MONITORING CORROSION RATE OF CONCRETE BY AC IMPEDANCE SPECTROSCOPY

M. A. ISMAIL and M. OHTSU
Department of Civil Engineering and Architecture, Kumamoto University
2-39-1 Kurokami, Kumamoto 860-8555, Japan

ABSTRACT

Assessment and monitoring of corrosion in steel reinforcement have been a prime concern for concrete structures. Over the past two decades, various techniques were implemented for corrosion assessment.

This paper summarizes results of a study on the corrosion assessment of reinforcing steel in concrete cylinders exposed to chloride ions. Fifty-two concrete cylinders, each with a single embedded reinforcing steel rod, were subjected to sodium chloride solution with 0%, 1%, 3% and 5% concentrations. Specimens were also subjected to pre-conditioning and drying-wetting cycles. Concrete mix proportion was designed with 60% water-to-cement ratio, containing plain Portland cement. AC Impedance Spectroscopy Technique (IS) was employed to determine the corrosion rate (CR) of the reinforced concrete cylinders. Electrical Equivalent Circuit was used to interpret the AC impedance spectra.

To study the reliability of IS, results were compared with those obtained by such corrosion assessment techniques as Tafel Plot (TP) and linear Polarization (LP). Results confirm that IS gives reliable results with respect to the effect of exposure conditioning on CR of steel reinforcement. They also show a good agreement with both of TP and LP techniques.

1 INTRODUCTION

Corrosion of reinforcing steel is of great concern, because it is probably the most widespread cause of degradation in reinforced concrete. Initially, reinforcing steel embedded in concrete is naturally protected from corrosion by the high alkalinity of its interstitial solution (Neville [1]). However, this passive state can be inhibited by the destruction of the passive film due to aggressive ions (chlorides, sulfates) or an acidification of the environment near the reinforcing steel (carbon-ation).

Electrochemical methods could be applied to measure the corrosion rate in concrete structures. Among various electrochemical methods, electrochemical impedance spectroscopy (EIS) seems to be reliable for monitoring the corrosion process in reinforced concrete (Lay et al. [2], Gu et al. [3]).

The measurement of AC impedance spectroscopy provides information on the electrical resistivity, the dielectrical properties of the concrete cover, the corrosion rate and the mechanism of reaction at the steel/concrete interface.

Experimental investigations (Qian et al. [4]) have shown a close relationship between the corrosion rate determined by weight loss and those calculated from AC impedance measurement. This paper aims to study the effects of pre-conditionings and chloride contents on the corrosion of steel reinforcement by using AC impedance technique.

2 EQUIVALENT ELECTRICAL CIRCUIT (EEC)

To interpret AC impedance spectra, an equivalent circuit is commonly applied via electrical fitting. Due to the complexity of reinforced concrete system, several models have been tested to obtain the best fit and to calculate the corrosion current (Hachani et al. [5], Grentsil et al. [6]).

When the corrosion current of reinforcing steel in concrete is determined using the AC impedance technique, the charge transfer resistance, R_{ct} which determined from the "best-fit" of the impedance spectra, applying an equivalent circuit is usually used instead of polarization resistance, Rp (Haruyama and Tsuru [7]). Four types of Equivalent Electrical Circuit (EEC) are used in this work. An example of the equivalent circuits used in this study is shown in Figure 1. Details of the definitions of the circuit components are described elsewhere (Lemoine et al. [8], Alonso et al. [9]).

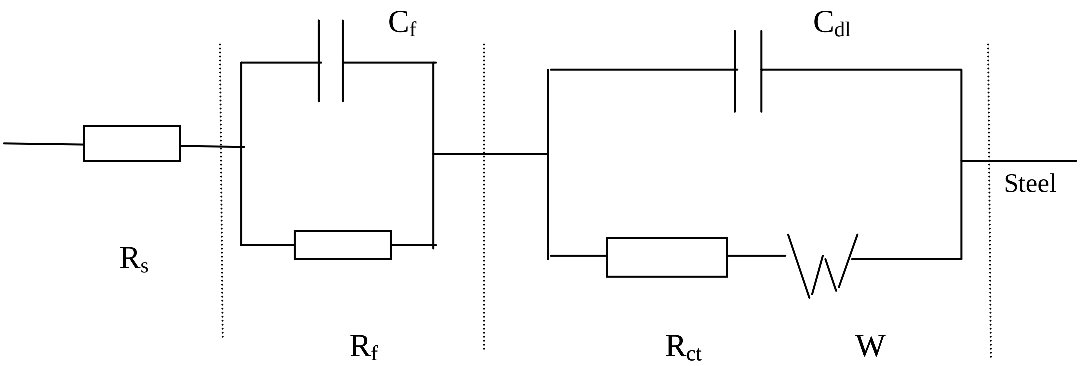

Figure 1: An equivalent electrical circuit used in fitting process of AC impedance.

3 EVALUATION OF CORROSION RATE

The density of corrosion current I_{corr} can be calculated from the Stern-Geary equation [10],

$$I_{corr} = B/R_p \tag{1}$$

Where

$$B = \frac{b_a b_c}{2.303(b_a + b_c)} \tag{2}$$

B is so called the "Stern-Geary constant", where b_a and b_c are the tafel slopes for the anodic and cathodic reactions, respectively. B value is taken as 26 mV. Derived from Faraday's law, the following equation is applied to calculate the corrosion rate (CR).

$$\text{CR } (\mu\text{m/y}) = \frac{3.27 \times I_{corr} \times E.W.}{d} \tag{3}$$

Where *E.W.* is the equivalent weight of steel in gram and *d* is the density of reinforcing bar in g/cm^3. By substituting eqn (1) into (3) and setting the values of *E.W.* and *d*, eqn (4) is obtained.

$$\text{CR(mm/yr)}=304.2/R_p \tag{4}$$

Where unit of resistance R_p is ohm.cm^2. R_p can be replaced by R_{ct} which determined from the best fitting of the spectra. An example of AC spectra fitted by equivalent circuit in Figure 1 is given in Figure 2. The values determined are shown in Table 1.

Table 1: Determined values of the equivalent circuit.

	R_s (Ω.cm^2)	C_f (nF/cm^2)	R_f (Ω.cm^2)	C_{dl} (μF/cm^2)	R_{ct} (Ω.cm^2)	W
B3(2)	790	10.1	85.2	12.56	23400	0.01

4 EXPERIMENTAL PROGRAM

Ordinary Portland cement concrete (OPC) was used and mixture proportion of concrete is given in Table 2, along with properties of fresh and hardened concrete. Cylindrical specimens of 150 mm diameter and 300 mm height were cast with one 13-mm diameter reinforcing steel at the center.

The reinforcing steel was sealed with anti-corrosion epoxy coating (SikaTop-Armatec 110 Epocem), except the area where corrosion was monitored. Both ends of concrete cylinder were also sealed with impermeable coating (Fosroc-nitoflor FC140), to insure the ingress of chloride only from the surrounding perimeter.

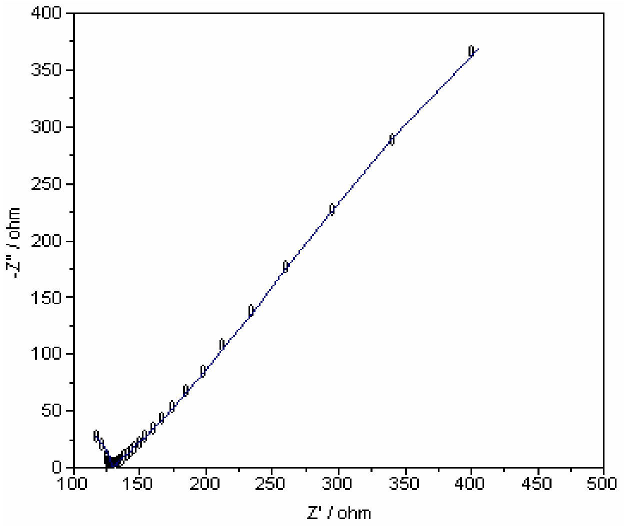

Figure 2: Nyquist format for specimen OPC B3(2).

Table 2: Mixture proportion of concrete and mechanical properties.

Materials and properties	Ordinary Portland cement Concrete
Cement- Type 10 (kg/m^3)	300
Water (kg/m^3)	180
Fine aggregate (kg/m^3) – Fineness Modulus =2.8	675
Coarse aggregate (kg/m^3) - max. size 20-mm	1250
Slump (mm)	125
Air content (%)	1
Compressive strength (MPa) at 28 days	32.5

Fifty-two reinforced concrete cylinders were tested to determine the corrosion rate of reinforcing steel under controlled exposure conditions in a laboratory. NaCl solution was made by dissolving in distilled water, of which concentration was monitored and adjusted regularly. The specimens were subjected to four different concentrations (weight/weight) of chloride solution (0%, 1%, 3%, and 5%). To accelerate the corrosion of the reinforcing steels, after 28 days cured in standard curing condition, two pre-conditionings of type B and type E were made. Then all specimens were exposed to cycles of drying and wetting. Type B specimens were treated without pre-drying in an oven, while type E specimens were subjected to drying in an oven before starting the first cycle. Each specimen was dried for one week followed by wetting for another week and then tested.

The test setup for the AC impedance spectroscopy consists of a potentiostat/galvanostat and Autolab General Purpose Electrochemical System (GPES) coupled with frequency response analyzer (FRA). A sketch of the test is shown in Figure. 3.

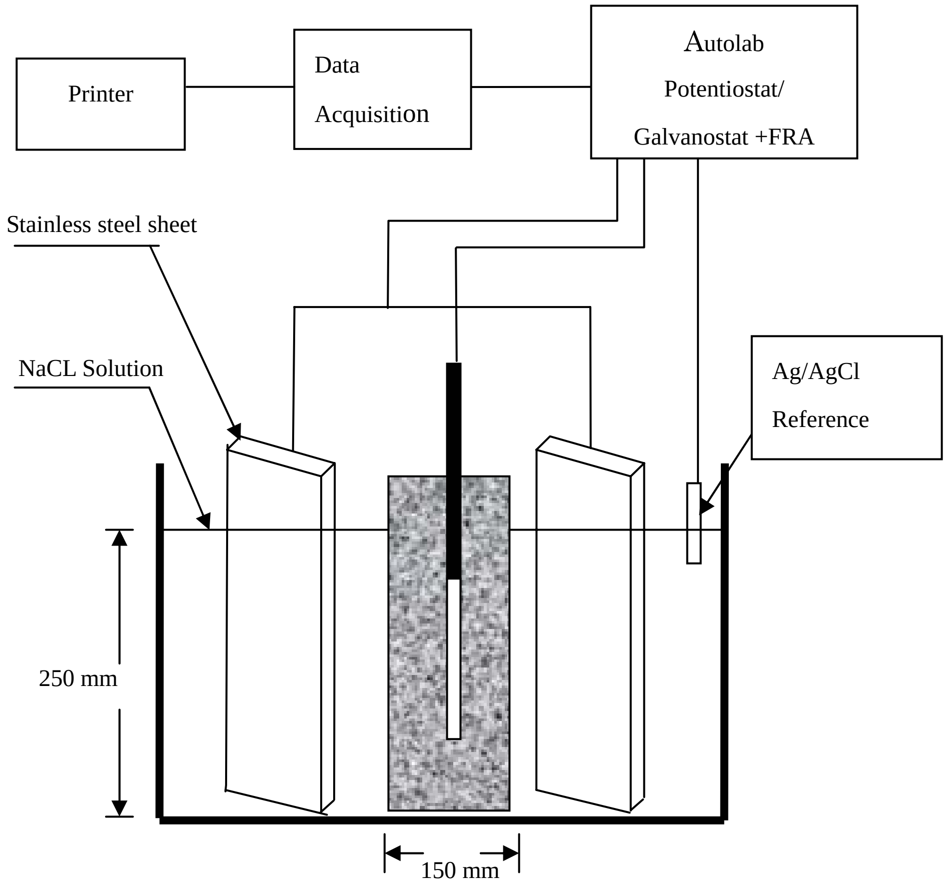

Figure 3: A sketch of corrosion rate measurement by AC impedance technique.

5 RESULTS AND DISCUSSION

5.1 Effect of pre-conditioning

Figure 4 shows the corrosion rates of specimens subjected to different pre-conditionings. It can be seen that specimens in case E4, which were subjected to cycles of oven drying and wetting, achieved the highest corrosion rates compared with the other cases. All specimens E type achieved higher results compared with specimens B type. The range of increase in corrosion rates for specimens E type over B type is between 4 % to 65%.

5.2 Effect of chloride contents

Figure 5 demonstrates the corrosion rates obtained by AC impedance for specimens subjected to 1%, 3%, and 5% NaCl concentrations. The corrosion rate increases as NaCl concentration increases for all conditions. As it can be seen in Figure 5, the increase in corrosion rate is from 1.15 to 2.50 times for 3% and 5% NaCl concentrations, compared to 1% concentration in all B and E specimens except for E4. In the case of E4 specimens, the increase in corrosion rate is from 3.4 to 4.4 times more for 3% and 5% NaCl concentrations, compared to 1% concentration.

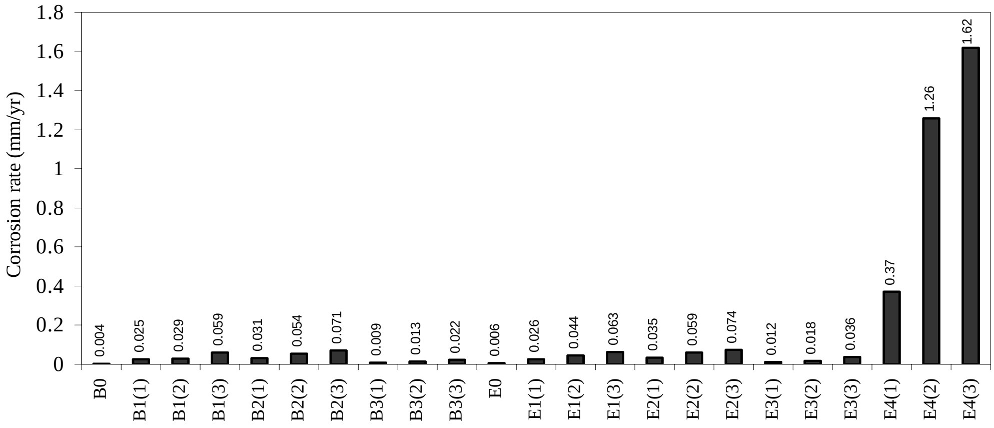

Figure 4: Corrosion rates of specimens subjected to different pre-conditionings.

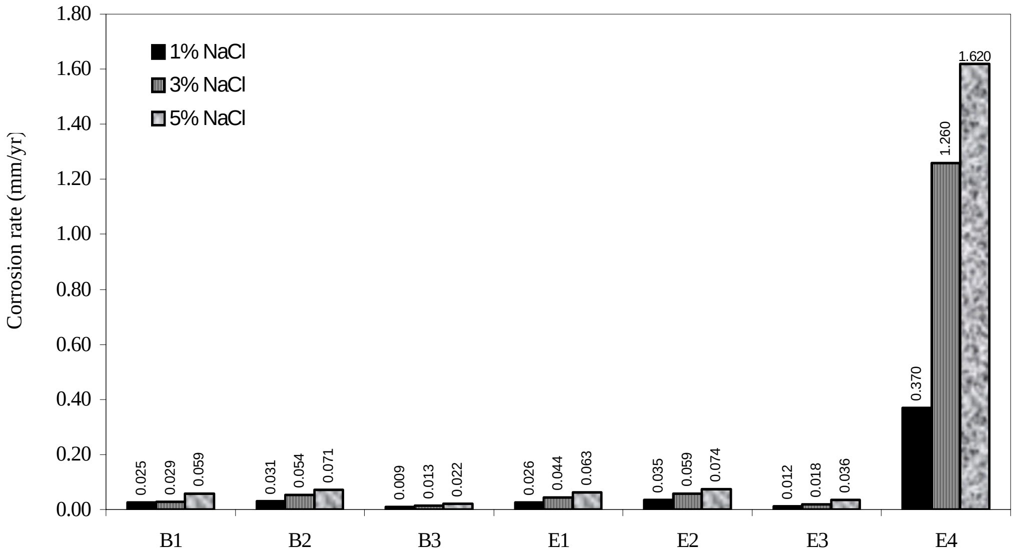

Figure 5: Corrosion rates of specimens subjected to 1%, 3%, and 5% NaCl.

5.3 Tafel plot, linear polarization resistance and AC impedance techniques

Results of AC impedance are compared with previous results obtained by Tafel Plot (TP) and Linear Polarization resistance (LP) techniques (Ismail and Soleymani [11]). Tables 3 and 4 show the corrosion rates of all specimens under different exposure conditions measured by TP, LP, and AC impedance techniques. From the table, reasonable agreement is observed in the corrosion rates by three techniques. Values obtained by AC impedance technique are lower than TP by 5% to 20%, while results of LP are 20% to 30% higher than those of TP.

Table 3: Corrosion rates of B specimens.

	B1(1)	B1(2)	B1(3)	B2(1)	B2(2)	B2(3)	B3(1)	B3(2)	B3(3)
AC	0.025	0.029	0.059	0.031	0.054	0.071	0.009	0.013	0.022
TP	0.028	0.035	0.065	0.037	0.060	0.084	0.01	0.016	0.026
LP	0.034	0.043	0.081	0.046	0.074	0.106	0.013	0.020	0.033

Table 4: Corrosion rates of E specimens.

	E1(1)	E1(2)	E1(3)	E2(1)	E2(2)	E2(3)	E3(1)	E3(2)	E3(3)	E4(1)	E4(2)	E4(3)
AC	0.026	0.044	0.063	0.035	0.059	0.07	0.012	0.018	0.036	0.37	1.3	1.6
TP	0.03	0.05	0.07	0.04	0.069	0.09	0.014	0.021	0.04	0.44	1.4	1.7
LP	0.038	0.064	0.089	0.05	0.089	0.12	0.018	0.027	0.052	0.56	1.8	2.1

6 CONCLUSION

The corrosion rate of reinforcing steel embedded in the concrete cylinders is investigated by AC impedance technique. Reinforced concrete cylinders are tested under different conditions. Results obtained are compared with those obtained by other techniques of Tafel Plot and Linear Polarization. These results can be summarized as follows:

1- Equivalent circuit models for electro-chemical reactions are constructed to fit the various experimental spectra.
2- Drying cycles in the oven accelerate significantly the corrosion rate for specimens.
3- Values obtained by AC impedance technique are lower than TP by 5% to 20%, while results of LP are 20% to 30% higher than those of T. P.

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