Item No. 24224 NACE International Publication 01105



This Technical Committee Report has been prepared By NACE International Task Group 047* on Concrete and Rebar

Sacrificial Cathodic Protection of Reinforced Concrete Elements— A State-of-the-Art Report

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Foreword

The purpose of this technical committee report is to present state-of-the-art information on several commercially available galvanic cathodic protection/prevention systems for protecting atmospherically exposed reinforced concrete structures. A summary of these systems is presented in Appendix A. It is beyond the scope of this report to fully address all factors associated with design, criteria, implementation, quality control, cost, maintenance, and monitoring of these systems. The information contained in this report has been provided by key manufacturers of these systems and is intended as a technical resource for engineers responsible for the rehabilitation of reinforced concrete structures. It may also be useful to owners, contractors, and other practitioners related to the field of galvanic cathodic protection (CP). All information as it relates to galvanic CP is intended for atmospherically exposed concrete structures and is not applicable to concrete containing epoxy-coated reinforcing steel, galvanized, or other coated or nonferrous reinforcement. Galvanic CP has also been successfully applied to buried or submerged reinforced concrete structures; however, this aspect is not addressed in this state-of-the-art report.

This NACE technical committee report was prepared by Task Group (TG) 047 on Sacrificial Cathodic Protection of Reinforced Concrete Elements. This TG is administered by Specific Technology Group (STG) 01 on Concrete and Rebar. It is also sponsored by STG 05 on Cathodic/Anodic Protection. This report is issued by NACE International under the auspices of STG 01.

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NACE technical committee reports are intended to convey technical information or state-of-the-art knowledge regarding corrosion. In many cases, they discuss specific applications of corrosion mitigation technology, whether considered successful or not. Statements used to convey this information are factual and are provided to the reader as input and guidance for consideration when applying this technology in the future. However, these statements are not intended to be recommendations for general application of this technology, and must not be construed as such.

Introduction

Over the past several decades the corrosion of steel reinforcement embedded in concrete structures has received considerable worldwide attention. In theory. concrete and reinforcing steel are very compatible. They have similar coefficients of thermal expansion. Concrete, because of its highly alkaline nature, creates a protective environment for the steel. Studies have shown that corrosion activity and damage result when critical quantities of aggressive ions penetrate through the concrete pore structure by diffusion and other transport phenomena and reach the embedded steel reinforcement. At this time, the naturally occurring passive film developed by highly alkaline concrete becomes saturated with these ions, eventually breaking down this protective layer. In regions of low resistance, aggressive ions, mostly in the form of salts, attack the passive film and develop localized anodic sites (pits) on the surface of the steel. Immediately adjacent to these anodic sites are oxygen-rich regions that cathodically "fuel" the corrosion reaction. As active corrosion proceeds, the lower pH in and around the anodic sites reduces the passive layer in greater proportions, making it more prone to iron oxide (Fe₂O₃) development. Because Fe₂O₃ (rust) is much more voluminous than solid steel, it imparts considerable tensile forces within the concrete matrix and eventually leads to cracking of the concrete cover.

There are several approaches that have been used to rehabilitate concrete structures suffering from the effects of corrosion damage. The most widely used approach typically involves removing the damaged concrete in and around the affected area and replacing it to the original dimension. The principal intent of this remove-and-replace approach is to return the form and function of the structure. Although this strategy is widely used, it rarely incorporates the complete removal of contaminated areas that surround the damaged region, and is sometimes regarded as only a

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Anodic Polarization: The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface. (See *Polarization*.)

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

short-term solution. Modifications to this technique include expanding the area excavated to include sound but chloride-contaminated or carbonated concrete, or to include areas where the steel-reinforcement potential is more negative than a defined threshold.

The remove-and-replace approach is normally broken into two general categories. The first is patch repair, and the second is rehabilitation. Patch repair is a short-term solution that makes no attempt to extend the structure life, but merely restores concrete back to dimension. The rehabilitation technique attempts to return the distressed area to uniformity with the pre-existing conditions and normalizes any conditions of further distress. The rehabilitation technique carries with it some expectation of an increase in service life. In some applications, a corrosion inhibitor is included either as an additive to the repair/replacement concrete mix or as a post treatment. These methods of concrete repair are much more involved than discussed in this report and are well integrated into most structure owner agencies and the civil engineering community.

Alternatively, CP applies electrochemistry to halt the corrosion process or reduce it to levels below engineering significance. Cathodic protection is an electrochemical technique used to reduce the corrosion of metallic materials. This is accomplished through the addition of a cathodic current to the metal-electrolyte system so as to increase the rate of the cathodic reaction (the formation of hydrogen [H₂] or hydroxide [OH]) on the metal being protected, and at the same time decrease the rate of the anodic reaction (metal dissolution). The source of this cathodic current is immaterial to the protection process, and can come from direct current (DC), alternating current (AC), or galvanic sources.

Definitions

Cathodic Prevention: The application of cathodic polarization to passive steel to prevent or delay a transition to the actively corroding condition.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Conductive Concrete: A highly conductive cement-based mixture containing coarse and fine coke and other material used as an impressed current anode on reinforced concrete surfaces.

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Current: (1) A flow of electric charge. (2) The amount of electric charge flowing past a specified circuit point per unit time, measured in the direction of net transport of positive charges. (In a metallic conductor, this is the opposite direction of the electron flow.)

Current Density: The current to or from a unit area of an electrode surface.

Depolarization: The removal of factors resisting the current in an electrochemical cell.

Dissimilar Metals: Different metals that could form an anode-cathode relationship in an electrolyte when connected by a metallic path.

Electrochemical Cell: A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

Electrochemical Potential: The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all other factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electrical as well as chemical contributions to the free energy.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field.

Embrittlement: Loss of ductility of a material resulting from a chemical or physical change.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Half-Cell: A pure metal in contact with a solution of known concentration of its own ion, at a specific temperature, develops a potential that is characteristic and reproducible; when coupled with another half-cell, an overall potential that is the sum of both half-cells develops.

Half-Cell Potential: The potential in a given electrolyte of one electrode of a pair relative to a standard state or a reference state. Potentials can only be measured and expressed as the difference between the half-cell potentials of a pair of electrodes.

Humectant: A substance that promotes retention of moisture.

Hydrogen Embrittlement: A loss of ductility of a metal resulting from absorption of hydrogen.

Hydrogen Overvoltage: Overvoltage associated with the liberation of hydrogen gas.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

Metallizing: The coating of a surface with a thin metal layer by spraying, hot dipping, or vacuum deposition.

Overvoltage: The change in potential of an electrode from its equilibrium or steady-state value when current is applied.

Passive: (1) The positive direction of electode potential. (2) A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product.

pH: The negative logarithm of the hydrogen ion activity written as:

$$pH = -log_{10} (a_{H}^{+})$$

where $a_{H}^{+} =$ hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion-activity coefficient.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarization Decay: The decrease in electrode potential with time resulting from the interruption of applied current.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Relative Humidity: The ratio, expressed as a percentage, of the amount of water vapor present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

Resistivity: (1) The resistance per unit length of a substance with uniform cross section. (2) A measure of the ability of an electrolyte (e.g., soil) to resist the flow of electric charge (e.g., cathodic protection current). Resistivity data are used to design a groundbed for a cathodic protection system.