ASSESSMENT OF REINFORCEMENT CORROSION BY MEANS OF GALVANOSTATIC PULSE TECHNIQUE

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Short Summary

The galvanostatic pulse technique was introduced for field application in 1988 to overcome problems with interpretation of corrosion risk assessment based on half-cell potential measurements of the reinforcement. Since then development work has been conducted in order to allow quantitative evaluation of the corrosion rate. FORCE Institute, DK, and the Institute for Materials Chemistry and Corrosion, ETH, CH, have independently developed devices based on galvanostatic pulse technique. These devices which differ in design were used in the comparative test on a post-tensioned bridge in Switzerland. Results of this test show that the two devices give the same specific concrete resistivity and the same specific polarization resistance on active rebars when the size of the counter electrode is taken into consideration in the evaluation. On passive rebars the results differ, the device without guard ring shows a deviation of the current signal.

1. INTRODUCTION

Corrosion of the rebars is the main cause of damage and early failure of reinforced concrete structures with enormous costs for maintenance, restoration and replacement worldwide. Maintenance and planning of the restoration of these structures as well as quality control needs a rapid, non-destructive inspection technique that detects corrosion of the rebars at an early stage, defines adequately which areas of structures require repair and provide a measure of the corrosion rate. The use of electrochemical potentials to determine areas of corrosion risk of reinforcing steel in concrete was pioneered in the United States [1, 2] and resulted in the development of an ASTM standard (ASTM C876-91). Today potential mapping is ”state of the art” to locate corroding zones precisely [3-5] and references cited therein). The extent of any corrosion problem of the structure being investigated can be mapped prior to more detailed and costly examination and repair. Potential readings however can be misinterpreted (lack of oxygen in very wet, dense or polymer-modified concrete leads to negative potentials), and the corrosion rate can only be estimated from the potential gradient and the concrete resistivity [5, 6]. The galvanostatic pulse technique introduced for field application already in 1988 [7] is a rapid, non-destructive technique to overcome these difficulties, used now by different groups as on site monitoring technique [8-10]. Since the introduction of this technique further work has been performed in order to allow a more quantitative evaluation of the ongoing reinforcement corrosion. FORCE Institute, DK and the Institute for Materials Chemistry and Corrosion, ETH, CH, have independently developed devices based on galvanostatic pulse technique. These devices which differ slightly in design were used in the comparative test on a post-tensioned bridge in Switzerland. Results of this test are reported and discussed in the present paper.

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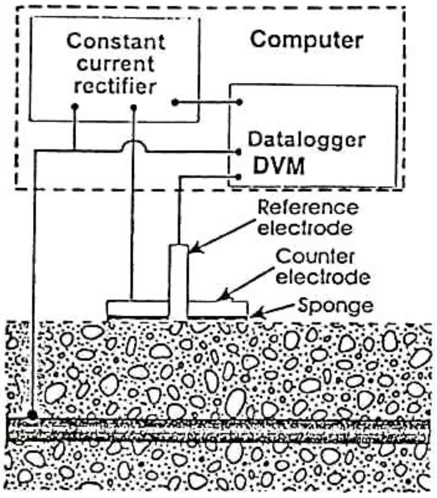
2. GALVANOSTATIC PULSE METHOD

Galvanostatic pulse method is a transient polarization technique working in the time domain. The method set-up is shown in Fig. 1.



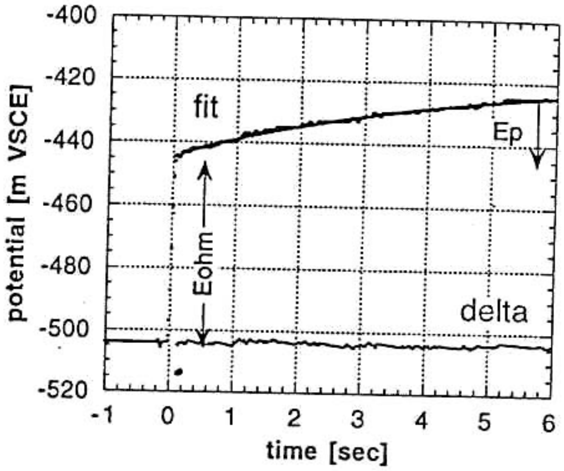


Figure 1: Set-up of the galvanostatic pulse technique
Figure 2: Typical potential time curve as a response to a galvanostatic pulse

A short time anodic current pulse is imposed galvanostatically on the reinforcement from a counter electrode placed on the concrete surface. The applied current is usually in the range of 10 to 200 μA and the typical pulse duration is up to 10 seconds. The reinforcement is polarized in anodic direction compared to its free corrosion potential. A reference electrode (usually in the center of the counter electrode) records the resulting change of the electrochemical potential of the reinforcement as a function of polarization time. Typical potential transient response is shown in Figure 2.

When the constant current I_{app} is applied to the system, an immediate ohmic potential jump and a slight polarization of the rebars occur (Figure 2). Under the assumption that a simple Randles circuit describes the transient behavior of the rebars, the potential of the reinforcement, $V_t(t)$, at a given time t can be expressed as [11]:

$$V_t (t) = I_{app} [Rp[1-\exp(-t / Rp\ Cdl))] + R_{\Omega}] \qquad (1)$$

where:

Rp = polarization resistance
Cdl = double layer capacitance
R_{Ω} = ohmic resistance

In order to obtain the values of Rp and C_{dl} and the ohmic resistance R_{Ω} (1) has to be evaluated further based on the experimental values. Two different methods, a linearity [8] and an exponential curve fitting procedure [12] have been proposed.

Linearity
Equation 1 can be transformed in a linear form

$$\ln (V_{max} - V_t (t)) = \ln (I_{app}\ Rp) - t/(RpC_{dl}) \qquad (2)$$

where V_{max} is the final (and experimentally unknown) steady potential value reached after long polarization. Extrapolation of this straight line to t = 0, using least square linear regression analysis, yields an intercept corresponding to $\ln(I_{app}*Rp)$ with a slope of $1/(Rp*C_{dl})$. The remaining over-potential corresponds to $I_{app}*R_{\Omega}$ which is the ohmic voltage drop.

Curve fit
Equation (1) can be transformed in a form suitable for curve fitting to determine all the relevant parameters:

$$V_t(t) = K_0 - K_1 \exp(-t / K_2) \qquad (3)$$

K_0 $(I_{app} Rp + I_{app} R_{\Omega})$ [[mV]
K1 $I_{app} Rp$ [mV]
K2 $(R_p C_{dl})$ [mV]

Extrapolation of the fitted potential response Vt(t) to time zero allows to calculate the ohmic resistance R_{Ω} (E_{ohm}/I_{app}), from extrapolation to infinity (t-> ∞ according to eqv. (3)) the steady state polarization resistance R_p (already corrected for $R_{\Omega)}$ can be determined.

2. EXPERIMENTAL

2.1 Equipment

Two different equipments both based on galvanostatic pulse technique have been used for the measurements. The principle is shown in figure 1, the main characteristics are summarized in table 1. Both equipments consist of a digital voltmeter to measure the half-cell potential of the rebars (different sampling time), a pulse generator (different current range) that allows to impose galvanostatically currents from the CE to the rebars and an evaluation procedure of the recorded potential-time curves.

Table 1: Main characteristics of the two pulse-measuring devices

Equipment	Current (μA)	Sampling time (sec)	Interval (msec)	Polarization	Evaluation	CE size guard ring
IBWK ETH	5 - 200	10	100	<20 mV	curve fit	12 cm / no
FORCE DK	12 - 400	4	27.5/125	no limit	linear	6.5 cm / yes

Equipment 1: This equipment has been developed by IBWK, ETH Zurich. Central unit of the equipment is a (portable) PC that runs special pulse software. The potential/time curve is displayed on the screen, the first second the open circuit potential is measured, in the last second the decay of the polarization is observed. The evaluation of the potential /time curve between 1 and 8 seconds is performed according to equation (3) and the ohmic resistance $R_{\Omega,}$ polarization resistance Rp and time constant is determined immediately after data registration. The results are calculated and displayed within some seconds on site. This allows adjusting the pulse current I_{app} to values that are high enough to avoid noise problems and low enough to polarize the rebars not more than 20 mV.

Equipment 2: This equipment has been developed and manufactured by FORCE Institute. In order to confine the current of the central counter electrode and therefore focus on a known reinforcement area, a concentric guard ring is built-in. The counter electrode is made of a corroding material and current density controlled. This arrangement is patent pending. Data evaluation is performed after the measurements on a computer.

2.2 Test site

The tests were performed on the outside of a reinforced girder of a post-tensioned bridge, where at several points corrosion of the reinforcement had started due to leaking salt water from the traffic lane. A corroding (site 1) and a passive zone (site 2) were used for the measurements. Concrete cover depth was ca. 30 mm. Temperature during the measurements was 2 degree Celsius.

3. RESULTS

3.1 Results from FORCE instrument

Some of the results obtained with the FORCE instrument with guard ring are given in table 2. It can be observed that the ohmic resistance measured at the three points shows considerable scatter, the polarization resistance Rp in general is slightly lower when measured with higher pulse current.

Table 2: Results obtained measuring with FORCE instrument. The values ”lin” are obtained by evaluation of the data according eqv. 1, the values ”fit” are obtained by evaluation with curve fit according to eqv. 3

Site 1	E corr	Current	R_Ω lin	R_Ω fit	Rp lin	Rp fit
	V AgCl	I app [µA]	kOhm	kOhm	kOhm	kOhm
Point 1	-0.043	12.5	15	14	0.64	0.77
	-0.042	50	15	14	0.72	0.64
	-0.038	100	14	14	0.72	0.57
Point 2	-0.026	12.5	32	29.1	1.2	1.2
	-0.023	25	39	29.0	0.84	0.86
	-0.023	50	28	29.1	0.69	0.64
Point 3	0.048	12.5	47	71	(7.1)	(6.3)
	0.057	25	56	72	1.78	2.0
	0.068	50	59	71	1.72	1.9

3.2 Results from IBWK/ETH equipment

Typical potential transients measured with the computer-assisted equipment developed at IBWK ETH are shown in figure 2. It can be noted that most of the potential change measured by the reference electrode is due to the ohmic potential ”drop”, the effective polarization of the rebars is always below 20 mV. The results obtained from the transients are summarized in table 3. Whereas the ohmic resistance measured is quite constant independent on the applied pulse current, the polarization resistance Rp tends to decrease slightly with applied current.

Table 3: Results obtained measuring with IBWK instrument. The values ”fit” are obtained by evaluation of the data according eqv. 3, the values ”lin” are obtained by evaluation with curve fit according to eqv. 2.

Site 1	E corr	Current	R_Ω fit	R_Ω lin	Rp fit	Rp lin
	V CuSO4	I app [µA]	kOhm	kOhm	kOhm	kOhm
Point 1	-0.15	10	3.50	3.40	0.44	0.39
	-0.15	20	3.45	3.44	0.34	0.24
	-0.15	50	3.50	3.78	0.34	0.24
Point 2	-0.116	10	8.1	8.4	0.40	0.44
	-0.115	20	7.8	8.1	0.41	0.49
	-0.112	50	7.9	8.2	0.39	0.37
Point 3	-0.003	10	9.86	10.4	0.75	0.96
	-0.004	20	9.9	10.5	0.67	0.86
	-0.002	50	9.9	10.5	0.73	0.83

The results obtained with the two different instruments in this comparative field test are evaluated first with regard to the calculation method and second with regard to the values of ohmic and polarization resistance measured with the two different instruments.

3.3 Comparison of the calculation method

Both sets of data measured have been evaluated independently by the curve fitting (eqv. 3) and by the linearity method (eqv. 2). The results calculated for the polarization resistance (Rp (figure 3b) are in very good agreement over a large range of Rp values from 0.2 to 25 kOhm. The standard deviation calculated from the linear regression is about 15% of the Rp values. The results calculated for the ohmic resistance (figure 3a) show that the values obtained by the curve fitting are slightly higher than those obtained by the linear method, but the results from curve fitting show less scatter. This is due to the difference in calculation: the curve fitting method extrapolates (eqv. 3) to zero, the linearity method takes the first potential reading after the pulse current is applied. This result in lower ”R_Ω” calculated values especially at high concrete resistivity. The same results were obtained with both data sets.

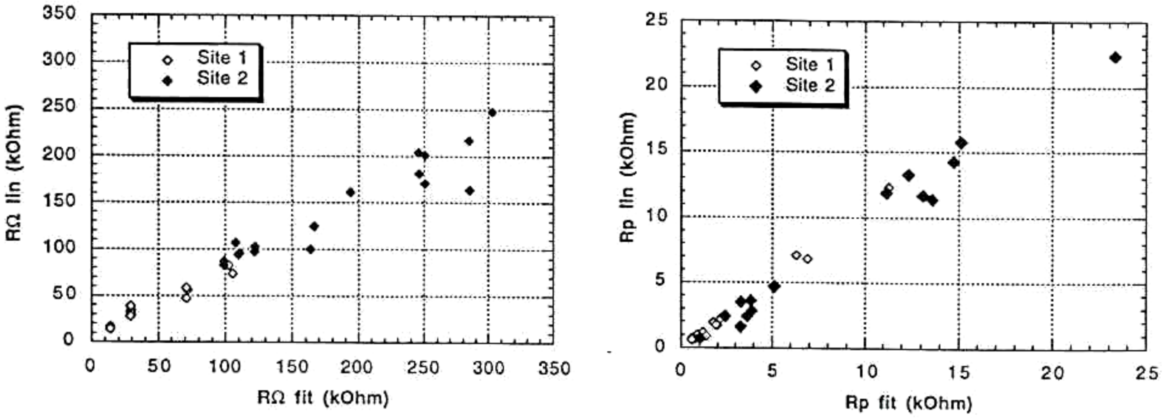


Figure 3: Comparison of ohmic resistance R_Ω and the polarization resistance Rp after evaluation by eq. 2 ("lin") and eq. 3 ("fit") on the data measured by the two devices.

3.4 Comparison of the results obtained with the two different instruments

As can be seen already by comparing the results in table 2 and table 3, the two instruments measure different values of the ohmic resistance R_Ω and of the polarization resistance Rp. A comparison of all data is shown in figure 4. The following points can be noted:

- In both the R_Ω and the Rp diagrams, the data are grouped according to the different measuring sites and points.
- For the polarization resistance Rp a clear proportionality between the data measured by the two different instruments is found over a wide range of values, independent on the applied current or the measuring position. The Rp values measured by the IBWK device are 2.5 - 3 times lower than those of the FORCE device are. The Rp values are related to the corrosion potential of the rebars at the measuring point.
- The ohmic resistance R_Ω measured by the two instruments is different by about a factor 4 to 6, the values obtained by the FORCE instrument are progressively higher at increasing concrete resistivity.

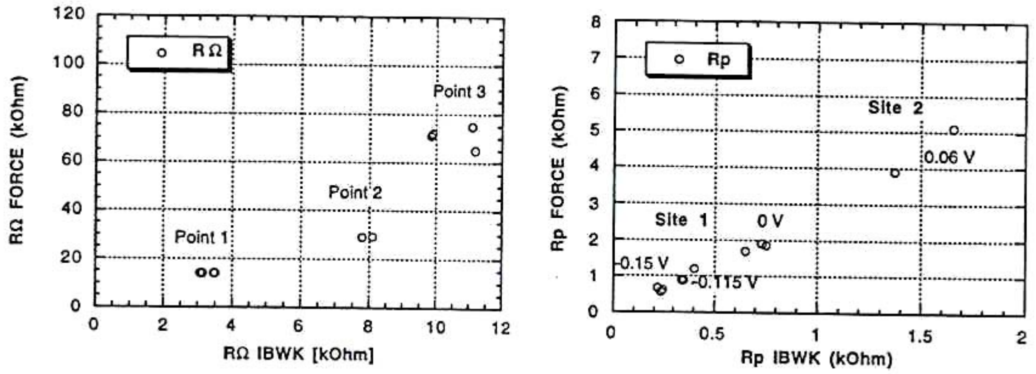


Figure 4: Comparison of the ohmic resistance R_Ω and the polarization resistance Rp as measured by the two devices (IBWK and FORCE). Evaluation method eq. 3.

4. DISCUSSION

In contrast to the laboratory, where homogeneous field distribution between working and counter electrode can be achieved, on real structures the area of the counter electrode put on the concrete surface is smaller than that of the working electrode (reinforcement). Measurements of the polarization resistance Rp and of the ohmic resistance R_Ω on site are thus influenced by geometrical parameters (cover depth of the concrete and diameter of the counter electrode of the measuring device) in addition to the concrete resistivity and the corrosion state of the rebars, all governing current distribution between the CE and the rebars [13, 14]. It is thus not surprising (and has been reported also in the SHRP tests [12, 15] that different devices measure different values of R_Ω and Rp. The discussion section concentrates on differences in the evaluation procedure of the pulse data and on the reasons for different results in the measured ohmic and polarization resistance.

4.1 Mathematical evaluation of pulse date

The evaluation of the pulse data (potential - time curve) can be performed according to eqv. 2 (linearity) or eqv. 3 (exponential curve fit). Independent evaluation of both data sets according to eqv. 2 and eqv. 3 have shown very good agreement in the results (figure 3).

- The ohmic resistance R_Ω shows fewer scatters when determined by the curve fitting procedure but it resulted in slightly higher values. Thus it can be concluded that the R_Ω values determined by eqv. 3 are more consistent and independent on the applied pulse current.
- The polarization resistance Rp obtained with both calculation methods is very similar. A trend in decreasing Rp with increasing pulse current I_{app} can be observed.

Especially on passive rebars in high resistive concrete deviations between experimental data and curve fitting was observed at short times (<1 sec). Thus under these circumstances a second time constant could be proposed.

4.2 Ohmic resistance R_Ω

Assuming that the specific concrete resistivity ρ and concrete cover d are the same for both sets of data, the difference in the values of R_Ω measured (figure 4a) can be explained only by a different ”cell constant” of the instruments. The cell constant k is given by the ratio volume / area, thus the CE size influences directly the value of R_Ω: the larger the area of the CE the smaller will result the measured ohmic resistance. This is observed: the FORCE instrument with CE area of ca. 35 cm^2 measures values for R_Ω that are in average about a factor 4 higher than the IBWK device with CE area of ca. 120 cm^2. This proportionality to the CE area further indicates that the ohmic resistance is governed by the primary current distribution [16], thus not depending on the corrosion state (active or passive) of the rebars. This behavior can be explained by the fact that measurements of the ohmic resistance are performed with AC impedance at high frequencies [17] or with pulse techniques at short times. In such condition the impedance Z of the rebars below the CE is determined by the double layer capacitance C_{dl}, the impedance $Z_c = 1/2*\pi*f*C_{dl}$ being very small at high frequencies f, thus no current deviation is occurring. For the measurement of the ohmic resistance R_Ω the current is self confined and a guard ring is not necessary.

4.3 Polarization resistance Rp

Measurements of Rp are performed at DC conditions (very low frequency resp. long times). In these conditions the electrical signal tends to vanish with increasing distance from the counter electrode, as a result, the measured polarization resistance Rp (from eqv. 2 and 3) can not be related a priori to the rebars under the CE area. One way in trying to overcome the problems of current deviation is the use of an additional concentric counter electrode, a guard ring, to confine the current to the area of the central CE [18]. Such a guard ring is integrated in the FORCE instrument. Assuming that the rebar area polarized equals the CE area (this is true for one bar with ca. 16 mm diameter) and that the guard ring is working ideally, a specific polarization resistance Rp* can be calculated from the FORCE data (table 4). The passive condition (site 2) results in specific polarization resistance Rp* of ca. 190 kΩcm^2, the most active condition (point 1 of site 1) to ca. 15 kΩcm^2..

Table 4: Polarization resistance for passive and active sites

Condition	Rp FORCE	Operation	Rp*	Operation	Rp calc IBWK	Rp exp IBWK
passive	5.6 kΩ	* 35 cm^2	190 kΩ cm^2	:60cm^2	3.2 kΩ	1.7 kΩ
active	0.45 kΩ	* 35 cm^2	15 kΩ cm^2	:60cm^2	0.25 kΩ	0.24 kΩ

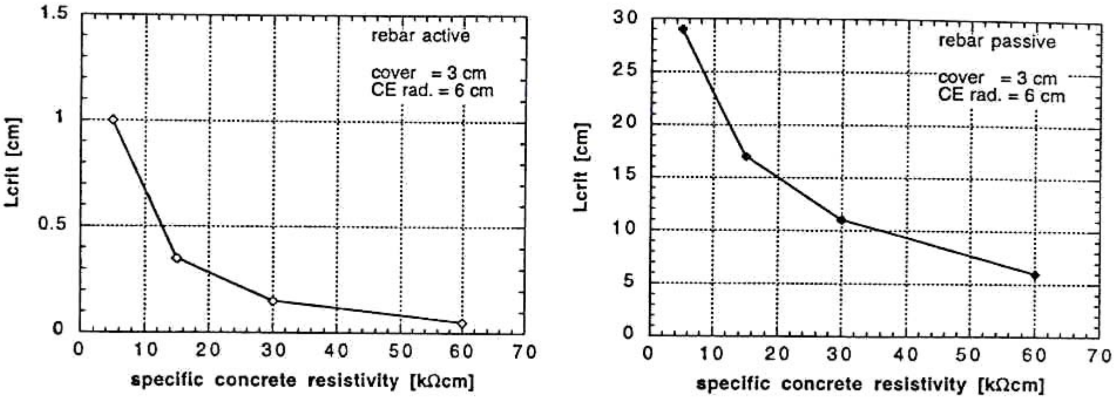


Figure 5: Simulation calculation with electrical network of the current spreadout on active and passive rebars as a function of concrete resistivity. Cover depth 30 mm.

For the IBWK device with CE diameter of ca. 12 cm and the same bar diameter of 16 mm a rebar area under the CE of 60 cm^2 can be calculated. A simple proportionality of the measured polarization resistance Rp to this rebar area under the CE should result in Rp values (Rp calc) obtained with the IBWK instrument of 3.2 kΩ (passive) and 0.25 kΩ (active) respectively for the two points (table 4). In reality, 1.7 kΩ and 0.24 kΩ are measured experimentally (figure 4b).

- For the active region (point 1 in site 1), the measured Rp value corresponds very well to the value calculated from the specific polarization resistance Rp*. This is in agreement with prior experience on site [17] and with simulation calculations (figure 5). The current deviation on active repairs is negligible (L_{crit} < 0.5 cm) and a guard ring is not necessary. The deviation will be slightly higher at lower concrete resistivity (figure 5) but decrease with decreasing Rp*.
- For the passive region (site 2) the measured value of the polarization resistance Rp is lower than the expected one (Rp calc). This indicates that the rebar area polarized by the galvanostatic pulse with the IBWK instrument without guard ring is higher (ca. 110 cm^2) than the area projected from the CE (60 cm^2). Thus on passive rebars a current deviation occurs and the length of rebar polarized is ca. 22 cm. With a CE diameter of 12 cm L_{crit} results to ca. 5 cm. This is in good agreement with simulation calculations for the very high concrete resistivity ($\rho>1500\Omega m$) measured at this region (figure 5).

4.4 Calculation of corrosion rate from Rp*

The corrosion rate i_{corr} from the specific polarization resistance value Rp* is calculated with the Stearn-Geary equation [19], i_{corr} = B / Rp*. The constant B for steel in concrete is usually taken as B = 0.026 V. Assuming homogeneous corrosion, an instantaneous corrosion rate of ca. 20 μA/year can be calculated for the active region (table 4). For the passive region a value of ca. 0.14 μA/cm^2 or 1.5 μm/year can be calculated. The device without guard ring measures the same corrosion rate for the active region, in the passive region values that are 2 times higher are obtained (ca. 3 μm/year).

It has to be pointed out that these corrosion rates are instantaneous values that strictly apply only to the measuring conditions. Exposure conditions, especially temperature and concrete humidity can alter i_{corr} by more than a factor of ten [20]. Further experimental data from on site measurements have shown [10] that in the frequent case of chloride induced localized corrosion, the average corrosion rate determined from Rp* measurements underestimate the real, local penetration rates by a factor of five to ten. From an engineering point of view such local reduction in cross section of the reinforcement is dangerous for the safety of structures when rebars are located in zone of high tensile or shear forces. For life time predictions more detailed knowledge of the daily and seasonal changes of the corrosion rate is required in order to obtain meaningful corrosion rates. It is essential to know the true local penetration rates. A first attempt to obtain local penetration rates based on a segmented counter electrode has been made [21].

5. CONCLUSIONS

From this comparative on site test with two different instruments using the galvanostatic pulse technique the following conclusions can be drawn:

1. The two instruments tested on the same sites measure different values of the ohmic resistance RΩ and of the polarization resistance Rp. The values obtained are not influenced by the evaluation method, which is either done by curve fittings or by linearity.

2. The apparent differences in the ohmic resistance RΩ can be explained by the different size of the counter electrode of the two instruments; values from the IBWK device are ca. 4 to 6 times lower in agreement with a CE area that is ca. 4 times larger. Thus the specific concrete resistivity ρ is the same for both instruments.

3. At corroding sites (low values of the polarization resistance) the Rp values measured by the two devices are proportional to the rebar area polarized underneath the CE, thus proportional to the diameter of the CE (factor 2.5). The specific polarization resistance Rp* is the same for the two instruments, deviation of the current signal on actively corroding rebars is negligible.

4. At passive sites (high values of the polarization resistance) the Rp values measured by the two devices are different. The FORCE instrument with guard ring confines the signal to the rebar area under the CE and a specific polarization resistance Rp* can be calculated. Using the same Rp* values for the results of the IBWK device without guard ring, the rebar area polarized results to be ca. two times higher than the area under the CE. This corresponds to a current deviation with L_{crit} = 5 cm, in good agreement with simulation calculations. Deviation of the current and thus the difference in measured Rp between the two instruments will be larger at lower RΩ values and at higher Rp* values.

5. The presence of a guard ring does thus not alter the results of the ohmic resistance RΩ and of the polarization resistance Rp for actively corroding rebars. On passive rebars in low resistive concrete values obtained with a guard ring are more accurate.

REFERENCES

1 J.R. Stratfull, *Corrosion NACE,* 1957, **13**, 173t.
2 J.R. Van Daveer, *Journal American Concrete Institute*, 1975, **12,** 697.
3 Arup H., ”Potential Mapping of Reinforced Concrete Structures”, The Danish Corrosion Centre Report, January 1984
4 Elsener B. and Böhni H., *Schweiz. Ingenieur und Architekt,* **105** (1987) 528
5 Elsener B and Böhni H., ”Potential Mapping and Corrosion of Steel in Concrete”, *Corrosion Rates of Steel in Concrete,* ASTM STP 1065, N.S. Berke, V. Chaker and D. Whiting, eds. American Society for Testing and Materials, Philadelphia, 1990 p. 143 - 156
6 C.C. Naish, A. Harker and R.R. Carney, in *’Corrosion of Reinforcement in Concrete’*, eds. C.L. Page, K.W. Treadaway and P.B. Bamforth, Elsevier Applied Science, London, 1990, 314.
7 B. Elsener, ’Elektrochemische Methoden zur Bauwerksüberwachung’, Zerstörungsfreie Prüfung an Stahlbetonbauwerken, SIA Dokumentation D020, Schweizer Ingenieur- und Architektenverein, Zürich, 1988, 27.
8 O. Klinghoffer, *Nordic Concrete Research,* Publication No. **16** (1995) 1
9 J. Mietz and B. Isecke, ’Electrochemical Potential Monitoring on Reinforced Concrete Structures using Anodic Pulse Technique’, in *’Non destructive Testing in Civil Engineering’* ed. H. Bungey, The British Institute of NDT, 1993, **2**, 567.
10 K.R. Gowers and S.G. Illard, in *Corrosion and Corrosion Protection of Steel in Concrete* (Ed. R. Swamy) Sheffield Academic Press, 1994, 186.
11 Newton C.J. and Sykes J.M., *Corrosion Science* **28** (1988) 1051
12 B. Elsener, *Materials Science Forum* **192194** (1995) 857-866
13 S. Feliu, J.A. Gonzales, C. Andrade and V. Feliu, *Corrosion NACE,* 1988, **44,** 761.
14 A.A. Sagues, S.C. Kranc and E.I. Moreno, *Corrosion Science* **37** (1995) 1097
15 Flis J., Sehgal A., Li D., Kho Y.T., Sabol S., Pickering H., Osseo K., Cady P.D., ”Condition Evaluation of Concrete Bridges relative to Reinforcement Corrosion”, Vol. 2: Method for Measuring theCorrosion Rate of Reinforcing Steel, SHRP-S-324, National Research Council Washington DC (1993)
16 J. Newman, *J. Electrochem. Soc.* **113** (1966) 501
17 B. Elsener, D. Flückiger, H. Wojtas and H. Böhni, Methoden zur Erfassung der Korrosion von Stahl in Beton, EVED undesamt für Strassenbau, Report 521 (1996) publ. VSS Zurich
18 D.G. John, D.A. Eden, J.L. Dawson and P.E. Langford, CORROSION ’87 San Francisco CA, paper No. 136
19 M. Stern and A.L. Geary, *J. Electrochem. Soc.,* 1957, **104**, 56.
20 L. Zimmermann, Y. Schiegg, B. Elsener and H. Böhni, Electrochemical Techniques for Monitoring the conditions of concrete bridge structures, this conference
21 B. Elsener, A. Hug, D. Bürchler and H. Böhni, Evaluation of localized corrosion of steel in concrete by galvanostatic pulse technique, Corrosion of Reinforcement in Concrete Construction, C.L. Page, P.B. Bamfort and J.L. figg eds. SCI Cambridge (1996) p. 264