



Application of carbon-fiber-reinforced polymer anode in electrochemical chloride extraction of steel-reinforced concrete



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HIGHLIGHTS

- Chloride was extracted from steel-reinforced concrete via electrochemical chloride extraction (ECE).
- Carbon-fiber-reinforced polymer (CFRP) served as external anode.
- Steel-concrete bond loss varied with samples' water-cement ratio and applied current density.
- CFRP anode performance showed no significant degradation after ECE treatment.
- ECE efficiency was compatible with that shown using activated titanium mesh anode.

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ABSTRACT

A carbon-fiber-reinforced polymer (CFRP) was adopted as an external anode in the electrochemical chloride extraction (ECE) of cylindrical steel-reinforced concrete samples with different water-cement ratios and chloride introduced during casting. Three constant current densities were applied between the steel cathode and CFRP anode, with the internal steel bar used as the cathode. The chloride extraction ratio, proportion of residual chloride, and Cl^-/OH^- ratio were obtained to assess the ECE efficiency; pullout tests were conducted to evaluate the post-ECE bonding characteristics between steel and concrete. A microscopic evaluation of both concrete and CFRP showed that the CFRP anode did not experience severe degradation after ECE. Comparison of the performance by using activated titanium mesh anodes confirmed the feasibility of ECE with an external CFRP anode.

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Abbreviations: CFRP, carbon-fiber-reinforced polymer; ECE, electrochemical chloride extraction; EDS, energy-dispersive spectroscopy; ICCP, impressed current cathodic protection; PVC, polyvinyl chloride; SEM, scanning electron microscopy; D , diameter of steel bar embedded in concrete; L_1 , test region of steel bar; L_2 , masked region of steel bar; A_{steel} , test area of steel bar; i , current density applied to the test area of steel bar; w_{12,Cl^-} , total chloride extraction on the 12th day; w_{28,Cl^-} , total chloride extraction on the 28th day; f_{max} , maximum bond obtained in pullout test; δ_{loss} , bond loss of test samples due to ECE treatment; w_{Cl^-} , chloride extraction ratio at two-day intervals; m_{Cl^-} , mass of chloride obtained by titrating the electrolyte solution at two-day intervals; M_{Cl^-} , total mass of chloride in the NaCl-modified mixing solution used for concrete casting; n_{OH^-} , concentration of OH^- ; pH, pH value of solution; P_{max} , maximum drawing force; $f_{0,\text{max}}$, maximum bond of control sample in each series; k_{Cl^-} , $\text{Cl}^-/\text{cement}$ ratio after ECE treatment; W , Cl^-/OH^- ratio after ECE treatment; f , steel-concrete bond obtained in pullout test; P_{cr} , critical load in a typical pullout load vs. displacement curve; U^* , displacement in a typical pullout load vs. displacement curve.

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1. Introduction

The corrosion of steel in reinforced concrete has been shown to directly degrade the durability of a structure. Specific features of this degradation include a decline in the load-carrying capacity and the appearance of cracks [1]. The ingress of chlorides mainly contributes to steel corrosion, although the carbonation of concrete can also be a contributing factor to steel corrosion [2]. Extensive investigations have been carried out in the laboratory and in the field on electrochemical methods for slowing down the corrosion of reinforced steel embedded in concrete through the penetration of chlorides [3,4]. Two primary rehabilitation methods are currently available—impressed current cathodic protection (ICCP) and electrochemical chloride extraction (ECE). The conventional ICCP technique is implemented throughout the entire service life of the structures, whereas the ECE treatment is implemented for a few weeks. The operating principle of ECE is similar to that of ICCP, but the applied current density employed in ECE is considerably

Notations

D	diameter of steel bar embedded in concrete	n_{OH^-}	concentration of OH^-
L_1	test region of steel bar	pH	pH value of solution
L_2	masked region of steel bar	P_{max}	maximum drawing force
A_{steel}	test area of steel bar	f_{0_max}	maximum bond of control sample in each series
i	current density applied to the test area of steel bar	k_{Cl^-}	$\text{Cl}^-/\text{cement}$ ratio after ECE treatment
$w_{12_Cl^-}$	total chloride extraction on the 12th day	W	Cl^-/OH^- ratio after ECE treatment
$w_{28_Cl^-}$	total chloride extraction on the 28th day	f	steel–concrete bond obtained in pullout test
f_{max}	maximum bond obtained in pullout test	P_{Cr}	critical load in a typical pullout load vs. displacement curve
δ_{loss}	bond loss of test samples due to ECE treatment	U^*	displacement in a typical pullout load vs. displacement curve
w_{Cl^-}	chloride extraction ratio at two-day intervals		
m_{Cl^-}	mass of chloride obtained by titrating the electrolyte solution at two-day intervals		
M_{Cl^-}	total mass of chloride in the NaCl-modified mixing solution used for concrete casting		

higher than that employed in an ICCP system [5]. The relatively high current density required for ECE treatment keeps harmful anions such as chlorides (Cl^-) and sulphates (SO_4^{2-}) away from steel bars for a short period.

The ECE treatment was investigated in several studies [6,7] in the 1970s. Very high current densities were used to decrease the treatment period; the permeability and bond loss of steel reinforcement were found to be major drawbacks. As research progressed, an increasing number of studies concerning the reduction in chloride content were reported at the beginning of the 1990s [8–10]. In addition, the post-treatment behavior has also been studied. Marcotte et al. [11] reported a comparison of the linear polarization resistance measurements and the full polarization curves before and after extraction, which indicated that while the ECE treatment halted chloride-induced corrosion, it increased the overall corrosion rate. The physical state of the steel reinforcement before and after ECE treatment has been investigated as well. Glass and Buenfeld [12] concluded that the formation of a $\text{Ca}(\text{OH})_2$ layer on the steel surface may be key to achieving successful ECE treatment, even if a significant quantity of chloride remains in the concrete.

Although the ECE mechanism has been extensively investigated, it should be noted that the external anode remains an indispensable part in the ECE system. The anode forms a current pathway and distributes the current uniformly, which allows harmful anions in concrete to migrate toward the electrolyte. Currently, an activated titanium mesh anode is widely used in ECE, and the majority of research studies on ECE have been carried out with activated titanium mesh anodes with the results being considerably reliable [11,13,14]. However, it is interesting to investigate alternative external anodes for ECE with lower cost and better workability, and those that facilitate easy installation.

Carbon-fiber-reinforced polymers or plastic (CFRPs) have become an attractive candidate as an external anode. CFRPs are composed of carbon fibers and an epoxy matrix, CFRPs are extensively used as structural strengthening materials in civil engineering because of their excellent mechanical properties and durability [15–17]. In addition, CFRPs have good conductivity and electrochemical stability, rendering them as a potential material for impressed-current anodes. Gadve et al. [18,19] presented ICCP tests using a CFRP as the anode. Recently, Zhu et al. [20] investigated the behavior of a CFRP anode in a simulated ICCP system. No significant degradation in electrical and mechanical properties was observed for a CFRP subjected to anodic polarization at the selected applied current density.

This study investigated the application of a CFRP as an external anode for ECE treatment to migrate harmful chlorides from

reinforced concrete. The ECE tests were conducted using different current densities. Pullout tests were performed to evaluate the bonding characteristics between steel and concrete after the ECE tests. A microscopic examination of both concrete and CFRP was also carried out. The performance of the ECE in this paper was compared with the results by using activated titanium mesh anodes.

2. Experimental investigation

2.1. Preparation of concrete samples

Fig. 1 shows a schematic diagram of the samples used for the ECE tests. Cylindrical concrete samples with diameters and heights of 100 mm were cast. A steel bar (hot-rolled plain bar, Q235) with a diameter (D) of 100 mm was centrally embedded in each concrete sample. The surface of the steel bar was cleaned chemically and physically prior to use. The test region of the steel bar was 50 mm (L_1) in length; the remaining 50 mm (L_2) was masked by a polyvinyl chloride (PVC) tube to evaluate the bonding behavior before and after ECE, as recommended by previous studies [5,21]. The test area of the steel bar (A_{steel}) was calculated using Eq. (1):

$$A_{\text{steel}} = \pi D L_1 = 1570 \text{ mm}^2 \quad (1)$$

The composition of the concrete samples (mix 1, mix 2, and mix 3) corresponding to three different water–cement (w/c) ratios (0.32, 0.4, and 0.5) is presented in Table 1. The 3% NaCl, corresponding to 1.82% chloride by weight of cement, was added to the mixing water to form the chloride-contaminated concrete. The bottom surface of the cylindrical concrete and external steel bar were masked by epoxy resin. All samples were demolded after 24 h and cured for 28 days at approximately 25 °C and 100% relative humidity. The compressive strengths of mix 1, mix 2, and mix 3 after curing for 28 days were 33.03, 41.33, and 45.58 MPa, respectively.

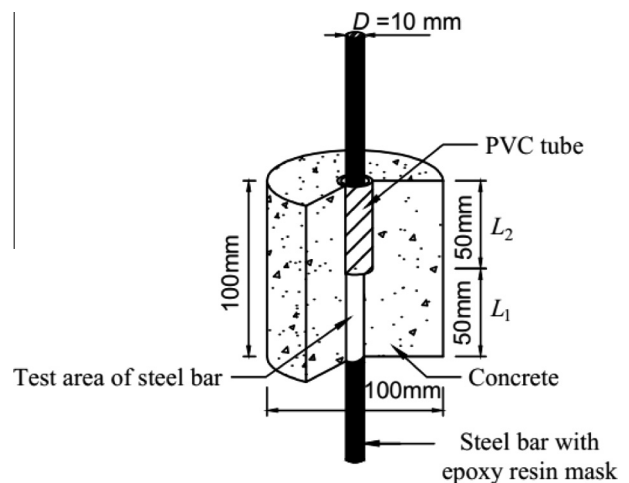


Fig. 1. Schematic diagram of a cylindrical concrete sample.

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