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Rehabilitation, repair, and maintenance of carbonated concrete members affected by corrosion of reinforcing steel by applying CP via a composite quantum anode.

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Abstract. Damage to concrete due to corrosion of the steel reinforcement in carbonated concrete is a frequent issue if the affected structures are to be maintained. Conventional repair by applying fresh mortar for realkalisation implies changes in the weight and dimensions of the structure and is costly. Soft realkalisation of the steel/concrete interface by applying cathodic protection (CP) via a conductive coating – Composite Anode System - was used for the corrosion protection of carbonated concrete structures in a parking deck of the central TV administration in Vienna/Austria in several installations from 2003–2008. Five examples of the application of an improved system – the Composite Quantum Anode System, consisting of the QAP60 primer and the CAST^{Q} paint– are presented: (1) the Slaughterhouse, an iconic building in the Antwerp (B) neighbourhood, transformed into a higher-education campus on a total of 1000 m^2 in 2021 to 2022, (2) in 2017, on the portal of the concrete structure on the roof of Pakhuys Afrika, Harbour of Amsterdam (NL) and the (3) on concrete panels of the Sint-Theodardus Church in Limburg (B), (4) 2023 on 3400 m^2 of carbonated concrete in a parking deck in Nürnberg (D), (5) in 2024, on 500 m^2 of the Bosc kiosk in Montpellier (F), built in 1927, the kiosk's architecture is based on four octagonal posts.

1 Introduction

Carbon steel reinforcement embedded in OPC concrete is protected from atmospheric corrosion due to an alkaline pore solution (pH > 12,5), alkalinity generated by the presence of large amounts of calcium hydroxide and small amounts of alkaline hydroxides such as NaOH and KOH in the concrete pores. The alkaline constituents in contact with atmospheric carbon dioxide are slowly neutralized, and calcium hydroxide is transformed into crystalline calcite and/or vaterite. Once the pH of the pore solution is reduced below pH 11,4, the passive layer on the steel reinforcement becomes unstable, and corrosion of the steel reinforcement occurs if there is enough moisture and oxygen present [1,2]. The voluminous corrosion products formed at the steel/concrete interface lead to cracking and spalling of the concrete overlay. Maximum carbonation rates are observed when the concrete is exposed to atmospheres with relative humidity in the 55–75% range. The corrosion rate of embedded steel in carbonated concrete in this humidity range is not of practical concern [1]. Carbonation of concrete is relatively slow under natural conditions and depends on porosity, moisture, saturation level, and binder composition [1-5]. The volume of formed calcium carbonate exceeds that of the parent hydrate. This is why the carbonation reaction generally causes a reduction in porosity [4]. According to [4], smaller pore diameters are reduced in diameter in carbonation. The effect does not seem to be significant in larger pores. The reduction of permeability due to carbonation is generally agreed upon, but contradictory results, especially concerning specimens with low strength have been published [6]. Carbonation rate and depth also depend also strongly on the cement composition, especially the alkalinity of the binder [1].

If the codes of practice [7], "how to avoid carbonation-induced corrosion" are observed, the service life of structures of 50–100 years may be expected [1]. However, many old reinforced concrete structures, built before modern standards were applied, are ageing and need to be maintained. The service life of concrete structures made with OPC can be predicted from the air permeability and corrosion rate determinations [1, 8-10]. The main parameter controlling the corrosion rate of steel in carbonated concrete is the exposure condition: at low RH, the corrosion rate is negligible, and significant values are reported only in very humid conditions and in direct contact with water [1].

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Corrosion rates of the steel reinforcement in carbonated concrete vary widely, from the average value of the minimum corrosion current of about 0.08 μA/cm^2 to the average of the maximum of about 2 μA/cm^2 [1]. These currents correspond to cross-section losses of the steel, ranging from 0.0008 mm/year (very low) to 0,02 mm/year (high) [11].

Concrete structures affected or endangered by the corrosion of the steel reinforcement induced by the carbonation of the concrete overlay may be repaired and maintained by the following methods:

(1) Dry out the carbonated concrete overlay and the affected steel reinforcement by removing the source of humidity ingress and applying a suitable water vapour permeable concrete coating.
(2) Remove the carbonated concrete overlay and subsequent patch repair [12, 13].
(3) Electrochemical realkalisation
(4) Cathodic corrosion protection by applying an impressed current

Method (1) may be applied if humidity ingress or access to liquid water can be stopped reliably, often impossible. Method (2) is work and cost-intensive and requires significant structure modification. Method (3) is reported to be unreliable in the long term [14, 15]. Method (4) – cathodic protection of the corroding steel in carbonated concrete proves to be a reliable method for repairing and maintaining concrete structures endangered or affected by corrosion of steel reinforcement induced by the carbonation of concrete overlay by repassivating the steel by realkalisation of the steel/concrete interface [16,17]. Classical anodes used for CP, such as MMO-titanium ribbon mesh anodes, require substantial changes in the appearance of the concrete structure, which may be unacceptable for historic buildings. Applying a “paint anode” such as the composite quantum anode [18,19], allows reliable and durable cathodic protection with virtually no changes to the surface structure of the protected concrete member. The composite quantum anode [18,19] is based on a carbon quantum dot modified electrically conductive paint that is usually applied in a layer thickness of about 0,3 mm. It may be covered with a wide range of cover coats that allow the preservation of the original appearance of the building.

2 Examples for the application of CP for the corrosion protection of steel in carbonated concrete elements

2.1 Parking deck in the central TV administration building in Vienna (ORF)

The parking deck at the centre of the Austrian TV (ORF) administration in Vienna (Fig. 1) was constructed between 1968 and 1972, based on Roland Rainer's plans, and is protected as a historic monument. The concrete structure of the parking deck showed damage typical of the carbonation-induced corrosion of the steel reinforcement, such as spalling and cracking of the soffits and deck ceilings (Fig. 2).

Fig. 1. View on the parking deck structure of the administrative centre of the ORF in Vienna, Austria.

Fig. 2. Concrete damage caused by the steel reinforcement corrosion induced by the concrete cover carbonation.

Measurement-based evaluation of the concrete cover showed carbonation depth > 35 mm and chloride levels 0,25-0,3 wt.%/wt. cem., in some exposed areas up to 0,9 wt.%/wt. cem. Therefore, the first layer of steel reinforcement was embedded in fully carbonated concrete. Chloride levels below critical chloride levels that are harmless in non-carbonated concrete may induce severe corrosion in carbonated concrete [20]. Concrete spalling and crack formation pose a danger to the structural integrity of the concrete member, especially spalling, which may cause damage to parked cars and may be human life if a big enough piece spalls.

Cathodic protection with conductive paint - the Composite Anode System - was chosen as it stopped the deterioration of the critical parking deck structure with minimal interference to the ORF employees' use of it. From October 2002 to July 20008, the Composite Anode System was installed in 20 protection zones on a total surface area of 1200 m^2.

The Composite Anode Paint CAS-T, the parent to CAST^Q composite quantum anode paint, was applied with rollers in two layers on the CAP60 primer-impregnated concrete surface. Current distribution was achieved by embedding Cu/Nb/Pt wires (Ø 0,8 mm) into the CAS-T paint (Figure 3). The Composite Anode was covered with an elastic acrylic top coat Stocryl V200 (Fig. 4 to 6).

Protection zones 2–5 started operating on 30 December 2002, 6–10 on 16 February 2004, 11–17 on 19 November 2004, 18&19 on 9 August 2006, and protection zone 20 on 4 February 2008.

Fig. 3. Application of the CAS-T Composite Anode on the soffit of the drive-in ramp of the ORF parking garage

Fig. 4. CAS-T Composite Anode covered with a polyacrylic cover coat on the soffits and beams of the drive-in ramp to the ORF parking garage.

Fig. 5. CAS-T Composite Anode applied to concrete beams and soffits, covered with an elastic acrylic cover coating.

Fig. 6. CAS-T Composite Anode applied to beams and soffits, covered with an elastic acrylic cover coating.

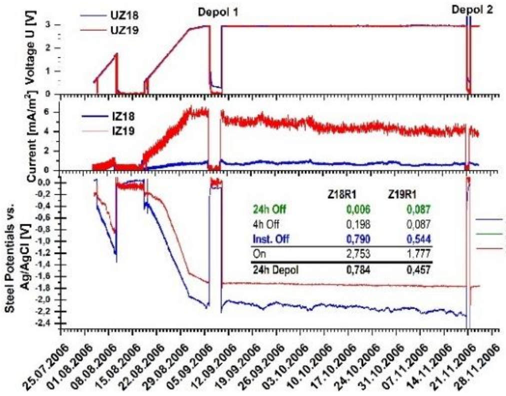


Fig. 7. Start-up and initial operational data for protection zones 18 and 19.

Figure 7 shows typical start-up and initial operational data. Carbonated concrete has a higher resistivity because with calcium- and hydroxyl- ions as calcite important charge carrier are removed from the pore solution and pore volume is reduced. Subsequently, higher voltages (3–5 Volts) have to be applied to assure protection according to EN ISO 12 696. After 4-10 years of the CAS-T Composite Anode operation, operational data are listed in Table 1. Except for protection zone 5, the protection zones 2–13 are fully protected according to EN ISO 12 696. Depolarisation measurements were not possible in the protection zones 14–20 due to the installation of high-power equipment in the nearby offices, emanating strong electromagnetic waves. Using shielded cables to the reference cells only lowered the impact. The operational data (voltage, current) conforms with the protection zones 2 – 13, so one may assume the corrosion protection is safe. The maintenance contract with the owner expired in 2012.

Table 1: Operating Data CP ORF recorded 16. 08. 2012

Prot. Zone	Area [m^2]	Voltage [Volt]	Current [mA/m^2]	24h Depol. [mV]
1	77	3M Zinc Hydrogel Galvanic Anode		
2	69	4,00	217,70	**140**
3	69	5,02	24,10	**266**
4	87	5,02	24,80	**127**
5	107	5,02	10,70	**44**
6	103	5,02	60,00	**134**
7	109	5,03	44,00	**116**
8	100	5,02	339,00	**193**
9/10	10	5,02	13,00	**122**
11	47,5	5,02	70,50	**98**
12	45,6	5,01	28,80	**117**
13	38,2	5,02	24,80	**132**
14	63,4	5,03	43,00	strong noise
15	17,8	5,02	6,70	strong noise
16	31	5,02	6,70	strong noise
17	41	5,02	24,00	strong noise
18	58	5,03	20,80	strong noise
19	25	3,00	20,0	strong noise
20	60	5,02	999,80	**128**

Conclusion: The application of the Composite Anode allowed the protection and maintenance of an important part of the historic building without intrusion into the exterior appearance.

2.2 Sint-Theodardus Church in Limburg, Belgium

The Sint-Theodardus Church (Fig. 8), designed by Henry Lacoste and built between 1939 and 1943, is one of Belgium's five mining cathedrals and holds protected heritage status due to its monumental value. Located on Koolmijnlaan in Beringen-Mijn, Limburg, the church is a single-nave cruciform structure featuring a 72-meter-high tower and distinctive glass-in-concrete windows. The windows, constructed with an experimental technique, exhibited severe damage due to carbonation of the cement stone and insufficient concrete cover over the steel reinforcement. This degradation also caused secondary damage to the glass elements, with some being affected by salts.

During the 2017-2018 restoration, 36 concrete window panels (Fig. 9 and 10) from the nave and baptistery were repaired. Approximately 3,000 damaged glass pieces were replaced out of a total of 8,000. Severely deteriorated panels were fully disassembled, and new concrete frames were reconstructed before reassembling the original glass elements. In contrast, panels in better condition (the "tips") underwent localized glass repairs and installation of a cathodic protection (CP) system to halt steel corrosion, preserving the original construction.

The CP system implemented used impressed current cathodic protection (ICCP) applied internally to the concrete panels. Based on EN 12696 standards for steel protection in concrete, the CP design included aluminosilicate conductive coatings CAST^Q and platinum-clad niobium/copper wire as the primary anode. Approximately 20 m² of concrete surface was treated with the conductive coating. The system's implementation involved applying a primer layer, followed by two layers of conductive coating in the workshop before final installation.

Two types of reference electrodes were embedded to monitor the system's effectiveness: silver-silver chloride and activated titanium depolarization sensors. These electrodes, installed near the protected steel, were connected to the system's measurement points via color-coded cables all within the masonry joints. The installed CP system was initially divided into two zones covering the north and south facades of the nave, with a dedicated power supply and data communication modem for remote control and monitoring.

The system was fully integrated into the church's architecture, ensuring minimal visual impact while preserving this historical monument's aesthetic and structural integrity. The results demonstrate the feasibility and effectiveness of cathodic protection in preserving heritage concrete structures with integrated glass elements. Based on the success in the first phase of the renovation, the second part was executed in 2022-2023, when it was possible to save more parts of the glass-in-concrete panels than had been expected. An additional 240 m^2 of concrete surface was protected in another five zones with the CAST^Q Composite Anode. A remarkable point is the small dimensions of the concrete protected as this typically is only a few centimetres wide between the glass elements.

Fig. 8. Sint-Theodardus Church in Limburg, Belgium, elements protected with CAST^Q Composite Anode, details see figure 9 below.

Fig. 9. Elements protected with the CAST^Q Composite Anode

Fig. 10. Element protected with the CAST^Q Composite Anode

2.3 Pakhuys Afrikain in Amsterdam, NL

In 2017, maintenance was carried out on a concrete structure on the roof of Pakhuys Afrika, the Amsterdam Harbour. This structure features a concrete portal with the inscription “Amsterdam-Rotterdam.” Following an inspection, maintenance was performed in 2018, including installing a cathodic protection (CP) system as part of the remedial measures.

Pakhuys Afrika, originally built between 1883 and 1885, is a historical monument known for its characteristic mushroom floors. It is one of the first buildings constructed to accommodate direct loading of goods from deep water. After a fire in 1913, the building was rebuilt using reinforced concrete under the direction of architect A.J. Joling. Due to insufficient concrete cover over the reinforcement, corrosion issues arose, leading to façade repairs in the 1930s.

Using the CAS anode system, the CP system installed on the portal covers approximately 66 m² of beam surface (Fig. 12) and 4 m² around the column. This system combines a primary anode (activated titanium wire) and a conductive coating (CAST^{Q}) based on aluminosilicate as the secondary anode. Four depolarization sensors verify compliance with NEN EN ISO 12 696 standards. The system is connected to a central control unit that enables remote monitoring and adjustment.

The CP system aims to maintain the structural and aesthetic integrity of the concrete portal, a vital feature of the building’s historical appearance. The monitoring results show a well-functioning CP system in its first six years of operation.

Fig. 11. Pakhuys Afrikain in Amsterdam, NL

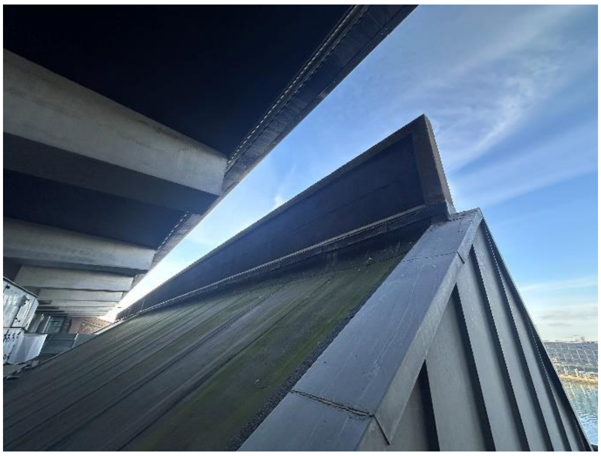


Fig. 12. Supporting Beams protected with CAST^{Q} Composite Anode.

2.4 . The monumental building on Slachthuislaan in Antwerp

The monumental building on the Slachthuislaan in Antwerp is a striking example of architecture and history that reflects the rich industrial heritage of the city of Antwerp. Located in an area once the beating heart of Antwerp's meat processing industry, the building symbolises the city's economic growth in the 19th and 20th centuries and the social changes that took place in the region. Due to its imposing appearance and historical value, the building has positioned itself as an important reminder of Antwerp's development as an industrial city, and today represents a valuable piece of heritage for both the city and its inhabitants that should be preserved. After the original construction of the slaughterhouse was bombed in World War II, it was rebuilt in its current form immediately after the war. The building is now an industrial construction with curved shed roofs consisting of 7 halls, each with a width of 16-19 metres. This brings the total dimensions to 60x126 metres.

The main structure consists of concrete columns, arches, and beams. The roof structure consists of purlins with prefabricated roof panels resting on them, forming a cassette ceiling (Fig. 13).

Fig. 13. Concrete elements of the main structure on the interior

On the exterior 7 arch-shaped concrete roof elements, with cantilever beams, are visible, as well as concrete columns, beams and façades with slender reinforced ribs (Fig. 14).

Fig. 14. Concrete elements of the main structure on the exterior

Fig. 15. Concrete damages due to carbonation

Over time, the building fell out of use as a slaughterhouse and the plan was recently conceived to reuse the monument for the benefit of the campus of a school of higher education. As the concrete showed widespread damage and this was undesirable for future use, a concrete survey was carried out in 2021. This revealed that the damage had been caused by carbonation (Fig. 15). The concrete cover on the steel varied widely from 5-99 mm. The average measured carbonation depth in 2021 varied from 30 to 150 mm inside (often the concrete was thoroughly carbonated) and from 22 to 71 mm outside. Particularly outside, the measured values varied greatly, from sometimes 0 mm to 100 mm (with carbonation through and through). No chlorides were present in the concrete.

As no future problems with the concrete in the (dry) interior were expected, the repair and prevention of future damages focused mainly on the exterior. Sustainable repair of carbonation damage is 'traditionally' quite possible by removing all the carbonated concrete, where necessary up to behind the reinforcement. However, for many slender elements and sections in the structure, such as the fragile concrete ribs in the façade elements, this would lead to severe damage to the monument and sometimes to complete demolition, which is undesirable in a historical monument. Moreover, large sections of concrete that are still attached and undamaged (but carbonated) by themselves would have to be removed. In addition, the structural function could be compromised at the roof overhangs and the beams, load-bearing elements with a large span, thorough chiselling work (up to behind the reinforcement). Thus, traditional concrete repair results in extensive and costly rehabilitation and repair work. The ribs, in particular, would be challenging to repair.

Therefore, CP with impressed current became a real and (also economically) attractive repair option. The carbonated concrete does not have to be removed up to behind the reinforcement, as the reinforcement will be protected in another way. Only the already loose and delaminated concrete parts of the cover need to be removed and repaired beforehand. This resulted in less labour-intensive, extensive and costly repairs (Fig. 16).

It was not considered necessary to apply CP to the entire concrete surface. Mainly for economic reasons, only locations with a large extent of damage would be provided with CP (Fig. 17). Local (mainly small and/or remote) damage would still be repaired traditionally because applying CP here does not result in a (significant) improvement in the quality and durability of these repairs, while in addition, the extra costs will be considerable.

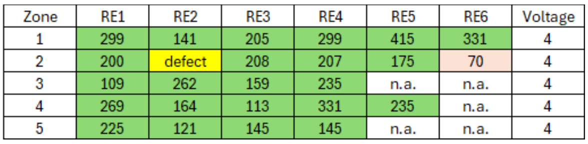
Fig. 16. Concrete repair with shotcrete at a roof element

Fig. 17. Applied anode material (black conductive coating) on ribs, beams and roof elements

Fig. 18. Applied anode material (black conductive coating) on roof elements and ribs

Conductive coating, CAST^{Q}, was chosen as the anode material (Fig. 17 and 18). Approximately 1,000 m^{2} was thus provided with anode material and the system, divided into five zones (2 zones with roof edges and cantilever beams, 2 zones with façade beams with ribs and 1 zone with the roof superstructures). The works were delivered by Vogel BV on 1 June 2022 and all zones started up with an initial 2 Volt and were adjusted in steps up to 4 Volt. By December 2022, all zones were commissioned and the measured values are shown in Table 2.

Table 2: 24 h Depolarisation values measured Dec 2022



Zone	RE1	RE2	RE3	RE4	RE5	RE6	Voltage
1	299	141	205	299	415	331	4
2	200	defect	208	207	175	70	4
3	109	262	159	235	n.a.	n.a.	4
4	269	164	113	331	235	n.a.	4
5	225	121	145	145	n.a.	n.a.	4

During this period, the different zones were protected by a current ranging from 2 to 14 mA per square metre of anode area.

Figures 19 to 21 give an impression of the end result.

Fig. 19. The historical monument after renovation

Fig. 20 The main entrance of the campus

Fig. 21. The interior after the renovation

The system is currently being repaired after damage was caused by the construction work following the installation and commissioning of the CP system. After this work is completed, the system will be restarted at the site of the various zones.

2.5 Underground parking garage Bertolt Brecht in Nürnberg, Germany

The structure in question is a single-story underground parking garage with approximately 123 parking spaces spread over an area of around 3,400 m². The garage was constructed using reinforced concrete and features a load-bearing floor slab.

As part of a corrosion assessment, it was determined that the lower reinforcement layer of the ceiling is at significant risk of corrosion due to carbonation. The investigation revealed that carbonation depths had reached the reinforcement layer, threatening the structure's durability and long-term stability.

Due to the identified corrosion risk and potential durability concerns, a rehabilitation concept was developed in accordance with the TR Instandhaltung (Technical Maintenance Regulation) from May 2020.
Two rehabilitation methods were considered: Method 7.4 – "Realkalisation of carbonated concrete by diffusion to maintain or restore passivity". Method 10 – Cathodic Protection (CP).

After evaluating both durability and cost-effectiveness, Method 10: Cathodic Protection was selected. This method involves lowering the reinforcement potential via external polarization, reducing the corrosion rate to a technically negligible level. As a secondary effect, the alkalinity of the reinforcement environment is restored over the long-term operation of the CP system.

For this project, a conductive coating anode system - specifically the CAST^{Q} system from Composite-Anode-Systems GmbH - was implemented. A conductive coating system is the preferred solution when additional weight or an increase in component dimensions is not feasible, particularly when requirements for surface preparation and protective measures are minimal.

2.5.1 General Assessment of Corrosion Risk Due to Carbonation

Based on component-specific carbonation values (see Table 3) and a comprehensive survey of the concrete cover, the local corrosion risk for individual test points and the overall risk for structural groups were derived using statistical distributions of concrete cover thickness.

Table 3: Carbonation Testing of Ceiling Underside

Inspec. Point	Component	Carbonation K [mm]	Concrete Cover c [mm]	Corrosion Risk [K | BD | c]
K1	Ceiling FS/SP8	33	28	Yes
K2	Ceiling BP02	18	7	Yes
K3	Beam at BP03	24	21	Yes

A comparison of the localized test parameters, concrete cover, and carbonation levels revealed the following findings:

- At 3 out of 4 column test points, sufficient corrosion protection for the reinforcement against carbonation-induced corrosion is present.
- At all three wall test points, the reinforcement lacks sufficient corrosion protection against carbonation-induced corrosion.
- At the ramp base test point, the reinforcement also lacks sufficient corrosion protection against carbonation-induced corrosion.

- At all three ceiling/beam test points, there is insufficient corrosion protection for the reinforcement against carbonation-induced corrosion.

The average carbonation depths obtained from the measurements are used to assess the corrosion risk due to carbonation. The results of the concrete cover measurements (see Figure 23) in conjunction with the component-specific carbonation depth indicate:

- 56.6% of the ceiling reinforcement (concrete cover **c** ranging from 7 mm to 75 mm, with an average of 26 mm) is at risk of carbonation-induced corrosion (average carbonation depth: 25 mm).
- 45.9% of the beam reinforcement (concrete cover c ranging from 0 mm to 93 mm, with an average of 33 mm) is also at risk of carbonation-induced corrosion (average carbonation depth: 25 mm).

2.5.2 Preliminary Concrete Technology Investigation

The Potential Field Measurement Plan indicates that the majority of the measured areas exhibit positive potentials. However, in zones with visual anomalies, such as moisture penetration and efflorescence, more negative potentials are present, indicating an increased likelihood of corrosion.

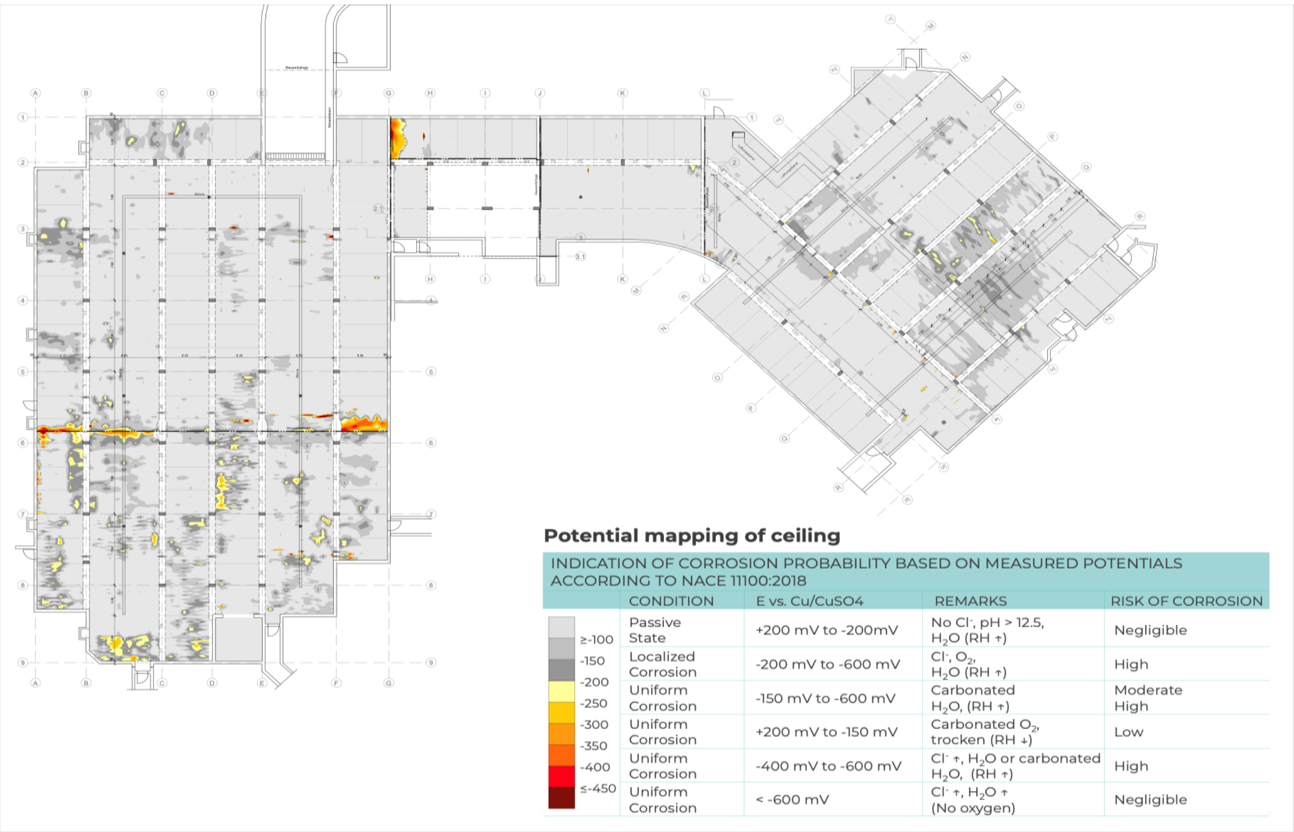
In the area of parking spaces 93/94, moisture penetration, efflorescence, and a crack are visible on the ceiling underside. The chloride levels at BP 02 (ceiling) and BP 03 (adjacent beam) are below the corrosion-inducing threshold, making chloride-induced corrosion unlikely.

Probes taken at BP 02 (ceiling) and BP 03 (beam) confirmed active corrosion processes in the reinforcement.

- These are attributed to concrete carbonation down to the reinforcement depth (carbonation depth: 18 mm / 24 mm).
- The presence of moisture, which contributes to the corrosion process.

In this context, reference is made to the statistical analysis of the concrete cover, highlighting the high proportion of reinforcement exposed to carbonation-induced corrosion risk.

The results further indicate that the penetrating moisture contains little to no chloride contamination. Only minor chloride accumulation was detected across all ceiling and beam test points.



Potential mapping of ceiling

INDICATION OF CORROSION PROBABILITY BASED ON MEASURED POTENTIALS ACCORDING TO NACE 11100:2018

	CONDITION	E vs. Cu/CuSO4	REMARKS	RISK OF CORROSION
≥-100	Passive State	+200 mV to -200mV	No Cl⁻, pH > 12.5, H_2O (RH ↑)	Negligible
-150	Localized Corrosion	-200 mV to -600 mV	Cl⁻, O_2, H_2O (RH ↑)	High
-200	Uniform Corrosion	-150 mV to -600 mV	Carbonated H_2O, (RH ↑)	Moderate High
-250 / -300	Uniform Corrosion	+200 mV to -150 mV	Carbonated O_2, trocken (RH ↓)	Low
-350 / -400	Uniform Corrosion	-400 mV to -600 mV	Cl⁻ ↑, H_2O or carbonated H_2O, (RH ↑)	High
≤-450	Uniform Corrosion	< -600 mV	Cl⁻ ↑, H_2O ↑ (No oxygen)	Negligible

Fig. 22. Potential Field Measurement Plan – Ceiling Underside

Fig. 23. Cover Measurement Plan - Ceiling Underside

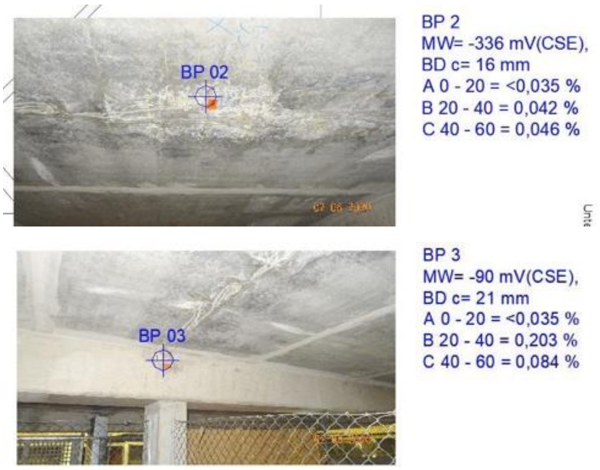


Fig. 24. Chloride Sampling Points (chloride wt.% per wt. cement)

Fig. 25. Image: Exploratory Openings

2.5.3 Repair measure

The TR Instandhaltung 2020 (Technical Maintenance Regulation Germany) outlines various repair methods for corrosion damage caused by carbonated concrete. These measures aim to restore the durability of the reinforced concrete structure and prevent future corrosion.

1) Reprofiling with carbonation-inhibiting mortar

- Damaged concrete areas are removed and replaced with a cement-based reprofiling mortar.
- These mortars have high alkalinity, which slows down the progression of carbonation.
- Suitable for surface-level damage of low to medium depth.

2) Surface Protection Systems (OS) According to DIN EN 1504-2

- Application of a coating system (e.g., OS 4, OS 5b, OS 11) to protect against CO_2 diffusion.
- These systems act as carbonation inhibitors, preventing further CO_2 absorption.
- Particularly useful in early carbonation stages, where reinforcement steel has not yet corroded.

3) Cathodic Protection (CP)

- Application of an electrochemical protection system stops steel corrosion through cathodic polarization.
- Especially effective for heavily carbonated concrete, where reinforcement steel has already undergone significant corrosion.

4) Concrete Replacement with CO_2-Resistant Concrete

- Complete replacement of carbonated concrete in damaged areas.

- Use of CO_2-resistant sprayed concrete or high-strength repair mortars.
- Suitable for deep carbonation with significant cross-section loss

5) Hydrophobization or Impregnation

- Application of a hydrophobic protective layer (e.g., silanes, siloxanes) on the concrete surface.
- Reduces the penetration of CO_2 and water.
- Primarily used as a preventive measure in combination with other repair methods.

2.5.4 Selected Repair Method

Due to the reinforcement's corrosion, a rapid and efficient repair was necessary. Since no additional weight could be applied and the electrical installations and ventilation systems were dismantled, the client opted for Cathodic Protection (CP) for economic and technical reasons.

Cathodic Protection (CP) is a proven method to prevent further corrosion by actively protecting the reinforcement steel. This process involves generating a cathodic polarization, which effectively halts corrosion. This method offers several advantages, including:

- No additional concrete application is required, ensuring the existing structural weight remains unchanged.
- Extensive concrete replacement measures do not complicate dismantling electrical and ventilation systems.
- The method provides long-term protection and is economically viable.

Implementing Cathodic Protection (CP) reliably restores the reinforced concrete structure's load-bearing capacity, significantly extending its remaining service life.

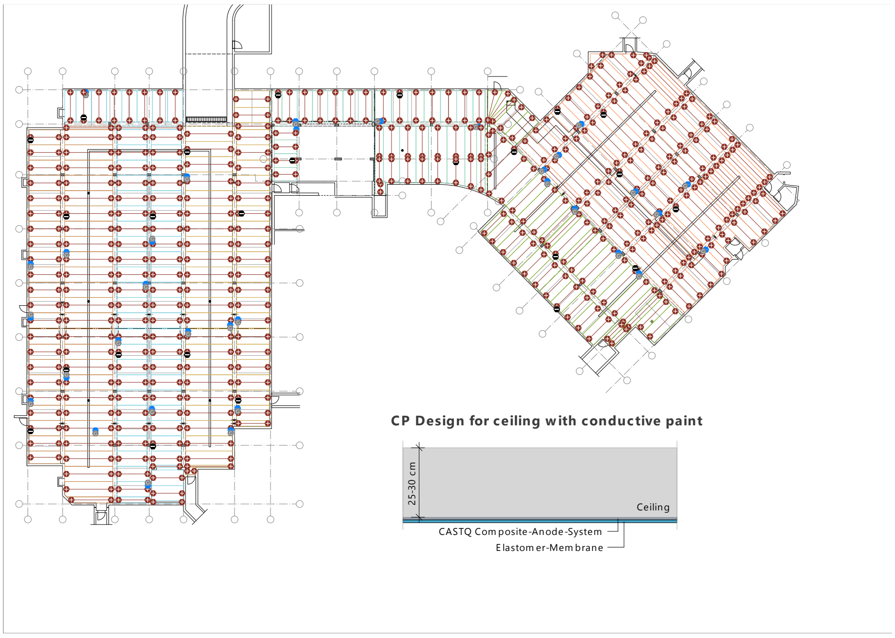


Fig. 26. CP Design plan

Fig. 27. Application of CAST^{Q}

Fig. 28. Application after hardening of CAST^{Q}

2.5.5 Performance Data according to DIN EN ISO 12696

The performance data of cathodic protection systems are assessed in accordance with DIN EN ISO 12696, which specifies the requirements for the electrochemical protection of steel in concrete. This standard defines key parameters such as:

- Protection potential: Ensuring that the reinforcement steel remains within the correct electrochemical range to prevent corrosion and be protected.
- Current density: Measuring the electrical charge applied to maintain protection.
- Depolarization values: Indicating the effectiveness of the cathodic protection system over time.
- Long-term system stability: Evaluating the durability and efficiency of the cathodic protection over extended periods.

2.5.6 Remote Monitoring and Visual Inspection

Traditionally, on-site manual inspections were required to verify performance data at different test points. However, most of these assessments are now conducted remotely with the integration of the Internet of Things (IoT) and Advanced ACTIVECONTROL Monitoring Systems.

Today, only localized visual inspections are performed on-site to check for physical signs of deterioration, while most performance monitoring and data analysis is carried out remotely through IoT-connected sensors. These advanced monitoring systems continuously track and adjust system parameters in real time, ensuring optimal corrosion protection without requiring frequent manual intervention.

This innovative monitoring approach enhances efficiency, accuracy, and cost-effectiveness while allowing for proactive maintenance before potential issues arise.

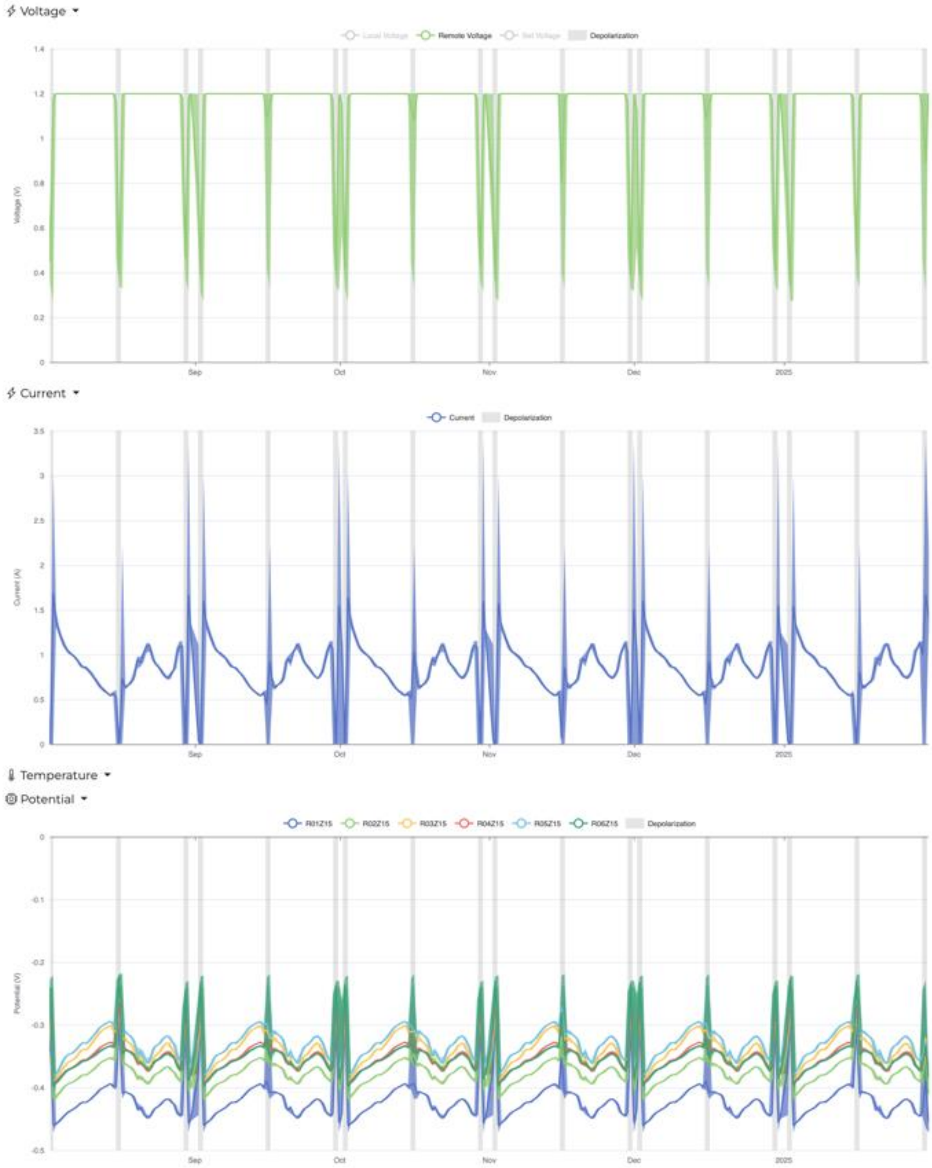


Fig. 29. Analysis of Output Voltage, Current, as well as Potential Measurements (Timeline August 2024 – February 2025)

Table 4: Exemplary Performance Assessment Data for Protection Area 15 (October 2024)

Unat = anode native potential vs. cathode
Uprot= anode protection voltage
Iprot = anode protection current
Iruprot = anode IR drop
Uinstoff = anode instant off
Udepol24h = anode depolarisation ≤ 24h
Udepol>24h = anode depolarisation > 24h

Enat = cathode native potential
Eprot = cathode protection potential
IRsensor = cathode IR drop sensor
Einstoff = cathode instant off
Edepol24h = cathode depolarisation ≤ 24h
Edepol>24h = cathode depolarisation > 24h

Name	Type	Unat	Uprot	Iprot	Iprot	Iru prot	Uinst off	Udepol 24h	Udepol > 24h	**Criteria**		
		[V]	[V]	[A]	[mA/m²]	[V]	[V]	[V]	[V]	**A**	**B**	**C**
Zone 15	Active control	0,120	1,197	1,123	2,042	0,000	1,197	0,875	0,881			
Name	Type	vs.Ag/ AgCl	Enat	Eprot	Irsensor	Einst off	Edepol 24h	Edepol >24h	Eoff 24h			
		[V]	[V]	[V]	[V]	[V]	[V]	[V]	[V]	[mV]	[mV]	[mV]
R01Z15	MnO_2 (NaOH 0,5 Mol/L)	0,164	-0.301	-0,445	0,000	-0,445	-0,148	-0,149	-0,297	**-445**	**148**	**149**
R02Z15		0,164	-0,278	-0,390	0,000	-0,390	-0,122	-0,123	-0,268	**-390**	**122**	**123**
R03Z15		0,164	-0,250	-0,371	0,000	-0,371	-0,129	-0,129	--0,242	**-371**	**129**	**129**
R04Z15		0,164	-0,267	-0,373	0,000	-0,373	-0,111	-0,112	-0,262	**-373**	**111**	**112**
R05Z15		0,164	-0,249	-0,356	0,000	-0,356	-0,116	-0,116	-0,240	**-356**	**116**	**116**
R06Z15		0,164	-0,245	-0,373	-0,001	-0,372	-0,142	-0,142	-0,230	**-372**	**142**	**142**

2.6 Kiosque Bosc - Montpellier

The Bosc Kiosk, located on Jean de Lattre de Tassigny Alley in Montpellier, France, is an iconic structure built in 1927 (Fig. 30). The kiosk exhibits a distinct architectural style, characterized by four octagonal columns supporting a circular beam and a reinforced concrete shell. Due to its exposure to environmental conditions over nearly a century, the structure has suffered significant corrosion caused by carbonation. An impressed current cathodic protection (ICCP) system using a carbon-based conductive coating, the CAST^Q Composite Quantum Anode, was implemented to ensure its long-term preservation while maintaining its original aesthetics.

Fig. 30. Overall picture of the Bosc Kiosk in Montpellier.

2.6.1 Corrosion Diagnosis and Structural Assessment

A thorough corrosion assessment was conducted in mid-2024, revealing advanced and widespread carbonation throughout the structure. The diagnostic report indicated that the carbonation front had surpassed the reinforcement depth, causing a decrease in concrete pH and initiating corrosion (figure 28). However, chloride contamination (0,01 – 0,02 wt.%/wt. cem.) was found to be below critical thresholds, ruling out chloride-induced corrosion as a contributing factor

Fig. 31. Cracks and spalling due to corrosion of steel rebars initiated by carbonation of their concrete cover.

The structural elements selected for cathodic protection with the CAST^Q Composite Quantum Anode System, include:

- Shell underside (210 m² of surface area).
- Circular beam connecting the hexagonal columns (35 meters of a complex-section beam).
- Network of structural beams above the roof framework (160 meters in total length).

The half-cell potential mapping and visual inspection highlighted widespread corrosion of steel rebars in concrete (Fig. 32). According to the Tuutti model [21], the degradation severity placed 80% of the structure in phase 3 (active corrosion propagation) and 20% in phase 4 (concrete deterioration).

2.6.2 Selection of the Protection Strategy

Simple patch repairs or localized galvanic anodes were deemed insufficient, considering the extent of carbonation. Instead, a comprehensive ICCP system utilizing a carbon-based conductive coating (Composite Quantum Anode System) was selected, ensuring long-term protection while preserving the structure's visual integrity.

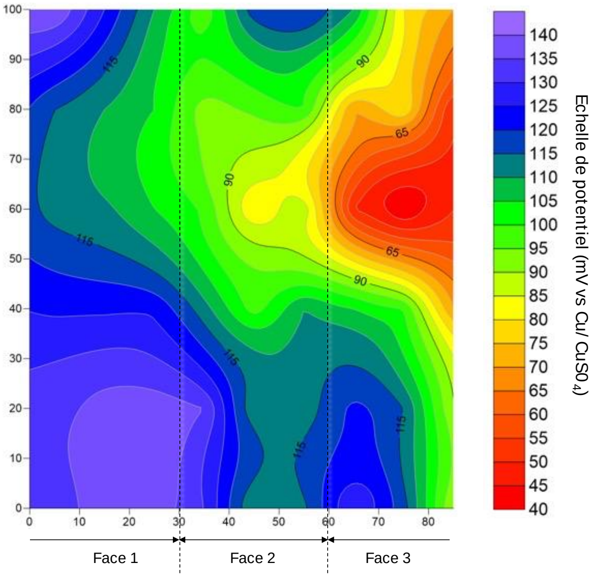


Fig. 32. HCP mapping of the circular beam (2 lateral faces and lower face) showing high corrosion activity.

Following the corrosion diagnosis, the rehabilitation process involved removing non-adherent concrete through chipping and installing sensors and connections to the reinforcement. These were routed to junction boxes equipped with double-membrane cable glands to ensure complete waterproofing of the connections.

One of the project's major challenges was restoring the continuity of the reinforcement. Indeed, no transverse reinforcement was continuous with the longitudinal reinforcement of the circular beam. To address this, an additional reinforcement bar was installed on the inner face of the beam and welded to each stirrup (Fig. 33). All missing concrete was reconstituted using repair mortar in compliance with the EN 1504-2 standard for concrete and mortar repair.

Fig. 33. Welding of the stirrups to an additional circular rebar to ensure steel continuity.

The conductive coating system was then applied as follows:

1) QAP 60 Primer application for enhanced adhesion and contact.
2) Installation of primary anodes (Ø 0,8 mm Cu/Nb/Pt wire):
   - Shell underside: Embedded in shallow grooves (Fig. 34).
   - Circular beam: Concealed in a corner of the complex beam section.
   - Roof structural beams: Positioned on the top surface without grooves, as these are not visible and thus do not require aesthetic treatment.
3) Secure connections using insulated splices to XLPE/XLPE cables embedded in the concrete, routed to the junction box (Fig. 35).
4) Application of two layers of CAST^{Q} paint ensuring uniform conductivity.
5) Final acrylic decorative coating to meet the architectural aesthetic requirements.

Fig. 34. Preparation of the grooves to dissimulate the XLPE/XLPE cables.

Fig. 35. Installation of one of the primary anodes.

This system is compatible with common exterior finishes, allowing aesthetic restoration while providing long-term protection.

2.6.3 Performance Design and Implementation

Performance verification was conducted using an advanced automated monitoring system capable of real-time data logging and analysis. The system continuously measured potential values from Mn/MnO₂ reference electrodes and decay probes across all protected zones. The ICCP system was designed to comply with EN ISO 12696 standards, incorporating embedded reference electrodes and decay probes for continuous monitoring. The required protection current was determined based on exposure class and corrosion severity:

- **5 mA/m²** for XC4-classified elements (circular beam, exposed structural beams).
- **2 mA/m²** for XC3-classified elements (shell underside, internal beams).

The effectiveness of the carbon-based conductive coating is optimized through careful spacing of the primary anodes, ensuring uniform current distribution. Given that the perimeter of the beam sections is less than 2 meters, a single primary anode was used per beam section for both the roof beams and the circular beam. For the shell underside, the surface was divided into two anodic zones, each treated with three primary anodes distributed evenly to ensure uniform protection (Fig. 36).

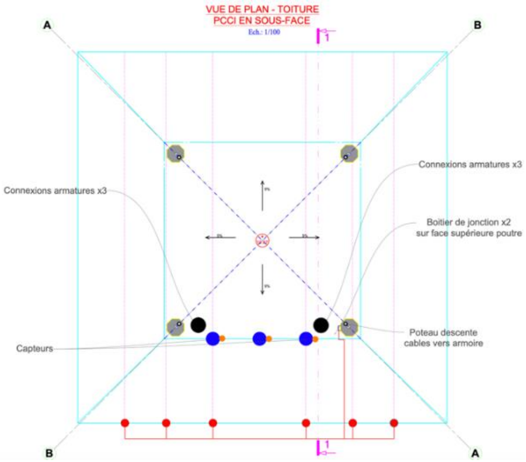


Fig. 36. Design of the shell underside – 2 anodic zones, 6 primary anodes.

2.6.4 Performance Assessment

System performance was verified through real-time data acquisition using an advanced automated monitoring system (Fig. 37). This system recorded potential values from Mn/MnO₂ reference electrodes and depolarization probes across all protected zones, ensuring a detailed assessment of the cathodic protection efficiency.

Depolarization measurements confirmed full compliance with criterion B of EN ISO 12696 in all monitored areas. The results demonstrated (Fig 38):

- Stable polarization levels before power shutdown.
- Consistent potential recovery curves after power interruption.
- Homogeneous distribution of protection current across all anode zones.

The monitoring system provided a comprehensive evaluation of the ICCP system's effectiveness, validating its ability to maintain reinforcement passivation and mitigate corrosion risks over time.

Fig. 37. Real-time data acquisition using an advanced automated monitoring system.

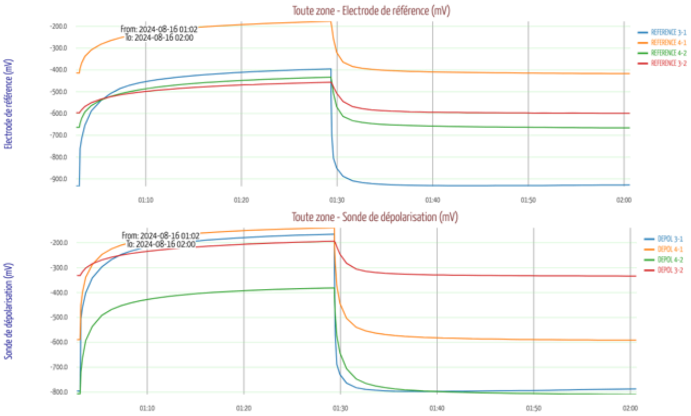


Fig. 38. Performance verification – depolarization data through reference electrodes and decay probes.

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