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KOROZJA I OCHRONA KATODOWA STALI ZBROJENIOWEJ W BETONOWYCH OBIEKTACH BUDOWLANYCH NARAŻONYCH NA ODDZIAŁYWANIA ATMOSFERYCZNE

CORROSION AND CATHODIC PROTECTION OF REINFORCING STEEL IN ATMOSPHERICALLY EXPOSED CONCRETE STRUCTURES

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Streszczenie

Stal zbrojeniowa jest kompatybilna z betonem nie tylko z powodu podobnej rozszerzalności temperaturowej, ale także ze względu na wysoką alkaliczność cementu Portlandzkiego, co pozwala na tworzenie się na powierzchni stali stabilnych warstw tlenkowych. Jeśli taka warstwa się wytworzy, może wystąpić korozja stali zbrojeniowej, która może osłabić, a nawet zniszczyć konstrukcję. Gdy warstwa ochronnych tlenków ulegnie destrukcji z powodu karbonizacji, lub działania chlorkowych zanieczyszczeń, ochrona katodowa może zapobiec korozji stali zbrojeniowej. W referacie omówiono przypadek praktyczny.

Abstract

Reinforcing steel is compatible with concrete not only because of similar thermal expansion properties, but also because the highly alkaline Portland cement concrete allows a stable, protective oxide film to form on the surface of the encased steel. If the film does not form or if it does not protect the steel, corrosion can occur. Corrosion of the reinforcing steel can weaken or even destroy a structure. Cathodic protection can prevent corrosion of the reinforcing steel and metallic embedments when the protective oxide film breaks down from carbonization or chloride contamination. A case history is discussed in this paper.

1. Introduction

Atmospherically exposed reinforced concrete structures such as bridges, parking structures, power poles, highway barriers, electrical vaults, etc. are subject to corrosion of the steel reinforcement from carbonation or salt contamination of the concrete. Corrosion protection is often not considered during the design and construction of reinforced concrete structures. Steel reinforcement corrodes readily when the pH of the concrete is less than 12.5. Lower pH values of concrete occur due to carbonation from atmospheric pollution or due to salt ingress. Around 450 BC when the Greeks were constructing the acropolis buildings of Athens, they were aware that steel corroded. To prevent damage to the stone work, they coated the steel ties securing the blocks with lead to prevent corrosion of the steel. Modern engineering dictates that reinforcing steel used in buildings or structures subject to chlorides be cathodically protected. Epoxy coated steel can be used. However, regardless of how much care is taken with the epoxy coated rebar, there will be coating damage and if it is not repaired, corrosion will ensue.

Fig. 1. Seventeen Year Old Building Being Demolished in Abu Dhabi due to Corrosion Damage

Corrosion of bridges, buildings, parking structures, etc. is costing billions of Euros annually around the world. Epoxy coating formulators are promoting epoxy coated reinforcement as the solution to corrosion of the reinforcement, but epoxy coating is only as good as the application and repair of damaged coating. The two major factors in reducing corrosion of the reinforcement in concrete structures are cover depth and concrete quality. Cathodic protection can be applied to existing structures as well as to new construction to reduce the corrosion rate. Atmospherically exposed concrete structures can have cathodic protection via a number of anode systems, such as:

– Mixed metal oxide coated titanium mesh, ribbon or wire,
– Platinum coated titanium or niobium,
– Conductive coatings, or
– Flame sprayed zinc or aluminum.

Cathodic protection of reinforced concrete is significantly different than cathodic protection of underground/underwater pipelines due to the alkalinity of concrete. Typically current required for cathodic protection of reinforcing steel in Portland cement concrete is perhaps one tenth of the current density required for cathodic protection of bare steel underground and may be as low as 2 mA/sq. M. Static potential of steel in the ground is approximately 450–550 mV. Static reinforcing steel to electrolyte potentials of steel in concrete where the pH of the concrete is greater than 13 falls in the range +200 to -200 mV with reference to $CuCuSO_4$ (mVcse) and are passive.

As cathodic protection current is applied to an atmospherically exposed concrete structure, the potential of the reinforcement initially becomes more negative then generally reverses direction and becomes less negative with time as the pH at the reinforcement increases and chloride ions migrate away from the steel reinforcement.

NACE Standard Practice SP0290-2007 states the following criterion for cathodic protection of reinforcement in Portland cement concrete.

"3.3.1.1 A minimum of 100 mV of polarization should be achieved at the most anodic location, typically in each 46 m2 (500 ft2) area or zone, or at artificially constructed anodic sites, in accordance with Paragraphs 3.1 and 3.2, provided its corrosion potential or decayed off-potential is more negative than -200 mVcse (versus a copper/copper sulfate reference electrode [CSE]). If the corrosion potential or decayed off-potential is less negative than -200 mVcse, then the steel is passivated and no minimum polarization is required".

It can be readily seen that applying additional current to try to achieve a 100 mV decay can have negative consequences on the structure with acid generation at the anode. It is vitally important that a static potential survey of the structure be undertaken before activating the cathodic protection system to provide base line potentials for comparisons with depolarized potentials to accurately determine the potential decay.

2. Case History

A bank in Saudi Arabia was designed by a French firm of architects and constructed by an Italian contractor in the mid 1980's. The bank remained unoccupied for approximately four years due to a dispute over payment. Soon after the building was occupied, there was evidence of corrosion and the concrete was delaminating in the underground section of the structure. The structure consisted of two underground levels supported by a three meter thick raft slab and exterior walls of approximately one meter thickness. At the site, the soil was sand and coral rock with brackish water approximately one meter below grade.

In the late 1980's, major renovation of the underground structure was undertaken by a Saudi contractor. The structure was failing before repairs were completed and results of a survey by a structural engineering firm specified further repairs with addition of cathodic protection. In 1992 tenders were called for this work.

3. Structural Repair

Cathodic Technology Limited, in a joint venture with United Saudi Contracting Est., were awarded the contract to repair the structure and install a cathodic protection system for the underground conventionally reinforced atmospherically exposed structure of the bank in Saudi Arabia. During the period November 1993 to April 1995 repairs were undertaken to the structure. Leaking cracks were sealed by epoxy injection. In specific prescribed areas, a cathodic protection system to protect the reinforcement was installed and activated after repairs were completed.

As delaminated concrete was removed, it became apparent that the reinforcing steel density and size of the reinforcement far exceeded the design drawings. This required several redesigns of the cathodic protection system to accommodate the larger current demand.

The cathodic protection system consisted of long life, low wear rate anode materials. Certain specific anode panels were of mixed metal oxide coated titanium embedded in a cementitious overlay. Other anode panels consisted of mixed metal oxide coated titanium ribbon embedded in saw slots in the floor slab. The third type of anode panels were of carbon and graphite loaded conductive coating. In areas where high steel density was encountered, a combination of the above anode materials was used along with probe anodes installed in cored holes in the slab.

Four rectifiers comprising 65 independent control zones powered the cathodic protection system. The computer controlled rectifiers supplied low voltage DC current to the anode panels. This DC current then flowed from the rectifier to the anode panels then through the concrete finally to be collected on the reinforcing steel where it returned to the rectifier. This DC current substantially reduced the corrosion rate of the reinforcement resulting in extended life of the structure.

Fig. 2. Electronically Controlled Multi-circuit Rectifier

This electronically controlled rectifier has eighteen individually controlled circuits capable of operating in constant current, constant potential or auto-potential modes and includes data logging and remote control.

During normal operation of the system, the rectifiers momentarily interrupted the DC current flow and logged the INSTANT OFF potential of the reinforcement as measured between the permanently installed silver-silver-chloride reference electrodes and the reinforcing steel at the programmed interval.

The computer-controlled rectifiers could be programmed to perform depolarization tests whereby the output current was halted for a period of time, usually seven days. The rectifiers logged the potential of the reinforcement as measured between permanent silver-silver-chloride reference electrodes embedded in the concrete at a programmed interval, usually every 10 minutes. Normal practice is an annual test.

4. Problems Encountered

The vault floor slabs were extensively delaminated. During the repair, it was discovered that there were three reinforcing mats installed one above the other, with rebar spacing of less than 75 mm. This presented a challenge in delivering sufficient current to the reinforcement to stop the corrosion of the reinforcement.

Water leakage through the walls had to be fixed prior to installation of the cathodic protection system. Over 3,000 meters of crack sealing by epoxy injection was undertaken to control the infiltration of water into the structure.

The silver-silver chloride reference electrodes specified had a smooth ceramic tip. This resulted in loss of contact between some of the reference electrodes and the non shrink grout used to embed the reference electrodes in the structure. The silver-silver chloride imbedded reference electrodes used had a potential with reference to hydrogen of +0.205 mV. The equivalent conversion to copper-copper sulphate required addition of 110 mV. The computer controlled rectifiers were programmed with the calibration value of each embedded reference electrode and automatically displayed and recorded the structure to electrolyte potential with reference to copper-copper sulphate.

Extensive water leakage through shrinkage cracks in the concrete resulted in some damage to the conductive coating on some anode panels. This problem was mitigated as the active cracks were discovered and sealed with epoxy injection.

Flooding in the structure occurred randomly due either to burst pipes or heavy rain which occurred infrequently in Saudi Arabia. The flooding damaged some of the anode panels but particularly the conductive coating anode system.

Repair of the structure was undertaken by poorly trained imported labor which required constant supervision and encouragement to work effectively.

5. Effectiveness of the Cathodic Protection System

The cathodic protection system was activated in 1994 and 1995 and until termination of the inspection and adjustment contract in 2009, there was no evidence of corrosion damage to the structure where cathodic protection was applied and operational. Considering that the structure built in the mid 1980’s, repaired in the late 1980’s and early 1990’s, then operated for 15 years without damage due to corrosion after activation of the cathodic protection system shows that a well maintained cathodic protection system will save millions of dollars in repairs over it’s life time.

Shortly after activation of the cathodic protection system, a significant increase in resistance of some of the anode panels was documented. The flow of cathodic protection current in the structure was polarizing the steel and increasing the pH at the reinforcing bar interface with the concrete. In addition, the current flow acted as an electro osmotic system drying the concrete and increasing the resistance of the anode circuits. This was evidenced by the reduction in evident moisture in the structure.

Where the concrete had low moisture content and was porous allowing oxygen ingress, depolarization of the reinforcing steel was rapid. In contrast, where the concrete was moist or oxygen was restricted from the concrete, depolarization of the reinforcing steel took weeks.

The vault floor slab contained three reinforcing mats in close proximity and was protected by mixed metal oxide coated titanium mesh supplied with DC current from the multi-circuit cathodic protection rectifier. The titanium mesh was embedded in a cementitious grout with an overcoat of 6 mm of epoxy. The graphed potentials recorded with reference to a silver-silver chloride reference electrode are Instant Off values.

Figure 3 is a graph of the reinforcement potential as the polarization of the reinforcing steel decayed with time. The initial instant off potential was recorded at -380 mV with reference to copper-copper sulphate (cse). The potential of the reinforcing steel was recorded every 10 minutes over a seven day period. At the end of the seven day depolarization, the decayed potential was -237 mV reference to cse. The above potential decay meets the NACE SP0290-2007 criterion of 100 mV decay where the decayed potential is more electronegative than -200 mV. The reinforcing steel in the floor slab was slow to decay as oxygen ingress was restricted by the thick epoxy wear surface.

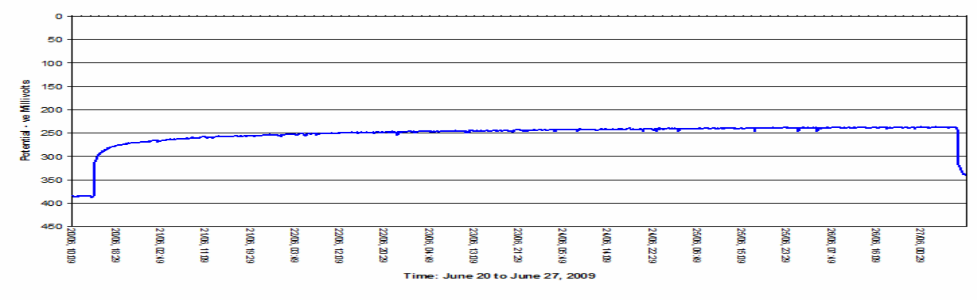

Fig. 3 Depolarization of Reinforcing Steel in Vault Floor SlabMesh Anode

Another example of polarization decay are the truck ramp walls which are protected by mixed metal oxide coated mesh in a cementitious overlay. The initial instant off potential as measured to an embedded silver-silver chloride reference electrode was -400 mV cse and after 24 hours the polarized potential of Reference #3 had decayed to -230 mV indicating a potential decay of 170 mV. After 12 noon on the 22 of June 2009, the potential trended towards a more negative value, perhaps indicating that corrosion had reinitiated. See Figure 4.

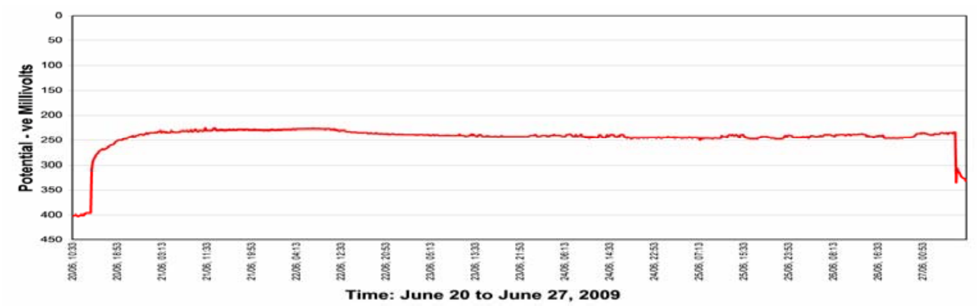

Fig. 4 Truck Ramp Walls

The other embedded reference electrodes in this reinforced concrete wall (Reference electrodes 1,2 and 4) have all failed probably due to lack of contact with the cementitious grout.

Figure 5 shows the seven day depolarization of the reinforcing steel in a section of floor slab where the reinforcing steel outside of the vault was protected by conductive coating. The initial instant off potential was -91 mV for embedded reference Number 1 and -55 mV for embedded reference Number 2 cse. After 24 hours, the reinforcement at reference Number 1 had decayed to -60 mV and reference Number 2 to -38 mV. After seven days the instant off potentials were recorded at -53 mV cse for reference Number 1 and -36 mV cse for reference Number 2. Thus the reinforcing steel in the vicinity of reference Number 1 depolarized 38 mV and at reference Number 2 depolarized 19 mV. The depolarized potential is less negative than -200 mV cse. The NACE International SP0290-2007 criterion for protection of 100 mV decay does not apply in this case.

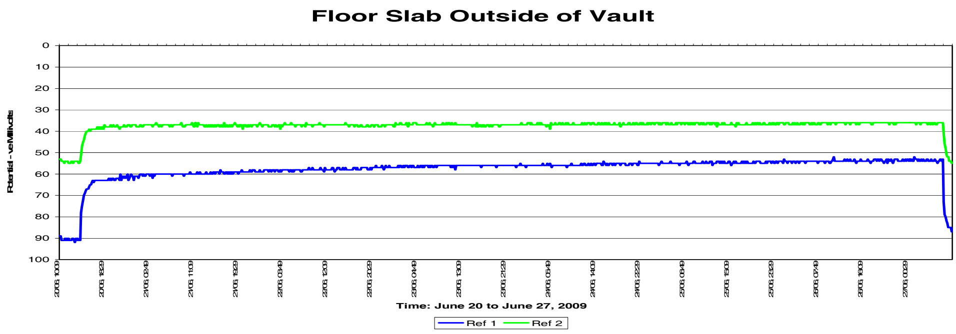

Fig. 5 Depolarization of reinforcing steel - anode material conductive coating

Figure 6 shows the depolarization of a different area of floor slab where the reinforcing steel is probably passive, exhibiting depolarized potentials of -40 to +10 mV cse. The NACE International Standard Practice SP0290-2007 in this case does not require a 100 mV polarization decay as the depolarized potential is in the -40 to +10 mV range.

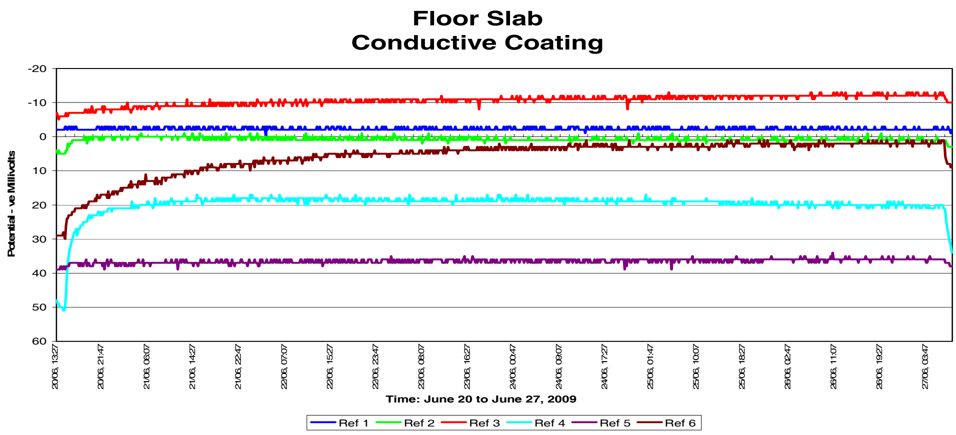

Fig. 6 Depolarization of reinforcing steel - anode material conductive coating

6. Conclusions

In conclusion, after 15 years experience with cathodic protection on a steel reinforced atmospherically exposed concrete structure, it is apparent that cathodic protection can significantly reduce corrosion of the reinforcing steel in chloride contaminated concrete structures, thus prolonging their life. Cathodic protection is a proven cost-effective method to reduce corrosion.

When cathodic protection is applied to an atmospherically exposed steel reinforced concrete structure, the depolarized potential becomes less negative with time perhaps indicating that the pH at the reinforcing steel is increased, probably due to migration of the chloride ion away from the steel concrete interface.

It is also apparent that the current required for cathodic protection of steel reinforcement in atmospherically exposed concrete structures is much lower than initially thought and may be as low as 2 mA per meter square of steel. Many cathodic protection specifications specify current densities 10 to 20 times that required and may cause significant damage to both the anode system and the concrete structure.

References

[1] NACE International RP0290-90 Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures (original Recommended Practice which is updated by SP0290-2007).

[2] NACE International SP0290-2007 (or Latest Revision) Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures.

[3] NACE International SP0390-2007 (or Latest Revision) Maintenance and Rehabilitation for Corrosion Control of Atmospherically Exposed Existing Steel Reinforced Concrete Structures.

[4] NACE International SP0308-2007 (or Latest Revision) Inspection Methods for Corrosion Evaluation of Conventionally Reinforced Concrete Structures.

[5] ASTM C876 (or Latest Revision) Standard test methods for half cell potentials of uncoated reinforcing steel in concrete.