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Application of CFRP as anode in cathodic protection for steel reinforced concrete – a review

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Abstract. Impressed current cathodic protection (ICCP) is an electrochemical method to prevent or stop corrosion of steel reinforcement in concrete structures. The use of this technique is limited although it has been proven to be effective. One of the reasons is the high cost of anode material, commonly titanium anode. Hence there is a need for alternative anode materials to lower the cost and at the same time to improve the performance of the ICCP system through design. This paper reviews carbon fiber reinforced polymer (CFRP) as an anode for ICCP systems in concrete and discusses the degradation mechanism and operating conditions of the anode. It also gives an overview of the performance of CFRP as an anode material, from laboratory experiments to field operation.

1 Introduction

Chloride-induced corrosion is one of the major causes of damage or deterioration of steel reinforced concrete structures. To deal with this problem, impressed current cathodic protection (ICCP) has been proven to be an effective method to stop, slow down or prevent corrosion, even in a highly corrosive environment [1–3]. The protection of the steel is achieved by shifting the electrical potential of the steel negatively which forces the reinforcement into a passivity or immunity state. An ICCP system consists an anode system which is usually laid on the concrete surface and connected with the positive terminal of a direct voltage source.

Depending on the level of current density, in some cases, cathodic protection is referred to as “cathodic prevention”. Cathodic prevention is a preventative approach when it is applied on new structures that are expected to become contaminated by chloride during their service life, using only small amount of current to suppress corrosion. According to the ISO 12696 standard, the current density for cathodic protection is 2-20 mA/m^2 (of steel surface) and for prevention it is 0.2-2 mA/m^2 [4].

For a cathodic prevention system, a small cathodic polarization of the steel should be applied early on in the beginning of the service life. The use of small current density has many advantages. The most important one is that it can reduce acid production at the anode area. Acidification at the anode area is an inevitable consequence of electrochemical reactions. The produced hydrogen will react with the anode and the cement paste, causing both anode and concrete to decompose, which will lead to a lowered protection efficiency and eventually may stop the protection [5].

As the most crucial component in a cathodic protection/prevention system, the anode material must be stable and functioning to secure the performance of such a protection system. Conventionally, the most commonly used anode material is titanium-based metal anode, because of its high current capacity, light weight and low consumption rate [6]. However, due to its high cost, it also hinders the wide application of ICCP systems.

On the other hand, in a cathodic prevention system, because of the use of low current density, the requirements of the anode material can be lowered. Therefore, as an alternative, carbon fiber reinforced polymer (CFRP) anodes have gained much interest because of their high conductivity and affordable price.

This paper is based on a literature study and reviews the usage of CFRP as anode for ICCP systems, in both laboratory experiments and field applications.

2 CFRP anodes

Carbon fiber reinforced polymer (CFRP) is a highly appreciated engineering material for its high strength, high conductivity and low weight. CFRP consists of carbon fiber threads and reinforcing polymer. Carbon fiber threads are made of thousands of carbon fiber filaments. This reinforcing polymer is usually epoxy for common engineering purpose. However, for special applications such as anodes, the reinforcing polymer can be other polymers with better electrical conductivity. For example, the resistivity of CFRP can be found between 0.015-0.05 Ω per unit length [7], [8].

Fig. 1 shows the three most common types of CFRP anodes that can be found in research for ICCP applications: woven mesh, fabric mat and rod. CFRP mesh is similar to titanium mesh which can be cast

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directly into concrete with or without a layer of conductive overlay [9] . CFRP fabric and rod are usually used as near-surface mounted anode material together with adhesive such as epoxy [10].

Fig. 1. Image of CFRP mesh (left), CFRP fabric (middle) and CFRP rod (right)

3 Degradation mechanisms of CFRP anode systems

3.1 Durability of CFRP anode

The degradation mechanism of a CFRP anode has been investigated in simulated solutions and a concrete environment [8], [11]–[14]. Based on their results, the authors suggested that the polymer matrix was sensitive to electrochemical degradation but the carbon fiber remained with very little loss of mass even at very high current densities (up to 3 A/m^2 of anode surface). This means that CFRP materials are suitable and capable to be used as an anode material, because carbon fibers are the key component for electrical conductivity but not the reinforcing polymer. The purpose of reinforcing polymer is like a glue to make carbon fibers easy to handle and to be installed. Fig. 2 shows the images of CFRP anodes after accelerated tests of ICCP.

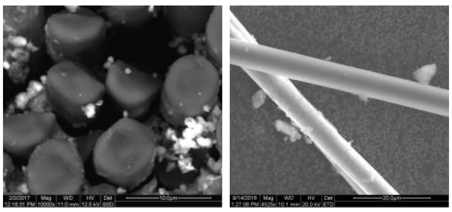

Fig. 2. CFRP anodes after accelerated test. (left) Image of the cross-section of CFRP. (right) Image of two single fibers with smooth surface[8]

3.2 Acidification at anode-concrete interface

To evaluate the anode system for ICCP applications, one must consider both the anode material and the anode-concrete interface, because the failure of either of these two parts can lead to the failure of the anode system. The most detrimental effect is the acidification at the anode area, which can lead to early failure or unplanned maintenance [15].

Owing to the nature of electrochemical reactions, ICCP transforms the microstructure of the concrete around the steel over time because of the migration of the ionic species and the chemical reactions [16]. The acidification at the anode-concrete interface reduces the pH value and is also associated with calcium leaching [17], [18]. Under the effect of acidification and calcium leaching, the degraded cement pastes turns into soft grey or white silica-gel-like substance, which are amorphous and have high electrical resistivity [19].

Anode degradation can cause an increase in the resistance and a loss of adhesion. This will in consequence increase the driving voltage and further accelerate the degradation process. Eventually it became impossible to maintain sufficient current for full protection to the steel reinforcement [5]. The service life of the anode system may be determined mainly by acid production due to current exchange [20]. A qualitative numerical model has been proposed to describe the acidification phenomenon under cathodic protection [21]. Accelerated tests have been conducted to investigate the relationship between the current exchange and the degradation area. Zhang and Tang suggested a non-linear relationship to describe that the total damage of the anode-concrete interface is related to both the total current exchange and the current densities [22].

4 Applications of CFRP as anode material

Only very few field operations have been reported using CFRP as ICCP anodes. Scandinavian countries have practiced their use in real construction projects as early as almost two decades ago. However, official full reports were rarely published and are difficult to find.

Vennesland et al. [23] described experimental work using CFRP mesh as anode on concrete specimens from a demolished bridge. The feeding voltage was 1 volt with a current density of 3-4 mA/m^2 and the protection criterion was achieved according to EN ISO standard 12696.

In a technical report, Mork et al. monitored and investigated a harbour structure in Honningsvaag in Norway [24]. The anode system consisted of carbon fiber mesh and cement-based mortar and the CP system was achieved with a current density of 2 to 5 mA/m^2 and a voltage of a maximum of 1.8 V. The system was functioning well as of the day of publishing, according to EN ISO 12696.

Based on these two field applications, CFRP mesh anodes have been demonstrated to be a proper alternative for cathodic prevention applications.

Studies have also been made to combine the reinforcing property together with the anode function [25], [26]. Zhu et al. [27] reported stable anode performance in accelerated ICCP tests of CFRP strip in simulated pore solutions. The stabilized potential was around 2 volts, the current densities were about 6 A/m^2 and the experiment duration was 50 days. Lee-Orantes et al. [28] performed experiments on CFRP anodes with several conductive adhered materials on reinforced concrete prisms. Nguyen reported that CFRP rod anode can operate at 128 mA/m^2 with a relatively low consumption rate, and the ultimate strength of the concrete increases by approximately 13.5% using a surface-mounted CFRP fabric [29], [30].

Based on existing research, to access the long-term performance of CFRP anodes in ICCP systems, accelerated tests have usually been adopted. To convert the results from accelerated tests to a normal current density level, the simplest rule is to apply the total charge quantity for calculation. However, according to electrochemical principles, the important effect of diffusion has been neglected because it is difficult to be quantified. The fact is that when the current density is lowered, the portion of diffusion can be increased, which helps reduce the damage of acidification and calcium leaching.

Polder and Peelen [31] described the electrochemical phenomenon under ICCP. They pointed out with low current densities (1-10 mA/m^2), the diffusion has the same order of magnitude as migration and thus the acid production is close to zero.

Other experimental works have also provided some evidence on that. Zhang et al. [22] investigated the electrochemical properties of CFRP mesh as anode in accelerated ICCP tests, with current density between 200-4000 mA/m^2 of anode area. Constant current was applied. The potential between the anode (CFRP mesh) and the cathode (steel bar) was monitored. Results showed that the potential increased dramatically after a certain period, which indicated degradation happens due to acidification and calcium leaching. The duration before potential changes was associated with current density, which was a power relation but not linear. The conclusion was that if only the total charge rule is used, it will underestimate the service life of anode systems.

Regarding the previous studies, CFRP mesh anodes are suitable and safe for cathodic prevention applications.

5 Summary and outlook

Research results have provided solid evidence that CFRP materials, especially meshes, are suitable as anode materials for cathodic prevention applications. Future investigation could focus on issues such as electrical connection. This issue is usually not highlighted or presented in research papers. However, in the authors' view, the connection points could become a weak link in the anode systems because they easily have the highest resistivity when two different materials are connected.

The connection of CFRP anode with the power supply or copper cable needs to be aided by, for example, highly conductive cement pastes. CFRP anode for ICCP systems has existed for almost 20 years. Unfortunately, still only a few field installations have been reported. This makes it hard to convince contractors and consultancy companies to use CFRP anodes instead of titanium anodes because of the lack of long-term credibility. More experiments and field installations are needed to prove the long-term durability of CFRP anode system for cathodic prevention applications.

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