Construction and Building Materials 153 (2017) 436–444

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Research of electrochemical chloride extraction and reinforcement of concrete column using MPC-bonded carbon fiber reinforced plastic sheet & mesh

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HIGHLIGHTS

- MPC is used as adhesive to bond Cs & Cm in formation of MPC-CFRP composite material.
- Cs and Cm electrodes could serve as the anodes of the ECE system.
- MPC-CFRP achieves the dual effects of reinforcing and repairing concrete structures.

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 27 March 2017
Accepted 14 July 2017

Keywords:
Magnesium phosphate cement
Carbon fiber reinforced plastic sheet
Carbon fiber reinforced plastic mesh
Electrochemical chloride extraction
Concrete column

ABSTRACT

Magnesium phosphate cement (MPC) is used as an adhesive that bonds carbon fiber reinforced plastic sheet (CFRP sheet-Cs) and mesh (CFRP mesh-Cm) in formation of the MPC-CFRP composite material. This type of MPC-CFRP composite material can serve as both an anode, Cs and Cm electrodes, for extracting chloride ions and a reinforcement material for concrete columns, and it contributes to bearing capacity improvement and electrochemical chloride extraction (ECE) of concrete structures. Compared with the traditional Ti-RuO_2 anode (T electrode), the MPC-CFRP composite material is used to strengthen concrete columns and extract chloride ions. Current density, $i = 4, 8\ A/m^2$, and power-on time, $t = 14, 28, 42$ d, are considered to illuminate the effect of the ECE system on the axial compressive strength, chloride ion concentration and bond strength of the rebar-concrete interface of concrete columns. Cs and Cm electrodes can be used as anodes of the ECE system to migrate chloride ions near the rebar effectively toward the concrete surface. The increase of power-on time and current density improves the chloride extraction efficiency. Cs electrode has similar chloride extraction efficiency as T electrode under the same experimental condition superior to Cm electrode. The bond strength of the rebar-concrete interface degrades after ECE and the degradation increases as the current density and power-on time increases. Cs and Cm electrodes significantly improves the bearing capacity and ultimate displacement of concrete columns. However, the strengthening effect decreases as the current density and power-on time increases. The mechanical properties of the strengthened concrete columns are still superior than those of the unstrengthened. Cs and Cm electrodes can achieve the dual effects of reinforcing and repairing reinforced concrete structures. The estimated equations of ECE efficiency and ultimate load of concrete columns agree with the test data.

1. Introduction

The long-term durability of corrosion resistance relies on stability conditions which is necessary for the passive layer on the steel surface. However, the presence of sufficient chloride ions causes the passive film to break down and steel is no longer protected against corrosion in the presence of moisture and oxygen [1].

Various protective methods, including epoxy-coated steels, overlays, membranes, impregnation and inhibitor, are used to prevent corrosion in new structures. For old structures, the conventional repair technique consists of locating the corroding areas through the potential mapping technique, determining the chloride ion concentration in the corroded and passive zone and removing the chloride-contaminated concrete [1]. Electrochemical

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.131

chloride extraction (ECE) is a nondestructive method to prevent corrosion of rebar, which is the main problem in structural concretes [2,3]. Successful application of ECE depends mainly on the selection of an appropriate anode system [4,5]. Many anode systems are currently available such as thermal sprayed zinc [6,7], titanium anodes [8,9], titanium mesh anodes [10,11], conductive paint [12], and coating overlay anodes [13,14]. Properties of anode materials need to be considered and examined carefully to ensure that they operate effectively during the required service life.

With the features of high strength-to-weight ratio, corrosion resistance, and easiness of site handling, carbon fiber reinforced plastic (CFRP) has been widely used to strengthen and retrofit concrete structures in the construction industry [15,16]. CFRP may also be a potential anode material in the ECE system due to its nice electrical conductivity and electrochemical properties.

Thus, using CFRP for both structural strengthening and ECE of reinforced concrete structures was proposed. The electrochemical method was simple in operation and economical in cost [17]. A comprehensive experimental program was carried out to study the electrical and mechanical behaviors of a CFRP plate in the simulated ECE system with various solutions [18], the dissolution of carbon fiber anode stabilized after a period of time, depending upon the size and shape of the surface [19]. Gadve et al. presented ECE tests using a CFRP as the anode [20,21]. Zhu et al. investigated CFRP's mechanical and electrochemical performance during accelerated polarization in the NaCl and NaOH solution environment and found that CFRP could be used successfully as the anode in the ECE system without suffering significant degradation of mechanical properties [22–24]. Researchers also investigated the degradation rate of CFRP in an ECE process being exposed to NaOH. Simulated pore water solution was approximately 12.4 and 13.6 μm/day with an applied current of 4mA, and the service life of CFRP was estimated to be >23 years [25]. The scanning electron microscope (SEM) micrographs and FTIR results showed that the degradation of anode occurred on the epoxy polymer and the breakage of C-N bond caused the epoxy to transform into fine powder. Van Nguyen et al. [26] studied the performance of CFRP fabric and rod as impressed current anodes in calcium solution and concrete. CFRP was employed to pre-corroded reinforced concrete beams for structural strengthening and ECE. The results showed that the ultimate strength of specimens with CFRP for structural strengthening and ECE decreased slightly in comparison to control specimens only for structural strengthening. Near-surface mounted (NSM) CFRP rod was successfully used as an ECE anode for corroded RC beams, the potential decays of the steel met recognized ECE standards and it also increased the ultimate strength of the damaged beams [27]. In previous studies, CFRP anodes in an ECE system were bonded with modified epoxy adhesives to extract chlorides in concrete. However, CFRP anodes bonded with epoxy resin adhesive had a relatively high resistance leading to a waste of electrical energy. Even worse, the modified epoxy adhesive belonged to organic material easy to age [28], thus hard to meet the requirement of durability.

Magnesium phosphate cement (MPC) is a new type of binder in which chemical bonding is formed by a through-solution acid-based reaction between dead burned magnesia and phosphate. Compared with Portland cement [29–31], MPC possesses the following characteristics: very rapid setting, high early strength, ability to set and harden at temperatures as low as −20 C, high bonding strength, and very good durability which includes chemical attack resistance and deicer scaling resistance. Therefore, application of MPC as a repair material has been receiving increased attention [32–34].

Based on the advantages of multi-function MPC cement materials, this study aimed to achieve the dual functions of extracting chloride ions and strengthening reinforced concrete structures. MPC-bonded carbon fiber reinforced plastic sheet (Cs) and carbon fiber reinforced plastic mesh (Cm) electrode served as the anodes in the ECE system. Current density, $i = 4$, $8\ A/m^2$, and power-on time, $t = 14$, 28, 42 d, were considered to illuminate the effects of the ECE system on axial compressive strength, chloride ion concentration and bond strength of rebar-concrete interface of concrete columns.

2. Experimental materials

2.1. MPC

MPC was prepared from a mixture of dead burnt magnesia powder, potassium di-hydrogen phosphate and retarder in a proportion and used in the same manner as Portland cement. The dead burned magnesia powder was calcined at >1600 °C with an averaged particle size of about 20 μm. The chemical composition of the powder is provided in Table 1. In addition, industrial grade potassium di-hydrogen phosphate (KH_2PO_4) and borax ($Na_2B_4O_7{\cdot}10H_2O$) and tap water were used in this study.

The potassium di-hydrogen phosphate, retarder and water were weighted and mixed in certain proportions and stirred for 60 s. Magnesia was then introduced into the mixer, and the mixture was agitated at 800 rpm for 30 s and then at 2000 rpm for 60 s [32–34]. After mixing, the mixture was poured into molds and compacted using a concrete vibrator. The specimens were demolded after 30–60 min and cured in lab at a temperature of 20 ± 1 °C and a relative humidity of 50 ± 1 °C. The mixing proportion and properties are listed in Table 2.

2.2. Concrete

Type I Portland cement was used in this study. The concrete mixtures were prepared with locally available aggregates: siliceous river sand and crushed limestone gravel. The specific gravity of gravel was $2.7\ g/cm^3$, the crush index of gravel was 4.5%, and its particle size distribution was continuous grading of 5–20 mm. The specific gravity of sand was $2.7\ g/cm^3$, the fineness modulus was 2.56, and particle size distribution was from 0.16 to 5 mm. The high-range water reducer JK-5 is naphthalene-based with water reduction rate 23%. The concrete was admixed with NaCl at a dosage of 0.75% Cl^- referred to concrete mass. All concrete columns were demolded after 24 h and cured in a lab for 28 days at a temperature of 25 ± 1 °C and a relative humidity that exceeded 90%. Proportions and mechanical properties of concrete is shown in Table 3.

2.3. Carbon fiber sheet

Mechanical properties of high-strength carbon fiber reinforced plastic sheet (Cs) & mesh (Cm) were tested in accordance with ASTM D3039M-08 [35]. According to the test results: the thickness of Cs was 0.19 mm, the areal density was $300\ g/m^2$, the ultimate tensile strength was 4200 MPa, the elastic modulus was 210 GPa, and the fracture strain was 0.02. Cm was bi-directional carbon fiber mesh, the thickness of Cm was 0.3 mm, the spacing of mesh was 20 mm, and the ultimate tensile stress in a 1.75% strain was 200 kN/m.

2.4. ECE anodes

Anodes in the ECE system were Cs electrode, Cm electrode and traditional Ti-RuO_2 anode (T electrode), as shown in Fig. 1.

Cs and Cm electrodes preparation. The pre-cut Cs and Cm were immersed in the MPC paste for a minute and squeezed repeatedly to make MPC paste immerse into Cs and Cm sufficiently. Then, the specimens were put into the mold. The specimens were demolded after 1 day curing. After 7 days curing in the environment like Section 2.1, then, Cs and Cm electrodes were tested according to ASTM D3039M-08 [35]. The dimension and mechanical properties were shown in Figs. 2 and 3. Each group consists of 5 samples, and the degree of uncertainty of the specimens in each group is less than 5%.

Fig. 3 shows that the tensile stress-strain relationship of Cs electrode was higher than that of Cm electrode, which increased by 472.74%. With high tensile strength, Cs and Cm electrodes were proved that they could be applied to strengthen concrete structures.

3. Strengthening and ECE reinforced concrete column by Cs & Cm electrodes

3.1. ECE system

Cathode in the ECE system. HRB335 twisted steel with a diameter of 8 mm and ultimate tensile strength of 37.56 MPa was set up