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Tower Type Sensors for Monitoring Corrosion Risk in Cover-zone Concrete

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Abstract. In order to monitor corrosion risk in cover-zone concrete, an integrated tower type sensor (TTS) was developed to obtain the electrochemical parameters such as concrete resistance, macro-cell current and the corrosion potential of built-in electrodes. To obtain valid macro-cell current value, specialized short-circuit acquisition time equal to 30 s has been defined in present cement mortar. The results indicate that the macro-cell current increases and cement mortar resistance decreases meanwhile with the content of chloride ions increase in imported chloride cement mortar. The effective measurement of the macro-cell current and cement mortar resistance allows TTS to be used as a corrosion risk monitoring system in cover-zone concrete.

Introduction

Corrosion of rebar embedded in concrete is one of the greatest civil engineering challenges all over the world. The major reason of the reinforcing steel corrosion is the presence of chloride ions. They caused localized breakdown of the passive film that initially forms on steel as a result of the alkaline nature of the pore solution in concrete structures [1]. The harmful chloride ions can be originated from the usage of deicing salt or from the marine environment. Service-life prediction of concrete structure requires quantitative information on cover-zone properties and threshold values for corrosion initiation and, once initiated, the rate of corrosion [2]. The development of sensors for monitoring concrete performance has been a hot issue dominated this research field these days [3, 4]. In-situ sensors for monitoring the electrical concrete conductivity were studied by W.J. McCarter *et al* [5]. M.A. Climent-Llorca *et al* [6] developed a novel Ag/AgCl wire electrodes as in-situ chloride concentration sensors in concrete structures. Anode-ladder-system designed by M. Raupach *et al.*, has been used widely to monitor the corrosion risk in concrete structures [7]. However, traditional sensor systems can't provide relatively all-around parameters in cover-zone concrete. In this paper, an integrated sensor system TTS was developed to monitor the corrosion risk by measuring the macro-cell current, open circuit potential and cement mortar resistance in cover-zone cement mortar.

Experiments

Materials. P·O 42.5 cement used was from Harbin cement factory. The river sand with fineness modulus of 2.4 was used as fine aggregate. In order to evaluate the performance of TTS in chloride-contaminated concrete, sodium chloride in different mass ratio were added into cement mortar. The mix proportions of cement mortar are given in Table 1.

Table l Mix proportions of cement mortar

Mix	Cement	Fine agg.	w/c	NaCl [%]
A	1	3	0.60	0
B	1	3	0.60	0.3
C	1	3	0.60	3

Tower Type Sensor. A typical layout of TTS system is shown in Fig. 1. Each of the four steel (Q235) anode rings with different diameter spaced 10 mm from each other was fixed on a fabricated nylon tower and a Ti/MnO_2 reference electrode (TMRE) was set in the bottom of tower [8]. To obtain valid dates from the anodes, the inside diameter of Anode 2 (A2) was equal to the outside diameter of A1. The same geometrical design was also applied to the other anodes. Cathode made of Ti/MMO mesh belt (10 mm in width) was positioned 5 mm under A4. Cables were led out from the cover-zone concrete after connected to A1~4, cathode and reference electrode, respectively.

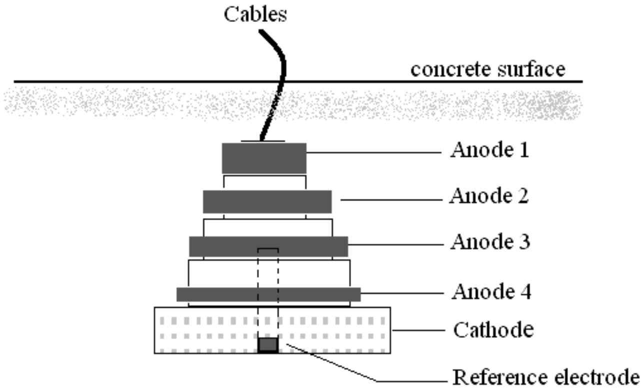

Fig.1 Typical layout of TTS system in cover-zone concrete

Experimental Program. All the measurements were performed by RST5200 electrochemical system at an ambient temperature of 25±1 ℃ and RH of 95% after the specimens cured for 28 days.

Macro-cell Current. Actually macro-cell current is determined by following equation [9]

$$I_{mac} = \frac{\Delta U}{R_{an} + R_{ca} + R_E} = \frac{U_{ca} - U_{an}}{R_{an} + R_{ca} + \frac{\rho_c}{L}} . \quad (1)$$

Where I_{mac} is macro-cell current, $\triangle U$ is driver force between corrosion potential of anode U_{an} and corrosion potential of cathode U_{ca}. R_{an}, R_{ca} and R_E are resistance of anode, cathode and cement mortar, respectively. L is characteristic length, which depends on concrete quantities, area of anodes and cathode, the electrical resistivity of cement mortar ρ_c and the distance between anode and cathode. To clarify the relationship among magnitude of macro-cell current, anode state, cathode state and cover-zone condition, the instant short-circuit current between cathodes and anodes was measured.

Cement Mortar Resistance. Fig. 2 depicts the equivalent circuit graphic of the specimens. Where C_{dl} is anode interface capacitance, R_s is cement mortar consistence, W is Warburg resistance and R_p is polarization resistance of anode. Nyquist plots were recorded at high frequencies (20 to 10 kHz). C_{dl} was directly short-circuited by means of the interference with high frequency current, and then the value of R_s would be obtained.

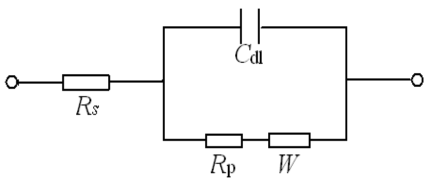

Fig. 2 Equivalent circuit for anodes in corrosion state

Results and Discussion

Macro-cell Current Tests. Fig. 3 shows the instant short-circuit current flowing between anodes and cathode embedded in cement mortar specimen C. The instant short-circuit current decays with time as a simple exponential function of first-order system (see Fig. 3).

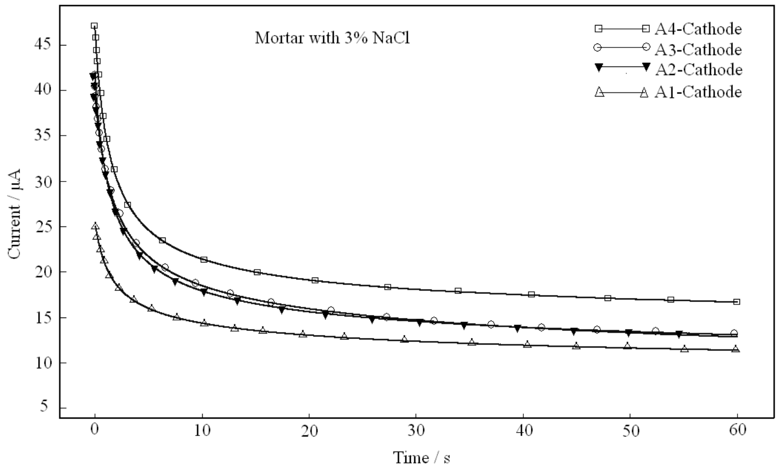

Fig. 3 Instant short-circuit current between anodes and cathode

To obtain a relative stable current value, standard short-circuit time can be defined as follows:

$$\frac{I_{ins}(t)-i_s}{i_0-i_s}=e^{-t/\tau}. \tag{2}$$

Where t is the measurement time, $I_{\text{ins}}(t)$ is instant short-circuit current varied with time t, i_0 is the initial value of the short-circuit current, i_{s} is the steady value of the short-circuit current and τ is time constant. The standardized values of τ will be deduced from all measured values of three specimens, and the average value of τ will be used as a parameter in definition of macro-cell current acquisition time. At the end of the exposure period, this average τ, ≈10 s for three cement mortar specimens. Regarding the most suitable short-circuit time for actual requirement, 3τ corresponding to a 95% degree of stability (see Eq.2) has been defined as short-circuit current acquisition time. A short measuring time about 5 s which has been defined as standard short circuit time in literature [5] may overestimate short-circuit current value. Table 2 shows the specified short-circuit current (or called macro-cell current) results from different cement mortar specimens.

Table 2 Specified short-circuit current at 30 s in different mortar [μA]

Cement Mortar	A1-Cathode	A2-Cathode	A3-Cathode	A4-Cathode
A	0.1	0.1	0	0
B	7.2	8.2	7.9	10.0
C	14.2	15.0	15.2	19.1

As shown in Table 2, the macro-cell current in specimen C was higher than that in B, and nearly tiny current was observed in A. With regard to given TTS, R_{an}, R_{ca}, surface area of electrodes and distance between anode and cathode may keep a constant. U_{an} and U_{ca} could be measured *vs.* embeddable TMRE sensor. As expected, it was found that the higher $\triangle U$ has be observed in cement mortar B and C with addition of sodium chloride. That indicated a higher macro-cell current in them if not considering the cement mortar resistance. In addition, tiny macro-cell current in A may be attributed to the lower $\triangle U$ and the imaginable high resistance of cover-zone concrete. Generally, to monitor the sudden change of macro-cell current in time may provide us an initial time of corrosion, while the anodes embedded in different depth of cover-zone has been de-passivated by chloride ions or the other impacts [10]. Further, to clarify the influence of the cement mortar resistance on the macro-cell current, AC impendence measurement was adopted after that.

Cement Mortar Resistance Tests. Table 3 shows the depth-related cement mortar resistance results from different cement mortar specimens.

Table 3 Resistance between adjacent anodes [Ω]

Cement Mortar	A1-A2	A2-A3	A3-A4
A	4215	4202	4477
B	1732	1800	2000
C	1002	1035	1070

Table 3 shows that, as the addition of sodium chloride increases, not only its macro-cell current increases, but also the resistance between the adjacent anodes associated with the corrosion risk becomes lower. Of course, resistance difference between anodes in different depth of the same mortar should be connected with the moisture gradient. Usually, the relative humidity was obviously different between the exposed and sheltered faces of the concrete specimens, with the exposed face generally having a higher RH [11]. Further, in such two-probe configuration the measured electrical contact resistance values are depth-related and effective, while in the traditional four-probe set-up the electrical resistance is a practically average value of cover-zone concrete. Thus all above-mentioned measurement parameters by TTS will provide us more precise depicts of the corrosion risk of the cover-zone concrete.

Conclusion

(1) An integrated TTS system, which allows depth-related electrochemical measurements within the cover-zone concrete, was employed to study the macro-cell current, open circuit potential and cement mortar resistance in the cement mortar with different mass ratio of sodium chloride.

(2) TTS can provide information on the macro-cell current for predicting the initial time of the de-passivation of anodes, namely, it could monitor the corrosion risk in cover-zone concrete in time.

(3) The experiment results verified that the fabricated TTS was sufficient to serve the purpose of the cover-zone concrete health monitoring.

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