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Sean Bond
Technological University Dublin

Lynette O'Callaghan
Technological University Dublin, lynette.ocallaghan@tudublin.ie

Niall Holmes Dr.
Technological University Dublin, niall.holmes@tudublin.ie

See next page for additional authors

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Authors

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Sean Bond[1], Lynette O Callaghan[2], Niall Holmes[3], Brian Norton[4]

[1,2]School of Civil & Structural Engineering, Dublin Institute of Technology, Bolton St, Dublin 1, Ireland

[3]School of Mechanical and Transport Engineering, Dublin Institute of Technology, Bolton St, Dublin 1, Ireland

[4]Dublin Energy Lab, Bolton Street, Dublin 1, Ireland

email: [1]seanbond2005@yahoo.ie, [2]lynette.ocallaghan@dit.ie, [3]niall.holmes@dit.ie, [4]president@dit.ie

ABSTRACT: Corrosion of embedded steel in reinforced concrete (RC) is a world-wide problem, that reduces structural performance and lifespan. Chloride attack may be a result of seawater, de-icing salts or contaminated admixtures, brought on by ingress of chlorides into the concrete.

Electrochemical Chloride Extraction (ECE) is a non-destructive treatment for contaminated RC structures, that due to uncertainty of treatment times and applied current densities, is only 50% effective. It is often diesel powered has an environmental impact and often very costly due to the long treatment times.

To improve the efficiency of ECE the influences of concrete resistance, cement type and duration of treatment have been investigated in an experimental programme.

The use of Photovoltaic (PV) panels to improve the efficiency of ECE is presented which replace fossil fuels as a power source enabling a more environmentally sustainable treatment. These findings will increase the life span of vital infrastructure and reduce expensive ongoing repairs with decreased traffic congestion and inconveniences associated with bridge repairs.

KEY WORDS: Electrochemical Chloride Extraction; Efficiency; Concrete Resistance; Current density; Photovoltaics.

1 INTRODUCTION

Corrosion of RC structures is a worldwide problem resulting in a loss of structural performance. Since concrete is permeable, it is susceptible to the ingress of chloride ions. The source of these chlorides are a combination of de-icing salts, seawater and contaminated admixtures [1].

Electrochemical Chloride Extraction of Chloride ions, embedded in reinforced concrete structures, operates by creating an electrical circuit between the surface of the concrete and the steel reinforcement. This process is driven by a direct current (DC) electricity supply. Previously, diesel powered generators have powered this treatment, leading to an inefficient process due to the long durations over which ECE operates.

In terms of the electrical requirements of ECE, a steady voltage of 25 to 40V is normally used to produce a current density of between 1 and 5 A/m^2. The power requirements of the system depend on the internal resistance of the concrete. The current paths travel through the pore water solution towards the surface. The more ions in the pore water solution, the higher the current since ionic flow is the basis for ECE. As the chlorides are removed, the concrete's resistance increases thus requiring a lower current later on in the treatment [2].

A photovoltaic (PV) device directly converts light into electricity at an atomic level. When solar energy, in the form of photons, is absorbed electrons are released from a PV material as shown in Figure 1. The operation of a photovoltaic array does not emit greenhouse gases nor particulates as is the case with a diesel generator.

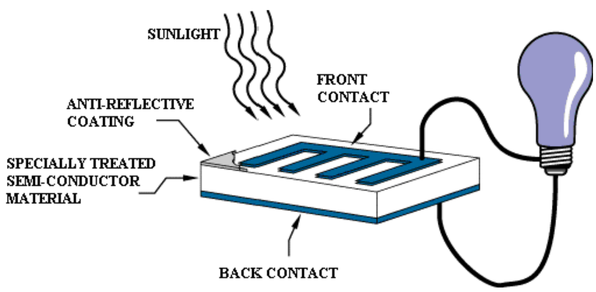

Figure 1 Operation of a Basic Photovoltaic Cell [7]

In order to size an appropriate PV array to replace traditional diesel generators, the electrical requirements must first be determined. Using RETScreen 4 [8], an appropriate panel array has been sized to meet the requirements of a system operating autonomously purely from PV.

2 BACKGROUND

2.1 How Electrochemical Chloride Extraction Works

A titanium mesh, submerged in an electrolyte, is used to create an anode at the concrete surface and connected to the positive terminal of the DC supply. The embedded steel reinforcement is then made cathodic by connecting it to the negative terminal of the DC supply. This arrangement is shown in Figure 2.

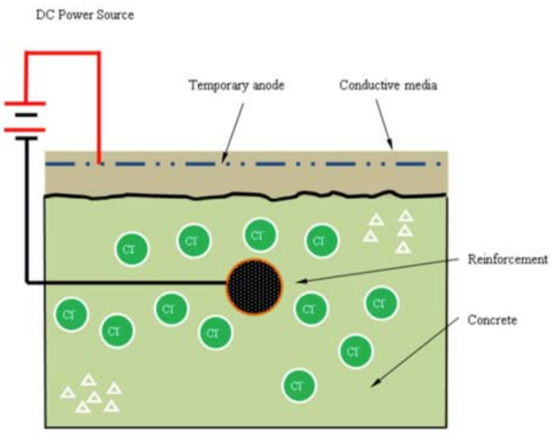

Figure 2 Setup of Electrochemical Chloride Extraction

In a conventional battery cell, the cathode is positive and the anode is negative. In an electrolytic cell, energy is repelled back through the negative terminal, provided externally, which makes the cathode negative and the anode positive. As electrons carry a negative charge, they are repelled from the negative terminal of the power supply and migrate towards the positive cathode. The circuit is completed through the pore water solution within the concrete. This system drives the negatively charged chloride ions towards the temporary anode as in Figure 3.

Hydroxyl ions will accumulate around the reinforcement surface to form a passive oxide film on the steel surface that helps fight against corrosion. The accumulation of these hydroxyl ions promotes regeneration of the steel surface, that may in turn repair this oxide film, previously damaged by corrosion.

By moving the chloride ions away from the reinforcing steel, further corrosion of the steel is prevented. Unfortunately, the return of the chlorides is inevitable but since a large proportion of the existing chlorides may be removed, the corrosion process is slowed down thus extending the useful life.

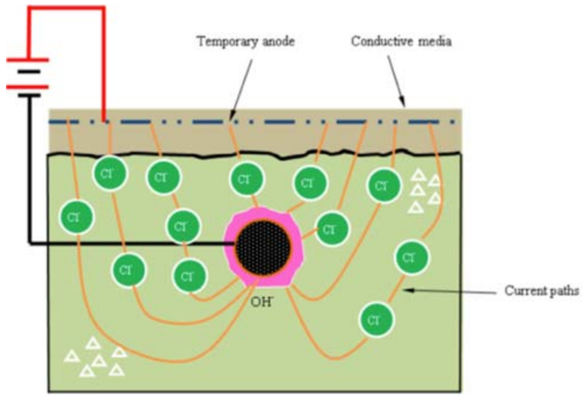

Figure 3 Complete Electrochemical Circuit

2.2 Treatment Times

Chlorides exist in the form of free, chemically bound and physically absorbed ions. The free chloride ions exist in the pore water solution of the concrete from de-icing salts or from sea-water. Under the effect of an electric field, adsorbed chlorides are released, which leads to an increase in free chloride concentration in the pore solution. Due to ECE treatment, the free chlorides are removed quickly. When the current is switched off, the dissolution of chemically bound chlorides leads to re-establishing of the equilibrium between chemically bound and free chlorides. Part of the dissolved chloride will be physically adsorbed on the pore walls and equilibrium between free and adsorbed chlorides is re-established [5]. Thus by allowing a break in the treatment, the efficiency of chloride removal is increased. Work carried out by Elsener [5] explored breaking the treatment into on/off phases. This promoted the dissolution of bound chloride ions into the pore-water solution of the concrete. The length of treatment depends on the concentration of chlorides in the concrete. However, 8 weeks of treatment is usually applied for ECE as to limit the accumulated charge passing through the concrete [2-5].

2.3 Photovoltaics

The photovoltaic effect was first noted in 1839, when Becquerel observed that "electrical currents arose from certain light induced chemical reactions" [9]. Later on in 1905, Einstein described the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel prize in physics [7].

In order to investigate the feasibility of using a PV panel to power ECE, the system must be able to provide a steady voltage and include battery storage for night-time use.

While there are many photovoltaic technologies [10] most PV panels are made of crystalline silicon cells. The efficiency of these panels are between 14 – 20% and depends whether the panel is a mono or poly crystalline structure with the former being more efficient. Thus, with an average radiation level of 1000W/m^2 and an area of 1m^2, one can expect 200W/m^2 with a panel rated at 20% efficient. At low irradiance levels (200W/m^2), the power output of such a panel would be 40W/m^2.

A PV panel is controlled using a maximum power point tracker (MPPT) controller. This regulates the output voltage of the panel in order to gain the ideal current. Since the power is dependent on current, the maximum power point must be maintained as shown in Figure 4. As the amount of available sunlight decreases, the level of voltage drawn must be decreased in order to achieve the most efficient current.

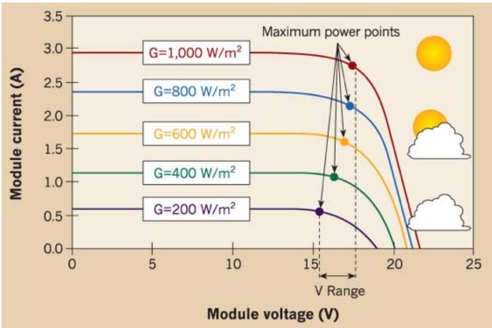

Figure 4 Typical maximum power point curve [11]

Once the PV panel and MPPT controller have been selected, the batteries can be sized. The panel cannot be directly connected to the steel since the voltage and current being delivered will not be steady which is a requirement of ECE. The batteries are charged by the PV panel, which are then used to power the treatment. In most cases, lead acid batteries are used. The system is illustrated in Figure 5.

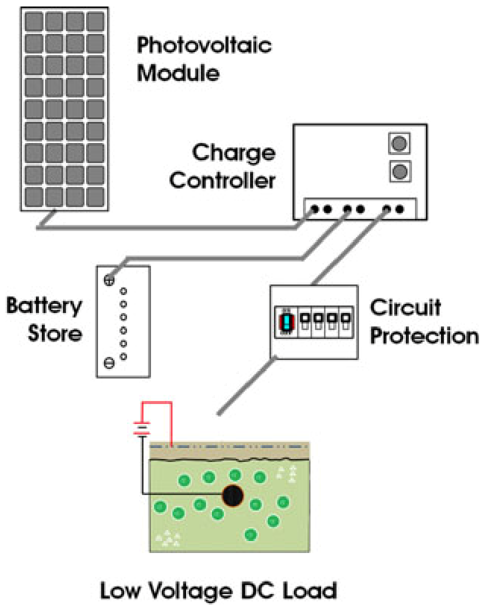

Figure 5 Block Diagram of DC PV system [12]

3 METHODOLOGY

3.1 *Resistivity Measurements*

By measuring the surface and internal resistivity of concrete, one may gain an insight into the electrical requirements of ECE and optimised for a more efficient process.

The resistivity of concrete increases rapidly during the first 20 days of moist storage, but after 30 days it becomes almost constant. Since conduction can be regarded as electrolytic in nature, the initial increase in resistivity is probably due to the continued hydration of the concrete.

To investigate this, a concrete specimen was cast with CEM I cement. The aim was to obtain a weekly value of resistivity up to 8 weeks (56 days) which may be predicted using simple electrical formulae. This allows the resistivity of particular concretes to be accounted for in the system.

Figure 6 Resipod used for Resistivity Measurements

To measure the resistivity, a commercial 4-point Wenner probe Resipod [14] shown in 6 was used. The probe induces a current between the two outer probes, while measuring the potential difference between the inner probes. The resistance may be calculated once the resistivity is measured using equation 1, where s is the distance between each probe (5cm for Resipod), ρ is the measured resistivity of the concrete surface ($k\Omega.cm$) and R is the resistance of the concrete (Ω).

$$\rho = R2\pi s \qquad (1)$$

Assuming the resistance calculated using current and voltage measurements of a previous treatment [15], a prediction of the resistivity of the specimen is possible. This allows verification of the methodology used by experimentally testing. This system used a constant 30V DC with a measured current of 34.6mA and current density (σ_s), equal to 4.5A/m^2 of the steel circumferential area (10mm diameter bar). Given the resistance of the circuit was 866 Ω (using ohms law), and distance s from the rebar to the titanium mesh was 5cm, the resistivity (ρ) may be predicted using Equation 1 as 27.2kΩ.cm. However, with different cement types, the resistance of the system may change.

4 EXPERIMENTAL WORK

The experimental work focused on attaining a resistivity value of concrete used in previous works [15]. The resistivity was of particular interest due to its variability in different cement types.

In order to measure the resistance of the concrete, a concrete slab (245mm wide x 245mm deep x 100mm thick) was cast along with 6 cubes for compressive strength testing at 7 and 28 days. The mix was designed for compressive strength of 35MPa using CEMI with a w/c of 0.5. The moisture content of the aggregate and sand was measured prior to casting in order to achieve the desired w/c ratio. The mix proportions are shown in Table 1.

The specimens were compacted using a vibration table to ensure no trapped air remained inside the mix. After curing for 24 hours in a sealed plastic bag, the concrete were placed into a curing tank for 7 days until the first series of cubes were tested. The specimen was painted on five sides leaving the top free. The resistivity of the specimen was measured weekly up to 56 days.

Table 1: Concrete Composition kg/m^3.

CEM I	Water	W/C	FA	CA	
				10mm	20mm
450	225	0.5	561	570	570

FA – Fine Aggregate, CA – Coarse Aggregate

4.1 Results

The average 7 and 28 day compressive strengths were 53 and 64.2MPa respectively. The results from the resistivity measurements are shown in 7. As expected the value of the resistivity gradually increased over the 8 week period.

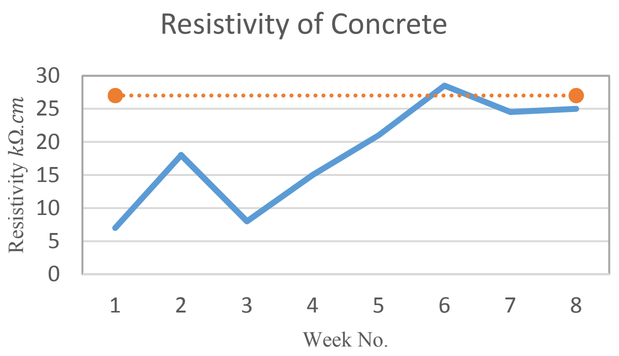

Figure 7 Resistivity Measurements

5 CASE STUDIES

5.1 ECE Treatment in Ottawa

Work carried out by Bennett and Fong [2] explored the trial application of ECE on a bridge deck in Ottawa. The deck had a surface area of 300m^2, of which half was treated and half left as a control. The start up current for both North and South spans was 48A with a total treatment area of 68m^2.

A 60kW diesel fuelled electricity generator was used to provide the three phase AC power for the system. Since ECE requires DC, an inverter was used. The requirements for the study are summarised in

Table 2.

Table 2 System Properties (Lab and Field)

	Unit	Field
Power, P	Watts, W	2304
Current, I	Amps, A	48.0
Voltage, V	Volts, V	48.0

5.2 ECE Treatment in Virginia

A field trial carried out by Clemeña and Jackson [4] on a highway overpass in Virginia used high currents for ECE treatment. With an area of 174m^2, the start-up current for ECE was around 160A, equating to around 4000A-hr. Therefore, it is clear that localising treatment to key structural elements in strategic locations, current requirements are lower. Focusing on regions of a structure more vulnerable to chloride ingress, for example piers of a bridge within the tidal zone or subject to ongoing sea spray, localisation of ECE may be achieved.

5.3 Cost of Diesel Generator

The cost of a diesel generator for an 8-wek period ranges from around €10,000 to €15,000. For the field trial carried out by Bennett and Fong [2], the fuel consumption was 6000 litres of diesel equating to €6000. Therefore, the total expected cost of using a diesel generator (excluding fittings and wiring) would equate to over €25,000 including inverters @ €2000 each.

6 APPLICATION OF PV TO AN EXISTING STRUCTURE

Photovoltaic technology is always being improved with new efficient panels being brought to the market constantly. During the period of writing this paper, the most efficient commercially-available panel was made by Panasonic with an output at low (200W/m^2) and normal (800W/m^2) irradiance levels summarised in Table 3.

Table 3 Power Output at Low and Normal Irradiance Levels

Irradiance Level	Low 200W/m^2	Normal 800W/m^2
Max. power (Pmax) [W]	63.5	247.2
Max. power voltage (Vmp) [V]	56.2	54.2
Max. power current (Imp) [A]	1.13	4.58
Open circuit voltage (Voc) [V]	66.0	65.1
Short circuit current (Isc) [A]	1.21	4.91

Considering that running the system in during the warmer months would be a lot more feasible than in winter, the lowest average daily solar irradiation levels for Dublin, between April and September will be used in the sizing calculations.

6.1 Sizing of PV System

Using the treatment area for the Ottawa bridge, a current of 48A was used. This level of current is too high for PV to supply and it would take 100m^2 of PV to provide which is unfeasible. Instead, by localising the treatment the efficiency would be improved.

By means of an example, an analysis of the Firth Bridge in Dornoch, Scotland (Figure 8) was undertaken. The piers of this bridge are susceptible to chloride ingress due to the marine environment and rising tides. The tidal levels at the bridge site rise and fall by 2m every day. The piers are shaped like an octagon with each face 300mm wide. This gives an effective localised treatment area of 4.8m^2/pier. Assuming the start-up current for the treatment area may be scaled down from the case studies, the piers would require 3.4A each (6.8A for the pair) to power ECE equating to approximately 326.4W at a 48V daily load.

Figure 8 Firth Bridge Dornoch, Scotland [16]

By using a simplified design method by Markvart [17], the number of solar panels required to provide power to the system may be calculated given local climate data. The average daily hours of sunshine over the 6-month period is 15. Therefore, the batteries must provide power ~37.5% of the time (nightime hours). The load must be increased by this value in order to account for this as calculated in eq 1-3. The efficiency of the battery, η_{bat}, is taken as 76%.

$$load \div \frac{\eta_{bat}}{1-f(1-\eta_{bat})}$$

$$326.4 \div \frac{0.76}{1-0.375(1-0.76)} = 390.8W \quad (3)$$

$$Daily\ Load = 390.8 \times 24 = 9379.2\ Wh$$

Intuitively, the number of panels required in series is one as the system voltage will never exceed 48V (a panels maximum rated output voltage is 58V).

The number of parallel panels is computed below, where I_L is the equivalent load current, E_L is the typical daily power requirements of the load, V_{DC} is the operating voltage of the system, I_{PV} is the nominal current of the PV array, PSH is numerically equal to the irradiation per day and I_{SC} is the short circuit current of the panel:

$$I_L = \frac{E_L}{24V_{DC}} = \frac{9379.2}{24 \times 48} = 8.14\ A \quad (4)$$

$$I_{PV} = \frac{24I_L}{PSH} = \frac{24 \times 8.14}{2.78} = 70.27A \quad (5)$$

$$No.\,in\ Parallel = \frac{I_{PV}}{I_{SC}} = \frac{70.27}{7.44} = 9.45 \approx 10 \quad (6)$$

A similar analysis using RETScreen 4 was performed using the same criteria as above with the requirements calculated as 14 panels with a battery capacity of 710A-hr. Being conservative, the higher number obtained from RETScreen will be used.

6.2 Batteries

A battery storage system with an output of 48V and 6.8A (for a pair) must then be developed in order to store and deliver the power. To validate the results from RETScreen, the battery system is sized numerically. Choosing two days of autonomy and a 60% depth of discharge, the daily capacity is equal to 9379.2 Wh/day. Assuming 97% wiring and distribution efficiency, the battery must be able to provide 9669.3 Wh/day. Dividing this by the voltage required, the daily amp-hour requirements is equal to 201.4 A-hr/day. The required system capacity is calculated below.

$$\frac{201.4 \times 2}{0.6} = 671.3\ A \cdot hr \quad (7)$$

The battery system therefore must have a rated capacity of approximately 671.3 A-hr/day at 48V. Again, a conventional approach has been taken in the sizing, so RETScreen values will be used for the battery system (14 panels, 710A-hr battery bank).

6.3 Cost of System PV System

The PV system designed above would require 14 no. HIT330 panels @ €400 each (€5,600) and 16 no. L16RE-B 370 AH 6V Trojan batteries @ €307 each (€4912). Include a charge controller (~€2,000) giving a total cost of using a PV system as €12,512.

7 DISCUSSION

7.1 Resistivity Measurements

The methodology for the resistivity measurements was mainly concerned with validating the prediction made in section 3.1. By showing that the resistivity may be used to determine the internal resistance of concrete specimens, an accurate prediction on the current and voltage to be used for treatment can therefore be determined. Since only one specimen was used to validate this principle, the results may not reflect the true nature of the concrete. Despite this, it is a reasonable method of determining the electrical properties of an RC structure. It should also be noted that the internal resistivity of the concrete will be lower than that at the surface. Thus the prediction made here is conservative.

7.2 Photovoltaics

Based on the PC costing, it can save up to 50% of existing investment for employing ECE. Aside from reduced costs, PV is a clean source of energy making the treatment more economically friendly compared to traditional diesel generators.

8 CONCLUSIONS

The following conclusions have been drawn:

- ECE treatment on large areas of RC structures requires a very high current. This prevents PV from being employed to power ECE in large areas.
- Localising the treatment reduces the area by focusing on key structural elements enabling ECE to be powered solely using photovoltaics.
- Measuring the resistivity of concrete tailors the PV system for specific requirements.
- RETScreen 4 together with simplified design methodologies are effective tools for preliminary sizing of PV arrays.

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