ELECTRO-CHEMICAL TREATMENTS FOR CORRODED PIERS IN MONTE CARLO

Naziha BERRAMDANE[1], Erik MELLIER[2], and Christian TOURNEUR[3]

[1] Freyssinet Internaltional, France
[2] Freyssinet Internaltional, France
[3] Freyssinet Internaltional, France

1 INTRODUCTION

Over the past two decades, the electrochemical techniques of prevention and protection of steel in concrete like cathodic protection with impressed current or re-alkalinisation /chloride extraction treatment are increasingly used in the rehabilitation of buildings and structures. These techniques have definitely caught on because they overcome the deficiencies of traditional techniques. These electrochemical techniques increase the life of reinforced concrete structures while decreasing energy consumption of traditional repairs which are unsustainable and must be renewed regularly.
Since 15 years, these techniques have been identified, evaluated and developed to ensure durable repairs and reduce environmental impact.

Fig. 1 : Monte Carlo Star building

The rehabilitation of Monte Carlo Star's piers in Monaco is a perfect illustration of the combination two of these corrosion protection techniques.
In the context of future development of the port La Condamine, the connection of the MSC's piers to the Yacht Club building involved their repair as a pre-requisite.
It required two electrochemical techniques in addition to traditional repair: a temporary

electrochemical treatment for extracting chlorides and permanent protection with impressed current.

This paper is made up of 4 parts: first a reminder of the principles of cathodic protection and chloride extraction treatment. then detailing the design method for both solutions, the way it is set up on site and the important checks. Finally, the results that were obtained will be discussed in the last chapter.

The objective of the electrochemical technique is reduction of reinforcing steel corrosion regardless of the aggressive environment and concrete cover quality. That is possible thanks to a current provided by an external power source (direct current DC).
It mainly consists of controlling the rebar's electrochemical potential to make them a cathode.

2 PRINCIPLE OF ELECTROCHEMICAL PROTECTION TECHNIQUES

2.1 Cathodic protection with impressed current

For metals and alloys in an electrolyte, a cathodic protection consists in applying a direct current from the electrolyte (i.e. the conductive environment: sea water, soft water, ground like sand or clay, polluted concrete or other) to the metal by ionic conduction in order to remove or reduce the anodic areas (dissolution areas) at the interface. This cathodic current induces a decrease of the corrosion potential.

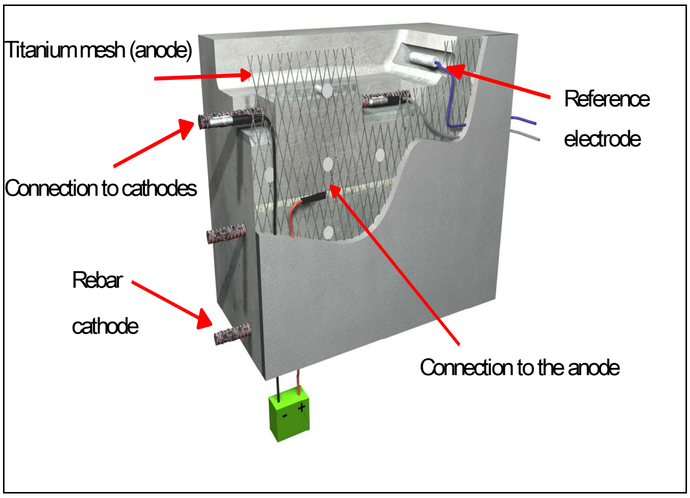

Fig. 2 : Scheme of a cathodic protection system with impressed current.

From a thermodynamic point of view (probability of reaction), in the potential-pH diagram of Pourbaix [1], it means having a point moved from the corrosion area to the immunity area.
From a kinetic point a view (reaction velocity), it means decreasing the potential below a value so that the anodic current density of the steel is negligible.
The cathodic current converts the interface (surface between steel and electrolyte) in a

cathode, removing the reaction of steel corrosion. The increase of the cathodic reactions (reactions which reduce the oxidizing agent) causes an alkalinisation of the environment at the surface of the steel.
In theory, in the case of the cathodic protection of a reinforced concrete structure, the value of potential to be exceeded must such that it avoids corrosion of the embedded depassivated rebar. The value generally admitted is –0.85V/ECS for underground structures and –0.8V/ECS for structures immersed in sea water.
Practically, at the startup of a protection system, the empiric criterion of depolarisation of 100mV by 24h is the most used value [2]. Experience shows that a difference of 100 to 300 mV against a natural potential value is enough to protect rebar (excluding the voltage drop due to concrete). That's why it is not necessary to apply an important amount of current to reach the immunity potential value, even in case of a very resistant circuit such as aerial carbonated concrete.
According to EN NF 12696 "Protection cathodique de l'acier dans le béton" that concerns the aerial structures, the current density value for designing a cathodic protection system is from 2mA/m² to 20mA/m² of steel without coating. Indeed, in protection, a maximum current density of 20mA/m² puts the potential of rebar in a range where the pitting corrosion (due to chlorides) can not begin.
For reinforced concrete structures immersed in sea water or buried (NF A05-611) the current density of protection can exceed 10mA/m² if the steels are degraded.

2.2 Chloride extraction / re-alkalinisation treatment

The first objective of the chloride extraction is to reduce the content of free chloride ions in concrete around the rebar (the chemical species which activates corrosion of rebar). The second objective is to form hydroxides OH^- ions to recreate propitious conditions to restore the passive layer on the surface of the steel. In other words, the goal is to reduce the ratio of concentration [Cl]/[OH]. The aggressiveness of the rebar environment will be decreased [3].
This treatment also consists of polarizing rebars so that they can become "Cathodes". This cathode is the negative pole of the electrical circuit since it receives electrons from the sacrificial anode reactions. The cathode is negatively polarized and repulses negative ions such as chloride ions to the anode (positive pole).
To reinforce the migration of chloride anions and to increase the hydrogen potential (pH) at the interface of the cathode, the system can be boosted with an external source of current which a maximum cathodic density of 0.2A/m² of steel. Such a treatment is applied for about 2 to 3 weeks.
The effectiveness of the treatment depends on several parameters [4], the main factors are:

- The initial content of Cl^-: the flow is proportional to the concentration and mobility of ions; efficiency increases with the initial concentration of chlorides
- The impressed voltage or current
- The depth of contamination chlorides: solely ions located in the concrete cover can be extracted
- The concrete resistivity: ionic current is a function of the resistivity of concrete.

2.2.1 Installation

After removal of all damaged concrete, the electrical continuity of the rebar must be checked. The steel connexions are brazed, the cables are put on hold then the covering of piers is being reconstructed.
The pulp is then applied in a thin layer over the perfectly cleaned concrete cover. The alkaline pulp facilitates the galvanic exchange between the steel and an aluminium alloy sacrificial anode grid which is flattened against the pier surface and covered with pulp (see the scheme Figure3). Then all cables are connected to the electrical source. During the treatment, the pulp is moisturized everyday and the output current is checked.

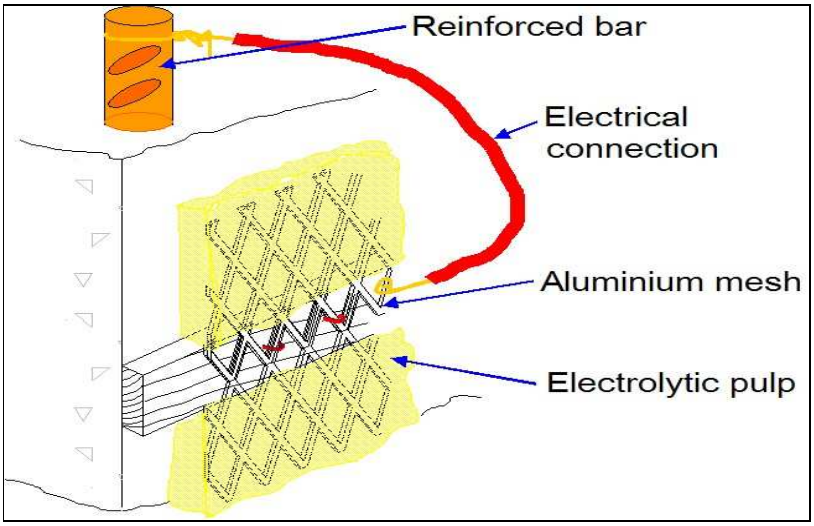

Fig. 3: scheme of a chloride extraction installation

2.2.2 Treatment efficiency

After treatment, several tests are possible to assess its effectiveness. To check the re-alkalinisation, a colorimetric test with phenolphthalein is performed in-situ. For the chloride extraction, since the hydroxyl ion concentration is difficult to determine, a lab analysis of the rate of free chlorides by weight of cement is necessary.

Fig. 4: anode installation, pulp installation, electrical connexions for the temporary chloride extraction system

3 REHABILITATION OF MONTE CARLO STAR

The Monte Carlo Star building in Monaco was built in 1973 over the Mediterranean sea. It is built on circular piers, 1.8 m diameter, anchored into the seabed rock. Since construction, these piers were exposed to mechanical and physico-chemical attacks from storms, marine spray, etc. In 2005, these piers were showing advanced damage like cracks, spalling areas, traces of corrosion and oxidation products.

The investigation works had shown that steel at the top of piers wasn't corroded. Indeed, these areas characterized by a high resistivity have preserved the majority of steel. However, a high concentration of chloride has been identified next to the rebar.

To decrease the corrosion risks in this area, a temporary treatment which can reduce the concrete pollutant was necessary. Indeed, the piers between 7.30m and 10.95m will be a part of an air conditioned marine museum. Moreover, the probability of chloride migration by capillary action from the bottom to the top of the pier is negligible.

Consequently, in addition to traditional repairs, it was necessary to decrease the chloride concentration and homogenise the electrochemical state of the steel/concrete interface. The chloride extraction treatment was applied during 21 days.

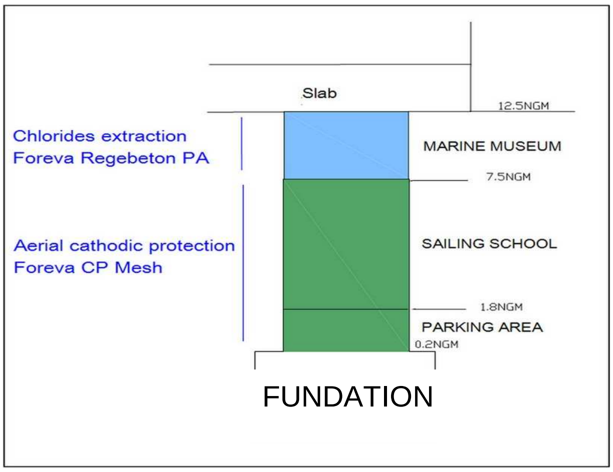

Fig. 5 : scheme of the different treatment locations on the piers

The lower parts of the structure were previously corresponding to splashing areas and had suffered a lot of damage. These areas were heavily aerated and humid and contained a high level of chlorides. This very aggressive environment induced an advanced corrosion of steel despite the quality of the concrete cover.

In the future the surface of the piers will be protected from marine atmosphere since they will be in the Yacht Club building. Nevertheless, the steel of lower areas will always be exposed to sea water which can rise by capillary action through the foundations.

The repair consists in removal of all concrete cover by hydro-demolition up to level 7.30m, and set up of a cathodic protection, then restoring the initial form of piers by shotcreting.

4 CONCEPTION

The design of a cathodic protection system requires a compromise between technical and economical needs. Indeed, for a same pier, the meshing of structure in many cathodic protection areas is related to the disparity of the concrete resistivity. An homogeneous distribution of cathodic current requires an increase in the number of protection areas. Although, increasing the number of areas leads to an increase of connexions, power supply and controls. This means an important increase in the material quantities (e.g. copper) and installation time.
Monte Carlo Star Piers were divided into two protection areas: the lower area, 3 meters high, considered as a humid structure (foundation in sea water), and the higher area which is designed according to the recommendations for a cathodic protection of aerial concrete, with a maximal current of protection of 20mA/m2.

4.1 System set up

All of the connections and the reference electrodes for current injection and monitoring are embedded in the concrete. For this reason, the installation is punctuated with many electrical tests.

4.1.1 Electrical continuity of reinforcing bar

A first step consists in checking the electrical continuity of the first stage of reinforcing bars with an ohmmeter with very high impedance. The electrical continuity of steel is essential because it guarantees an homogeneous injection of the current in the framing. A maximum difference of 5 ohm between two reinforcing bars is generally admitted.
In the case of the Monte Carlo Star piers, this task was easier in the cathodic protection area (lower area) with the integral hydro-demolition of the concrete cover, as all the steel bars were uncovered, and so, many of the steels could be checked. For the higher areas, the chloride extraction treatment also required control. In this case, the electrical continuity was only checked at the points of connexion of the reinforcing bars, and when necessary the number of points was increased.
These measures are also made after each connexion to the reinforcing rebars and titanium mesh to check welding and electrical cables. The control values are systematically recorded by operators into QA files.
The monitoring and control of the system are performed with silver/ chloride silver reference electrodes. These electrodes are put next to reinforcing bars, they follow the electrochemical potential of bars. Each area contains at least one electrode. The potentials are recorded thanks to a measurement device inserted in the electrical cabinet. The data can be remotely collected thanks to a computer system using GPRS technology.

4.1.2 Anode planting

The Cathode pole is established and the sensors are installed, the first stage of shotcreting is performed. After the hardening of concrete, the titanium mesh is unfolded and fixed at the pier wall. Then, the connexions to the anodic titanium mesh are welded and connected to the positive pole thanks to red cables. Each cable is checked, identified and protected.
Then, the second stage of shotcreting is performed to restore the initial pier shape. It is a

very delicate process because the connexion and the protective duct of the cable must not be damaged. During this process the nozzle man and the cathodic protection operator work as a team, the CP operator tests the voltage and electrical resistance between the cathode and the anode to detect a possible short circuit.
Once the electrical tests are successfully accomplished, the cables are connected to the electrical device and monitored to start the CP system. 28 days later, the protection current is then injected gradually. A first assessment of the CP effectiveness is achieved after one month of power-up by a depolarisation test in 24 hours in accordance with standard NF EN 12696.

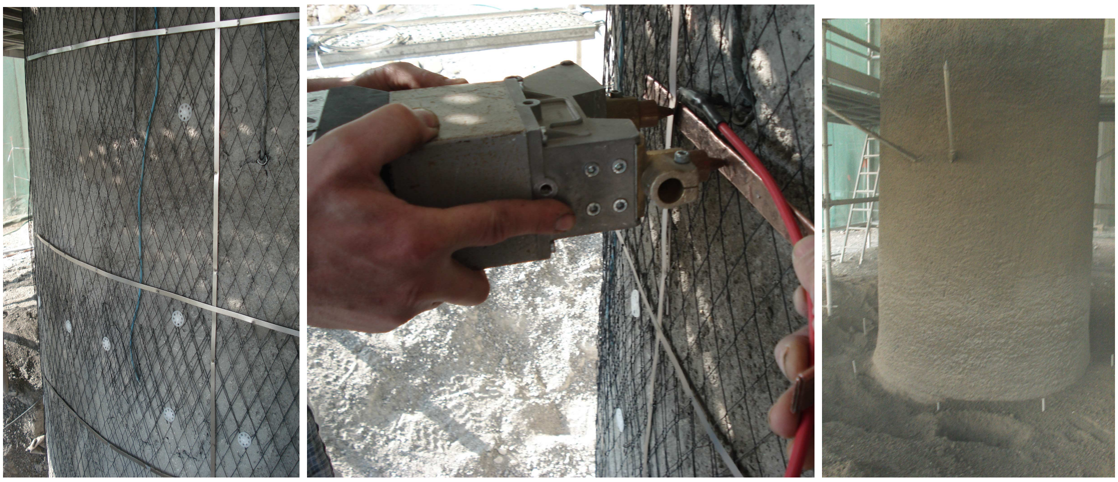

Fig. 6 : titanium mesh installation, electrical continuity checking and final shotcreting for the cathodic protection system.

5 RESULTS AND DISCUSSION

To estimate the effectiveness of the chloride extraction treatment, many trial holes were made before and after treatment for a chloride content analysis. The concrete powder removed next to reinforced bars were analysed by an independent laboratory.
The sampling operations have been difficult to perform. Indeed, the significant thickness of cover (up to 17 cm in some places) has made the detection and localization of bars with the traditional measuring device, very difficult.
The analysis results were used to evaluate the percentage of extracted chlorides. Despite the variations in concrete cover thickness, all the percentages of extraction evidence good extraction results. These percentages vary between 40 and 97%, placing the majority of results below the admissible 0.4% / weight of cement. The treatment generally operates efficiently at a range of 10mm around the bars where the concentration of hydroxyl ions increases. However, a minority of sampling showed a concentration of chlorides at 20mm from the steel. The purge of these areas was been decided.

Furthermore, many electrochemical potential measurements were performed before and after the extraction of chlorides, the measurement concerned a majority of piers.
The electrochemical potentials recorded after a total depolarisation (after 10 days) are

less electronegative than the initial potentials. For all areas, the potential values vary between -200mV/ECS and -300mV/ECS. In this case, from a thermodynamic point a view, the corrosion probability of reinforced bars is low to uncertain for the highest electronegative potentials. These values and notably the absence of gradient potential show a good polarisation thanks to the treatment. The polarization of steel induced an alkalinisation of the medium's bars (alkaline medium promoting steel passivation) and a low content of chlorides (corrosion potential steel in concrete contaminated by chlorides are included in general between -650mV/ECS and -400mV/ECS). A uniform potential mapping without gradient especially after treatment indicates the removal of macro-corrosion cells.

In cathodic protected areas, the potential value of steel versus permanent reference electrodes are homogeneous. They vary from –450/Ag/AgCl to -550mV/Ag/AgCl. The depolarisation test results after 1 month of service show that the steel is adequately protected with a protection current density of 12 to 17 mA/m² of steel. The depolarisation values are higher than 200mV. Accordingly, the protection current intensity has been reduced in order to obtain a maximum depolarisation of 150mV.

6 CONCLUSION

The Monte Carlo Star building provides a tangible example of chloride extraction possibilities for important concrete cover thickness since the treatment acts at reinforced bars with 17 cm concrete cover. To regenerate the carbonated and/or chlorinated concrete, the electrochemical treatment solution is operated in impressed current or galvanic mode. This treatment provides passivation properties to concrete.

A cathodic protection installation is easy to place if the preparation and executions methods are carried out with care. This solution is the primary technique of protection for reinforcement of concrete with a clear criterion to estimate its effectiveness. The example of Monte Carlo Star piers shows that the cathodic protection can protect reinforced bars with a current consumption which doesn't exceed 50kW/year.

7 ACKNOWLEDGEMENT

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8 REFERENCES

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