A STUDY ON THE EFFECTIVENESS OF CATHODIC PROTECTION FOR STEEL BARS IN CONCRETE STRUCTURES

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論 文 名　：A STUDY ON THE EFFECTIVENESS OF CATHODIC PROTECTION FOR STEEL BARS IN CONCRETE STRUCTURES
（コンクリート構造物に埋設された鉄筋に対する電気防食の効果に関する研究）

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論　文　内　容　の　要　旨

Deterioration of reinforced concrete (RC) structures is commonly caused due to corrosion of steel bars. Exposure to de-icing salts, seawater and chloride containing set accelerators play an important role in the corrosion process. Long term exposure to carbon dioxide is also cited as a main factor to the corrosion of steel in concrete as well. Cathodic protection (CP) system has been introduced as an effective technique of corrosion protection of steel for both new constructions and repair of concrete member in severe environments. However, there is still debate regarding the CP design for reinforced concrete structures. This study evaluated the effectiveness of cathodic protection (CP) for reinforced concrete structures. This dissertation consists mainly of the eight chapters.

In **Chapter 1**, the research background, research objectives and dissertation arrangement in this study are explained. Two types of CP system were evaluated namely Sacrificial Anode Cathodic Protection (SACP) and Impressed Current Cathodic Protection (ICCP). SACP system was applied in chloride contaminated concrete, repaired concrete and cracked concrete. While, ICCP system was performed in chloride contaminated concrete exposed to the atmospheric condition. Also, an appropriate CP design for RC structures was proposed.

In **Chapter 2**, previous study relates to the corrosion and corrosion protections of steel bar in concrete and issues addressed in this study are described. Experimental works which have been conducted to examine the CP criteria are reviewed.

In **Chapter 3**, the effectiveness of commercially available sacrificial point anode for corrosion prevention of steel in concrete structure is presented. In this study, three types of concrete specimens with sacrificial point anode were prepared: (1) chloride contaminated concrete; (2) repaired concrete; and (3) cracked concrete. Specimens were exposed to three conditions namely air curing (T: 20±2ºC, RH: 60%), immersion in 3% NaCl solution and dry/wet cycles. Electrochemical tests include the potential, protective current, polarization behavior of sacrificial point anode, anodic-cathodic polarization curve, polarization resistance and visual observation. The test results conclude that sacrificial point anode is effective to prevent microcell and macrocell corrosion of steel bar and it becomes much remarkable in high moisture condition. In addition, the specimen with gap between steel bar and sacrificial point anode provide a stable protective current than without gap.

In **Chapter 4**, the environment improvement of the steel surface as a secondary effect of CP was studied. Nine levels of constant current densities were applied on the steel bar embedded in concrete specimens in the size of 120 mm x 120 mm x 200 mm with water to cement ratio (W/C) of 55% and chloride ion of 2 kg/m^3, 5 kg/m^3 and 10 kg/m^3. Prior to CP tests, accelerated corrosion test were performed to generate initial corrosion on the surface of steel bar. The instant-off potential (E_{io}), depolarization test, anodic-cathodic polarization curve, corrosion rate and visual observation were evaluated. From test results, it was found that the 100 mV decay potential was achieved even with small protective current after certain periods in all chloride contents due to the “Environment Improvement” effects. It means that the protection of steel bar is not instantaneous but gradual process to achieve. In the concrete with 10 kg/m^3 of chloride, the decay potential slightly decreased at 230 days due to the diffusion of dissolved oxygen (DO). Also, a small current density has improved the passivity film of steel bars. In addition, the corrosion rate of steel under protection is approximately 20, 16 and 100 times lower than the open-circuit corrosion rate for initial potential shift of 25 mV, 50 mV and 100 mV respectively.

In **Chapter 5**, three levels of depolarization value of 25 mV, 50 mV and 100 mV were examined in concrete specimen with different chloride content. All the materials, concrete composition, dimension of specimens and CP arrangement are identical as in **Chapter 4**. The protective films of steel bar were removed before being embedded in the concrete specimen and then subjected to the accelerated corrosion test. From the test results, it is concluded that the depolarization level of 25 mV and 50 mV is adequate to protect the steel bar in concrete, with chloride lower than 5 kg/m^3. However, the depolarization level higher than 100 mV is necessary when the chloride content in concrete is more than 5 kg/m^3. In addition, the protective current may be reduced under the CP of stable condition after a certain periods.

In **Chapter 6**, two CP methods were used: (1) constant current density and (2) constant potential shift from its natural potential of steel bar 24 hours after the switch off. Both CP methods were examined in the concrete specimens with corrosive steel bar and high chloride concentration. Concrete with water to cement ratio (W/C) of 60% with initial chloride content of 10 kg/m^3 were prepared. The initial corrosion of steel bars were formed by dry/wet cycles of 3% NaCl solution spray (1W:1D) about two weeks before concrete casting. In the case of constant current density, additional accelerated corrosion tests were performed for 15 days prior to CP tests. Protection levels of 25 mV, 50 mV and 100 mV were maintained. The results showed that a larger protective current was not required at early time to satisfy the 100 mV, which leads to the earlier deterioration of anode. Therefore, reduction of current density is necessary after achieving the 100 mV criterion to reduce the negative effects of large CP current. Although the protective current decreased, the depolarization value of steel bar is kept higher than 100 mV (constant potential shift of 100 mV). This would indicate that the steel bar is protected even the current density is decreased after the 100 mV depolarization value is achieved. The test results also showed that corrosion rate under protection are lower than the open-circuit condition due to the presence of protective current at the surface of steel bar.

In **Chapter 7**, an appropriate CP design for reinforced concrete structures exposed to the atmospheric zone is discussed. By considering the amount of chloride content in concrete, 50 – 100 mV depolarization value is enough to protect of steel bar in concrete at chloride lower than 5 kg/m^3. However, depolarization value more than 100 mV should be applied if chloride content is larger than that value. CP design of decreasing the protective current after achievement of specific protection level is recommended for reinforced concrete structures. In addition, an adjustment of the protection level of steel bar in concrete depends on the chloride concentration, corrosion degree and the environmental condition. In the implementation of cathodic protection, many factors are found in adjusting the protection level, such us actual chloride content, corrosion degree of steel bar and non-homogenous environmental condition of structures. An accurate analysis data relates to these factors is needed before installing a CP system.

In **Chapter 8**, finally a conclusion and recommendations for future works is presented.