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Nondestructive Surface Measurement of Corrosion of Reinforcing Steel in Concrete

Mauricio Mancio, M. Eng.
Department of Civil and Environmental Engineering
University of California at Berkeley
Berkeley, CA USA

Jieying Zhang, Ph.D.
Research Associate, Concrete Structures
Institute for Research in Construction
National Research Council of Canada
Ottawa, ON

Paulo J. M. Monteiro, Ph.D.
Department of Civil and Environmental Engineering
University of California at Berkeley
Berkeley, CA USA

Introduction

The modern approach of designing structures includes a careful analysis the long-term durability. The escalation of the replacement costs of structures and the growing emphasis of life-cycle cost rather than first cost are forcing engineers to become durability conscious[1].

Although the combination of concrete and reinforcing steel has been regarded as an optimal one, the lack of durability of some reinforced concrete structures has become a topic of great concern, since the corrosion of steel embedded in concrete is the major cause of the deterioration of concrete structures. This article presents a brief overview about the nondestructive measurement methods for corrosion, with special emphasis on the electrochemical impedance spectroscopy technique and on the development of a new surface-based measurement method (SMM).

Economic Impact of Corrosion

The total direct cost of corrosion in the U.S. is estimated at $267 billion per year, which is equivalent to 3.1% of the U.S. gross national product (GNP), according to a recent study done by the Federal Highway Administration (FHWA)[3]. The economic implications of corrosion to the civil infrastructure are also significant. For instance, approximately 15 percent of the 586,000 bridges in the U.S. are recorded as structurally deficient, primarily due to corrosion of steel and steel reinforcement. The annual direct cost of corrosion for highway bridges is estimated to be $8.3 billion.

Nondestructive Testing Methods

The anticipated economic impact of an extensive infrastructure repair scheme has produced a renewed interest in improving non-destructive testing methods for assessing concrete structures[1].

The early detection of corrosion damage in reinforced concrete is challenging because the steel bars are embedded in the concrete, and inaccessible for visual inspection. When typical manifestations of corrosion distress become evident (e.g., stains on the concrete surface and cracking), the structure may already be seriously compromised [5]. Also, the earlier the deterioration processes is detected, the lower the costs for maintenance and repair. Therefore, it is clear that appropriate detection techniques highly needed to assess the corrosion in reinforced concrete structures.

Several electrochemical methods have been used to evaluate corrosion activity of steel reinforcement. Among such techniques, the most commonly used test methods for *in-situ* measurements are half-cell potential, polarization resistance, and electrochemical impedance spectroscopy.

The half-cell potential method (figure 1a) is described in ASTM C 876, and basically consists of a simple test to measure the corrosion potential, used to estimate the likelihood of corrosion activity at the time of the measurement; however, it does **not** provide any information on the rate of corrosion of the reinforcement. The linear polarization resistance technique (figure 1b) is a well-established method for determining corrosion rate by using electrolytic test cells (ASTM G 59). The technique basically involves measuring the change in the open-circuit potential of the electrolytic cell when an external current is applied to the cell. For a small perturbation about the open-circuit potential, there is a linear relationship between the change in applied current per unit area of electrode (Δi) and the change in the measured voltage (ΔE). The ratio $\Delta E/\Delta i$ is called the polarization resistance (Rp). The corrosion rate, expressed as the corrosion current density, is inversely related to the polarization resistance. Note that, for both methods, one terminal must be electrically connected to the reinforcement, that is, physical access to the reinforcement must be provided.

The electrochemical impedance spectroscopy (EIS) method is the most informative technique currently available, and forms the basis for the development of the new surface-based measurement method described later in this paper. This technique is briefly described in the next section.

Electrochemical Impedance Spectroscopy

The electrochemical impedance spectroscopy method, or AC impedance, can determine a number of fundamental parameters related to corrosion kinetics, and it has been extensively used in corrosion research. The method analyses the response of corroding electrodes to small-amplitude alternating signals (AC) that vary in a wide range of frequencies. The input is usually a sinusoidal wave of AC current with magnitude I and frequency f, and the output is a voltage response with magnitude $V(f)$ and phase difference $\phi(f)$ with respect to the current. Figure 3 illustrates the experimental setup[8]. Following this procedure, one determines experimentally the impedance $Z\ (=V/I)$ as a function of ω, and then tries out different ways of representing the electrode process in terms of its electrical analogue of resistance, capacitance and/or inductance in various arrangements corresponding to the possibilities of the physical model. The three most important physical quantities responsible for the impedance measured in a cell are: (1) The solution (or electrolyte) resistance, (2) The resistance of the interface, and (3) The capacitance of the Double Layer [5, 7, 8]. The simplest and mostly used equivalent circuit for the electrochemical interface is represented in figure 3. In this model, R_{soln} represents the resistance of the electrolyte (or R_c, in the case of concrete resistance). The interfacial resistance (also referred to as polarization resistance) is represented by R_p, while the capacitance in parallel represents the double-layer capacitance (C_{dl}). Figures 4 (a) and (b) illustrate typical plots and indicate the information obtainable from this method[1]. Figure 5 shows actual results from an EIS experiment.

Development of a New Surface-based Measurement Method

As briefly stated earlier, the currently available methods used to evaluate the corrosion rate of steel embedded in concrete require that at least one electrode be connected to the steel, so that the concrete cover must be removed to expose the rebar. Besides labor-intensive and time consuming, this operation may induce further damage on the deteriorating structure.

Under this scenario, the concrete surface-based measurement method (SMM) appears as a powerful nondestructive technique to assess deteriorated structures and study the corrosion process, both in the laboratory and in the field. The method is able being to determine the position and corrosion state of the reinforcing bars, as well as the resistivity of the concrete itself, from the concrete surface and with no need of connection to the reinforcement. Initially conceived at Berkeley by Monteiro and Morrison[5], and subsequently developed by Zhang [9-12], the method uses a four-electrode electrical resistivity array on the surface of concrete to indirectly measure the complex frequency-dependent interfacial impedance between the reinforcing steel bars and the concrete. Besides that, the measurement is localized over a small portion of the rebar located between the electrodes, being possible to distinguish corroding and protected areas in a same bar.

As represented in figure 6, a four-electrode array is placed on the concrete surface, current is injected between the two outer electrodes, and the voltage drop produced by the current flow is measured across the two inner electrodes. This array has equal electrode separation "*a*" and is known as Wenner array[a].

As the current is injected into the concrete, the rebar surface becomes polarized, i.e., charges accumulate on the rebar surface as represented in figure 6, creating a net dipole which is added to the voltage read by the inner electrodes. Figure 7 shows the equivalent circuit that represents the concrete surface-based measurement method. In this figure, R_c represents the concrete resistance, while R_1, C_{dl} and R_p represent the path offered to the current through the concrete and into the rebar through the interfacial impedance.

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[a] Notice that the Wenner array has been used to determine the resistivity of the concrete itself. However, in this work it has been shown that this setup can be used to **measure the complex impedance** and consequently evaluate the corrosion state of the rebar.

According to figure 7, to study the frequency dependent electrical properties, the input current I is a cosine wave, of amplitude I_0 and angular frequency ω (in complex notation $I = I_0.e^{i\omega t}$), varied over a wide range of frequencies. Then the voltage response V will have magnitude V_0 and a phase angle shift ϕ with respect to the current ($V=V_0.e^{i(\omega t+\phi)}$).

For a Wenner array, the resistivity of a uniform half space of resistivity is given by $\rho = (V/I).2\pi a$. In fact, the resistivity obtained from this expression for an inhomogeneous subsurface is referred to as apparent resistivity (ρ_a), which is equal to the true subsurface resistivity only for a uniform half space. When V and I are not in phase, the above equation implies a complex apparent resistivity. It turns out that the complex apparent resistivity can be expressed by the resistivity modulus $|\rho_a|$ and the phase angle ϕ, or it can be written in terms of its real (in-phase) and imaginary (out-of-phase) parts.

The corresponding impedance spectrum over frequency will be a resistivity spectrum, because it has units $\Omega.m$ (Ohm-meter). It is important to notice that the measured impedance on the concrete surface does not reflect directly the interfacial impedance, because it is diluted due to the presence of concrete and therefore is influenced by the concrete resistivity. However, it has been demonstrated that every change in the interfacial impedance, or a change in the corrosion state of a rebar, will be reflected in the measurement on the concrete surface, and given the concrete resistivity and measurement geometry, the impedance response is unique with interfacial impedance.

Figure 8 shows the array setup, and figure 9 illustrates that the method is able to capture the corrosion process in reinforced concrete structures. Details of the experimental program can be found in Zhang et al. [9-11] and

Final Remarks

This article presented a brief review on the main nondestructive methods currently available to evaluate corrosion activity in rebars, and introduced the new surface measurements method, which is can to determine the position and corrosion state of the reinforcing bars from the concrete surface, with no need of connection to the reinforcement. Extensive work has been performed on this method [5, 9], including experimental analyses[10], forward modeling[11] and evaluation of the effects of geometry and material properties[12]. A thorough description of the technique can be found on the indicated references.

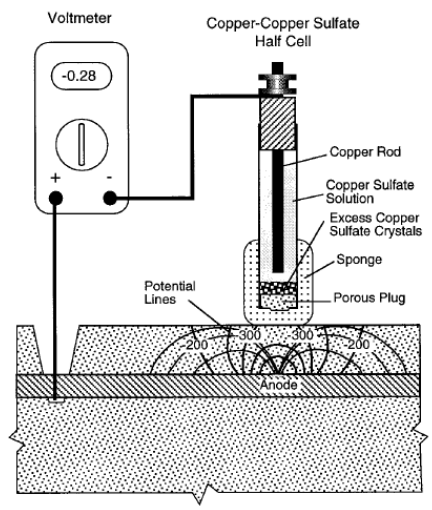

Fig. 1a

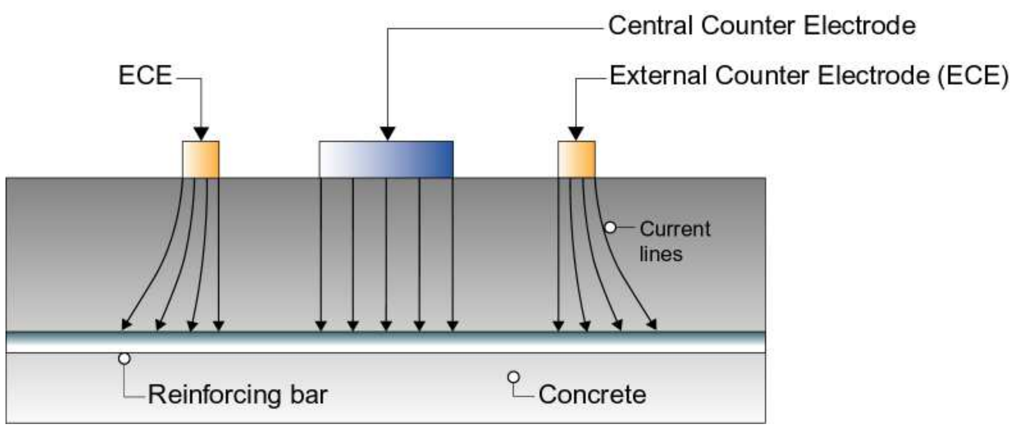

Fig. 1(b)

Figure 1 (a) Half-cell potential From ref. (6).; (b) Linear polarization resistance (after S. Feliu, J.A. Gonzalez, M.S. Feliu and M.C. Andrade, ACI Materials Journal, V. 87, p. 458, 1990.)

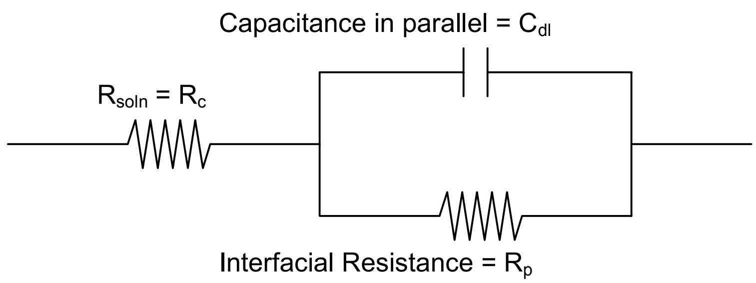

Figure 2 Equivalent circuit used to model the electrochemical interface

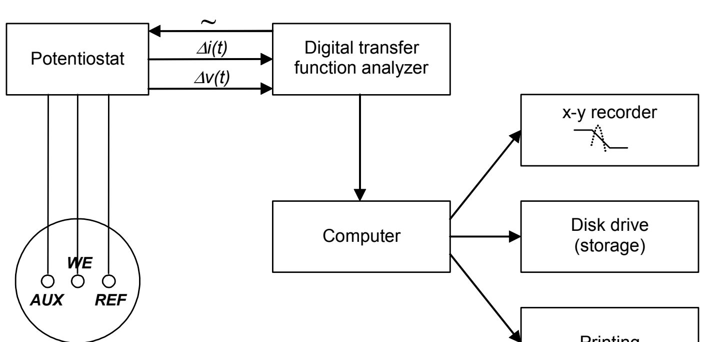

Figure 3 Instrumentation for conducting EIS[8]

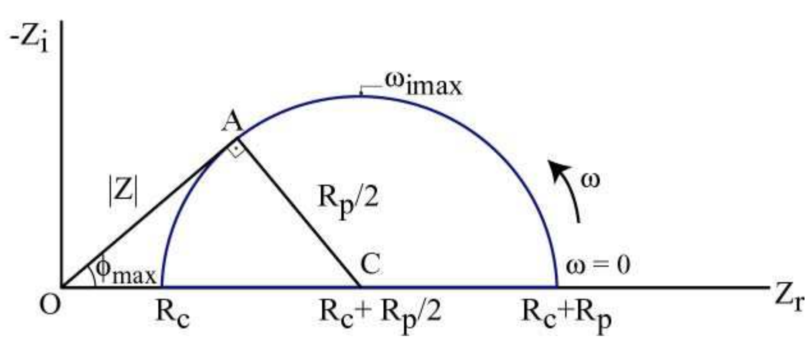

Fig. 4(a)

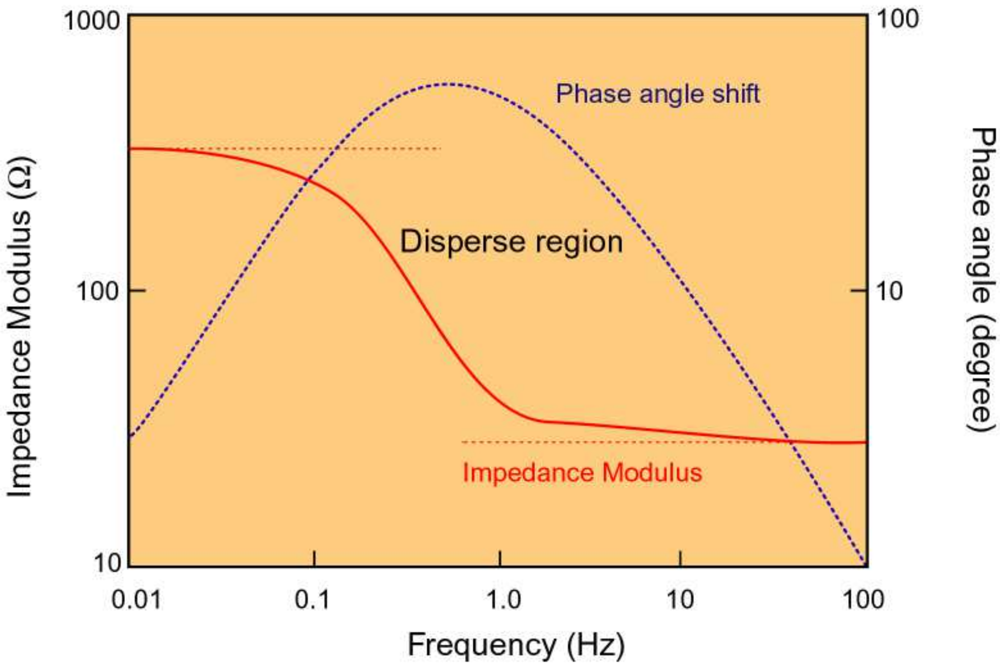

Fig. 4(b)

Figure 4 (a) Nyquist plot; (b) Bode plot. From ref. (1).

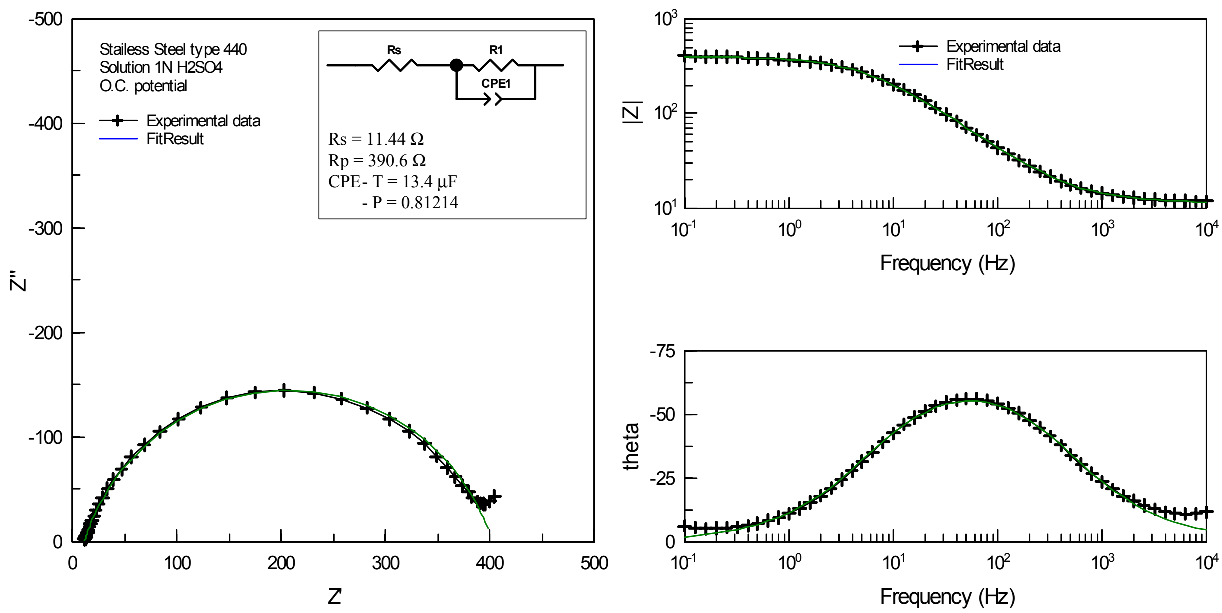

Figure 5 Typical results from an EIS experiment.

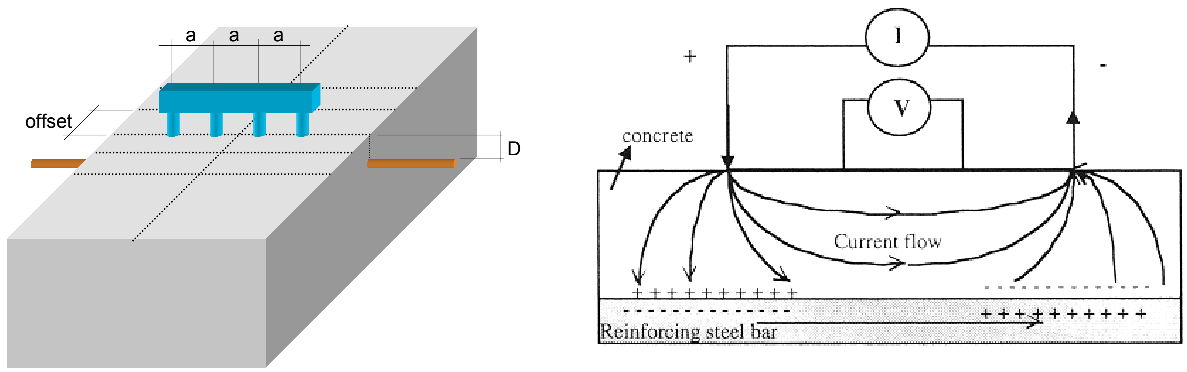

Figure 6 Four-electrode array (Wenner array) placed on the concrete surface [9, 12]

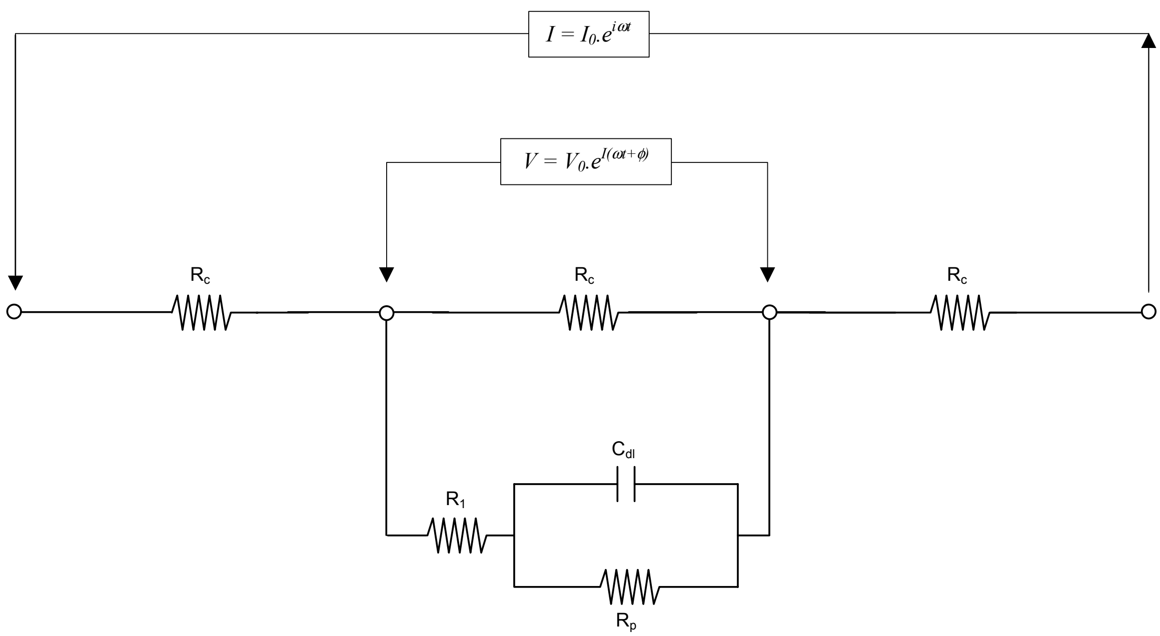

Figure 7 Schematic equivalent circuit for the surface measurement method.

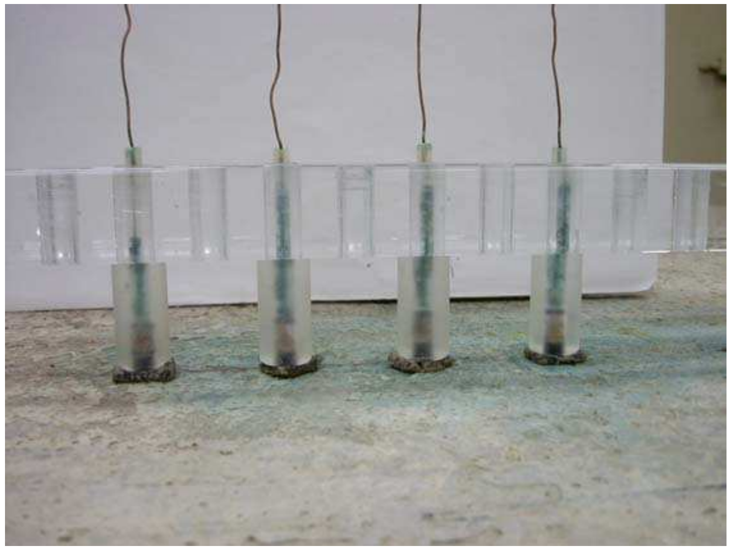

Figure 8 Wenner array placed on the surface of the concrete, above the rebar.

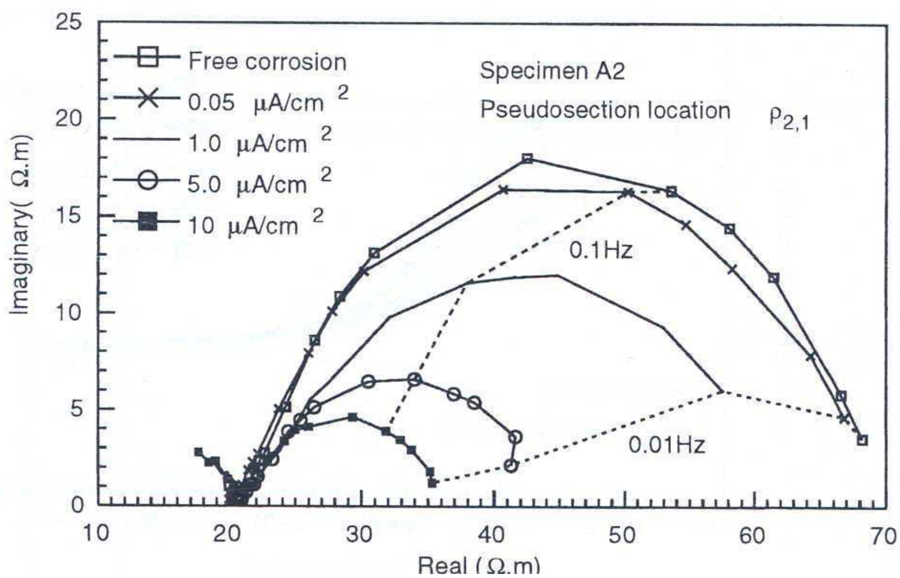

Fig. 9(a)

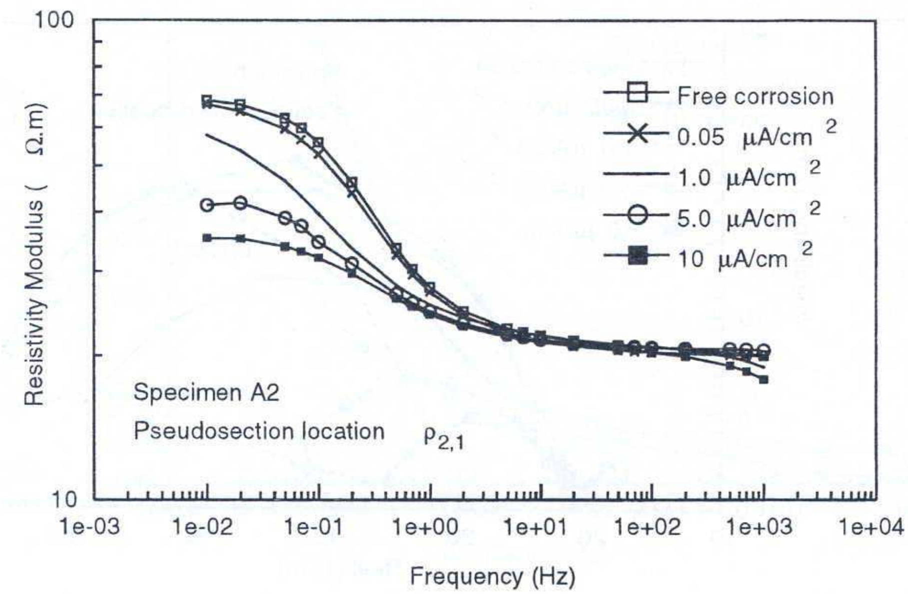

Fig. 9(b)

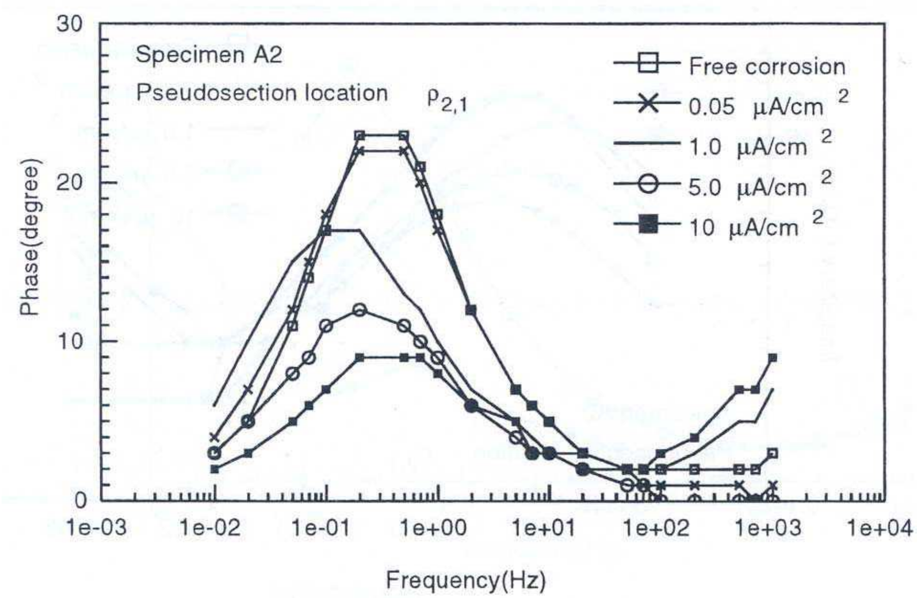

Fig. 9(c)

Figure 9 (a) Nyquist plot - Imaginary versus real component; (b) Modulus versus frequency; (c) Phase difference versus frequency.

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