Australia's novel approach to chloride extraction

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Abstract. A driving factor of concrete marine structure service life in Australia is the presence and ingress of chlorides into concrete cover which can ultimately initiate corrosion of the steel reinforcement. Electrochemical Chloride Extraction (ECE), once a dormant technology in Australia has recently re-emerged due to a novel application technique which is providing asset owners a sustainable alternative to other corrosion protection strategies. The ECE process mitigates chloride-induced corrosion of steel reinforcement by extracting chlorides. It also alters the material properties in the concrete cover and at the steel surface, including an increase in near-surface depth concrete resistivity, a measurable increase to the pH around the steel reinforcement, and the re-formation of the protective passive layer on the steel. This paper documents the history of ECE system's in Australia, discusses variables that may influence efficiency of the process, and analyses results achieved using various system configurations.

1 Introduction

Until the 1970s, reinforced concrete was widely regarded as a maintenance-free building material. It was only when concrete codes of practice began addressing issues of durability and long-term performance that this misconception was challenged. Today, it is well understood that reinforced concrete structures require appropriate durability design, high quality construction and regular inspections and maintenance to ensure operational reliability throughout their service life. This reality has become especially apparent in coastal structures, particularly those constructed during the 1960s and 1970s, many of which now exhibit cracking, delamination, and spalling. As a result, asset owners face increasingly significant costs for infrastructure maintenance or upgrades to sustain operations.

The corrosion of steel reinforcement within concrete structures is now recognized as a critical global challenge in maintaining modern infrastructure. According to Koch et al. [8], data from the U.S. National Bridge Inventory Database estimated that between 1999 and 2001, the annual cost of steel corrosion in highway bridges exceeded $8 billion in the United States alone.

A comprehensive study by NACE International in 2016 [9] estimated the annual global cost of corrosion to be approximately US$2.5 trillion, which equated to about 3.4% of the world's Gross Domestic Product (GDP) at that time. Beyond the financial implications, steel corrosion significantly contributes to global CO_2 emissions.

According to the World Steel Association [5], steel production accounts for about 10.5% of total global CO_2 emissions. Notably, between 20% and 40% of the steel produced today is used to replace corroded steel. If current practices continue, it's projected that by 2030, as much as 9.1% of total CO_2 emissions will be associated with steel production intended to replace corroded materials.

Among the primary drivers of corrosion, particularly in coastal and Pacific regions, is the ingress of chlorides. Chlorides, which are water-soluble, infiltrate concrete cover through its pores during wetting and drying cycles. Once they reach the steel reinforcement, they disrupt the passive oxide layer, initiating destructive pitting corrosion processes. Despite advances in durability design, such as increased concrete cover and resistance to chloride migration, a vast number of older reinforced concrete structures constructed with minimal durability considerations are nearing the end of their service lives.

The effective repair and maintenance of reinforced concrete structures affected by chloride ingress demands a comprehensive approach, factoring in the structure's condition, environmental exposure, budget constraints, power source reliability, and the need for continuous monitoring. Accurate diagnosis by qualified professionals is essential to identify the underlying causes of deterioration and determine the most appropriate intervention strategy. Among the available techniques, for chloride contamination of the concrete cover layer, electrochemical chloride extraction (ECE) offers a promising solution, often used alongside other repair methods.

While ECE may not be universally applicable, it significantly broadens the spectrum of electrochemical protection strategies, enabling asset owners to optimize maintenance plans and maximize investment returns. In the Pacific region, ECE is gaining renewed recognition as an efficient, sustainable, and innovative treatment for reinforced concrete. This process not only reduces chloride concentrations to acceptable levels but also

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promotes the reformation of the protective passive layer on steel reinforcement. Compared to alternative methods, ECE offers distinct advantages, including reduced material usage, faster installation, and lower waste and emissions. As such, it represents a practical and sustainable approach to extending the service life of aging concrete infrastructure.

2 History of Electrochemical Chloride Extraction

Research into electrochemical chloride extraction began in the United States during the 1970s [2]. Initial studies were spearheaded by government transportation agencies, including the Kansas Department of Transportation (KDOT), the U.S. Federal Highway Administration (FHWA), and the U.S. Strategic Highway Research Program (SHRP). These organizations identified the significant potential of ECE to address costly maintenance challenges associated with chloride-induced deterioration. By the 1980s, field trials of ECE were introduced, and a commercially viable Norwegian patent for the technology became available.

Since these pioneering efforts, the majority of ECE applications have taken place in North America and Europe, particularly on inland highway bridges and overpasses where chloride contamination from de-icing salts is prevalent. In these environments, exposure to waves and tides is not a concern. De-icing salts, applied to roadways during winter, are transferred by vehicle tires onto concrete structures, such as parking garages, where they accumulate on entry ramps and other high-traffic zones. For such structures, which often experience localized defects, ECE provides an ideal solution due to its temporary and rapidly deployable nature.

Although the potential for ECE to be used in marine environments was recognized, its traditional application methods posed significant limitations in these settings. Historically, ECE has involved the use of a metallic mesh fixed to the surface of the concrete and encapsulated within a spray-applied absorbent cellulose fibre, as illustrated in Figure 1. This approach is impractical for coastal structures, particularly those located within tidal ranges and splash zones, due to the risk of washout. Consequently, the adoption of ECE for marine applications has been limited, particularly in regions like Australia, where chloride contamination primarily affects coastal infrastructure.

While a handful of ECE projects have been carried out in Australia, the technology's use declined as the conventional application methods did not offer practical benefits for marine environments.

However, advancements in innovative application techniques are now revitalizing interest in ECE, making it a more viable and effective solution for addressing chloride-induced deterioration in diverse structural contexts.

Fig. 1. ECE System installation circa 1990

3 Electrochemical chloride extraction: Principles, Innovations, and Practical Considerations

Electrochemical Chloride Extraction (ECE) involves the use of a temporary anode, typically constructed from titanium mesh or another inert material, applied to the surface of the concrete. A direct electrical connection is established between the steel reinforcement, which acts as the cathode, and the anode by creating a small, localized breakout. Electrical cables link the system to an external power source and control unit. During operation, an electrical current is applied to the system while the concrete is saturated with an electrolyte solution. This process repels chloride ions away from the steel reinforcement, drawing them toward the anode. Simultaneously, hydroxyl ions migrate toward the steel reinforcement, increasing alkalinity around the bars and facilitating the reformation of the passive protective layer on the steel surface. This mechanism is illustrated in Figure 2.

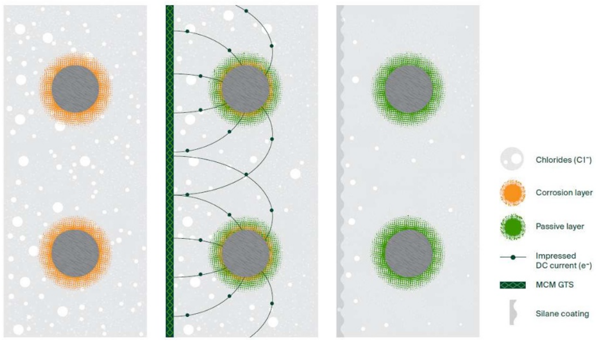

Fig. 2. Electrochemical chloride extraction process

Recent innovations in Australia, introduced in 2020, focus on the application methodology rather than altering the established technical principles of ECE. A prefabricated system has been developed where the anode, electrical components, and electrolyte dosing equipment are integrated into a single, modular unit. This design prevents the system from being affected by environmental factors such as wind or waves, making it particularly suitable for marine and coastal applications.

These prefabricated units are lightweight, allowing two personnel equipped with basic electrical or battery-powered tools to install and remove them without the need for heavy equipment, scaffolding, or large-scale access installations. The modularity of the system enables scalability to accommodate varying geometries and treatment areas, while multiple power supplies can be run in parallel to optimize the application duration. Compared to hybrid cathodic protection systems, this innovative approach allows for ECE installation in less than half the time, offering a practical and efficient solution for asset owners seeking to minimize operational disruptions.

3.1 Benefits and Limitations of Electrochemical Chloride Extraction

The advancements in ECE application procedures have enhanced its practicality, yet the technology retains inherent benefits and limitations.

Benefits:

- Resets the service life of structures by reducing chloride contamination and passivating steel reinforcement within the treated area.
- Minimizes waste generation and environmental risks due to its non-destructive nature.
- Significantly reduces construction time and associated costs.
- Reduces the need for ongoing monitoring and maintenance.
- Can be applied over large areas or targeted to specific zones, depending on requirements.
- Effectiveness and compliance can be readily verified through established testing methods.

Limitations:

- Chloride ions that have migrated beyond the depth of the steel reinforcement may not be removed, as they may be repelled deeper into the concrete.
- Application on pre- or post-tensioned slabs poses a risk of hydrogen embrittlement if excessive current or potential leads to hydrogen gas generation at the steel surface.
- Use on concrete containing reactive aggregates may exacerbate alkali-silica reaction (ASR); however, adding lithium salts to the electrolyte can help mitigate this risk.
- The effectiveness of ECE is contingent on the electrical continuity of the steel reinforcement. Additional connections may be required in structures where reinforcement is not electrically continuous.

3.2 Standards and Compliance

The recognized standard for ECE is AMPP SP107-2021, "Electrochemical Realkalization and Chloride Extraction for Reinforced Concrete" [6]. This standard defines three endpoint criteria for ensuring effective treatment:

- Criterion A – Reduction of chloride content in concrete to a predetermined level.
- Criterion B – A specific charge density, measured in ampere-hours (A-h) per square meter of steel surface area, to ensure adequate treatment.
- Criterion C – Chloride-to-hydroxyl ion ratio at the steel/concrete interface, ensuring suitable electrochemical conditions for passivation.

These criteria are straightforward to specify during the design phase, implement during application, and validate through testing, providing stakeholders with meaningful and measurable results.

4 Operational Considerations for Electrochemical Chloride Extraction

The duration of Electrochemical Chloride Extraction treatment typically ranges from several weeks to several months. The exact timeline depends on multiple factors, including initial chloride concentrations, concrete resistivity and cover depth, environmental conditions, steel density, structural geometry, and the driving voltage and current settings.

4.1 Concrete Resistivity and Cover Depth

The electrical resistivity of concrete plays a critical role in determining the efficiency of the ECE process. Resistivity influences the current flow through the electrochemical circuit, impacting the strength of the electric field and overall system resistance. Low-resistivity concrete facilitates greater current flow, often resulting in higher efficiency and reduced treatment times. Conversely, high-resistivity concrete and deeper concrete cover to reinforcement may reduce efficiency and necessitate longer treatment durations to achieve the desired chloride reduction. Factors affecting resistivity include porosity, permeability, constituent materials, temperature, and relative humidity.

4.2 Environmental factors

The efficiency of ECE can vary significantly due to environmental conditions within the treatment area:

Ambient Temperature: Higher temperatures enhance ion mobility within the concrete, accelerating chloride extraction. Conversely, lower temperatures reduce the efficiency of ion migration, potentially prolonging treatment times. Temperature fluctuations can significantly influence current output, as illustrated in Figure 3, where daily temperature variations resulted in a current output change of approximately 1 Amp.

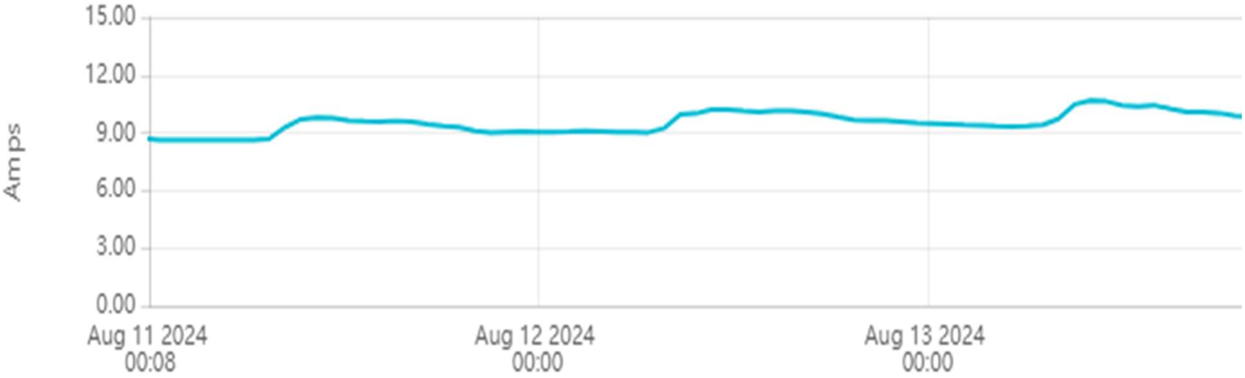

Fig 3: Daily temperature fluctuations observed during application

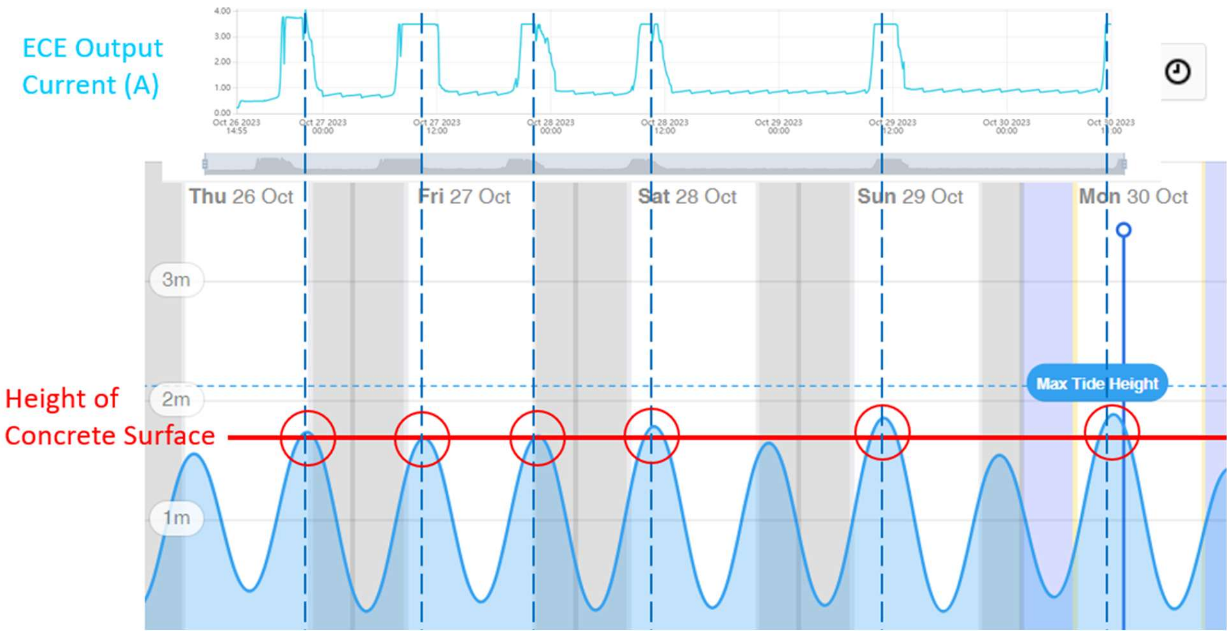

Fig. 4. Tide chart overlaid with current output monitoring data

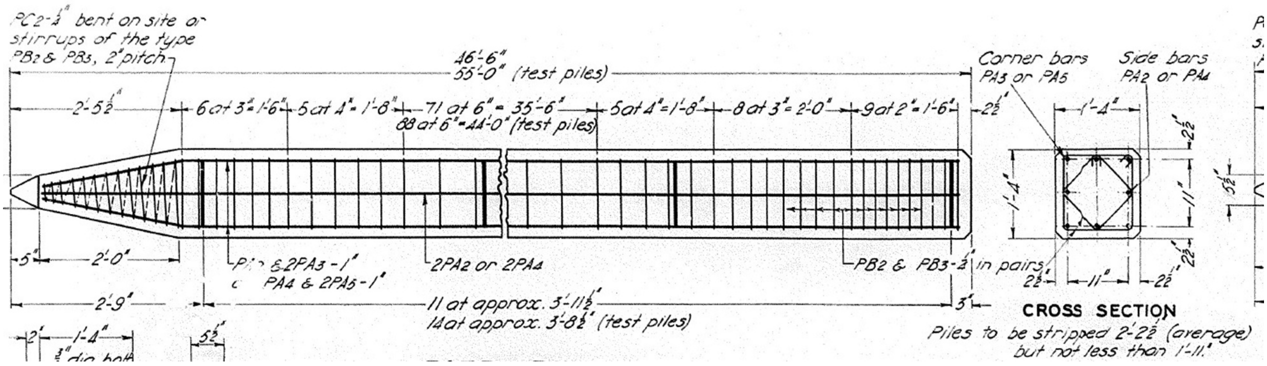

Fig. 5. Sample concrete pile with congested reinforcement and varying depths of ligatures

Humidity and Moisture Content: Adequate moisture levels in the concrete improve conductivity, facilitating ion movement. Regular saturation of the treatment area is critical to ensure optimal results.

Tidal Movement: While ECE is generally not applied within tidal zones due to high corrosion rates requiring constant protection, it can be effective near the high tide level as a preparatory treatment before applying barrier protection. In cases of king tides or temporary flooding, the system may be submerged, leading to current dumping as ground resistance becomes significantly lower than the concrete's resistance. To prevent damage to electrical components, a current output limit should be set on the control unit. This phenomenon is depicted in Figure 4.

4.3 Dimensional Impacts on Efficiency

The geometry and arrangement of steel reinforcement significantly influence the efficiency of ECE.

Reinforcement Arrangement and Geometry: Structures with curved geometries and spiral ties, such as circular columns, generally exhibit better chloride extraction compared to planar surfaces with rectangular hoops. Uniform bar spacing enhances ion migration, whereas more complex reinforcement cages may trap chloride ions, leading to uneven extraction. For instance, trials on square piles with varying ligature configurations demonstrated increased runtimes and the need for additional sampling and testing (Figure 5).

Stirrup Influence: Stirrup arrangements can have dual effects. They may accelerate chloride migration by increasing the cathodic area, but can also shield enclosed regions, reducing the driving force for ion migration. While chloride ions beyond the first reinforcement layer may not be efficiently removed, conventional concrete repair is often a more appropriate solution in such cases.

4.4 Chloride Sampling

Accurate chloride sampling is critical to evaluate ECE performance, particularly given the influence of structural configurations. Sampling near reinforcement bars can yield misleading results, as chloride ions adjacent to the steel may migrate toward the sampling point, temporarily increasing local concentrations. To ensure reliable data, sampling locations should adhere to the following criteria:

- Known depth and size of reinforcement to determine appropriate sampling depths.
- Reinforcement spacing in all directions to minimize the influence of adjacent bars.
- Sampling within 25 mm or one diameter of reinforcement, as per AMPP SP107-2021 standards.
- Proximity (within 100 mm) to baseline sample locations for comparative analysis.

For marine structures, chloride concentrations vary with height relative to water level. For example, samples taken 3 m above high tide will typically exhibit lower concentrations than those 1 m above high tide. Best practices for chloride sampling are illustrated in Figure 6.

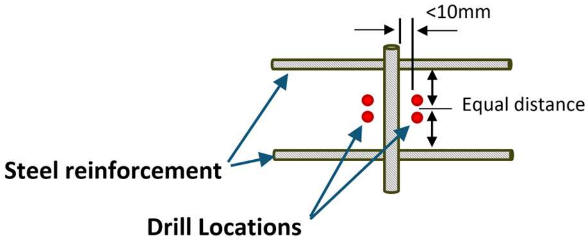

Fig. 6. Best practice for chloride sampling

A thorough understanding of reinforcement configuration is essential for effective sampling. Tools such as ground-penetrating radar or cover meters are often employed to map reinforcement bar locations in situ.

5 Sustainability Improvements

With a clear understanding of the functionality of electrochemical chloride extraction (ECE) and the various factors influencing its implementation, ECE emerges as a compelling alternative to other electrochemical protection methods, often matching or even surpassing them in terms of efficiency and outcome quality. In addition to its technical benefits, ECE offers notable environmental advantages, including significant reductions in carbon dioxide emissions. On average, maintenance activities utilizing ECE generate 183% fewer greenhouse gas emissions per square meter when compared to new construction efforts [7, 8]. Furthermore, each square meter maintained can prevent approximately 3.3 tons of CO_2-equivalent emissions [9]. Considering that concrete production is responsible for 8% of global anthropogenic greenhouse gas emissions [10], the use of ECE in repair and remediation significantly diminishes the carbon footprint associated with infrastructure projects. By leveraging advanced electrochemical protection techniques, ECE extends the lifespan of existing structures, thus avoiding the high emissions and resource intensity of complete reconstruction. This strategy can lead to reductions of over 91% in carbon emissions relative to rebuilding.

While other electrochemical protection systems may also provide sustainable benefits, recent advancements in ECE enhance its efficacy in reducing emissions and waste. In contrast to embedded anode systems such as Impressed Current Cathodic Protection and Hybrid Anode Cathodic Protection, ECE's surface-mounted design eliminates the necessity for removing intact concrete, thereby reducing waste generation. Additionally, its lightweight and modular framework allows for rapid installation and enables continuous operation with minimal labour. This decrease in labourintensive tasks can result in savings of approximately 2-3 kg of CO2 emissions for every hour of labour avoided.

6 Conclusions

Electrochemical Chloride Extraction (ECE) offers an effective solution for the maintenance and prolongation of the service life of reinforced concrete structures suffering from chloride-induced corrosion. As evidenced in the findings, ECE not only equals other electrochemical protection methods in terms of efficiency and quality of results but also provides notable environmental benefits, including significant reductions in carbon dioxide emissions. Recent advancements in ECE technology, particularly the introduction of prefabricated, modular systems, have enhanced its practicality and effectiveness in challenging marine environments, addressing the limitations associated with traditional application methods.

This paper discusses several key factors that impact the efficiency of ECE, such as concrete resistivity, cover depth, environmental conditions, and reinforcement geometry. A thorough understanding of these variables is essential for optimizing the application process and achieving the desired performance outcomes. Furthermore, innovations in ECE have strengthened its sustainability profile by decreasing waste generation and minimizing labour requirements compared to conventional methods, which further contribute to lower carbon emissions.

In summary, ECE represents an innovative, sustainable, and practical strategy for tackling the challenges posed by chloride-induced corrosion in reinforced concrete structures, especially in coastal and marine settings. By incorporating ECE into maintenance agendas, asset owners can significantly enhance the lifespan of existing infrastructure while reducing environmental impacts, thus providing a cost-effective and eco-friendly alternative to complete reconstruction. With the emergence of additional case studies and ongoing technological advancements, the role of ECE in the remedial market is expected to grow.

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