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COMPILATION AND INNOVATION OF TECHNICAL SPECIFICATION OF ELECTROCHEMICAL TECHNOLOGY FOR DURABILITY OF CONCRETE STRUCTURES

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The Chinese *Technical Specification of Electrochemical Technology for Durability of Concrete Structures* was compiled on the basis of the overseas and domestic development, practice and research of durability electrochemical technology for concrete structures. The Specification stipulated the general provisions, scope of application, main parameters, quality control and inspection etc of electrochemical technology. Main innovation of Technical Specification appears as: 1. An extensive introduction highlighted the operation and requirement of electrochemical technology for durability of concrete structures, including cathodic protection, electrochemical desalination, electrochemical deposition, bi-directional electromigration etc. 2. The mechanism and application of a new-type electrochemical technology, bi-directional electromigration, was described and its advantages were illustrated in case study. Accompanied by the implementation and application of the technical specification, the durability enhancement and control of concrete structures in China will have another level.

Keywords: Bidirectional electromigration, Organic corrosion inhibitors, Hydrogen embrittlement, Cathodic polarization curve.

1 INTRODUCTION

With the extensive application of concrete structure, the durability of concrete structure has attracted more and more attention. Durability of concrete can be influenced by several factors such as the quality of cement, steel and other materials, the design and construction. There are also environmental factors, including carbonation, corrosion (chloride salt erosion), freeze-thaw, alkali aggregate reaction and so on while the corrosion (chloride salt erosion) is considered to be the main factor (Jin 2012, Ihekwaba 1996, Jin and Zhao 2014). It is generally accepted by scholars at home and abroad that electrochemical technology is the only non-destructive repair technology to stop steel corrosion in concrete structures (Sohanghpurwala *et al.* 2002). Since the 1970s, electrochemical techniques for durability of concrete have emerged and developed such as cathodic protection, electrochemical re-alkalization, electrochemical chlorine removal, electrochemical deposition, bi-directional electromigration etc (Bi *et al*. 2007, Jin *et al.* 2016). However, there are still many problems to be solved, such as defining application condition of these electrochemical technologies in the types of concrete structures as well as concrete deterioration stages, specifying the range of electrochemical parameters and the implementation process of these technologies, proposing a set of acceptance indicators appropriate for the domestic present status. Therefore, Zhejiang University united with domestic universities, research institutes, design, construction and management departments, to form a force to focus on the compilation of the technical specifications.

This paper will focus on the compiling process of the specification, expounding the main innovations as well as the case study. The implementation and application of the technical specification will play an important role in promoting and controlling the durability of concrete structures in China.

2 COMPILING PROCESS

2.1 Preliminary Work

Investigation, experiment as well as monographic studies focusing on the electrochemical technology has provided the theoretical basis to the compilation. During the compilation of the specification, the National Natural Science Foundation of China, the International Cooperation Fund of the Ministry of Science and Technology of China and Zhejiang Province Natural Science Foundation etc have given a great help.

2.2 Chapters and Sections

The specification set up a systemic frame of electrochemical technology by defining the range of application, introducing specific methods of implementation and recommending acceptance indicators. The specification consists of nine chapters in all, including three chapters to overview named general provisions, terms and symbols, basic requirements and six chapters to introduce the electrochemical technologies named impressed current cathodic protection (ICCP), sacrificial anode cathodic protection (SACP), electrochemical realkalization, chloride extraction, electrochemical deposition, bi-directional electromigration. Every technology introducing chapter consists of five sections including general requirements, design, installation and commissioning, quality control and inspection, operation and maintenance.

2.3 Review and Approval

During the compilation process, two expert consultation meetings were held, relevant experts were invited, and their latest research results were also absorbed to form a consultation paper. Through an extensive consult on the *National Standardization Information Network for Construction of Engineering* and 32 copies of consultation paper sending to relevant units and experts, the compiling group received 213 suggestions and with a painstaking sorting and studying, the draft paper came into being. Afterward, an expert review committee was convened to examine the draft paper and 90 suggestions were proposed to form the version to be approved.

3 MAIN INNOVATION

3.1 Bi-directional Electromigration

Bi-directional electromigration (BIEM) is a new-type electrochemical technology focusing on both chloride and corrosion inhibitor migration, distinct from the chloride extraction technology. Shown as Figure 1, the electric field was formed with a metal mesh in the solution as anode and the rebar in the concrete as cathode, causing the corrosion inhibitor cation migrates to the rebar while the chloride ion migrate to the metal mesh (Wu H. 2018).

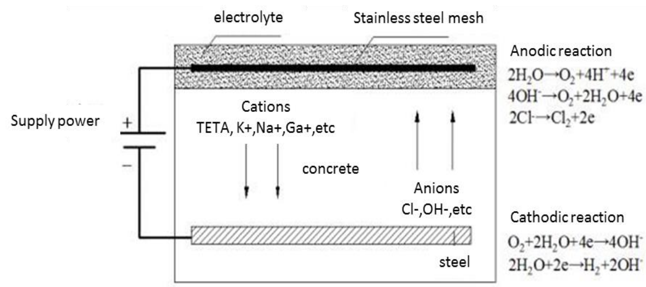

Figure 1. BIEM interactions diagram.

The corrosion inhibitor apply to bi-directional electromigration must have follow performance: 1. Effectively preventing or delaying the occurrence of corrosion of steel bars, can reduce the corrosion rate of corroded steel bars or stop the corrosion of steel bars. 2. Soluble in water and will provide positively charged ions while the solution is alkaline. 3. Can't react with the concrete composition when it migrates into the concrete. 4. Showing a great chemical stability in concrete and can persist for a period of time. 5. Economic and environmentally-friendly, conducive to extensive application in engineering.

After preliminary selection, several organic corrosion inhibitors were tested with potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) to find out their impact on steel corrosion in chlorinated simulated concrete pore solution. At the same time, the electromigration ability of these organic corrosion inhibitors in concrete, the effect on chloride ions and reinforcement corrosion were studied by using organic element analyzer, rapid chloride test (RCT), EIS, weak polarization method and scanning electron microscopy (SEM). Finally, triethylenetetramine (TETA) behaved the best comprehensive performance and was selected as the recommended electromigration corrosion inhibitor (Zhang 2012).

During the bi-directional electromigration, provided that the protection current density is too high, hydrogen evolution reaction will occur at the cathode. When hydrogen enters into the stressed steel bar, it will induce crack, reduce the plasticity of the steel bar and lead to brittle failure of the steel bar, named hydrogen embrittlement of reinforcement (He and Wang 1995, Liu *et al.* 2008). Hydrogen embrittlement of prestressed reinforcement is the main technical bottleneck in the application of electrochemical technology, and how to evaluate and control the hydrogen embrittlement of prestressed reinforcement is the premise and foundation for the further application of electrochemical technology. The compiling group has studied the chloride removal effect, corrosion inhibitor migration effect and hydrogen embrittlement risk of ordinary concrete structure and prestressed concrete structure under different current densities. The research results show that with a current density less than $1000mA/m^2$, it is not possible to ensure the removal of chloride while provided that the current density exceeds $3000mA/m^2$ (the prestressed structure $2000mA/m^2$), the plasticity of steel bar will decrease to less than 80% of the initial plasticity with a high risk of hydrogen embrittlement. The effective range of bi-directional electromigration current density in ordinary concrete structure is $1000\text{-}3000mA/m^2$ (the prestressed structure $1000\text{-}2000mA/m^2$) (Chen 2016, Wu X. 2018). At the same time, it is suggested that the current density implemented on the prestressed concrete structures should be lower than the hydrogen evolution current density during the bidirectional electromigration, which can be obtained by analyzing the cathodic polarization curve.

It was found that the surface strength of the specimens decreased linearly with the prolongation of the electrification time. When the current density is $3A/m^2$ and the electrification time reaches 15 days, the ratio of the corrosion inhibitor and chlorine has exceeded 1, presenting a great effect on corrosion resistance. When the current density is $3A/m^2$ and the electrification time is longer than 30 days, the loss of concrete surface strength and steel bar bonding force is close to 50% of the initial plasticity (Huang 2014). Therefore, the specification suggests that the normal duration of bi-directional electromigration is 15-30d.

3.2 Electrochemical Deposition

The purpose of electrochemical deposition is to repair cracks and fill pores in reinforced concrete structures, as shown in Figure 2. The area of reinforced concrete structure to be repaired is immersed with electrolyte, and the positive electrode of the power supply is connected with the metal plat while the negative electrode of the power supply is connected with the internal steel bar. Under the action of electric field, cations migrate to the cathode reinforcement, anions migrate to the external anode electrode, and electrochemical deposition occurs, so the deposited products fill the pores of reinforced concrete structure and finally repair the cracks.

Current density is an important parameter of electrochemical deposition (Otsuki and Ryu 2001): the smaller the current density, the longer the time needed for crack healing; and the deeper the filling depth of sediment, the better the healing effect. The compiling group studied the effects of different current densities on electrochemical deposition and took the effects of crack repair and desalination into consideration, setting $1.0A/m^2$ as the most appropriate current density (Chinese code 2012, Japanese code 2001). Referring to the existing specification parameters and experimental research results, the suggested range of current density is $500mA/m^2$ to $1000mA/m^2$ and the suggested electrolyte are $MgCl_2$, $ZnSO_4$ and Mg $(NO_3)_2$.

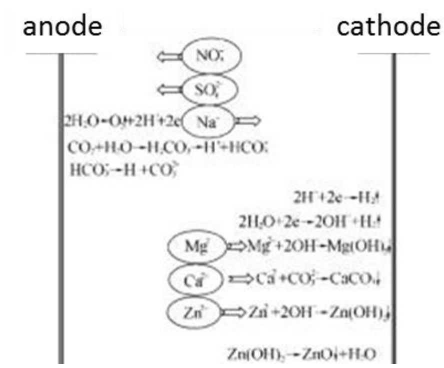

Figure 2. Electrochemical deposition interactions diagram.

3.3 Impressed Current Cathodic Protection Structure Strengthening (ICCP-SS)

Structural reinforcement and cathodic protection are often needed in engineering practice to address both the symptoms and root-cause, while since they belong to structural engineering and electrochemistry respectively, causing each one has its own material system, technical requirements and design methods. The compiling group studied and compounded these two technologies and put forward the normative provisions suitable for the popularization of ICCP-SS. The main innovations include: The mechanical strength of carbon fiber mesh cloth is required according to the current national standards. The shear strength of adhesive (polymer mortar, epoxy resin adhesive) is tested (Dai *et al.* 2016), and the ultimate shear capacity is proposed to prevent interlaminar failure (Xu 2015). The resistivity of the adhesive is required to ensure the normal operation of the cathodic protection. The bearing capacity amplification of the repaired members is limited to prevent the brittle fracture (Chen 2017, Chu 2000).

4 CASE STUDY

A bridge is Chinese first sea-crossing bridge built on the same plane by highway and railway. The width of the bridge is 28.2 meters, of which 7.2 meters are single track and others are lanes and sidewalks on each side. It was opened to traffic on April 27, 2001 and has been in operation for 15 years with annual traffic volume of approximate four million 620 thousand times and daily average of 12600 times. Site investigation shows that the pier exists rust induct cracking, the main reasons are: The pier is in the splashing zone, high concentration chloride and thin thickness of protective layer of certain part result in significant rust induct cracking. Since the cracks provide a smooth path for chloride ions to reach the surface of steel bars, the durability of concrete will deteriorate significantly, and the corrosion rate of steel bars will be multiple increased.

In order to ensure the life expectancy of the bridge, the durability safety hazards of concrete must be reduced to a minimum. The project adopts bi-directional electromigration technology to rehabilitate the pier. As shown in Figure 3, the trend map of residual chloride content before rehabilitation and after rehabilitation in different parts of the pier is drawn.

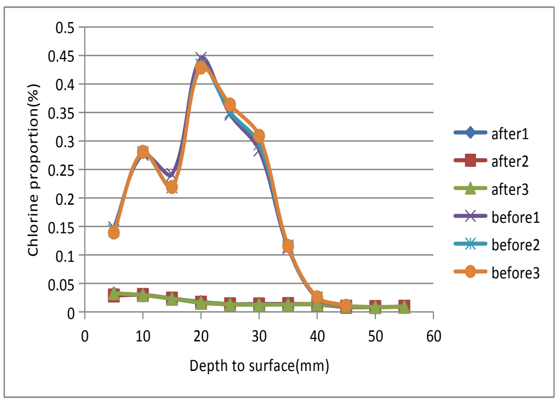

Figure 3. Distribution of chloride before and after rehabilitation.

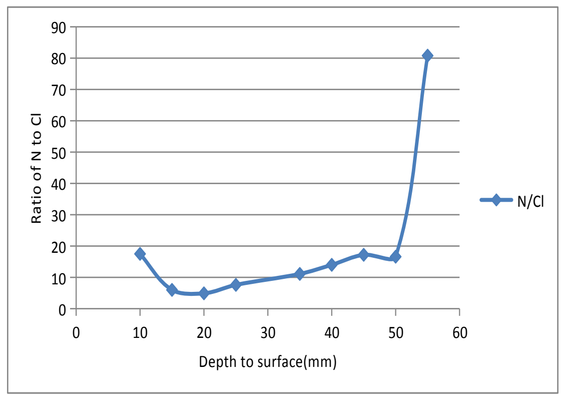

Figure 4. Evaluation of rehabilitation effect.

The chloride ion concentration before rehabilitation, from the surface of concrete to the depth of 35mm, was higher than the standard threshold, while the chloride ion concentration after rehabilitation has decreased obviously even to 80% of initial concentration and every part's chloride concentration is within the security range. The ratio of Nitrogen concentration to chlorine ion is an index to evaluate the effect of bi-directional electromigration and the higher ratio, the greater the effect. The N/Cl- distribution of different parts of the pier is drawn according to the collected data as shown in Figure 4. The ratio is much higher than 1.0 at the stress reinforcement of the pier, indicating that the overall effect of bi-directional electromigration is satisfactory, especially concrete surround the reinforcement.

5 CONCLUSIONS

It is necessary to establish a set of electrochemical technology for improving durability of concrete since the electrochemical methods for improving durability of concrete structures are developing and new technologies and methods are emerging constantly. According to the accumulated engineering experience and the new frontier technologies at home and abroad, the compiling group of Chinese *Technical Specification of Electrochemical Technology for*

Durability of Concrete Structures has perfected the traditional electrochemical technology, so as to popularize the new technologies and test their effectiveness and innovation by engineering practice.

The bidirectional electromigration technology has undergone the theoretical exploration, the selection of corrosion inhibitors, the optimization of electrification parameters, the evaluation of rehabilitation effect, and has already achieved the practical application in major projects. Bi-directional electromigration technology has been proved to have the advantages of both chloride extraction and corrosion inhibitor migration, and has a broad engineering application prospects.

Several mature and having engineering background technologies have been incorporated into this specification, while other new electrochemical technologies will be considered for adoption in the revision process of the specification after subsequent research and mature application.

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