (0.32, 0.4 and 0.5) and chloride extraction efficacy. Other authors [48, 81-
98 83, 104] found that specimens with high water/cement ratio exhibit a higher chloride extraction
99 efficacy due to their greater porosity. In his thesis, Orellan [104] showed that the w/c ratio (0.45
100 or 0.7) influences the efficacy of the average chloride extraction value but does not influence
101 chloride extraction efficacy in the vicinity of the rebar. Swamy et al.[55] observed that the
102 efficacy of chloride removal from reinforced concrete beams was neither consistent nor
103 concurrent with the w/c ratio (0.6 or 0.75).

104 4.1.3.1.2 *Concrete cover*

105 Several authors found that a thinner concrete cover permits a more effective chloride extraction
106 due to lower electrical resistance and shorter chloride transport distances [45, 81, 104]. As an
107 example, Fajardo et al. [45, 107] obtained a chloride extraction efficacy that varied between
108 75% and 30% respectively for specimens with a 20 mm and 50 mm concrete cover after
109 applying a current density of 1 A/m² RS for 90 days.

110 4.1.3.1.3 *Binder type*

111 When Polder [43, 63, 85] applied ECE to reinforced concretes cast with OPC or BFSC, no
112 impact on chloride extraction efficacy was observed. However, it is important to note that the
113 driving voltages needed to obtain the required current density were significantly different given
114 the resistivity of each binder: whereas OPC specimens with resistivity in the range of 100-200
115 ohm.m required 3-5 V to obtain a current density of 1 A/m² RS and 16-30 V for 4 A/m² RS,
116 BFSC specimens with resistivity in the range of 400-1000 ohm.m needed 16 V (1A/m² RS) and
117 38 V (4A/m² RS) to obtain the same density. Kim et al. [84] found that it was easier to remove
118 chlorides from concretes made with Portland cement than from cements containing GGBS
119 (40%OPC+60%GGBS) or ternary mixtures (40%OPC+40%GGBS+20%FA). A higher binding
120 capacity of chlorides in concrete may therefore result in a lower chloride extraction efficacy.

121 4.1.3.1.4 *Concrete contamination*

122 Tissier et al. [68, 69] obtained a chloride efficacy of above 90 % for specimens that had been
123 carbonated and chloride contaminated (via different methods) prior to ECE. The high efficacy
124 was obtained for all binder types (OPC or CEM III/A) This very good result was explained by
125 two factors, namely the thinness of the concrete cover (17.5 mm), and the fact that carbonation
126 tends to release the bound chlorides into the matrix as free chlorides.

127 4.1.3.2 Chloride characteristics

128 The efficacy of ECE treatment is affected by chloride characteristics, namely the method of
129 contamination, the initial content and the type of chlorides analysed (total, free).

130 4.1.3.2.1 *Method of chloride contamination*

131 Chloride contamination can result from different methods:

- 132 - Mix addition is the most common means of contamination, because the chloride
133 contamination is immediate. Studies have used NaCl (Cl⁻ range 1 % - 8 % bwce) [35,

134 40, 41, 46, 47, 55, 61, 69, 75, 77, 79, 80, 82-84] or CaCl₂ (Cl⁻ range 2.35 % - 3 %bwce)
135 [59, 60],
136 - Wetting/drying cycles in NaCl solution [54, 57, 69] or in artificial sea water [45],
137 - Submersion in NaCl [48],
138 - Salt spray chamber [81],
139 - Outdoor exposure conditions or real structures: splash zone (8 years) [43], sea water
140 (16 years) [43, 51], sea water tide (40 years) [67].

141 Marcotte et al. [79] used rather strong ECE conditions (8.37 A/m² RS for 56 days) and found
142 that admixed chlorides are more difficult to extract than ingressed chlorides: chloride extraction
143 efficacies in the vicinity of the rebar were respectively 79 %, 74 % and 3 % when chloride
144 contamination was achieved by mix + ingress additions (initial Cl⁻ 0.36 % bwmo), ingress (initial
145 Cl⁻ 0.38 % bwmo) or mix (initial Cl⁻ 0.25 % bwmo). The study did not clearly indicate whether
146 the chloride was free or total.

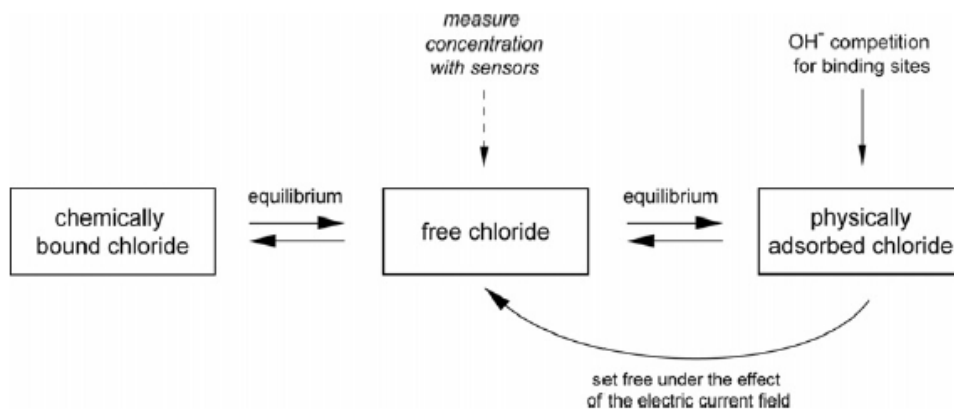
147 4.1.3.2.2 *Initial chloride content*

148 Several authors stated that chloride extraction is greater for concretes with a higher initial
149 chloride content [43, 48, 78, 90, 108, 109]. Tang [90] concluded that ECE treatment has a limit
150 beyond which the further removal chloride becomes difficult. Finally, no correlation was found
151 between the initial chloride and the remaining chloride after treatment.

152 4.1.3.2.3 *Type of chloride analysed (free, total or bound)*

153 Elsener [48] described the equilibria between chemically bound, physically adsorbed and free
154 chlorides in the ECE treatment (Figure 4). Part of the remaining chloride measured was in an
155 insoluble form after one or more ECE treatment cycles [48]. On the other hand, Orellan et al.
156 [54] found that ECE efficacy on concrete was slightly affected by the C₃A content (4.3 or 9.5%)
157 in OPC cement because only a part of the bound chloride ions was released.

158



159

160 *Figure 4: Equilibria between bound, adsorbed and free chloride in the ECE treatment*

161

(from [48]).

162

163 4.1.3.3 Electrolyte

164 A study by Monteiro et al. [81] reported that the use of tap water as the electrolyte caused an
 165 increase in the resistance and thus also in the polarization of the anode. Polder found no
 166 difference in chloride extraction efficacy between tap water and saturated calcium hydroxide
 167 solutions [43]. Polder et al. [63] compared sodium carbonate (Na_2CO_3) and calcium hydroxide
 168 ($\text{Ca}(\text{OH})_2$) solutions, and found that extraction with calcium hydroxide was more efficient. The
 169 use of $\text{Ca}(\text{OH})_2$ electrolyte produced a 67% extraction of total chlorides ($0.7 \text{ A/m}^2 \text{ RS}$, 42 days),
 170 whereas the proportion of chloride extracted over the same period with Na_2CO_3 electrolyte was
 171 respectively only 35 % and 55 %, with current densities of 1 and $4 \text{ A/m}^2 \text{ RS}$ respectively. Using
 172 an electrolyte with Na causes Na^+ migration into the pore solution, thus reducing the Cl^-
 173 transport number. Bouteiller et al. [67] used sodium tetraborate ($\text{Na}_2\text{B}_4\text{O}_7$) solution to extract
 174 chloride from a reinforced concrete beam (4 cm cover) that had been exposed to a marine
 175 environment in France for 40 years. The treatment allowed the removal of up to 70 % of the
 176 free chlorides located in the vicinity of the rebar, 50 % of those in the intermediate cover and
 177 5 % of those located at the surface of the concrete. In his thesis, Orellan [104] used identical
 178 experimental conditions and ranked different electrolytes from the most to the least effective

179 in terms of chloride extraction, namely tap water (60 %), sodium-based electrolyte (54 %), and
180 calcium and lithium-based electrolytes (40 %).

181 4.1.3.4 Duration

182 Although most ECE treatments last 28 or 56 days, other periods were reported ranging from
183 3-112 days. The extraction of chlorides was reported to be at its highest at the beginning of
184 the treatment [35, 41, 45, 48, 54, 83, 90]. This phenomenon is easily explained: at the
185 beginning of the process, chloride ions are the main negative ions that migrate through the
186 current flow. After some time, the chloride transport number decreases (due to the extraction)
187 and the hydroxyl ions that are formed at the cathode compete as negative charge carriers.
188 Tang et al [90] suggested that there is a limit beyond which the further removal of chloride ions
189 becomes difficult.

190

191 4.2 Steel corrosion mitigation

192 The characterization of ECE efficacy requires evidence that steel rebar corrosion has been
193 mitigated following the extraction of chloride ions (Table 4). Table 6 presents published results
194 on resistivity, half-cell potential and corrosion current density.

195 The resistivity of the concrete is a key parameter that affects both corrosion behaviour (a
196 concrete resistivity below 10 kohm.cm is linked to a high corrosion probability [110]) and ECE
197 treatment conditions (the voltage increases with resistivity).

198 Half-Cell Potential (E_{corr}) indicates the probability of corrosion. When the measured potential
199 is more positive than -250 mV CSE, there is a 90 % probability that rebar corrosion is absent
200 [102]. An increase of potential values after treatment indicates a lower probability of corrosion
201 [111]. Miranda et al. [59, 60] warned, however, that this approach might give rise to serious
202 errors when evaluating the active or passive state of the rebar if the saturation degree of the
203 pores is not identical. A significant ennobling of potentials after the application of ECE cannot

204 therefore be deemed sufficient evidence to demonstrate the efficacy of the treatment; evidence
205 of a decrease in corrosion current density is also needed.

206 Corrosion current density (I_{corr}) is an instantaneous value. A value in the range of above 1, 1-
207 0.5, 0.5-0.1 or less than 0.1 $\mu A/cm^2$ respectively indicates a high, moderate, low or negligible
208 corrosion level [103]. A decrease in corrosion current density after treatment will therefore
209 highlight mitigation of corrosion.

210 The efficacy of ECE treatment is dependent on the mitigation of corrosion. The latter must be
211 evaluated by comparing electrochemical characterizations before ECE, immediately after ECE
212 and after the depolarization of the steel rebar.

213 It is important to highlight the following conditions:

214 a) The comparison of electrochemical results is only valid if the "steel rebar in concrete"
215 system is at its equilibrium (i.e.; not polarized) and

216 b) The comparison of electrochemical results should only be carried out for the same
217 sample if conditions of temperature, humidity and oxygen availability remain identical.

218 Finally, it is important to note that increasing E_{corr} and decreasing I_{corr} can indicate a
219 mitigation of corrosion, but this in itself does not suffice to conclude that the rebar is passivated.

220 No clear demonstration of re-passivation has been published to date.

221

222

Table 6: Published results for electrochemical chloride extraction (*italic values for non-treated samples*)

223

Reference	Condition	Resistivity		Half-cell potential					Corrosion current density			
		Before ECE (kohm.cm)	Just after ECE (kohm.cm)	Reference Electrode	Before ECE (mV)	Immediately after (mV)	Depolarization ECE time (days)	After depolarization (mV)	Before ECE ($\mu\text{A}/\text{cm}^2$)	Immediately after ECE ($\mu\text{A}/\text{cm}^2$)	Depolarization time (days)	After depolarization ($\mu\text{A}/\text{cm}^2$)
Buenfeld [76]		<206> (223; 89; 255; 255)	<1245> (541; 509; 745; 3183)									
Polder [43]				Ag/AgCl	-400 to -260 -420 to -230		39	-400 to -330 -130 to +140				
Marcotte [79]	Ingressed Admixed + ingressed			SCE	-	-1200		-375 1year after ECE (but no O2)	<0,1 (18 (5% surface)) <0,1 (or 27 (5% surface))	7 19		
Monteiro [81]				SCE		-900	30	-157				
Orellan [54]				SCE	-647 (10d) -626 (30d) -589 (50d)	-1123 (10d) -1075 (30d) -1053 (50d)	61	-335 (10d) -153 (30d) -172 (50d)	5.76 (10d) 6.73 (30d) 6.26 (50d)	5.02 (10d) 5.08 (30d) 4.70 (50d)	61	2.65 (10d) 2.19 (30d) 2.89 (50d)
Fajardo [45]	Cover 20			SCE	-570	» -1000 (90d)	42	-380 (42d) up to - 300 (147d)	9		90	4

	Cover 50			-600	» -1000 (90d)		-400 (36d) up to -	3				
						36	400 (142d)		90	2		
Bouteiller	B4B3			SCE	» -500;	-800 to -700	60	-550 to -500 ; -	» 0.6;	2 to 3.5	60	» 0.6;
[67]					-500			600 to -500	0.6 to 1			2 to 2.5
	B2B1				-600 to -550	-900 to -700	60	-600 to -550 ; -	» 0.6;	3 to 4	60	» 0.6;
					-650 to -600			550 to -500	0.6 to 1.5			2 to 2.75
Yeih [82]	Cover 25	6.3 to 9.6	11.1 to 13.3	CSE	-500 to -450	-1110	60	» -230 ; -200	0.45		60	1.04
	Cover 50	7.1 to 10.7	10.8 to 13.3		-450 to -390							0.17
Miranda				SCE	-650	-350	90	-50	» 10	» 10	90	» 10
[59, 60]												
* Elsener				SCE		-1100 to -800	12 (first	-600 to -400				
[48]							current off					
							phase)					
Shan [83]				SCE		» -1225	30	-200 (after 30d of	10		30	<0.1
								immersion after				
								ECE)				
Kim [84]	OPC			SCE	-650		?	-475	110		?	8.0
	GGBS				-500			-300	100			2.5
	Ternary				-700			-320	100			4.3
Tissier	OPC,			SCE	-600 to -550	-1200	70-90	-450 to -200 (14d)	10	10	70-90	0.01 to 1 (14d)
[68, 69,	GGBS							-300 to -150 (28d)				0.04-0.1 (28d)
105, 106]								-250 to -160 (56d)				< 0.03 (56d)

224 * Stainless steel rebar

225

226 4.2.1 **Electrical resistivity**

227 Polder [43] states that no major changes occurred during the ECE process, resulting in the
228 relatively stable driving voltages needed to obtain the fixed currents. In contrast, Miranda [59]
229 found that the voltage increased from 7 to 40 V due to the progressive elimination of the
230 chlorides and the increase in mortar resistivity. Buenfeld [76] and Yeih [82] also reported an
231 increase in resistivity due to the extraction of chlorides.

232 Despite obvious differences between studies, resistivity is not conclusive with regard to
233 corrosion mitigation.

234 4.2.2 **Half-cell potentials**

235 Half-cell potential is an interesting measurement for evaluating ECE. Immediately after the
236 treatment, potential values are highly electronegative due to the polarization of the steel rebar
237 [45, 48, 54, 67, 68, 79, 81-83]. This confirms that the treatment has been applied correctly. It
238 is impossible to predict how long it will take for the rebar to depolarize, and the results from
239 Table 6 show this process to take 1 to 4 months. As depolarization occurs over time, the half-
240 cell potential gradually becomes nobler [45, 54, 59, 60, 69, 82, 84] and reaches a stable value.
241 If the latter is less electronegative than the value obtained prior to ECE, it can indicate a
242 decrease in corrosion activity that is consistent with the reduction in chloride ions around the
243 rebar.

244 4.2.3 **Corrosion current density**

245 Before ECE, corrosion current densities are in the range of 5 to 27 $\mu\text{A}/\text{cm}^2$ (Table 6), with the
246 highest density reported at 100 $\mu\text{A}/\text{cm}^2$ in reference [84]. Higher corrosion current densities
247 immediately after ECE can be explained by (i) the polarization of the steel, (ii) the accumulation
248 of hydroxyl ions at the rebar (iii) a decrease in oxygen at the rebar/mortar interface [79]. After
249 depolarization (over 1 to 4 months), decreases in corrosion current density ranging from fifty
250 percent [45, 54] to even 1 or 2 orders of magnitude were obtained [69, 83, 84].

251 4.2.4 **Influencing factors on steel corrosion mitigation**

252 4.2.4.1 ECE conditions

253 At a chosen ECE current flow, the increase in duration (and thus an increase in the total
254 charge) increases the efficacy of corrosion mitigation [68, 82, 83]. Kim et al. [84] studied the
255 optimisation of current density applied during ECE (varying from 0.25 to 0.75 A/m² RS). They
256 observed that an increase in current density resulted in an increase in the half-cell potential
257 and a decrease in the corrosion rate.

258 4.2.4.2 Binder types

259 Kim [77] reported that in ECE treatment carried out at 0.75 A/m² RS, the corrosion rates were
260 2.5 and 4.3 $\mu\text{A}/\text{cm}^2$ for GGBS and ternary mixes respectively. These rates are substantially
261 lower than those found for OPC mix (8 $\mu\text{A}/\text{cm}^2$), presumably due to a lower supply of water
262 and oxygen (i.e. cathodic reactions) through concretes that contain pozzolanic materials.

263 Tissier et al. [68, 69] found that corrosion rates decreased by two orders of magnitude for
264 micro-concrete specimens that had been contaminated by both carbonation and chloride ions
265 prior to ECE, whatever the binder used (OPC or CEM III/A (max 68% slag)).

266

267 4.3 **Evolution of pH**

268 The evolution of pH has been studied in two main contexts, namely the pH of the electrolyte,
269 which is central to determining a suitable treatment, and the pH of the rebar/concrete interface,
270 which should provide evidence of improved treatment efficacy.

271 4.3.1 **pH of the electrolyte**

272 The pH of the electrolyte has been studied throughout the ECE treatment to ensure that the
273 electrolyte does not become acid or differ too greatly from the concrete pH. Maintaining a high

274 pH also allows monitoring of Cl in the electrolyte; at low neutral to pH it is oxidised and
275 disappears as Cl₂ (Equation 8).

276 Water has a pH of 7 and is not a suitable electrolyte; during ECE, its pH will decrease to 3.5
277 (and produce a chlorine gas smell) without circulation, whereas the use of circulation will lead
278 pH to decrease to 4-6 [43], 6.5 [45] and 5-5.5 [40]. Using calcium hydroxide (Ca(OH)₂)
279 electrolyte (pH=12.5), Polder et al. [43] observed a local acidification in which the pH dropped
280 to about 5.5. While performing ECE on beams, Swamy et al. [55] also observed the
281 acidification of the calcium hydroxide electrolyte and chlorine smell in the laboratory for 2-8
282 weeks. A renewal of the calcium hydroxide electrolyte prevented these reactions (stable 12.5
283 pH and no chlorine smell).

284 4.3.2 pH of the rebar/concrete interface

285 During ECE, pH values increase at the rebar/concrete interface because of the formation of
286 hydroxyl ions at the cathode (Equation 5). This should play a role in corrosion mitigation and
287 durable protection. In an ECE set-up with water electrolyte, Buenfeld [35] used a
288 phenolphthalein indicator and found that a uniform purple staining was obtained 48 h after the
289 spraying on areas that included the concrete adjacent to the rebar. Zhu et al. [41] used calcium
290 hydroxide electrolyte and found an increase in pH close to the rebar. The use of sodium
291 hydroxide (NaOH 0.1M) solution in a study by Yeih et al [82] led pH values to increase to 12.4,
292 with the total charge attaining 8064 A.h/m². These authors suggested that a pH value of 11.5
293 in the vicinity of the rebar might be one of the performance criteria for determining ECE
294 efficacy. Finally, in the case of a realkalisation treatment, an increase in pH at the rebar was
295 also consistent with halting the corrosion [112, 113].

296

297 4.4 Visual observations and gravimetric analysis performed on the rebar

298 Table 7 summarizes the published results of visual observations and gravimetric analysis
299 before and after ECE treatment.

300

301

Table 7: Visual observations and gravimetric analysis before and after ECE

302

Reference	Before ECE	After ECE
Buenfeld [35, 76]	- Substantial amount of corrosion particularly associated with entrapped air voids in the concrete at the surface of the rebar	- Less evidence of corrosion - A rusty brown coloration was revealed beneath the brittle black surface layer - Air voids were partially filled with a soft black deposit
Marcotte [79]	- Corrosion pits covering 5 % of the surface for samples exposed to ingressed chlorides - No observable corrosion pits for samples with admixed chlorides	- Fine white products cover the steel surface - All steel samples had large areas (50 to 100 % of the surface area) of black-brown discolouring
Vennesland [77]		- Blackish deposits at the concrete/rebar interface
Ihekwaba [78]		- Accumulation of whitish deposits around the rebar treated at high impressed cathodic current densities
Orellan and Fajardo [45, 57]	- Substantially corroded	- Slight white deposit on the surface of the rebar
Miranda [59, 60]	- Corrosion products have a reddish colour	- Corrosion products are dark brown

Kim [84]	- Weighable rust was present on the surface of steel rebar rather than pit corrosion	- Rust stain was still present on the surface rather than pit corrosion - Mass loss: 0.48-0.55 %, 0.27-0.32 % and 0.26-0.29 % respectively for 2.5, 5 and 7.5 $\mu\text{A}/\text{cm}^2$ RS (Mass loss 0.79-0.88 % without ECE treatment).
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303

304 Corrosion products are observed before treatment: they do not usually cover the entire surface
305 of the steel rebar and they do not always appear as pits, although corrosion is induced by
306 chloride ions (Table 7). After ECE, whitish deposits [57, 78, 79] or black-brown products [35,
307 59, 76, 77, 79] were observed on the surface of the steel rebar (Table 7). Ihekweba [78]
308 reported that the whitish deposits are due to the alkali hydroxides formed as a result of cathodic
309 action during ECE application. Vennesland [77] studied the blackish products and found that
310 ECE induced an accumulation of cations (sodium and potassium) close to the rebar. Marcotte
311 [79] explained the black products by the formation of magnetite: although HFeO_2^- and FeO_2^{2-}
312 ions are likely to have been formed in the high pH/ low potential conditions of the treatment,
313 the steel would become more noble as the effect of the cathodic polarization decreased over
314 time and, with the redistribution of the OH^- ions, magnetite (Fe_3O_4) would become the dominant
315 product formed. Miranda [59, 60] considered that the changing appearance of the corrosion
316 products from reddish to dark-brown was due to the ECE-induced reduction of ferric
317 compounds in magnetite (very small portion of goethite), as determined by X-ray diffraction.
318 Finally, based on gravimetric analysis, Kim [84] found that the mass loss of corrosion products
319 on samples with no treatment was in the range of 0.79 to 0.88 % whereas this value was
320 significantly reduced in samples treated with different strengths of cathodic current.

321

322 5 SIDE EFFECTS

323 ECE treatment may also modify the characteristics of the reinforced concrete. It is therefore
324 important to know to what extent this occurs, and whether such effects can be detrimental to
325 the concrete or the steel rebar.

326 5.1 Modifications of concrete characteristics

327 5.1.1 Porosity

328 Buenfeld [76] and Monteiro [81] did not observe any change in the porosity induced by the
329 treatment. In contrast, other authors found that ECE treatment modifies the concrete porosity:
330 Castellote [114] reported an increase in total porosity as the electrical current was applied
331 through the concrete. Siegwart et al. [47]'s study based on visual observations and scanning
332 electron microscopy images of concrete treated samples (1 A/m² RS 42 d) at four different
333 locations found that the number of pores (2309-4296) was larger and the average pore size
334 (0.35-0.47 μm) was smaller than those observed in the control sample (1479 and 0.7 μm).
335 Shan [83] also found a modification in the pore size distribution in mortar samples after ECE:
336 the number of small pores (<100 nm) increased whereas the number of larger, harmful pores
337 (≥100 nm) decreased.

338 5.1.2 Ion migration

339 Polarization applied during ECE treatment induces an ionic redistribution. A decrease in
340 chloride concentration is observed in regions close to the steel rebar, as well as an increase
341 of hydroxyl ions. Moreover, the accumulation of alkali ions (K⁺, Na⁺) is found to increase with
342 time and/or current and varies according to the concrete cover. Orellan [57, 104] observed an
343 increase of alkali ions in Na₂Oequiv/m³ from 12 to 27 kgs of concrete located close to the steel
344 rebar, and attributed this event to the introduction of Na⁺ during the immersion-drying cycles
345 (NaCl was used to contaminate the specimens). This phenomenon was more pronounced

346 when the concrete cover was thin and the alkali ion concentration levels were sufficiently high.
347 Fajardo [45] also observed an increase compared to the control specimen, according to the
348 thickness of the concrete cover (20 or 50 mm) for Na⁺ (20 to 40%), for K⁺ (42 to 30%) and for
349 Ca²⁺ (30 or 17%). Ihekwaba [56] found that the accumulation of alkali ions at the rebar/concrete
350 interface is higher in carbonated than in non-carbonated concrete.

351 5.1.3 New phases formed

352 Marcotte et al. [80] used environmental scanning electron microscopy and energy dispersive
353 X-Ray microscopy to study the effect of ECE on the microstructure of concrete, and observed
354 that chlorides were no longer detectable at the surface of the steel after treatment. They also
355 noted the absence of C-S-H and suggested that it had decomposed into cationic (calcium-rich)
356 and anionic (silicate-rich) species under the impressed current. The formation of new
357 cementitious phases (i.e., calcium-aluminium-rich, sodium-rich, iron-rich and silicon-poor
358 phases) and their type depended on the source and magnitude of the chloride exposure.

359 Orellan [57, 104] monitored the evolution of concrete microstructure at different times after
360 treatment. Immediately after treatment, he observed the systematic formation of a new thin,
361 cementitious layer at the steel/concrete interface. This layer was composed of Ca, Si, Na, Al,
362 and K. New compounds including Na, Ca and Si were observed, and the formation of
363 secondary ettringite was reported in some cases. Two months after treatment, small amounts
364 of alkali-silicate gel had formed near the steel rebar but no cracks were observed. Six months
365 after treatment, large hexagonal crystals composed of Ca, Al and Cl had formed, as well as a
366 large amount of alkali-silicate gel.

367 5.2 Potential risks to reinforced concrete

368 Although ECE is shown to be an effective treatment for extracting chlorides, mitigate corrosion
369 and increase pH, there are a number of questions concerning potential harmful effects on the
370 reinforced concrete.

371 5.2.1 Concrete cracking

372 Hydrogen gas produced during the treatment causes localised increases in concrete pressure
373 and may promote concrete cracking. Polder et al. [43] observed a slight increase in micro crack
374 density that appeared to be related to the material composition rather than the applied current
375 density (1 and 4 A/m² RS). Indeed, it seemed that the high w/c ratio of OPC concrete made it
376 sufficiently permeable to allow the gas to escape at a relatively low pressure without causing
377 crack formation/expansion.

378 5.2.2 Steel embrittlement

379 Part of the hydrogen gas formed during the ECE process can be adsorbed on the metal surface
380 as atomic hydrogen and may then enter the steel, contributing to its embrittlement. This risk
381 can be monitored: no potential more negative than -1 100 mV with respect to Ag/AgCl/0,5 M
382 KCl shall be permitted for plain reinforcing steel or -900 mV for prestressing steel for an alkaline
383 concrete. Ordinary reinforcing steel does not suffer embrittlement [4] on the contrary to
384 prestressed steel [28, 88, 115]. Siegwart et al. [88] observed hydrogen embrittlement in their
385 study of prestressed concrete, using tendons stressed to the same degree. They investigated
386 the role of stress in hydrogen-induced stress corrosion cracking (HISCC) on the central wire
387 of the 7-wire strand of pre-stressed concrete samples which was post-tensioned to 90% of its
388 proof stress and subjected to ECE treatment at 2 A/m² RS for 40 days. The test was repeated
389 three times, but none of the samples failed prematurely due to HISCC. Other authors think that
390 the risk of HISCC depends on the type of prestressed steel and on levels of prestressing [28,
391 115]. Therefore, it is not advised to use ECE on prestressed concrete structures.

392 5.2.3 Modification of mechanical properties

393 The chemical changes occurring during electrochemical chloride extraction, and particularly
394 those in the vicinity of the steel rebar, can lead to modifications of concrete mechanical
395 properties. These changes deserve some attention.

396 5.2.3.1 Loss of bond at the steel rebar/concrete interface

397 The bond strength between steel rebar and concrete occurs through adhesion, friction and the
398 mechanical interlocking of surface deformation. Several authors have studied the impact of
399 ECE on bond strength [35, 59, 76-78, 80, 82]. Marcotte et al. [80] observed a change in the
400 microstructure of the mortar at the rebar/concrete interface (no C-S-H, an increase in the
401 proportion of Ca(OH)₂ and the formation of new cementitious phases) that may explain a loss
402 of bond. Miranda et al. [59] suggested that a treatment-related reduction of certain ferric
403 compounds in magnetite probably weakens the bond at the interface.

404 Buenfeld et al. [35, 76] studied plain rebar treated with a current density of between 0.02 and
405 0.75 A/m² RS for periods of up to 32 weeks. They found that prior to ECE the bond strength of
406 specimens containing chlorides was around 57 % higher than that of specimens with no
407 chlorides. This was attributed to corrosion enhancing the bond through a combination of
408 prestressing and mechanical interlock. After 2 weeks of ECE, the enhanced bond strength was
409 eliminated. The authors explained this result by the removal of corrosion products, as
410 confirmed by visual examination. They also noted that the bond strength was heavily
411 dependent upon the time interval between the ECE current being turned off and the bond test
412 being carried out. Vennesland et al. [77] monitored bond stress evolution for samples
413 subjected to ECE for 26 days and for different applied currents (1.6, 4 and 8 A/m² RS) after 1,
414 2, 7, 17 and 27 days. They noted extreme decreases in bond strength when higher currents
415 were applied. After the end of ECE, they first observed a drop in bond stress between 7 and
416 17 days post treatment, followed by an increase when compared to the level of the reference
417 specimen. Chang [116] reported significant bond loss and softening around rebars due to
418 applied charge at ECE levels and proposed a parameter based on the impressed current
419 density and polarization time. Ihekweba et al. [78] performed pull-out tests and found that the
420 specimens that were electrochemically treated with a very high impressed current density of
421 28.6 A/m² RS consistently showed increased degradation in bond strength and rebar slippage
422 compared with specimens that had been impressed with a lower current density of 9.5 A/m²

423 RS. Yeih et al.[82] based their research on the “pushing-away concept”, which does not aim
424 to completely remove free chloride but rather seeks a compromise between corrosion
425 prevention and bond degradation.

426 5.2.3.2 Loss of compressive strength

427 Marcotte et al. [80] found that a reduction of compressive strength is one of the consequences
428 of the cement phase alteration (composition and morphology) at the concrete/steel interface.
429 Swamy et al. [55] also noted a loss in compressive strength and attributed it to ASR.

430 5.2.4 Alkali-silica reaction (ASR)

431 Sodium or potassium cations migrate towards the steel rebar during ECE (§5.1.2). If the
432 concrete contains reactive aggregates, this increase in alkaline content may lead to alkali silica
433 reaction (ASR). To avoid adding sodium or potassium ions to concrete, a $\text{Ca}(\text{OH})_2$ solution is
434 usually chosen as the electrolyte. Work by Swamy et al [55] demonstrated that ECE could
435 trigger ASR in concretes that contain a reactive aggregate, i.e. synthetic fused silica (5 % or
436 15 % by mass of total aggregates). The concrete beams studied in the aforementioned article
437 exhibited significant cracks after an 8-week treatment at a current density of 1 A/m² RS.

438 Miller [117] states that ECE will not cause ASR in the field mainly due to ECE being a short
439 term treatment and ASR development is slow. On the other hand, Banfill [89] based on a
440 mechanistic model for ASR found ECE to enhance the reaction, depending on the presence
441 of chloride. It is therefore important to consider aggregate ASR reactivity before performing
442 ECE.

443

444 In the case of structures contaminated by chlorides and already suffering from ASR, the
445 literature reported that lithium-based electrolytes could be suitable for use in ECE treatment.

446 In Ueda's studies [70, 71], the current flow concerns the concrete surface and not the steel
447 surface, it was found that ECE treatment could inject Li^+ into the concrete from the electrolyte
448 solution (Li_3BO_3 , 40° C) and produce an accumulation of Li^+ around the rebar. Indeed, Li^+ ions

449 competed with the alkali ions (Na^+ and K^+) and would therefore limit or suppress/prevent the
450 ASR-induced expansion of concrete. Ueda [71] studied the penetration of Li^+ ions using
451 different electrolyte solutions (Li_3BO_3 , LiOH , Li_2CO_3 , Li_2SiO_4 , LiNO_3) at various temperatures
452 (30 or 40 C). Results showed that the transference number of Li^+ increases with temperature
453 and that Li_2CO_3 and LiNO_3 would be the most effective in terms of concrete penetration. LiNO_3
454 at 40 °C was the most suitable electrolyte for the prevention of ASR-related expansion.

455 6 LONG-TERM PERFORMANCE

456 Remaining chloride ions in concrete may redistribute and migrate back to the rebar and
457 eventually result in the (re)initiation of corrosion. The protective effect of ECE treatment would
458 thus be limited in time. Therefore, long-term performance of ECE treatment needs to be
459 evaluated. Very few laboratory studies report the long-term durability of ECE treatment; the
460 majority of publications describe periods ranging from 2 months to two years after the end of
461 treatment [40, 48, 51, 55, 67, 79, 80, 83, 118].

462 Marcotte et al. [79] observed significant corrosion rates one month after treatment, and
463 attributed this to the reduction of the passive film along with any existing corrosion products
464 during the treatment. This would lead to general corrosion, and the reduction of dissolved
465 oxygen in the concrete pore solution would prevent repassivation. They added that the
466 increase in pH at the steel surface puts it in the alkaline corrosion region of the Pourbaix
467 diagram (HFeO_2^- and FeO_2^{2-} formation). However, it is important to note that samples were
468 maintained in solution in this study, thus limiting the oxygen supply and preventing
469 repassivation.

470 Elsener et al. [48] used chloride sensors to confirm that only a negligible amount of bound
471 chloride was released two years after the end of ECE treatment.

472 Bouteiller et al. [67] reported no difference between steel potential values obtained 2 months
473 after ECE and those obtained after 17 months of immersion of the beam in sea water. They

474 also noticed that the free chloride concentration remained stable close to the steel rebar for
475 both the treated area and the control area.

476 Carmona et al. [40] tested chloride penetration sensitivity after treatment. They found that the
477 capacity of chloride absorption during the 24 weeks of contamination was 17.4 % lower in the
478 treated specimens than in non-treated samples.

479 Shan et al. [83] immersed the samples in a salt solution after ECE treatment. EIS, Ecorr and
480 Icorr values showed that corrosion of the rebar resumed after 50 days.

481 Finally, Stoop et al. [51] studied the chloride ion redistribution within the cover over a one-year
482 period, then developed a model to predict redistribution and thus risks of corrosion re-initiation
483 over a 10-year period.

484 Swamy et al. [55] studied the effect of ECE on structural strength and bond for 400 days
485 following the end of treatment. They did not report any adverse effect, although some of the
486 treated specimens did contain fused silica (which is ASR reactive).

487 7 REGULATIONS

488 Different projects completed in North America have followed guidelines developed by the
489 Strategic Highway Research Program (SHRP) [20-23] and by the Federal Highway
490 Administration [72, 87]. A NACE international publication on electrochemical chloride
491 extraction from reinforced concretes was published in 2001 [119] and re-approved in 2018
492 [120].

493 In Europe, the technical guidelines written in 2003 in CEN TS 14038-2 were replaced in 2018
494 by an AFNOR draft standard (PR NF EN 14038-2) entitled "Electrochemical realkalization and
495 chloride extraction treatments for reinforced concrete - Part 2: Chloride extraction" [15].

496 8 MODELLING

497 Although experiments are a relevant approach when investigating ECE, this type of

498 investigation comes at a significant cost and requires time. It therefore appears interesting to
499 approach the processes through modelling. This approach requires a good knowledge of the
500 materials and the chemical and electrochemical mechanisms involved in ECE, and makes it
501 possible to determine influencing factors, carry out a first approach for the planned objectives
502 and predict the evolution of the process over time.

503

504 Several authors used the Nernst-Planck equation to model the migration of chlorides during
505 extraction. Yu et al. [121] presented a computer simulation of multicomponent ionic migration
506 that did not take binding and desorption effects into account, leading to a description of
507 experimental features that was qualitative but not quantitative. Andrade et al. [33] presented
508 the different mathematical models that were available related to the treatment conditions. They
509 first compared the mathematical solutions provided in the literature for constant initial chloride
510 concentrations in order to define the chloride concentration gradient throughout ECE treatment
511 under voltage or current control modes (easier mathematical calculation is possible with the
512 former). They then suggested a new computer program that could calculate the treatment
513 duration in the case of an initial gradient of chloride concentration (the model is based on
514 diffusion coefficient determination as a function of electrolyte conductivity, and on Fick's
515 second law). Only voltage control mode was considered. Andrade et al. [33] finally showed
516 that mathematical modelling can be performed. However, few data were available to validate
517 their proposal at the time of their study.

518 Polder [85] used diffusion modelling of chloride remaining after ECE to approach the time until
519 corrosion might reappear.

520 Sa'id-Shawqi et al. [122] used the Nernst-Planck and Laplace (potential and current
521 distributions determination) equations to predict the amount of extracted chloride and the
522 remaining chloride profile in a ECE treatment (voltage mode). The study solely considered free
523 chloride removal from concrete. Despite some differences between experimental and
524 modelling data, they highlighted that the chloride transport number decreases with increasing

525 treatment time or chloride concentration and found that the quantity of free chloride removed
526 from behind the rebar can increase with treatment duration.

527 Bound chlorides were not considered in the models in the second and third studies presented
528 above [25, 112], yet this phenomenon could have an influence on mechanisms.

529 Hassanein et al. [123] developed a model to predict chloride extraction during a constant
530 current ECE, in a two-step process. The first step corresponds to the rapid removal of free
531 chloride ions and the second concerns the release of bound chloride ions. In their experiments,
532 they found that a significant amount of chloride was removed during the first 4 weeks of
533 treatment and very little during the next 4 weeks. The rate of release of bound chloride was
534 determined using the difference between the chloride concentration at 4 and 8 weeks of
535 treatment, assuming that all chlorides were all either initially bound or free (an intermediate
536 value for their model was chosen). Several other input parameters were also used for chloride
537 ions (diffusion coefficient, initial concentration, percentage of initially bound, etc.), concrete
538 (pore solution fraction, density, cover thickness, etc.) and the electric field. They validated their
539 model based on 12 cases and obtained reliable accuracy despite the use of estimated values
540 for many parameters.

541 In 2007, Toumi et al. [124] also used the Nernst-Planck equation, with concrete porosity
542 density, pore solution composition, chloride-binding isotherm, and diffusion coefficients as
543 input data. They found good accordance between the model and the experimental results and
544 highlighted the important role played by the binding isotherm in the prediction of chloride
545 removal.

546 Li et al. [125, 126] investigated the effect of ionic concentrations on diffusion and migration of
547 ions in a concentrated pore solution when a constant current is applied. They revealed that the
548 higher the current density applied or the concentration of the species, the more the “activity
549 coefficient” (chemical potential change arising from ion-ion and ion-solvent interaction) can
550 affect ionic diffusion and migration. The authors then presented a finite element model and
551 performed numerical investigations in order to show the effects of applied current density,
552 treatment duration, the diffusion coefficient of different ions, ionic binding, boundary conditions

553 and medium porosity. They highlighted that even if the removal of chloride ions increases with
554 both applied current density and time, a long-term treatment is likely to be less effective in
555 decontaminating the zone at the steel/concrete interface and would even be
556 counterproductive: their results show that during the treatment, the potential gradient
557 decreases near the steel but increases near the anode. They also show the influence of
558 chloride binding on chloride removal. The same authors (Wang et al. [127]) presented a two-
559 dimensional computer model that considered the electrostatic coupling of ions and other
560 factors (ionic adsorption, porosity and tortuosity of pore structure). Based on their results, they
561 underlined that when possible, the use of anodes on two opposite sides of the structure
562 improves the removal of chloride in the area behind the rebar. This is in accordance with results
563 obtained during experimental studies [36, 52]. Castellote et al. [108], sought to identify an
564 optimum treatment duration beyond which no further chloride is extracted due to the decrease
565 in chloride transfer number through the increase of hydroxyl ions near the rebar. This
566 theoretical optimum duration was defined as a function of the electrical charge passed, and
567 was calculated using an empirical equation that considered the chloride diffusion coefficient
568 decrease during the treatment. They also predicted chloride profiles after treatment according
569 to the current applied.

570

571 While the previous works considered electro-neutrality condition, works conducted at the
572 University of Plymouth [128-130] used Poisson's equation to determine the electrostatic
573 potential. However, Poisson's equation is theoretically applicable when no electrical field is
574 applied. When ECE treatment is applied, the electrolysis of water ensures the electro
575 neutrality. In the study [128], the concrete was treated as a heterogeneous composite structure
576 with two phases (mortar and aggregates that were assumed to be impermeable). The finite
577 element model was developed for a voltage control mode and provided information about the
578 migration of four ionic species (Cl^- , Na^+ , OH^- , K^+) during the treatment. The analysis of the
579 results highlighted the variation and the influence of migration speed, distribution and total
580 amounts of ionic species. They also found that local diffusion could have a significant influence

581 on the evolution of migration speed. In the study [129], the concrete was presented as a three-
582 constituent composite (i.e. a mortar matrix, aggregates and the interfacial zone between them).
583 This two-dimensional model was also used to study how current flow pattern and the evolution
584 of chloride concentration are affected by the use of different configurations of multiple rebars
585 as cathodes. The authors underlined that the configuration of the rebars (cathode) in ECE is
586 very important; a single well-located rebar provided a better extraction than the same rebar
587 coupled with another rebar that was located closer to the anode. As described in numerous
588 other experimental and numerical studies, although the amount of removed chloride increased
589 with applied current density and treatment time, the daily removal rate decreased with
590 treatment duration. Finally, they found that the two opposite effects on chloride extraction that
591 resulted from the presence of aggregates, namely an increase in current and a change in
592 porosity and tortuosity, almost cancelled each other out. Liu et al. [128] also studied different
593 parameters (aggregates and their effect on interfacial zone effect of rebar position, etc.) using
594 a finite element model based on inverse parameterization of chloride diffusion coefficients.
595 They notably found that Na^+ and OH^- were mainly located around the rebar at the end of the
596 treatment, while K^+ was widely distributed between the rebar and the anode. They also studied
597 the influence of cracks and found that chloride extraction was slower when cracks were
598 perpendicular to the electric field (the study excluded aggregates for this analysis). These
599 recent types of modelling were developed to facilitate the study of structures with complicated
600 geometries and of numerous physical parameters, but have not always been validated with
601 experimental data.

602 An experimental analysis by Cheng et al. [131] of how ECE affects the evolution of porosity in
603 concrete structure observed a decrease in porosity with treatment time close to the cathode
604 and anode regions of the concrete, with a higher decrease noted near the anode region. They
605 proposed a numerical simulation of this aspect and highlighted that taking the evolution of
606 porosity into account led to a better accuracy in ECE treatment prediction.

607

608 Following this analysis of some of the attempts to model the ECE treatment of concrete, we
609 can conclude that there are a great number of parameters which can (or should) be considered.
610 Some authors proposed interesting models but did not always validate them by a comparison
611 with experimental data. The use of some of the models can currently be considered to define
612 or validate certain issues that are specific to concrete or inherent to the application of the
613 treatment, but much work remains to be done. In particular, the type of used cement has a
614 major influence on the porosity and the characteristics of the porous network (pore sizes and
615 connectivity) and this aspect must be better defined in future models. Moreover, still in relation
616 to the nature of the cement, the quantity of bound-free-total chlorides can be very different
617 depending on cement and the kinetics of these chloride forms must be better evaluated.
618 Finally, models involving electrochemical data would be a step forward.

619 9 CONCLUSIONS

620 Based on this literature review the following conclusions and recommendations can be drawn:

621

- 622 1. Electrochemical chloride extraction has proven to be an efficient treatment for the
623 extraction of chloride ions from the concrete cover. In order to continuously protect the
624 rebar, constant current mode is preferred (when using a constant voltage mode the current
625 received by the rebar will decrease over time as the resistance of the medium increases).
626 Moreover, as ECE seeks to protect the steel rebar from corrosion in concrete, the current
627 density must be calculated according to the area of the steel rebar surface (A/m^2 RS) and
628 not the concrete surface. Finally, it is important to specify the duration of the treatment in
629 order to calculate the total charge (in $A.h/m^2$), which is useful data when comparing results.
- 630 2. Design is an important step to achieve successful ECE (steel rebar surface, choice of
631 electrolyte, position of the anode, continuous or intermittent treatment, etc.)

- 632 3. ECE efficacy should be determined according to multiple criteria: extraction of chlorides
633 (free and total), mitigation of corrosion (half-cell potentials, corrosion current density,
634 resistivity, etc.), pH and visual inspection.
- 635 4. ECE efficacy has been demonstrated based on analyses performed before and
636 immediately after the ECE, and after steel rebar depolarization, with full consideration of
637 treated and control samples.
- 638 5. Optimisation of ECE (current density and duration) is needed to successfully demonstrate
639 its efficacy without causing detrimental effects (such as altered composition and
640 morphology at the rebar/concrete interface, loss of bond, etc.) and to propose performance
641 criteria.
- 642 6. Limitations of ECE are:
- 643 ○ Chloride ions penetrated behind the rebar (in this case Cathodic Protection should
644 be preferred to ECE).
 - 645 ○ Prestressed concrete (hydrogen embrittlement)
 - 646 ○ Reactive aggregates (ASR risk)
- 647 7. ECE-related rebar repassivation should be studied in greater depth using in-situ
648 techniques such as micro-Raman spectroscopy in laboratory. The only evidence provided
649 in the literature concerns corrosion mitigation; no evidence of repassivation has been
650 presented to date.
- 651 8. Models still need to be validated with experimental data.
- 652 9. Further work is needed to demonstrate the long-term efficiency of ECE 1, 2, 5 and 10 years
653 after treatment.

654

655 Finally, this literature review clearly highlights the urgent need to transfer technology from a
656 state of laboratory knowledge (experimental and modelling) to functional use in the practical
657 field.

658

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664

665 **References**

- 666 [1] J.P. Broomfield, Corrosion of steel in concrete - Understanding, investigation and repair,
667 E&FN SPN, London, 1997.
- 668 [2] A. Bentur, S. Diamond, N.S. Berke, Steel corrosion in concrete - Fundamentals and civil
669 engineering practice, E&FN SPON, London, United Kingdom, 1997.
- 670 [3] Woodward R, Cullington DW, Daly AF, Vassie PRW, Haardt P, Kashner R, Astudillo R,
671 Velando C, Godart B, G. B, C. C, Mahut B, B. Mahut, A. Raharinaivo, M.I. Lau, Bevc L et Perus
672 I, C. C, Bridge management in Europe (BRIME)-Deliverable D14- Final Report, 2001, pp. 228.
- 673 [4] L. Bertolini, B. Elsener, P. Pedferri, R.B. Polder, Corrosion of steel in concrete: prevention,
674 diagnosis, repair, Wiley Vch Verlagsgesellschaft Mbh, Weinheim, 2004.
- 675 [5] G.P. Tilly, J. Jacobs, CONREPNET - Concrete repairs - Performance in service and current
676 practice, IHS BRE Press, Watford, UK 2007.
- 677 [6] E. Marie-Victoire, M. Bouichou, T. Congar, R. Blanchard, Concrete cultural heritage in
678 France: inventory and state of conservation Rehabilitation and Retrofitting (ICRRR-4),
679 Concrete repair, rehabilitation and retrofitting IV: Proceedings of the 4th international
680 conference on concrete repair, Leipzig, Germany 2015, pp. p. 343-350.
- 681 [7] U. Angst, B. Elsener, C.K. Larsen, O. Vennesland, Critical chloride content in reinforced
682 concrete - A review, Cement and Concrete Research, 39 (2009) 1122-1138 DOI:
683 10.1016/j.cemconres.2009.08.006.
- 684 [8] J.Y. Hu, S.S. Zhang, E. Chen, W.G. Li, A review on corrosion detection and protection of
685 existing reinforced concrete (RC) structures, Construction and Building Materials, 325 (2022)
686 126718 DOI: <https://doi.org/10.1016/j.conbuildmat.2022.126718>.
- 687 [9] C. Liang, Z. Cai, H. Wu, J. Xiao, Y. Zhang, Z. Ma, Chloride transport and induced steel
688 corrosion in recycled aggregate concrete: A review, Construction and Building Materials, 282
689 (2021) 122547 DOI: <https://doi.org/10.1016/j.conbuildmat.2021.122547>.
- 690 [10] R.N. Cox, R. Cigna, O. Vennesland, T. Valente, COST 509 - Corrosion and protection of
691 metals in contact with concrete - Final Report, European Commission, Directorate General
692 Science, Research and Development, Brussels, EUR 17608 EN 1997.
- 693 [11] R. Cigna, C. Andrade, U. Nürnberger, R. Polder, R. Weydert, E. Seitz, COST 521 -
694 Corrosion of steel in reinforced concrete structures - Final Report, European Commission,
695 Directorate-General for Research, Brussels, EUR 20599 2003.
- 696 [12] S. Matthews, M. Sarkkinen, J.R. Morlidge, Achieving Durable Repaired Concrete
697 Structures: Adopting a Performance-based Intervention Strategy, CONREPNET Project
698 Report IHS BRE Press, Watford, UK 2007.
- 699 [13] S. Matthews, CONREPNET: Performance-based approach to the remediation of
700 reinforced concrete structures: Achieving durable repaired concrete structures, Journal of
701 Building Appraisal, 3 (2007) 6-20 DOI: 10.1057/palgrave.jba.2950063.
- 702 [14] AFNOR, NF EN ISO 12696 - Cathodic protection of steel in concrete 2017.
- 703 [15] AFNOR, PR NF EN 14038-2, Electrochemical realkalization and chloride extraction
704 treatments for reinforced concrete - Part 2: Chloride extraction 2019.
- 705 [16] J.E. Slater, D.R. Lankard, P.J. Moreland, Electrochemical removal of chlorides from
706 concrete bridge decks Materials Performance, 15 (1976) 21-26.

707 [17] G.L. Morrison, Y.P. Virmani, S.F. Wayne, W.J. Gilliland, Chloride removal and monomer
708 impregnation of bridge deck concrete by electro-osmosis - Report FHWA-KS-RD-74-1, (1976).
709 [18] D.R. Lankard, J.E. Slater, W.A. Hedden, D.E. Niesz, Neutralization of chloride in concrete
710 - Final report FHWA-RD-78-60, Federal Highway Administration, Washington DC, 1975, pp.
711 pp.136
712 [19] O. Vennesland, O. Opsahl, Removal of chlorides from concrete, European Patent
713 Application N°86302888.2 Norwegian Concrete Technologies AS 1986.
714 [20] J. Bennett, Evaluation of NORCURE Process for electrochemical chloride removal from
715 steel reinforced concrete bridge components , SHRP-C-620, Strategic Highway Research
716 Program, 1993.
717 [21] J. Bennett, Chloride removal implementation, SHRP-S-347, Strategic Highway Research
718 Program, 1993.
719 [22] J. Bennett, Electrochemical chloride removal and protection of concrete bridge
720 components : laboratory studies, SHRP-S-657 Strategic Highway Research Program, 1993.
721 [23] J. Bennett, Electrochemical chloride removal and protection of concrete bridge
722 components : field trials, SHRP-S-669, Strategic Highway Research Program, 1993.
723 [24] D. Pocock, Chloride extraction and realkalisation - six years on Corrosion and protection
724 of reinforced concrete Dubai, 1994.
725 [25] J. Mietz, Electrochemical rehabilitation methods for reinforced concrete structures – a
726 state of the art report. European Federation of Corrosion Publications EFC N°24, IOM
727 Communications Ltd, London, 1998.
728 [26] B. Elsener, L. Zimmermann, D. Bürchler, H. Böhni, Repair of reinforced concrete
729 structures by electrochemical techniques - Field experience, European Federation of
730 Corrosion Publication EFC N°25, J. Mietz, B. Elsener and R. Polder, European Federation of
731 Corrosion Publications ed., IOM n°25 communications Ltd, London, 1998.
732 [27] M. Raupach, B. Elsener, R. Polder, J. Mietz, Corrosion of reinforcement in concrete -
733 Mechanisms, monitoring, inhibitors and rehabilitation techniques, European Federation of
734 Corrosion Publication EFC N°38, Woodhead Publishing and Maney Publishing 2007.
735 [28] R. Polder, M.C. Alonso, D.J. Cleland, B. Elsener, E. Proverbio, O. Vennesland, A.
736 Raharinaivo, COST 534 - New materials, systems, methods and concepts for prestressed
737 concrete structures- Final Report 2009.
738 [29] E. Julio, E. Cavaco, C. Andrade, V. Bouteiller, M. Carballo, C. Christodoulou, A. Costa,
739 J.G. Lopes, X. Hallopeau, K. Kobayashi, A. Mateus, J. Mercier, A. Monteiro, R. Paula, E.
740 Pereira, J. Ribeiro, J. Appleton, S. Cabral Fonseca, M. Chrappa, M.J. Correia, J. Garcia, T.
741 Habuchi, E. Kikuta, J. Laco, L. Lima, A. Meillier, K. Miyaguchi, F. Papworth, J. Paulo Costa, S.
742 Ribeiro, M.P. Rodrigues, Fib Bulletin 102 Guide for protection and repair of concrete structures
743 - Guide to good practice Task Group 8.1, 2022.
744 [30] K. Kobayashi, C. Andrade, V. Bouteiller, T. Habuchi, X. Hallopeau, K. Miyaguchi, R. Paula,
745 T. Ueda, Chloride extraction/Desalination, in: F.I.d.B. (fib) (Ed.) Guide for protection and repair
746 of concrete structures 2022.
747 [31] I.L.H. Hansson, C.M. Hansson, Electrochemical extraction of chlorides from concrete part
748 I - A qualitative model of the process, Cement and Concrete Research, 23 (1993) 1141-1152
749 DOI: 10.1016/0008-8846(93)90174-8.
750 [32] J. Tritthart, K. Pettersson, B. Sorensen, Electrochemical Removal of Chloride from
751 Hardened Cement Paste, Cement and Concrete Research, 23 (1993) 1095-1104 DOI: Doi
752 10.1016/0008-8846(93)90169-A.
753 [33] C. Andrade, J.M. Diez, A. Alaman, C. Alonso, Mathematical-Modeling of Electrochemical
754 Chloride Extraction from Concrete, Cement and Concrete Research, 25 (1995) 727-740 DOI:
755 Doi 10.1016/0008-8846(95)00063-I.
756 [34] J. Tritthart, Electrochemical chloride removal - a case study and laboratory tests Fourth
757 International Symposium on corrosion of reinforcement in concrete constructionThe royal
758 society of chemistry, Cambridge, 1996, pp. 433-447.
759 [35] N.R. Buenfeld, J.P. Broomfield, Influence of electrochemical chloride extraction on the
760 bond between steel and concrete, Magazine of Concrete Research, 52 (2000) 79-91 DOI: DOI
761 10.1680/macr.2000.52.2.79.

762 [36] C. Arya, Q. SaidShawqi, P.R.W. Vassie, Factors influencing electrochemical removal of
763 chloride from concrete, *Cement and Concrete Research*, 26 (1996) 851-860 DOI: Doi
764 10.1016/0008-8846(96)00067-1.

765 [37] T. Ueda, T. Kameda, A. Nanasawa, A new electrochemical rehabilitation method for
766 reinforced concrete employing the DFRCC anode system, *Separation and Purification*
767 *Technology*, 79 (2011) 204-207 DOI: 10.1016/j.seppur.2011.02.027.

768 [38] A. Pérez, M.A. Climent, P. Garcés, Electrochemical extraction of chlorides from reinforced
769 concrete using a conductive cement paste as the anode, *Corrosion Science*, 52 (2010) 1576-
770 1581 DOI: 10.1016/j.corsci.2010.01.016.

771 [39] A. Cañón, P. Garcés, M.A. Climent, J. Carmona, E. Zornoza, Feasibility of electrochemical
772 chloride extraction from structural reinforced concrete using a sprayed conductive graphite
773 powder–cement paste as anode, *Corrosion Science*, 77 (2013) 128-134 DOI:
774 10.1016/j.corsci.2013.07.035.

775 [40] J. Carmona, P. Garces, M.A. Climent, Efficiency of a conductive cement-based anodic
776 system for the application of cathodic protection, cathodic prevention and electrochemical
777 chloride extraction to control corrosion in reinforced concrete structures, *Corrosion Science*,
778 96 (2015) 102-111 DOI: 10.1016/j.corsci.2015.04.012.

779 [41] J.H. Zhu, L.L. Wei, Z.H. Wang, L.C. Ke, Y. Fang, F. Xing, Application of carbon-fiber-
780 reinforced polymer anode in electrochemical chloride extraction of steel-reinforced concrete,
781 *Construction and Building Materials*, 120 (2016) 275-283 DOI:
782 10.1016/j.conbuildmat.2016.05.103.

783 [42] B. Elsener, M. Molina, H. Bohni, The Electrochemical Removal of Chlorides from
784 Reinforced-Concrete, *Corrosion Science*, 35 (1993) 1563-1570 DOI: Doi 10.1016/0010-
785 938x(93)90385-T.

786 [43] R.B. Polder, Electrochemical chloride removal from concrete prisms containing chloride
787 penetrated from sea water, *Construction and Building Materials*, 10 (1996) 83-88 DOI: Doi
788 10.1016/0950-0618(95)00062-3.

789 [44] G.E. Abdelaziz, A.M.K. Abdelalim, Y.A. Fawzy, Evaluation of the short and long-term
790 efficiencies of electro-chemical chloride extraction, *Cement and Concrete Research*, 39 (2009)
791 727-732 DOI: 10.1016/j.cemconres.2009.05.015.

792 [45] G. Fajardo, G. Escadeillas, G. Arliguie, Electrochemical chloride extraction (ECE) from
793 steel-reinforced concrete specimens contaminated by "artificial" sea-water, *Corrosion Science*,
794 48 (2006) 110-125 DOI: 10.1016/j.corsci.2004.11.015.

795 [46] P. Garcés, M.J. Sánchez de Rojas, M.A. Climent, Effect of the reinforcement bar
796 arrangement on the efficiency of electrochemical chloride removal technique applied to
797 reinforced concrete structures, *Corrosion Science*, 48 (2006) 531-545 DOI:
798 10.1016/j.corsci.2005.02.010.

799 [47] M. Siegart, J.F. Lyness, B.J. McFarland, Change of pore size in concrete due to
800 electrochemical chloride extraction and possible implications for the migration of ions, *Cement*
801 *and Concrete Research*, 33 (2003) 1211-1221 DOI: 10.1016/S0008-8846(03)00047-4.

802 [48] B. Elsener, U. Angst, Mechanism of electrochemical chloride removal, *Corrosion Science*,
803 49 (2007) 4504-4522 DOI: 10.1016/j.corsci.2007.05.019.

804 [49] M. Sánchez, M.C. Alonso, Electrochemical chloride removal in reinforced concrete
805 structures: Improvement of effectiveness by simultaneous migration of calcium nitrite,
806 *Construction and Building Materials*, 25 (2011) 873-878 DOI:
807 10.1016/j.conbuildmat.2010.06.099.

808 [50] O. Vennesland, E.P. Humstad, O. Gautefall, G. Nustad, Electrochemical removal of
809 chlorides from concrete - Effect of bond strength and removal efficiency, in: C.L. Page, P.B.
810 Bamforth, J.W. Figg (Eds.) *Corrosion of reinforcement in concrete construction* Royal society
811 of Chemistry, Cambridge, 1995, pp. 448-455.

812 [51] B.T.J. Stoop, R. Polder, Redistribution of chloride after electrochemical chloride removal
813 from reinforced concrete prisms, in: HERON (Ed.) 1999, pp. 31-44

814 [52] N.M. Ihekweba, Aspects of electrochemical rehabilitation of chloride contaminated
815 concrete structures, *Civil Engineering, Thesis, Queen's University (Canada)*, 1996, pp. 227.

816 [53] W.K. Green, S.B. Lyon, J.D. Scantlebury, Electrochemical Changes in Chloride-
817 Contaminated Reinforced-Concrete Following Cathodic Polarization, *Corrosion Science*, 35
818 (1993) 1627-1631 DOI: Doi 10.1016/0010-938x(93)90392-T.

819 [54] J.C. Orellan Herrera, G. Escadeillas, G. Arliguie, Electro-chemical chloride extraction:
820 Influence of C3A of the cement on treatment efficiency, *Cement and Concrete Research*, 36
821 (2006) 1939-1946 DOI: 10.1016/j.cemconres.2006.03.030.

822 [55] R.N. Swamy, S. McHugh, Effectiveness and structural implications of electrochemical
823 chloride extraction from reinforced concrete beams, *Cement & Concrete Composites*, 28
824 (2006) 722-733 DOI: 10.1016/j.cemconcomp.2006.05.012.

825 [56] N.M. Ihekwaba, B.B. Hope, C.M. Hansson, Carbonation and electrochemical chloride
826 extraction from concrete, *Cement and Concrete Research*, 26 (1996) 1095-1107 DOI: Doi
827 10.1016/0008-8846(96)00076-2.

828 [57] J.C. Orellan, G. Escadeillas, G. Arliguie, Electrochemical chloride extraction: efficiency
829 and side effects, *Cement and Concrete Research*, 34 (2004) 227-234 DOI:
830 10.1016/j.cemconres.2003.07.001.

831 [58] J.J. Chang, Bond degradation due to the desalination process, *Construction and Building*
832 *Materials*, 17 (2003) 281-287 DOI: Pii S0950-0618(02)00113-7
833 Doi 10.1016/S0950-0618(02)00113-7.

834 [59] J.M. Miranda, J.A. Gonzalez, A. Cobo, E. Otero, Several questions about electrochemical
835 rehabilitation methods for reinforced concrete structures, *Corrosion Science*, 48 (2006) 2172-
836 2188 DOI: 10.1016/j.corsci.2005.08.014.

837 [60] J.M. Miranda, A. Cobo, E. Otero, J.A. Gonzalez, Limitations and advantages of
838 electrochemical chloride removal in corroded reinforced concrete structures, *Cement and*
839 *Concrete Research*, 37 (2007) 596-603 DOI: 10.1016/j.cemconres.2007.01.005.

840 [61] L. Bertolini, S.W. Yu, P.C. L., Effects of electrochemical chloride extraction on chemical
841 and mechanical properties of hydrated cement paste *Advances in Cement Research*, 8 (1996)
842 93-100

843 [62] K. Armstrong, M.G. Grantham, B.J. McFarland, The trial repair of Victoria Pier, St Helier,
844 Jersey using electrochemical desalination, Royal Society of Chemistry, Cambridge ed.1996.

845 [63] R.B. Polder, J.R. Walker, C.L. Page, Electrochemical desalination of cores from a
846 reinforced concrete coastal structure, *Magazine of Concrete Research*, 47 (1995) 321-327

847 [64] S. Chatterji, Simultaneous Chloride Removal and Realkalinization of Old Concrete
848 Structures, *Cement and Concrete Research*, 24 (1994) 1051-1054 DOI: Doi 10.1016/0008-
849 8846(94)90028-0.

850 [65] R.B. Polder, R. Walker, P.C. L., Electrochemical chloride tests of concrete cores from a
851 coastal structure, in: R.N. Swamy (Ed.) *Proceedings of International Conference on Corrosion*
852 *and corrosion protection of steel in concrete* Sheffield Academic Press, University of Sheffield,
853 1994, pp. 1463-1472.

854 [66] C.L. Page, S.W. Yu, Potential Effects of Electrochemical Desalination of Concrete on
855 Alkali-Silica Reaction, *Magazine of Concrete Research*, 47 (1995) 23-31 DOI: DOI
856 10.1680/macr.1995.47.170.23.

857 [67] V. Bouteiller, A. Laplaud, A. Maloular, R.S. Morelle, B. Duchesne, M. Morin,
858 Electrochemical chloride extraction of a beam polluted by chlorides after 40 years in the sea,
859 *Journal De Physique Iv*, 136 (2006) 331-340 DOI: 10.1051/jp4:2006136033.

860 [68] Y. Tissier, Etude des processus de corrosion et de la réparation par traitement
861 électrochimique d'extraction des ions chlorure dans les bétons armés doublement contaminés
862 (carbonatation et chlorures) Thèse, Université Paris-Est, 2017, pp. 313.

863 [69] Y. Tissier, V. Bouteiller, E. Marie-Victoire, S. Joiret, T. Chaussadent, Y.Y. Tong,
864 Electrochemical chloride extraction to repair combined carbonated and chloride contaminated
865 reinforced concrete, *Electrochimica Acta*, 317 (2019) 486-493 DOI:
866 10.1016/j.electacta.2019.05.165.

867 [70] T. Ueda, K. Wakitani, A. Nanasawa, Influence of electrolyte temperature on efficiency of
868 electrochemical chloride removal from concrete, *Electrochimica Acta*, 86 (2012) 23-27 DOI:
869 10.1016/j.electacta.2012.05.026.

870 [71] T. Ueda, J. Kushida, M. Tsukagoshi, A. Nanasawa, Influence of temperature on
871 electrochemical remedial measures and complex deterioration due to chloride attack and ASR,
872 Construction and Building Materials, 67 (2014) 81-87 DOI:
873 10.1016/j.conbuildmat.2013.10.020.

874 [72] G.G. Clemena, D.R. Jackson, Pilot applications of electrochemical chloride extraction on
875 concrete piers in Virginia - Interim report VTRC-96-IR4, US Department of Transportation
876 Federal Highway Administration, 1996.

877 [73] C.C. Chang, W. Yeih, J.J. Chang, R. Huang, Effects of stirrups on electrochemical chloride
878 removal efficiency, Construction and Building Materials, 68 (2014) 692-700 DOI:
879 10.1016/j.conbuildmat.2014.06.091.

880 [74] I. Martinez, F. Rozas, S. Ramos-Cillan, M. Gonzalez, M. Castellote, Chloride
881 Electromediation in reinforced structures: preliminary electrochemical tests to detect the
882 steel repassivation during the treatment, Electrochimica Acta, 181 (2015) 288-300 DOI:
883 10.1016/j.electacta.2015.06.005.

884 [75] W. Yeih, J.J. Chang, C.C. Chang, K.L. Chen, M.C. Chi, Electrochemical chloride removal
885 for reinforced concrete with steel rebar cage using auxiliary electrodes, Cement & Concrete
886 Composites, 74 (2016) 136-146 DOI: 10.1016/j.cemconcomp.2016.08.002.

887 [76] N.R. Buenfeld, J. Broomfield, Effect of chloride removal on rebar bond strength and
888 concrete properties, in: R.N. Swamy (Ed.) Proceedings of International Conference on
889 Corrosion and corrosion protection of steel in concrete Sheffield Academic Press, University
890 of Sheffield, 1994, pp. 1438-1450.

891 [77] O. Vennesland, E.P. Humstad, O. Gautefall, G. Nustad, Electrochemical removal of
892 chlorides from concrete - Effect of bond strength and removal efficiency, in: B.P. Page CL.,
893 Figg JW. (Ed.) Proc. Fourth. Int. Symp. Corrosion of reinforcement in concrete construction,
894 Bohni, H., Society of Chemical Industry, Cambridge, 1996, pp. 448-455.

895 [78] N.M. Ihekweba, B.B. Hope, C.M. Hansson, Pull-out and bond degradation of steel rebars
896 in ECE concrete, Cement and Concrete Research, 26 (1996) 267-282 DOI: Doi 10.1016/0008-
897 8846(95)00210-3.

898 [79] T.D. Marcotte, C.M. Hansson, B.B. Hope, The effect of the electrochemical chloride
899 extraction treatment on steel-reinforced mortar - Part I: Electrochemical measurements,
900 Cement and Concrete Research, 29 (1999) 1555-1560 DOI: Doi 10.1016/S0008-
901 8846(99)00118-0.

902 [80] T.D. Marcotte, C.M. Hansson, B.B. Hope, The effect of the electrochemical chloride
903 extraction treatment on steel-reinforced mortar - Part II: Microstructural characterization,
904 Cement and Concrete Research, 29 (1999) 1561-1568 DOI: Doi 10.1016/S0008-
905 8846(99)00117-9.

906 [81] P.J.M. Monteiro, P. Helene, I. Aoki, P. Barbosa, E. Monteiro, Influence of water-cement
907 ratio and cover thickness on chloride extraction of reinforced concrete, Aci Materials Journal,
908 102 (2005) 9-14.

909 [82] W.C. Yeih, J.J. Chang, C.C. Hung, Selecting an adequate procedure for the
910 electrochemical chloride removal, Cement and Concrete Research, 36 (2006) 562-570 DOI:
911 10.1016/j.cemconres.2005.12.008.

912 [83] H.Y. Shan, J.X. Xu, Z.Y. Wang, L.H. Jiang, N. Xu, Electrochemical chloride removal in
913 reinforced concrete structures: Improvement of effectiveness by simultaneous migration of
914 silicate ion, Construction and Building Materials, 127 (2016) 344-352 DOI:
915 10.1016/j.conbuildmat.2016.09.137.

916 [84] K.B. Kim, J.P. Hwang, K.Y. Ann, Influence of cementitious binder on chloride removal
917 under electrochemical treatment in concrete, Construction and Building Materials, 104 (2016)
918 191-197 DOI: 10.1016/j.conbuildmat.2015.12.052.

919 [85] R. Polder, A.W.M. Van Den Hondel, Laboratory investigation of electro-chemical chloride
920 extraction from concrete with penetrated chloride, HERON, 47 (2002) 211-220.

921 [86] N.M. Ihekweba, B.B. Hope, C.M. Hansson, Structural shape effect on rehabilitation of
922 vertical concrete structures by ECE technique, Cement and Concrete Research, 26 (1996)
923 165-175 DOI: Doi 10.1016/0008-8846(95)00192-1.

924 [87] S.R. Sharp, G.G. Clemena, Y.P. Virmani, G.E. Stoner, R.G. Kelly, Electrochemical
925 chloride extraction: influence of concrete surface on treatment - Report FHWA-RD-02-107,
926 Federal Highway Administration, 2002, pp. 43.

927 [88] M. Siegwart, J.F. Lyness, B.J. McFarland, G. Doyle, The effect of electrochemical chloride
928 extraction on pre-stressed concrete, *Construction and Building Materials*, 19 (2005) 585-594
929 DOI: 10.1016/j.conbuildmat.2005.01.012.

930 [89] P.F.G. Banfill, Electrochemical re-alkalisation, chloride extraction and alkali-silica reaction
931 in concrete Concrete Solutions Thessaloniki, Greece 2016, pp. 38

932 [90] L. Tang, L. Bertsson, J. Aavik, L.O. Nilsson, Effect of an electrical field on the removal of
933 chloride ions from concrete slabs, in: V.M. Malhorta (Ed.) 3rd CANMET/ACI International
934 Conference on Durability of Concrete Nice, France, 1994, pp. 597-608.

935 [91] M.A. Climent Llorca, M.J. Sanchez de Rojas, G. de Vera, P. Garcés, Effect of type of
936 anodic arrangements on efficiency of electrochemical chloride removal from concrete *ACI Mat*
937 *J*, (2006) 243-250.

938 [92] O. Vennesland, O. Opsahl, Removal of chloride(s) from reinforced concrete| by
939 electrolysis using voltage applied between reinforcement and electrolyte coating on the
940 concrete, *Noteby Norsk Teknis*, (1986).

941 [93] H.Y. Shan, Z.Y. Wang, J.X. Xu, L.H. Jiang, Influences of Fly Ash, Slag and Silica Fume
942 on Electrochemical Chloride Removal Treatment with Simultaneous Migration of Silicate Ion,
943 *International Journal of Electrochemical Science*, 13 (2018) 1120-1130 DOI:
944 10.20964/2018.01.58.

945 [94] M. Castellote, L. Fernandez, C. Andrade, C. Alonso, Chemical changes and phase
946 analysis of OPC pastes carbonated at different CO₂ concentrations, *Materials and Structures*,
947 42 (2009) 515-525 DOI: 10.1617/s11527-008-9399-1.

948 [95] J.S. Reou, K.Y. Ann, The distribution of hydration products at the steel-concrete interface
949 for concretes subjected to electrochemical treatment, *Corrosion Science*, 52 (2010) 2197-2205
950 DOI: 10.1016/j.corsci.2010.02.037.

951 [96] N.R. Buenfeld, J. Broomfield, Influence of electrochemical chloride extraction for the bond
952 between steel and concrete *Magazine of Concrete Research*, 52 (2000) 79-91 DOI:
953 <https://doi.org/10.1680/macr.2000.52.2.79>

954 [97] AFREM, Extraction et dosage des chlorures libres et totaux dans le béton, Mode
955 opératoire, 1996.

956 [98] M. Castellote, C. Andrade, RILEM TC 178-TMC : Testing and modelling chloride
957 penetration in concrete - Round robin test on chloride analysis in concrete Part 1 : Analysis of
958 total chloride content, *Materials and Structures*, 34 (2001) 532 (Procedure A533-C534*).

959 [99] M. Castellote, C. Andrade, RILEM TC 178-TMC : Testing and modelling chloride
960 penetration in concrete - Round robin test on chloride analysis in concrete Part 2 : Analysis
961 water soluble chloride content, *Materials and Structures*, 34 (2001) 589 (Procedure B581).

962 [100] H. Shan, J. Xu, Z. Wang, L. Jiang, N. Xu, Electrochemical chloride removal in reinforced
963 concrete structures: Improvement of effectiveness by simultaneous migration of silicate ion,
964 *Construction and Building Materials*, 127 (2016) 344-352 DOI:
965 <http://dx.doi.org/10.1016/j.conbuildmat.2016.09.137>.

966 [101] ASTM, ASTM C 876-91, Standard test method for half-cell potentials of uncoated
967 reinforcing steel in concrete, ASTM, 1999.

968 [102] ASTM, ASTM C 876-09, Standard test method for half-cell potentials of uncoated
969 reinforcing steel in concrete, ASTM, 2009.

970 [103] C. Andrade, C. Alonso, RILEM TC 154-EMC:Electrochemical Techniques for Measuring
971 Metallic Corrosion - Recommendations - Test methods for on-site corrosion rate measurement
972 of steel reinforcement in concrete by means of the polarization resistance method, *Materials*
973 *and Structures*, 37 (2004) 623-643.

974 [104] J.C. Orellan Herrera, Efficacité et effets secondaires des techniques électrochimiques
975 de maintenance des structures en béton armé, Thèse, Université de Toulouse, 2002.

976 [105] Y. Tissier, V. Bouteiller, E. Marie-Victoire, S. Joiret, T. Chaussadent, Study of an
977 electrochemical chloride extraction treatment on a both carbonated and chlorinated reinforced
978 concrete, EUROCORR'17Prague, Czech Republic 2017.

979 [106] Y. Tissier, V. Bouteiller, E. Marie-Victoire, S. Joiret, T. Chaussadent, Corrosion
980 processes of carbonated chloride-contaminated reinforced concrete and electrochemical
981 chloride extraction (ECE) efficiency Springer, (2017).

982 [107] G.d.J. Fajardo San Miguel, Limites d'utilisation des techniques électrochimiques de
983 maintenance non permanentes pour les ouvrages en béton armé, Thèse, Université de
984 Toulouse, 2004.

985 [108] M. Castellote, C. Andrade, C. Alonso, Electrochemical removal of chlorides - Modelling
986 of the extraction, resulting profiles and determination of the efficient time of treatment, Cement
987 and Concrete Research, 30 (2000) 615-621 DOI: Doi 10.1016/S0008-8846(00)00220-9.

988 [109] BAEL révisé 83, (1983).

989 [110] R. Polder, RILEM TC 154-EMC:Electrochemical Techniques for Measuring Metallic
990 Corrosion - Recommendations - Test methods for on-site measurements of resistivity of
991 concrete, Materials and Structures, 33 (2000) 603-611.

992 [111] B. Elsener, RILEM TC 154-EMC:Electrochemical Techniques for Measuring Metallic
993 Corrosion - Recommendations - Half-cell potential measurements - Potential mapping on
994 reinforced concrete structures, Materials and Structures, 36 (2003) 461-471.

995 [112] W.C. Yeh, J.J. Chang, A study on the efficiency of electrochemical realkalisation of
996 carbonated concrete, Construction and Building Materials, 19 (2005) 516-524 DOI:
997 10.1016/j.conbuildmat.2005.01.006.

998 [113] Y.Y. Tong, V. Bouteiller, E. Marie-Victoire, S. Joiret, Efficiency investigations of
999 electrochemical realkalisation treatment applied to carbonated reinforced concrete - Part 1:
1000 Sacrificial anode process, Cement and Concrete Research, 42 (2012) 84-94 DOI:
1001 10.1016/j.cemconres.2011.08.008.

1002 [114] M. Castellote, C. Andrade, M.C. Alonso, Changes in concrete pore size distribution dur
1003 to electrochemical chloride migration trials, ACI Materials Journal, 96 (1999) 314-320.

1004 [115] L. Bertolini, B. Elsener, P. Pedefferri, E. Redaelli, R.B. Polder, Corrosion of Steel in
1005 Concrete: Prevention, Diagnosis, Repair (2nd edition), 2013.

1006 [116] J.J. Chang, A study of the bond degradation of rebar due to cathodic protection current,
1007 Cement and Concrete Research, 32 (2002) 657-663 DOI: [https://doi.org/10.1016/S0008-
1008 8846\(01\)00740-2](https://doi.org/10.1016/S0008-8846(01)00740-2).

1009 [117] J.B. Miller, The perception of the ASR problem with particular reference to
1010 electrochemical treatments of reinforced concrete in EFC N°25, in: E.F.o.C.P.E. N°25
1011 (Ed.)1998, pp. 141-149

1012 [118] A.A. Sohahghpurwala, W.T. Scannell, Long-Term Effects of Electrochemical Chloride
1013 Extraction on Laboratory Specimens and Concrete Bridge Components, Publication No.
1014 FHWA-HRT-10-069, October 2011, U.S. Departement of Transportation - Federal Highway
1015 Administration, 2011.

1016 [119] NACE, Electrochemical chloride extraction from steel reinforced concrete—A State-of-
1017 the-art report, Publication 01101 - Item No. 24214, International Task Group 054, 2001, pp.
1018 1-14.

1019 [120] NACE, Electrochemical chloride extraction from steel reinforced concrete - A state of the
1020 art report, Publication 01101, 2018.

1021 [121] S.W. Yu, C.L. Page, Computer simulation of ionic migration during electrochemical
1022 chloride extraction from hardened concrete, British Corrosion Journal, 31 (1996) 73-75.

1023 [122] Q. Sa'id-Shawqi, C. Arya, P.R. Vassie, Numerical Modeling of Electrochemical Chloride
1024 Removal from Concrete, Cement and Concrete Research, 28 (1998) 391-400 DOI:
1025 10.1016/s0008-8846(98)00002-7.

1026 [123] A.M. Hassanein, G.K. Glass, N.R. Buenfeld, A mathematical model for electrochemical
1027 removal of chloride from concrete structures, Corrosion, 54 (1998) 323-332 DOI: Doi
1028 10.5006/1.3284859.

1029 [124] A. Toumi, R. Francois, O. Alvarado, Experimental and numerical study of electrochemical
1030 chloride removal from brick and concrete specimens, Cement and Concrete Research, 37
1031 (2007) 54-62 DOI: 10.1016/j.cemconres.2006.09.012.

1032 [125] L.Y. Li, C.L. Page, Modelling of electrochemical chloride extraction from concrete:
1033 Influence of ionic activity coefficients, Computational Materials Science, 9 (1998) 303-308 DOI:
1034 Doi 10.1016/S0927-0256(97)00152-3.
1035 [126] L.Y. Li, C.L. Page, Finite element modelling of chloride removal from concrete by an
1036 electrochemical method, Corrosion Science, 42 (2000) 2145-2165 DOI: Doi 10.1016/S0010-
1037 938x(00)00044-5.
1038 [127] Y. Wang, L.Y. Li, C.L. Page, A two-dimensional model of electrochemical chloride
1039 removal from concrete, Computational Materials Science, 20 (2001) 196-212 DOI: Doi
1040 10.1016/S0927-0256(00)00177-4.
1041 [128] Q.F. Liu, L.Y. Li, D. Easterbrook, J. Yang, Multi-phase modelling of ionic transport in
1042 concrete when subjected to an externally applied electric field, Engineering Structures, 42
1043 (2012) 201-213 DOI: 10.1016/j.engstruct.2012.04.021.
1044 [129] Q.F. Liu, J. Xia, D. Easterbrook, J. Yang, L.Y. Li, Three-phase modelling of
1045 electrochemical chloride removal from corroded steel-reinforced concrete, Construction and
1046 Building Materials, 70 (2014) 410-427 DOI: 10.1016/j.conbuildmat.2014.08.003.
1047 [130] J. Xia, L.Y. Li, Numerical simulation of ionic transport in cement paste under the action
1048 of externally applied electric field, Construction and Building Materials, 39 (2013) 51-59 DOI:
1049 10.1016/j.conbuildmat.2012.05.036.
1050 [131] X. Cheng, J. Xia, W.L. Wang, S.J. Jin, N. Huang, W.L. Jin, Numerical modeling of the
1051 effect of concrete porosity evolution on electrochemical chloride removal from concrete
1052 structures, Construction and Building Materials, 267 (2021) 120929 DOI: ARTN 120929
1053 10.1016/j.conbuildmat.2020.120929.
1054