

# On-site measurements of corrosion rate of reinforcements

C. Andrade\*, C. Alonso

*Institute of Construction Sciences, 'Eduardo Torroja', CSIC, Serrano Galvache s / n, Apdo 19002, E-28033 Madrid, Spain*

## Abstract

The increasing number of structures suffering corrosion makes the study of their structural safety of importance. The assessment of the residual load-bearing capacity based on the quantification of the actual degree of damage and the prediction of its evolution needs measurement of the steel corrosion rate. Electrical potential and resistivity mapping are the most commonly known techniques, although they are merely qualitative. The measurement of the corrosion rate itself is now feasible. However, the technique is still not extensively used. In this paper, a brief basis of the correct measurement of the corrosion rate is given. The most accurate method is based on the modulated confinement of the current which enables us to limit the steel area polarized by the current. The method is based on the determination of the polarization resistance. In the second part of the paper, the variability of the measured corrosion current due to weather variations is commented on, and values of the time of wetness, as well as of the climatic parameters which influence the moisture content of the concrete, are given in order to obtain the representative value of the corrosion current to be implemented into the structural calculations. The paper ends with a brief description of this implementation. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

The presence of chlorides in the surroundings of the reinforcement or the drop in pH induced by carbonation of the concrete cover, usually result in the development of active corrosion, providing the concrete is moist enough. The consequences of reinforcement corrosion are [1]:

1. a decrease of the steel cross-section;
2. the possible loss of steel ductility;
3. the cracking of the cover; and
4. the loss of the steel/concrete bond.

The safety and serviceability of the structure are thereafter affected. The rate of the general deteriora-

tion is a function of the corrosion rate, defined as the amount of metal oxidized by unit of metallic surface over a certain period of time.

There is a need to use non-destructive techniques able to measure the corrosion rate in order:

1. to detect the steel depassivation;
2. to predict the residual life of the structure when actively corroding; and
3. to monitor the efficiency of repair systems.

Because of its simplicity, the measurement of  $E_{\text{corr}}$  (rest or corrosion potential) is the method most frequently used in field determinations. From these measurements, potential maps are drawn which reveal those zones that are most likely to undergo corrosion in the active state [2]. However, such measurements have a qualitative character which may make the data difficult to interpret [3]. In particular, the plot of  $E_{\text{corr}}$  values relates to those of corrosion current  $I_{\text{corr}}$  values. However, when the relation between many results is stud-

\* Corresponding author. Tel.: +34-9-1302-0440; fax: +34-9-1302-0700.

E-mail address: andrade@ietcc.csic.es (C. Andrade).

ied, this ratio leads into a scattered cloud of points which does not represent a single relation.

The same can be stated of resistivity,  $\rho_e$ , measurements [4], which sometimes are used jointly with  $E_{\text{corr}}$  mapping. The  $\rho_e$  values indicate the degree of moisture content of the concrete, which is related to the corrosion rate when the steel is actively corroding, but which may mislead the interpretation in passive conditions.

The only electrochemical technique with a quantitative ability regarding the corrosion rate is the so-called polarization resistance,  $R_p$  [5]. This technique has been used extensively in the laboratory. It is based on the application of a small electrical perturbation to the metal. Providing the electrical signal is uniformly distributed throughout the reinforcement, the  $\Delta E/\Delta I$  ratio defines  $R_p$ . The corrosion current,  $I_{\text{corr}}$ , is inversely proportional to  $R_p$ ,  $I_{\text{corr}} = B/R_p$  where  $B$  is a constant.  $R_p$  can be measured by means of d.c. or a.c. techniques [6], both of which have specific features in order to obtain a reliable corrosion current value in agreement with gravimetric losses.

## 2. On-site measurement of $R_p$

The direct estimation of true  $R_p$  values from  $\Delta E/\Delta I$  measurements is usually unfeasible in large concrete structures. This is because the applied electric signal tends to vanish with distance from the counter electrode, CE, rather than spread uniformly across the working electrode, WE, as shown in Fig. 1. Therefore, the action of the electric signal cannot be related to any specific area.

Hence,  $\Delta E/\Delta I$  measurements on large structures using a small counter electrode provides an apparent polarization resistance ( $R_p^{\text{app}}$ ) that differs from the true

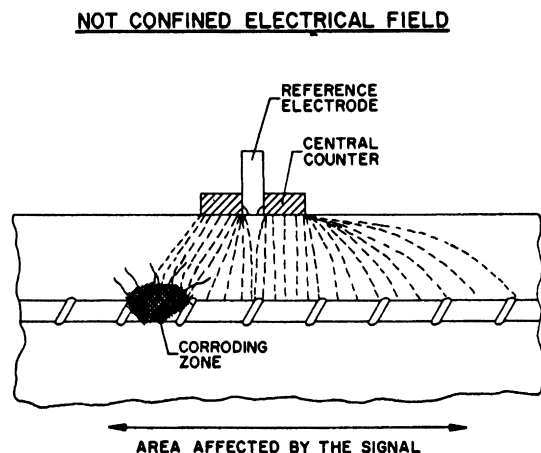


Fig. 1. The electrical signal applied from a small counter electrode tends to vanish with the distance. The active spots have a higher drainage ability.

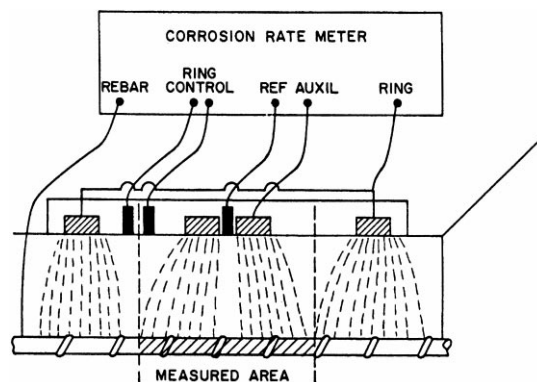


Fig. 2. Principle of the modulated confinement of the current by means of two sensors (ring control) placed between the central auxiliary electrode and the ring.

$R_p$  value, depending on the experimental conditions [7]. Thus, if the metal is actively corroding, the current applied from a small CE located on the concrete surface is 'drained' very efficiently by the rebars and it tends to confine itself on a small surface area (as shown by the dashed area in Fig. 1). Conversely, if the metal is passive and  $R_p$  is high, the current applied tends to spread far away (e.g. approx. 50 cm) from the application point (right part on the rebar of Fig. 1). Therefore, the apparent  $R_p$  approaches the true  $R_p$  for actively corroding reinforcement. However, when the steel is passive, the large distance reached by the current necessitates a quantitative treatment.

There are several ways of accounting for a true  $R_p$  value, among which the most extended one is the use of a guard ring [7], in order to confine the current in a particular rebar area, as Fig. 2 depicts. However, not all guarded techniques are efficient. Only that using a 'modulated confinement' controlled by two small sensors placed between the central auxiliary electrode and the ring, is able to efficiently confine the current within a predetermined area.

Other methods such as the direct measurement of the so called critical length,  $L_{\text{crit}}$ , (the distance reached by the current) [7] or minimizing the error by using large auxiliary electrodes, present the inconvenience of being unable to detect localized corrosion, as was shown in Fig. 1. Due to the draining effect of the active spots on the current, they will take most of the current when applied within the area of influence of the  $L_{\text{crit}}$ . Thus, although the  $R_p$  so obtained could be correct, the localization of the corroding spots is uncertain.

The measurement of the value of  $\Delta E/\Delta I$  in large structures without any mathematical correction or confinement (called apparent  $R_p$ ) gives erroneous values of the corrosion rate. This is the case when using pulse techniques or a galvanostatic pulse [8], with which gross errors can be obtained.

A Rilem recommendation is being prepared [9] de-

Table 1  
Levels of corrosion rates measured in laboratory and on-site

Corrosion rate ( $\mu\text{A}/\text{cm}^2$ )	Corrosion level
< 0.1	negligible
0.1–0.5	low
0.5–1	moderate
> 1	high

scribing the fundamentals of the  $R_p$  technique when applied on site, as well as the principles for its interpretation.

### 3. Ranges of corrosion rate values measured on-site

The experience on real structures [10] has confirmed the ranges of values previously recorded in laboratory experiments [5]. In general, values of corrosion rates higher than  $1 \mu\text{A}/\text{cm}^2$  are seldom measured, while values between  $0.1\text{--}1 \mu\text{A}/\text{cm}^2$  are the most frequent. When the steel is passive very low values (smaller than  $0.05\text{--}0.1 \mu\text{A}/\text{cm}^2$ ) are recorded. The  $I_{\text{corr}}$  values found in the laboratory and on real size structures on-site are ranked in the levels shown in Table 1.

A comparison of on-site  $I_{\text{corr}}$  values to electrical resistivity has allowed the authors to also rank the resistivity values, as described in Table 2. The values apply to either OPC or blended cements.

#### 3.1. Influence of climatic parameters

The most challenging aspect of on-site measurement is the fact that the corrosion current is weather dependent and, therefore, its actual value will depend on the particular climatic conditions around the structure.

When a single value of the corrosion current is measured on-site, it may happen that the concrete is dry at the time of measurement and therefore, mislead the deduction of its corrosion state. Two main alternatives have to be considered when measuring on site: (a) to take several readings during a certain period of time, or (b) to make a single isolated measurement.

#### 3.2. Several measurements

The optimum would be to take at least four mea-

surements over a 12-month period to take into account the different weather seasons. Thus, the following extreme climatic conditions should be considered for the sake of taking measurements:

- dry periods with low temperatures;
- period of low temperatures after raining continuously during at least 1 or 2 days;
- dry periods and high temperatures; and
- periods at high temperatures 1 week after raining continuously for 2 or 3 days.

Measurements during these periods will enable the recording of nearly minimum and maximum values of the corrosion current. A representative value can be obtained by averaging the values recorded:

$$I_{\text{corr}}^{\text{Rep}} = \sum_0^n \frac{I_{\text{corr}}(t)}{n} \quad (1)$$

#### 3.3. Single measurements

When isolated measurements are the only possibility, obtaining representative  $I_{\text{corr}}$  is very uncertain; however, in order to interpret the readings in the most accurate way, the following procedure is recommended.

After having measured the corrosion current, cores are taken close to the measurement points. Cores are returned to the laboratory. After vacuum water saturation, their minimum electrical resistivity,  $\rho_{\text{min}}$  is recorded. Then, the values of the  $I_{\text{corr}}\text{--}\rho$  registered on-site are plotted in a graph of the type shown in Fig. 3, together with the pair of values of  $\rho_{\text{min}}\text{--}I_{\text{corr}}$  resulting from fitting a straight line as depicted by the figure.

Once the ratio of  $I_{\text{corr}}\text{--}\rho$  is established for the particular structure, its representative corrosion current value (that to be implemented into the structural calculations),  $I_{\text{corr}}^{\text{Rep}}$  may be obtained through the expression:

$$I_{\text{corr}}^{\text{Rep}} = I_{\text{corr,av}} \cdot t \quad (2)$$

where  $t$  = time in years,  $w_t$  = wetness time in fraction of the year and  $I_{\text{corr,av}}$  is the averaged  $I_{\text{corr}}$  which can be expected in the climatic conditions of the particular structure. This averaged value of the corrosion current,

Table 2  
Levels of concrete resistivity regarding risk of corrosion

Resistivity ( $\text{k}\Omega\text{cm}$ )	Corrosion risk
> 100–200	negligible corrosion, concrete too dry
50–100	low corrosion rate
10–50	moderate to high corrosion when steel is active
< 10	resistivity is not the controlling parameter of the corrosion rate

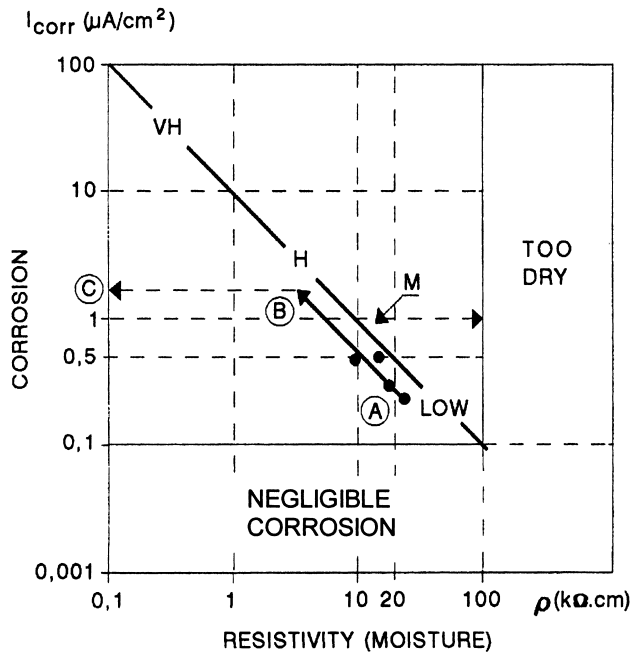


Fig. 3. Graph of  $I_{\text{corr}}-\rho$  where VH — very high; H — high; M — moderate; and L — low. (a): Measurement points; (b): extrapolation to minimum  $\rho$ ; and (c): maximum expected  $I_{\text{corr}}$ .

$I_{\text{corr,av}}$  can be obtained from the values of yearly averaged resistivity,  $\rho_{\text{av}}$  given in Table 3.

In Table 3, suggestions are also given for the values of  $w_t$  as a function of a range of climatic parameters, which should be used alternatively (they do not correlate between themselves necessarily). The table also contains the  $\rho_{\text{av}}$  values which will give the  $I_{\text{corr,av}}$  ones from the graph of Fig. 3. Thus, in a climate having between 4000 and 6000 h/year, the  $w_t$  will be 0.75 and the  $\rho_{\text{av}}$  to be used to deduce  $I_{\text{corr,av}}$  from the plot of  $I_{\text{corr}}-\rho$  recorded on-site, will be 30 kΩcm if the concrete is sheltered from rain and of good quality ( $f_c \geq 30$  MPa for instance). The  $\rho_{\text{av}}$  would be 10 kΩcm if the  $I_{\text{corr}}$  measurements made were of  $f_c < 30$  MPa and subjected to direct rain (non-sheltered).

This table has been developed with the experience accumulated by the authors up to the present and when more data become available, a better precision will be achieved.

Table 3

Values of wetness,  $w_t$ , and of yearly averaged in resistivity,  $\rho_{\text{av}}$ , for several ranges of climatic characteristics, which are listed as alternative possibilities

Climatic characteristics			Wetness time $w_t$	Yearly averaged resistivity $\rho_{\text{av}}$ (kΩcm)			
h/year	mm rain	days/year rain		Sheltered concrete		Non-sheltered	
				$f_c > 30$ MPa	$f_c < 30$ MPa	$f_c > 30$ MPa	$f_c < 30$ MPa
< 2000	< 250	< 50	0.25	100	50	50	30
2000–4000	250–750	50–100	0.5	50	30	30	20
4000–6000	750–1500	100–150	0.75	30	20	20	10
> 6000	> 1500	> 150	1	10	5	5	3

#### 4. Implementation of $I_{\text{corr}}$ values into calculations of loss in bar cross-section

Corrosion leads into four main structural consequences:

1. reduction of bar cross section;
2. reduction of steel ductility;
3. cracking of concrete cover and;
4. reduction of steel/concrete bond (composite effect). All these effects occurring in isolation, or simultaneously, will result in a loss in the load bearing capacity of the structure [11].

The primary information obtained from corrosion measurements is that concerning the loss in cross section of the bar. This parameter controls all the other effects of the corrosion process. The attack penetration  $P_x$  is defined as the loss in cross radius as shown in Fig. 4. It is obtained through the expression:

$$P_x = 0.0115 \cdot I_{\text{corr}}^{\text{Rep}} \cdot t_p \quad (3)$$

where  $t_p$  = the time in years after corrosion started and 0.0115 is a conversion factor of  $\mu\text{A}/\text{cm}^2$  into mm/year (for the steel). This expression implies that we need to know when corrosion has started in order to account for  $t_p$ .

When the corrosion is localized (right part of Fig. 4), the maximum pit depth is calculated by multiplying Eq. (3) by a factor named  $\alpha$  which usually takes a value of 10. Hence, Eq. (3) above becomes:

$$P_{\text{pit}} = 0.0115 \cdot I_{\text{corr}}^{\text{Rep}} \cdot t_p \cdot \alpha \quad (4)$$

##### 4.1. Calculation of the length of the propagation period

The calculation of  $t_p$  can be made if the carbonation front is known or the chloride profile is recorded. By

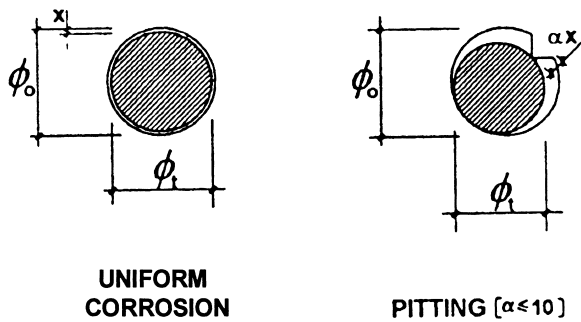


Fig. 4. Residual steel section loss considered for the cases of uniform and localized corrosion.

extrapolating back the rate of carbonation or chloride penetration, the time when corrosion started can be approximated (assuming a certain chloride threshold value) by finding out when these fronts reached the rebar. This is shown in Fig. 5, where the penetration depth of the aggressive front is plotted vs. the log of the time. The back extrapolation of the line of slope equal to 0.5 passing by the point of the front depth gives the time when this front reached the bar [12].

## 5. Final considerations

The assessment of the safety of corroding structures is one of the main concerns. However, the state of knowledge is still not able to give a complete satisfactory methodology for their appraisal.

Nevertheless, several advances have been made during the last decade, of which the possibility of on-site measurement of corrosion current has been one of the most relevant. In spite of some uncertainties of how to obtain a yearly representative  $I_{\text{corr}}$  value, the quantification of the rate of corrosion enables an approach to

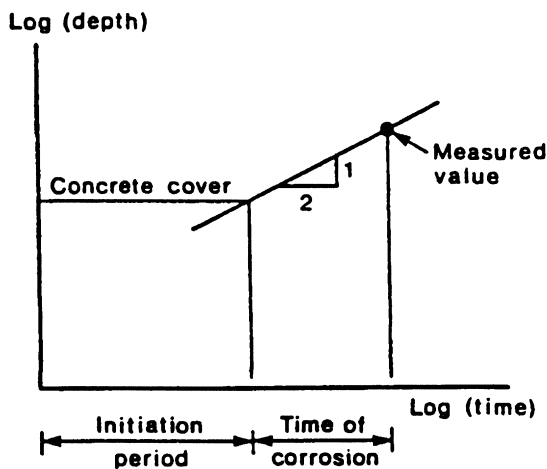


Fig. 5. When the carbonation or chloride threshold front is beyond the rebar, it can also inform on the time when depassivation was produced. This back extrapolation allows the evaluation of the time of corrosion (propagation period).

the calculation of the residual load-bearing capacity of the structure.

Weather conditions influence the moisture content of the concrete, which in turn induces the corresponding changes in the corrosion current. Climate characterization and its relation to the corrosion process remains an issue to be studied more in detail.

This paper presents a methodology for obtaining a yearly representative value of  $I_{\text{corr}}$  together with the conditions to measure correctly the corrosion current on-site. Its implementation in expressions for obtaining the loss in bar cross section has been also given.

## References

- [1] Rodríguez J, Ortega LM, Casal J, Díez JM. Corrosion of reinforcement an service life of concrete structures. 7th Int. Conference on Durability of Building Materials and Components, Stockholm, June 1996, 1996.
- [2] ASTM C876-91. Standard test method for half cell potentials of uncoated reinforcing steel in concrete.
- [3] Elsener B, Böhni H. In: Berke NS, Chaker V, Whiting D, editors. Corrosion rates of steel in concrete. ASTM STP 1065, 1990:143–156.
- [4] Millard SG, Gowers KR. Resistivity assessment of in-situ concrete: the influence of conductive and resistive surface layers, Proc. Inst. Civil Engrs. Struct. Bldgs, 94, paper 9876, 1992:389–396.
- [5] Andrade C, González JA. Quantitative measurements of corrosion rate of reinforcing steels embedded in concrete using polarization resistance measurements. Werkst Korros 1978;29:515.
- [6] Andrade C, Castelo V, Alonso C, González JA. The determination of the corrosion rate of steel embedded in concrete by the Rp on ac impedance methods. ASTM-STP 906, 1986:43–64.
- [7] Feliú Jr. S, González JA, Feliú S, Andrade C. Confinement of the electrical signal or in-situ measurement of polarization resistance in reinforced concrete. ACI Mater J 1990;87:457.
- [8] Elsener B, Klinhoffer O, Frolund T, Rislund E, Schiegg Y, Böhni H. In: Blankvoll A, editor. Assessment of reinforcement corrosion by means of galvanostatic pulse technique. International Conference on Repair of Concrete Structures. From theory to practice in a marine environment. Svolvær, Norway 20–30 May 1997. Norwegian Public Road Administration, 1997:391–400.
- [9] Rilem Recommendations of TC 154-EMC-Electrochemical Techniques for measuring corrosion in concrete. Progress Report 1994–97 Materials and Structures, 1998;31:153–157.
- [10] Rodríguez J, Ortega, L.M. García, A.M., Johansson, L. Pettersson, K. On-site corrosion rate measurements in concrete structures using a device developed under the Eureka Project EU-401-Int. Conference on Concrete Across Borders, Odense, Denmark, vol. I, 215–226.
- [11] Rodríguez J, Ortega LM, Casal J, Díez JM. In: Dhir RK, Jones MR, editors. Assessing structural conditions of concrete structures with corroded reinforcements. Conference on concrete repair, rehabilitation and protection, Dundee (UK). E&FN Spon, June 1996:65–77.
- [12] Tuutti K. Corrosion of steel in concrete. Stockholm: Swedish Cement and Concrete Research Institute (CBI) no.4-82, 1982:486.