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Extraction of chloride from chloride contaminated concrete through electrochemical method using different anodes

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HIGHLIGHTS

- ECR process development by using three different anodes and current densities.
- ECR process was carried out under laboratory and field exposed concretes.
- The CCPA is stable at 0.5 A/m^2 and suitable for long-time application.
- The higher current density is not suitable for continuous ECR process in all anodes.
- ON_C and OFF_C method increases the chloride removal efficiency.

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ABSTRACT

Electrochemical chloride removal is one of the superior healing methods for chloride affected reinforced (RC) concrete structures. In the present study, the effect of electrochemical chloride removal (ECR) of chloride contaminated concrete consisting of embedded rebar in corroded condition was assessed by measuring the corrosion rate and rebar potential after the ECR treatment at a current density of 0.5, 1.0 and 2.0 mA/m^2 and by using three types of anodes namely, TiSA, SSA and, CCPA. Here, 'current ON' (ON_C) and 'current OFF' (OFF_C) method was adopted to obtain an efficient and uniform ECR throughout the specimen. From the results, it is found that the increase in current density (1.0 and 2.0 A/m^2) increases the chloride removal efficiency. However, the corrosion rate of the rebar was increased at higher current densities and some damage on the CCPA anode material was noticed due to the hydrogen gas evolution in the rebar. It is found that the CCPA is more stable and the chloride removal efficiency was improved at 0.5 A/m^2 current density and hence it is suitable for long-time application of ECR process under ON_C and OFF_C method. This approach allows the easier passage of chloride ions from the cathode to the anode and the current OFF_C period allows the system to re-establish the equilibrium between the anode and cathode. From this study, it was found that the "ON_C and OFF_C method" increases the chloride removal efficiency and thereby preventing the rebar from corrosion.

1. Introduction

Chloride-induced corrosion of steel in concrete structures is a major threat to the construction industry in affecting the durability of reinforced structures [1]. Chloride ions can destroy the passive film on the reinforced steel surface and induce the corrosion damage, results in an unexpected failure of the RC structure leads to catastrophic failures [2]. Hence, enhancing the durability of concrete has become a highly a challenging task in the construction industry, and numerous efforts are made by civil engineers to prevent the reinforced steel in concrete structures from corrosion. Different techniques were proposed to prevent the corrosion of steel viz. using blended cements [3], corrosion inhibitors [4,5], coating to steel rebar [6,7], cathodic protection [8,9], electrochemical realkalization of concrete [10], electrochemical chloride removal (ECR) [11,12], electrochemical injection of corrosion inhibitor [13,14], etc. Considering both the cost and efficiency of the rehabilitation methods, electrochemical chloride removal (ECR) is a conventional and curative way to prevent the steel reinforced concrete structure from corrosion [15]. ECR consists of applying

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an electric current through DC rectifiers between the steel rebar (cathode) and an externally mounted electrode (anode) at the concrete surface. Since the chlorides (Cl^-) are negatively charged ions, the imposed electric field causes the chloride ions to migrate from the rebar to the outer electrode through the concrete pores. The hydroxyl (OH^-) ions migrate from the surface of the concrete to the level of the rebar which improves the alkalinity of the concrete near the rebar surface area [16–18]. Reports revealed that ECR is one of the best method adopted to rehabilitate the chloride contaminated concrete structures [19–22]. The effectiveness and efficiency of the ECR process have an advantage of being a fast and temporary treatment, although chloride ions cannot be removed in these methods [23–26]. Orellan et al. [26]; Fajardo et al. [27] reported that 50–60% of the chloride was extracted from the steel-concrete interface and 1% chloride by mass of cement remained around the steel after ECR process. Several authors have reported that increasing the current density in ECR process may produce the hydrogen gas evolution around the cathode steel surface and produces crack around the cathode steel, due to the corrosion of the rebar. Consequently, it may reduce the bond strength between the steel and concrete [28–32]. An attempt was made to diminish the risk of side-effects with reduced current densities of 250, 500 and 750 mA/m^2 were used for chloride extraction to achieve the chloride removal efficiency, without any adverse effect [33]. It was further reported that the introduction of anode material based on the Ti-RuO_2 mesh and platinized titanium were efficiently used for removing the chloride from the concrete [34]. The short and long-term effects of ECR treatment of corroded reinforcement have been studied with chloride contaminated OPC and SRC and found that ECR is more efficient in reducing the corrosion rate of reinforcement embedded in OPC matrix than SRC matrix [35].

Chang et al. studied the effect of stirrups on electrochemical chloride efficiency. The results revealed that the chloride enclosed by the steel rebar cage is hard to remove by ECR process [36]. Some researchers have used multifunctional, cement-based, conductive materials as anodes for ECR process. Cement paste was a bad conducting material and the conductivity of the cement paste was improved by the addition of conductive materials like carbon fibers or graphite powder. This type of anode material has been used in the recent years [37–43]. Perez et al. [44] reported that the conductive cement paste anode (CCPA) in ECR process has a great influence to retain an important part of the extracted chlorides after finishing the ECR process. It was also reported that CCPA used ECR process may be severely damaged during the repeated treatments and this damage can produce malfunctions of the electrochemical system at a current density of 2 A/m^2 [44]. All the above studies revealed that continuous application of current (0.5–5 A/m^2) removes only 50–70% of the chlorides exist in the concrete structure. Besides this, higher current density will lead to the damage of the anode material and debonding of the steel rebar due to hydrogen gas evolution.

Because of the above, the present study focused on passivating the corroded rebar in the chloride contaminated concrete through ECR process by applying three different current densities (0.5, 1.0 and 2.0 mA/m^2) and by using three different anode materials such as TiSA, SSA and CCPA. These current densities were chosen to find out the optimum current density at which one among the three anode materials is performing better and providing higher efficiency under long-term application without damaging the structure. Simultaneously, the influence of current ON_C and OFF_C method was chosen to have the uniform and greater protection efficiency with long-term benefits. The effect of ECR for embedded steel in chloride contaminated concrete was assessed by measuring the corrosion rate and rebar potential under ONc and OFFc condition.

2. Experimental methods

The experimental section was divided into two parts. The first part deals with the ECR under laboratory condition with various anodes such as, TiSA, SSA and CCPA. The current densities of 0.5, 1.0, and 2.0 A/m^2 was applied for one-week current under ON_C and another one week under OFF_C (one cycle) and evaluated the optimum current density of ECR process. The second part deals with the application of the optimum current density in the one-year-old chloride contaminated concrete slab.

2.1. Laboratory studies

2.1.1. Preparation of concrete specimen

The concrete specimens prepared in this study consist of 60 mm dia. and 100 mm length cylinder with centrally embedded steel rebar of 10 mm dia. and 70 mm length to maintain a cover thickness of 25 mm. Ordinary Portland Cement (OPC) was used to prepare the concrete specimens, and the chemical composition of the cement used for this study is shown in Table 1. Concrete specimens were cast using cement, fine and coarse aggregate (10 mm size and downgraded) in the ratio of 1: 1.56: 3.36 [cement: 372 kg/m^3; sand: 580 kg/m^3; coarse aggregates: 1250 kg/m^3 with a water content of 204.60 lit/m^3]. The concrete mix was admixed with 3% NaCl by weight of cement. The specimens were cast in PVC molds and kept at room temperature for 24 h without humidity exchange. Then the specimens were demolded and stored in water for 28 days curing at room temperature.

2.1.2. Preparation of anodes

The cylindrical anodes of the size of 110 mm height and 80 mm dia. TiSA was prepared by rolling of titanium mesh through Tungsten Inert Gas weld-TIG method. SSA was prepared by using perforated stainless-steel sheet with arc welding process. CCPA was fabricated by the addition of cement, graphite, water in the ratio of 1: 0.5: 0.5 along with discrete carbon fibers. All the materials are mixed together and make it into a paste and moulded into the required shape. After 48 h. the moulding was dismantled and it can be used. The electrical resistance of the fabricated CCPA was 6.3 Ω.m [44]. The different types of anodes fabricated are shown in Fig. 1.

2.1.3. ECR process

During the ECR process, a constant supply of current leads to the formation of negative and positive charged layer around the cathode surface (Fig. 2). When using the DC, the thickness of the negatively charged layer was increasing which obstruct the flow of chloride ions from the cathode to the anode and it creates the stress around the cathode causing the corrosion of the steel. Hence, the current applied is periodically turned off to discharge this layer. This allows easier passage of the flow of ions uniformly throughout the surface of the rebar [45].

After curing (before ECR treatment) the half-cell potential of the embedded rebar was monitored over a period of 30 days to get the stabilized potential. Then, the concrete specimens were immersed in an electrolyte containing a mixture of 0.03 M NaOH, 0.3 M KOH, 0.003 M $Ca(OH)_2$) and direct electric current (DC) was applied between the cylindrical shaped (TiSA, SSA and CCPA) anodes and embedded steel rebar as a cathode. Various current densities of 0.5, 1.0 and 2.0 A/m^2 were applied to three different specimens using three different anodes for 49 (28 + 21) days under the current ON_C (4 cycles) and OFF_C (3 cycles) condition. After ECR process, the embedded rebar potential was continuously monitored for 51 days to understand the behavior of the steel rebar embedded