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Light-weight cementitious conductive anode for impressed current cathodic protection of steel reinforced concrete application

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HIGHLIGHTS

- Lightweight cementitious anode for ICCP system using pumice aggregate (PA).
- The weight of the anode is reduced by 50%.
- Highest conductivity of 0.2 S/cm is achieved at 1.1% addition of carbon fibres.
- Lower shift in anode potential at 30% replacement level of PA.

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ABSTRACT

This paper presents the results of a study of the effectiveness of lightweight conductive cementitious mortar as an anode material for impressed current cathodic protection of concrete structures. The anode is made up of pumice aggregate (fine), carbon fibres and cement with MMO-Ti as a primary anode. Accelerated galvanic test, conductivity measurement, dry density and compressive strength were carried out and compared with the cement mortar without fibres. Results have shown that the mortar at 20–30% replacement level of pumice aggregate with 1.1% carbon fibre content is a percolation threshold at which highest conductivity of 0.2 S/cm is achieved. The weight of the anode was found to have reduced to half of the weight of the conventional anodes. Polarisation and impedance studies confirmed the possible use of this material as an anode in cathodic protection of reinforced concrete structures.

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1. Introduction

Reinforcing steel bar (rebars) in concrete, normally does not corrode because of the formation of the passive film on the surface of the steel. Though the precise nature of the film is unknown, it is generally believed that it isolates the steel from the environment and slows down corrosion as long as the film is intact. However, when structure exposed to the environment, there are two situations such as carbonation and chloride contamination in which corrosion on rebar can occur. It is now fairly well understood that the corrosion of steel in concrete is a micro/macro galvanic electrochemical process, results flow of electricity from the anode (the site where chloride ion comes in contact with the steel) through the electrolyte to the cathode (the rebar located, where there is little or no chlorides). Once chloride entered into the concrete, other rehabilitation techniques such as overlays, sealers and waterproofing membranes, high build coatings on concrete were found no longer effective. After extensive research and testing, the Federal Highway Administration, USA issued the policy statement that the only rehabilitation technique that has proven to stop corrosion in salt contaminated bridge decks, regardless of the chloride content of the concrete, is cathodic protection [1]. Hull reported that cathodic protection is a cost effective method for rehabilitating damaged bridge decks to extend the service life instead of replacing them [2]. Therefore, its use should be considered whenever a structure is located in severe chloride (marine) environment.

The principle of cathodic protection is applying a DC current in opposition to corrosion current. It consists in the application of cathodic current density of 5–20 mA/m^2 (British standard BS 7361-Part-1) to the steel reinforcement in order to reduce its corrosion rate to negligible values [3]. Relatively moderate current densities are able to restore passivation and have various beneficial chemical effects: hydroxide ion production at the steel increases the pH; migration of chloride ions to the anode away from the steel rebar. It is done by using an extended inert anode laid on the surface of the concrete and a current feeder in order to impose the required current and widely known as impressed current anode

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system [4,5]. The current can also be obtained from naturally occurring voltage difference between the metals present in the galvanic series as anodes, called a sacrificial anode system [6,7]. Sacrificial anode system will work well for concrete structures immersed in water and structures in a very moist environment (tidal zone). Because of high resistivity of concrete and the complex geometry of reinforcing bars, to provide sufficient protection current for long enough the anodes that covered the entire concrete surface using impressed current systems is laid emphasis in research studies on gradually [4,8].

The first major use of cathodic protection to halt corrosion damage of bridge members was done by Stratfull with the installation of a coke–asphalt cathodic protection system on the Sly Park bridge deck in California [9]. Later on different types of anodes such as slotted anode system surrounded by conductive anode materials, catalyzed titanium anodes with concrete encapsulation, conducting polymer overlay, titanium ribbon anode system and thermally sprayed zinc anode (without an external power supply) were used in variety of bridge deck cathodic protection systems [10–20]. Conductive polymer rods, zinc ribbon (sacrificial), platinized niobium embedded in conductive paste and graphite rods were tried on piers of the Burlington Bay Skyway bridge by the research and development branch of the Ministry of Transportation and Communications of Ontario during the year 1982–83 [21]. Kessler and Langely [22] had evaluated cathodic protection systems using conductive mastics and conductive concrete in two deteriorated reinforced concrete bridge structures in Melbourne and Florida and found not so effective in a marine substructure environment, particularly in the tidal zone and observed that they could not be able to supply current density greater than 20 mA/m^2 for longer time [23].

Kessler and Powers [24] had evaluated the performance of conductive rubber anodes to protect the steel reinforced concrete piles in the marine environment. The studies concluded that the conductive rubber could be used effectively to distribute the current uniformly in the splash and submerged zones and able to operate at low rectifier output voltage. Kurt and Nielsen had evaluated the performance of internal anodes mounted in drilled holes inside the structures [25]. They are found to be more suitable where hot spot protection is required and was used in various structures in Denmark.

Sprayed zinc had been experimented as sacrificial and impressed current systems and found the later appears to be more effective [26–30]. The extensive research studies concluded that to avoid disbondment, the coating thickness shall be limited to 20 mils (0.5 mm). In addition to this, the concrete surface should be kept dry, warm and grit blasted at low air pressure. Rolled zinc as anode was found unsuitable owing to poor adhesion to the concrete substrate [31].

Each type of anode has its own advantages and disadvantages [32,33]. Selection of anode system mainly depends upon the many structural factors such as substructure and deck structure, environmental condition (wet or dry) and economic consideration. For example an activated titanium anodes having very long service life and able to supply high current densities, but they are very expensive. Furthermore, these anodes have to be embedded in an overlay that adds to the weight to the structure to be protected [34–36]. Whereas, conductive paints are cheaper, but they could not able to supply current density greater than 20 mA/m^2 and their use is limited to 10–15 years [37]. Brown et al. [38] reported that the failures in the CP system were, either due to deterioration of anode materials or mechanical incompatibility of anodes such as differences in thermal expansion coefficient or curing shrinkage.

To reduce the contact resistance and difference in thermal expansion coefficient, the conductive cementitious anode has been investigated by many researchers [39–43] as secondary anode. These types of anode have been laid as an overlay over the structures. Either steel or carbonaceous material has been added to reduce the resistance of the mortar. Steel scrap, steel fibres, steel powder, acetylene carbon black, graphite powder, carbon nano fibres and carbon nanotubes had been tried as a conducting admixture in the cementitious mortar. The main limitations of using steel scrap and fibres are unpredictable corrosion rate, high anode consumption rate and low operating current density while used as anode [44]. Acetylene black and graphite with higher addition (above 35%) only reduced the conductivity which decreases the compressive strength ultimately [45]. More promising results were reported with addition of carbon fibres [46–49]. CF are inert in aggressive environments, more chemically stable in alkaline environments, abrasion resistant, stable at high temperatures, safe in handling and low in density when compared to steel fibres. Their strength to density ratio is one of the highest among all fibre types.

From the foregoing discussion, it can be inferred that the development of new types of anode shall be made up of lightweight materials is of great technological interest in the ICCP application of concrete structures. In the present study, conductive cementitious anode consists of carbon fibres, cement and lightweight aggregate (pumice aggregate) has been evaluated as a secondary overlay anode along with MMO coated titanium wire as a primary anode. Results were compared with conductive mortar containing other conductive fillers such as activated charcoal and graphite powder.

2. Experimental

2.1. Materials

Polyacrylonitrile (PAN) based carbon fibres (CF) (from Zoltek, India), activated charcoal (AC) and graphite powder (GP) were used as conductive fillers. The properties of carbonaceous materials are given in Table 1. The SEM images of conductive fillers are given in Fig. 1. Portland pozzolana cement conforming to BIS 1489 was used throughout [50]. Natural sand (NS) was used as fine aggregate with a fineness modulus of 2.55 whereas pumice aggregate (PA) having a fineness modulus of 1.82 was used as lightweight (fine) aggregate. The grain size distribution of natural sand and pumice aggregate is compared in Table 2. The chemical composition of pumice aggregate is given in Table 3. The Potable water was used as mixing water. The details of mix proportion used for specimen preparation are given in Table 4. The pumice aggregate was replaced in the range between 10% and 50% by weight of natural sand. In the case of pumice aggregate mortar mixes, the fluidity could not able to increase by adding superplasticizer up to 1.5%. Hence, the w/c ratio was changed at different replacement level of PA in order to maintain the constant fluidity. The addition of carbon fibres varied from 0% to 1.1%; graphite powder (GP) was 30%; activated charcoal (AC) was 1.5% and 2%; by volume respectively. The cementitious mortar without any conductive filler acted as control specimen.

2.2. Specimen preparation

For electrical conductivity measurement, a rectangular specimen of size 40 × 40 × 160 mm, were cast. Two stainless steel plates of size 30 × 30 mm and having a thickness of 3 mm were embedded at a distance of 120 mm in the mortar during casting as shown in Fig. 2. Cubical mortar specimens of size 50 × 50 × 50 mm were cast for compressive strength test. The small cylindrical probe specimens of size 45 mm in diameter and 30 mm in height were cast for accelerated galvanostatic test. It was conducted only on cement mortar specimens containing 0.3%, 0.7% and 1.1% carbon fibres. Primary anode of MMO-Ti wire having a size of 3 mm diameter was embedded at the center of cylindrical probe. The upper and lower surface of all cylindrical probes was sealed with epoxy resin before testing to allow the diffusion of chloride through their lateral direction only. The surface area ratio of the mortar to the primary anode was 20:1. All the specimens were removed from the moulds after 24 h of casting and kept immersed in the lime saturated water for 28 days. Curing was done at room temperature.

2.3. Testing

2.3.1. Compressive strength and dry density

Compressive strength measurements were carried out using Universal testing machine as per the procedure outlined in BIS 4031 [51]. Dry density of specimens was carried out according to the requirements of BS EN 1015-10 [52]. Tests were conducted on triplicate specimens at each replacement level of PA and the average value was reported.

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