A Review of Cathodic Protection in Repairing Reinforced Concrete Structures

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ABSTRACT

Corrosion of steel in concrete structures is an electrochemical process and it occurs when material's property losses over time due to concrete is exposed to corrosive environments. Cathodic Protection (CP) is a method to repair reinforced concrete structures by making the embedded steel reinforcement cathodic. Impressed Current Cathodic Protection (ICCP) offers flexibility and durability since it is able to deliver essential current in a condition where high resistivity of the reinforced concrete structures. A continuous direct current power supply is needed in order for the ICCP system to be operated. This paper focuses on the review of CP systems for RC structures and the potential of using the cement battery in delivering power to the ICCP system toward reducing the energy consumption. The optimum power generated is discussed as to satisfy the standard current density required for ICCP system.

Keywords: *Corrosion, Cathodic Protection, Reinforced Concrete, Power Supply, Energy Consumption.*

Introduction

Steel corrosion in concrete structures continues to be the main concern in the construction industry where it can eventually affect the structural performance and integrity. Corrosion is an electrochemical process and it occurs when steel in concrete structure is deteriorating after being exposed to the corrosive environment [1]. The mechanical properties of steel in terms of its bond strength is loss due to corrosion effect. Cathodic protection is a technique used

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to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. This process can be used to repair reinforced concrete structures especially bridges and jetties by the embedded steel reinforcement cathodic. This method has been proven to stop the existing of corrosion in reinforced concrete structures, regardless of the chloride content in the concrete [2]. CP reduces the corrosion rate by cathodic polarization of a corroded metal surface [3]. The application of CP can lead to the formation of a deposit on the steel which give surface changes on steel in concrete when it is submerged in seawater and a protective oxide (magnetite, Fe_3O_4) causes the corrosion rate to be reduced [4]. CP divided into two types which are sacrificial anode system (SACP) and impressed current cathodic protection (ICCP). SACP system consists of an external sacrificial anode such as metal with larger electrode potential than steel, electrically connected to the steel reinforcement. ICCP consists of an anode system that corrodes at a very slow rate, an external current power supply to force a small amount of electric current through the reinforcing steel to counteract the current flow from the corrosion effect and also a monitoring system. Both methods of CP are practicable to use in repairing RC structures, but the ICCP system gives better flexibility and durability [5] due to the current output which can be adjusted in order to deliver an essential current in conditions in the high resistivity of concrete structures. The selection of anode systems also important which contributes to the durability of the system due to the removal of damage reactions from the steel to the installed anode. However, the application of ICCP leads to high energy consumption from the continuous direct current (DC) power supply for the system. Differ to SACP system, where it depends only on the average current output of the anodes that have the larger electrode potential than the steel. Anode materials for the ICCP system include conductive coatings, titanium based mesh in cementitious overlay, conductive overlay with carbon fibers, flame-sprayed zinc, and discrete anode systems [5]. However, the most currently anodes used are not proof to be effective and suitable for the selection of anode materials, mostly depends on the life of the structures, types of corrosion and construction, anode installation methods, operation and requirement of regular maintenance and life cycle cost of the CP system [6]. Zinc is generally used as sacrificial protecting coating since it is less noble than most common metal [7] and able to protect the reinforcement from corrosion. Zinc-rich paints (ZRP) is an alternative to hot-dip galvanizing (HDG) where it is widely used as an anticorrosion paint on steel substrates. Two types of zinc-rich paints (ZRP) which are organic (binder-epoxy) and inorganic (binder-silicate) coating. Organic coating of ZRP is easier to top coat and are compatible with more coatings due to their denser surface compared to inorganic coating which requires more expertise to carefully monitor the ambient temperature in order to assure appropriate inorganic zinc curing before top coating. Bond strength can be an important role to evaluate the existing structures, especially when steel corrosion is predictable [8]. The structural performance can reduce when the steel in concrete is corroded due to the reduction of bond strength between steel embedded in the concrete surface as the steel have loss its property.

This paper briefly reviews on steel corrosion process in RC structures, cathodic protection systems for RC structures, anode systems of cathodic protection, corrosion monitoring technique and power supply used in the conventional ICCP system. This paper also highlights on the possibility of using cement battery to constantly power the ICCP system, in order to generate optimum and sustainable energy towards reducing the high energy consumption.

Steel Corrosion in Reinforced Concrete Structures

Corrosion occurs when steel in concrete structure is deteriorating after being exposed to the environment that can cause the steel to be corroded [1]. Corrosion is an electrochemical process where the current flow out of a structure at the anode site, flow through an electrolyte, and returns to the structure at the cathode site. Electrons are transferred between the anode and the cathode by means of an electrically conductive solution known as the electrolyte [9]. Figure 1 shows a diagram of the steel corrosion process at anode and cathode.

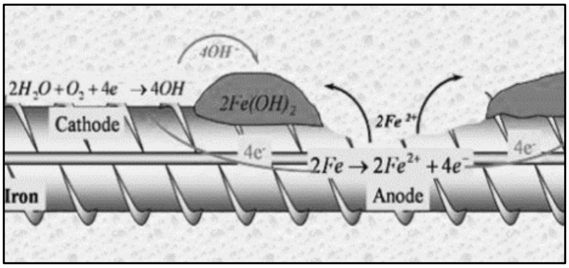

Figure 1: Diagram of the steel corrosion process [10].

The process of anodic and cathodic can be written as in Equation (1) and Equation (2), respectively.

Anodic: $$2Fe \rightarrow 2Fe^{2+} + 4e^{-} \quad (1)$$

Cathodic: $$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \quad (2)$$

The combination of two separate reactions to produce iron (II) hydroxide as in Equation (3) which further oxidized forms iron (III) hydroxide as in Equation

(4). Equation (5) is shows the dehydration of iron (III) hydroxide that form $Fe_2O_3.nH_2O$ which called as rust. The equations are written as follows:

(Iron (II) hydroxide) (3)

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \text{ (Iron (III) hydroxide)} \quad (4)$$

$$Fe(OH)_3 \rightarrow Fe_2O_3.nH_2O \text{ (Rust)} \quad (5)$$

Steel in reinforced concrete structure is protected from corrosion by a passive oxide film, which created from alkaline Portland cement around the steel reinforcement bars. However, carbonation or chloride induced could contaminate the concrete around the steel bar which cause corrosion and resulting a weakened or destroyed of the oxide film. The further corrosion process can cause cracking and spalling of the concrete. The presence of high concentration of hydroxide of calcium, potassium and sodium from the cement hydration caused the concrete pore solution to be highly alkaline (pH 12.6-14) [10]. Corrosion is generally stopped by films (or protective layers) containing of corrosion products or adsorbed oxygen and the rate of corrosion on steel surfaces can be reduced with high alkalinity of water. Steel corrosion in RC structures can be stopped or reduced by using an existing method of repairing such as cathodic protection.

Cathodic Protection

Sacrificial Anode Cathodic Protection (SACP)

SACP system consist of an external sacrificial anode such as metal with larger electrode potential than steel reinforcement electrically connected to another metal that becomes the anode as shown in Figure 2.

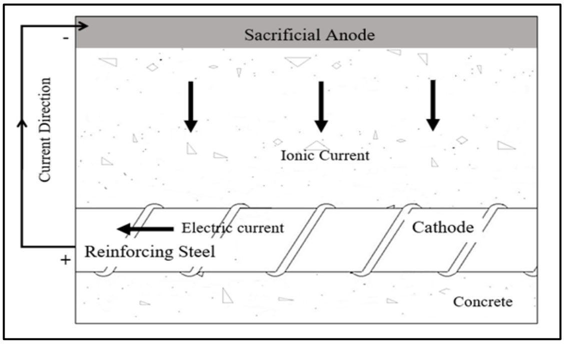

Figure 2: Circuit diagram for SACP system.

However, galvanic anodes normally cannot economically provide enough current because of high concrete resistivity. Therefore, impressed current cathodic protection (ICCP) is used [5] to repair the RC structures. This method is considered more expensive and it requires a constant low direct current (DC) power supply to impressed current for the system.

Impressed Current Cathodic Protection (ICCP)

In the case of ICCP, an external power supply is used to force a small amount of current through the reinforcing steel to counteract the flow of metal which normally platinum as a node that the rate of corrosion is slow as shown in Figure 3. External anode will deliver electrons to the steel reinforcement in the RC structures in order to make the steel become cathodic and to prevent further corrosion [11]. A real system in practical applications will normally include DC power supply, cabling, and monitoring devices [5].

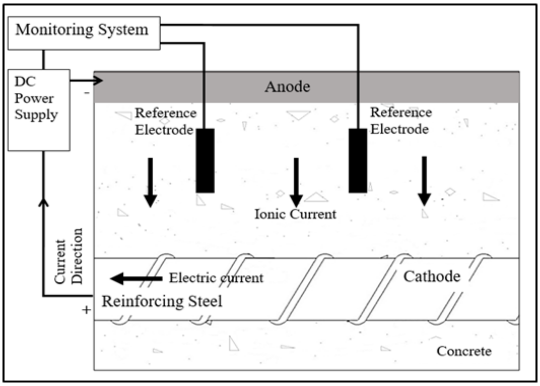

Figure 3: Circuit diagram for ICCP system.

ICCP is ideally used for large structures where galvanic CP would not be able to economically provide a sufficient level of current to ensure full protection. The ICCP is commonly used in concrete structures due to its ability in delivering high voltages compared to the SACP. Normally, a 1-5A and 2-24V of DC power supply will be used to each independently controlled anode zone [5]. It is important to ensure that the protected metal and anode have to be in contact through an electrolytic medium (concrete) in order to allow the path and flow of current through the application of the ICCP. The presence of pore solution which acts as electrolyte helps the current to pass through, although concrete has high electrical resistance.

Comparison of Cathodic Protection Methods

Cathodic protection has more advantages in repairing RC structures compared to other methods since it allows less concrete removal and repair work, variety of anode systems, and less monitoring and inspection time [12]. Though, it is important to consider hydrogen embrittlement in the steel, alkali-silica reaction in aggregates and interactions with adjacent structures during the application of the method ICCP is better in terms of flexibility and durability compared to SACP system [5]. Table 1 compares the advantages and disadvantages of the SACP and ICCP for reinforced concrete structures.

Table 1: Advantages and disadvantages of SACP and ICCP [5,13]

Method	Advantages	Disadvantages
SACP	• Easy to design and install • It does not require external power source • It does not require a control system	• High-resistance environments is impossible and rare i RC • Current cannot be controlled and limited • Degree of protection cannot be determined • Anodes need to be added if current requirement change • Requires a regular visual and delamination survey to monitor the condition
ICCP	• High-resistance environments is applicable • Current output can be adjusted • Cost saving due to minimal concrete removal • Can be applied to specific elements	• Continuos of DC power supply is required • Need monitoring system • Higher risk of interaction

Although the ICCP system is more applicable especially for concrete with high resistance environment, it requires continuous direct current (DC) power supply. Besides, it is important to ensure that the anode material used in the ICCP system has a good electrical conductor, low rate of corrosion, good mechanical properties, cost-effective, readily fabricated in a variety of shapes, easy to install and able to withstand high current densities.

Anodes System Of Cathodic Protection

Rapid development in technology promotes the industry to search for better anode material to be used in CP system. Anode materials that normally used for ICCP include conductive coatings, titanium based mesh in cementitious overlay, conductive overlay with carbon fibers, flame-sprayed zinc and discrete anode systems [5]. Jeong and Jin [14] found that zinc bulk anode is suitable for SACP while Ti-ribbon anode for ICCP. ICCP anode system must have good electrical conductors, low rate of corrosion and the ability to resist high currents without forming resistive oxide layers [15]. The anodes with spacing of 0.45m are enough to protect corroding reinforcement in most exposure conditions, even in thin parts of element [16]. Nevertheless, the electrical resistivity of concrete and corrosion rate of bars influenced by moisture content in concrete where the decrease of resistivity can increase moisture content up to 1 per cent [17]. The titanium rod anode is more effective to be used in freshwater while titanium mesh anode seems to be more effective to be used in atmospheric condition [14]. A thin layer of semi-conductive material combined with a mixed metal oxide-coated titanium tape anodes can solve the poor CP current distribution, acid generation at the anode-concrete interface and dryness of the anode-concrete interface for some structures [18]. However, MMO-Ti mesh anode is effective in atmospheric condition with depolarization potential more than 100mV compared to MMO-Ti-ribbon and MMO- Ti-Rod [14]. However, the interface between cementitious overlay and bearing shelves in the case of the MMO/Ti anode turns a potential point of weakness as excess seepage can potentially cause freeze or thaw action [5].

Carbon fiber reinforced polymer/plastic composes of carbon fibers and epoxy matrix which widely used as a structural strengthening material also can serve as ICCP anode material [19]. The bonding at the CFRP rod anode and concrete interface was improved by using a combination of geopolymer and epoxy resin and as a result increased in ultimate strength [20]. CFRP could improve the load-carrying capacity and durability of RC structure and stably in pore solution performance maintained for 50 days of polarization current densities of $6.15 A/m^2$ [21]. The U-shape wrapping of CFRP fabric as anode bonded with epoxy resin and it's capable to operate at very high current densities more than $128 mA/m^2$ [22]. However, although CFRP is less expensive compared to titanium anodes [2] yet it is not easy recyclable.

The multi-scale carbon-admixtures can be used as anode for ICCP in order to improve the conductivity of the cementitious composites [23]. The different carbon-textiles anodes and different mortar mixtures could provide high mechanical properties and also conducted for the CP of steel in concrete [24]. Anwar et al. [25] found that lightweight cementitious overlay mortar as anode consists of pumice aggregates, carbon fiber and cement with MMO-Ti (primary anode) gives high conductivity value of 0.20 S/cm and by adding pumice and carbon fiber and potential value of 600mV to 2.5V. However, concrete overlays may provide disadvantages with the added dead load problems which can cause instability of existing structures and it is required for anode material to be covered all concrete surfaces that require protection

[2]. The application of three layers of ZRP coatings as anode material able to withstand high current densities which more than 300mA/m^2 [26]. By conducting coating anode consist of graphite powder and cement-graphite cement paste gives current density of 25.5mA/m^2 [27]. However, the conductive coating anode cannot tolerate water during installation or prolonged wetting during operation [5] and also cannot tolerate abrasion. The adhesion of coating application should be concerned to ensure that the anode coating material can have a longer lifespan. Zinc is generally used as sacrificial protecting coating in process industries, constructions and buildings due to less noble than most common metal [28,7]. Thus, zinc is able to protect the steel from corrosion. The paint coatings are commonly used to provide a barrier between the substrate such as steel or concrete and the environment [29]. The optimum thickness of metallic zinc is generally between 0·1 mm and 0·4 mm [30].

Coatings can be classified into two which are organic and inorganic coatings. The zinc dust can be in spherical or lamellar shape or a combination of both is dispersed in an inorganic or organic binder [31]. The difference between organic and inorganic coatings is the binder, normally epoxy for the organic and a silicate for the inorganic. Organic coatings are most widely applied method of corrosion protection of metallic materials in transport and infrastructure [29]. Organic anode coatings are applied by brush, roller or air spray to thicknesses of 0.25-0.50 mm [30]. Disbandment can caused by common failure mechanisms such as loss of adhesion of the coating due to anodic reaction products, which may be acidic to the alkaline concrete [30]. However, according to Sofian and Noda [32], the application of an epoxy coating to a substrate pre-treated with 3-glycidoxyy propyl silane can increase the wet adhesion and improved resistance to cathodic disbonding.

Zinc-rich paints (ZRP) is an alternative to hot-dip galvanizing (HDG) where it is widely used as an anticorrosion paint on steel substrates. It can be applied as an undercoat or top coat, and also as a touch-up coat on galvanized steel to provide corrosion protection of steel in mild corrosive environments [33] - [35]. ZRP are used for the prevention of corrosion when they have direct contact with aggressive matters such as caused by the seawater [36]. It has also been efficiently used to protect steel structures fully and/or partially submerged in chloride water [37]. Organic coating of ZRP is easier to top coat and are compatible with more coatings due to their denser surface compared to inorganic coating which requires more expertise to carefully monitor the ambient temperature to assure appropriate inorganic zinc curing before top coating. Auxiliary pigments added must be controlled in order to avoid damage of the film's physical and chemical characteristics.

The corrosion protection behaviour of zinc rich epoxy paint on steel substrate with coating thicknesses of 80µm in 3% NaCl solution and after 180 days zinc content with more than 80% continue to provide cathodic protection effect [38]. However, by adding 5-10% nanoparticulates zinc extended the galvanic action of the coating compared to standard zinc-rich coating [39]. The micaceous iron oxide, MIO particles could improve the cathodic protection duration of the zinc-rich coating by improving its barrier properties and reducing the zinc particle oxidation rate [40]. The coatings of the silicate base of ZRP are not fit as well to each other and better to coat the metal substrate using an organic ZRP [28]. The protection of metallic structures by using ZRP have recognized as excellent paint for galvanized surface to against corrosion. ZRP has good adhesion which values obtained ranged between 1.65 and 3.5MPa with and without applying current [26]. Electrochemical tests showed that metallic substrates coated with 96 % ZRP have better corrosion resistance (galvanic protection) while those coated with 74% ZRP have a better barrier effect [32]. Consequently, organic ZRP has good adhesion to steel substrate and can continue to protect the steel in corrosive environment. However, lack of research and studies on application of ZRP to the concrete substrate, especially as anode material for ICCP system. The successful of application of the CP method to the RC structures is basically the used by the effective anode system which can efficiently generate required protective current to the steel in concrete. The ease of installation of anode system is an important criteria and also the long term durability is considered through the application. The power supply and monitoring technique of cathodic protection system can choose according to the selected anode system.

Corrosion Monitoring Techniques

It is recommended to monitor the performance every three months for the first year and then every six or twelve months later if the performance has been satisfactory [12]. The shift in potential due to the impressed current shows the level of protection provided [41]. Table 2 shows a summary of non-destructive techniques (NDT) methods for corrosion monitoring using electrochemical method. GPM give better result about the steel condition in concrete and the corrosion rate compared to the LPR method [42]. The corrosion rate measured by GPM is almost similar to the results produced by gravimetric method and other methods [43]. Therefore, GPM is considered to be used in corrosion monitoring compared to other electrochemical methods.

Table 2: Comparison of NDT methods for corrosion evaluation

NDT Methods	Advantages	Disadvantages
Open Circuit Potential (OCP) monitoring	• Result in form of single value to indicate steel condition and not in the form of equipotential contours.	• Time consuming. • Need to be closed several hours during the assessment.
Resistivity Method	• Economical method. • Can be used for regular inspection since it is easy, fast, and portable.	• A short circuit path may occur in the test region of reinforcement and cause incorrect reduction in measurement.
Linear Polarization Resistance (LPR)	• Can measure in a short of time and apply small perturbations that do not interfere with the present electrochemical processes.	• Time consuming due to electrical capacitance between steel and concrete. • IR drop in the concrete between WE and RE causing error in voltage reading.
Galvanostatic Pulse Method (GPM)	• A rapid device for corrosion rate measurement in RC. • Can display the corrosion rate, electrical resistance and potential value simultaneously.	• Unstable reading due to parallel or crossing of the steel reinforcement. • Error in reading due to cracks and delamination.
Electrochemical Noise (EN)	• Easy to use, no interference to the system and measured signals can be analyzed by mathematical analysis.	• The complicated kinds of noise due to steel corrosion which results of unsuccessful mathematical analysis.

Power Supply for ICCP System

Normally, the power supply in ICCP system is via a transformer-rectifier system [11]. The transformer reduces the mains voltage and the rectifier converts alternating current (AC) to direct current (DC). However, it is difficult to predict the required current due to several factors such as chloride, moisture content and pH. The requirements are between 1-5A and 2-24V to each independently controlled anode zone [5]. The recommended design current density is 20mA/m^2 by referring to the circumferential surface of the bars [44]. A performance standard for the design of CP system for steel in concrete as stated by ISO 12696:2012 should be in a constant value [30]. Previously, the ICCP systems were based on wind power system. However, photovoltaic (PV) modules have been used recently compared to wind power system. Renewable energy systems for power output in ICCP system has been mainly for metallic buried pipelines [45] rather than reinforced concrete. Solar energy systems are mainly being explored and industries produce renewable energy source for CP[45- 46]. Photovoltaic array is used to can generate the required energy for ICCP in order to protect buried steel pipelines [3]. However, both wind and solar systems require batteries or other energy storage mechanisms due to the intermittency of their supply. Figure 4 shows the solar panel used in an ICCP system for steel pipeline protection.

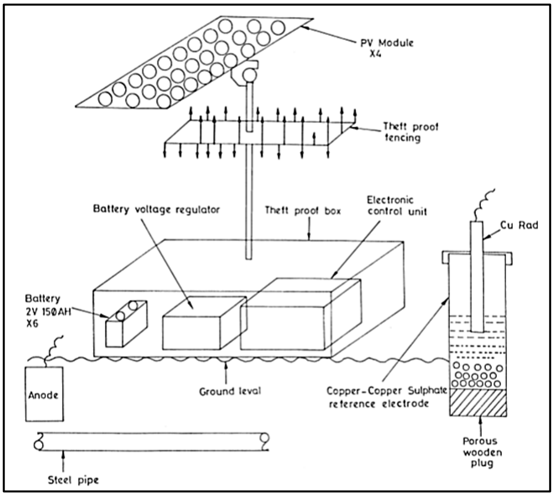

Figure 4: Solar panel in ICCP system for steel pipeline protection [47].

Studies show that less focus on using the battery only system for power generation, even though it may provide an adequate protection. Burstein and Speckert, [48] found that a small current density was generated from cement battery designed with the used of steel as cathode and aluminium as anode protruding from a concrete electrolyte which is cement paste without aggregate and mixed with water. However, Meng and Chung [49] have designed a layered cement where the cement paste which is the electrolyte as the matrix, the zinc particles (anode), manganese dioxide (cathode) and carbon black (conductive additive) were mixed together and found that an open circuit voltage of up to 0.72V and current up to 120μA (current density 3.8μA/cm^2) were produced.

Rampradheep et al. [50] have used similar ingredients in a layered battery, but self-curing agent (polyethylene) was added to the mixture to maintain the moisture content, and also activated charcoal was added to improve the conductivity, and as a result, it can produce a maximum voltage of 0.6V and an undisclosed current. Qiao et al. [51] found that cement batteries cast together with carbon fibers, carbon nanotubes and carbon black can improve the conductivity in the electrolyte layers besides the used of separator between cathode and anode layer. The battery design proposed can produce a maximum power output of 0.7V and 35.21µA/cm2. However, according to Holmes et al. [52], those layered design cement batteries are poor in workability and electrolyte layer was too wet and sandwiched out of the mix when the top layer was placed. It also did not work once it is dried. Recently, a block cement battery design consists of copper (cathode) and aluminium (anode) embedded in the cement paste (electrolyte) with a mixture of carbon black, plasticizer as additives were developed which can produce an average current of 0.35MA through 10Ω resistor [52]. The standard requirement of current density for the ICCP system required 20mA/m^2 and lack of research on the use of cement battery as a power supply for ICCP. However, cement battery cannot continually supply the essential power to the system. Therefore, the need of combination with solar energy is considered to continuously recharge the batteries.

Conclusion

Steel corrosion in concrete structures is a main issue in the construction industry, which affect the structural performance. A review has covered studies on steel corrosion process in RC structures, CP systems for RC structures, anode systems of CP, corrosion monitoring technique and power supply used in the conventional ICCP system. ICCP method gives more advantages compared to SACP method, as it offers better flexibility and durability since it is able to deliver essential current in a condition where high resistivity of concrete structures. However, the ICCP system depends more on continuous DC power supply to impress the current towards reducing the corrosion in RC structures which caused high energy consumption. Therefore, the possibility of using cement battery to constantly power the ICCP system has been reviewed in order to reduce the power consumption used in the application of the ICCP system in order to repair existing RC structures.

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