

# Usage of Portable Equipment for Determination of Corrosion Stage of Concrete Structures

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## ABSTRACT

Galvanostatic pulse method (GPM) is a rapid non destructive polarization technique which is used since 1988 for evaluation of reinforcement corrosion in laboratory as well as on site.

To provide quick information of actual corrosion stage hand held easily to handle portable equipment of GPM was developed and tested on several materials and at different environmental conditions. Key parameters were concrete material, rebar conditions, humidity, temperature. Special attention was paid on the comparability of instrument readings to real behavior. Various combinations were tested. The response of the instrument under various circumstances were be compared to the real materials loss of the evaluated rebars.

At laboratory conditions actual corrosion stage could be detected. Evaluation of results obtained during long-term investigations showed a very good correlation to real corrosion stage and enables users to estimate corrosion behavior of reinforcement. However exact life time estimations using only GPM-results are only semi successful and needs a lot of further considerations because measurement conditions (moisture content, temperature, unknown active area etc.) mainly infect obtained values.

These results combined with other results obtained during an EU research project will contribute to improve evaluation procedures for estimation of life time predictions of concrete structures. End-users become able to optimize their maintenance management systems and can therefore reduce costs and traffic impairments.

**Keywords:** Portable Equipment, Corrosion Risk, Humidity, Chloride Induced Corrosion, Reinforced and Prestressed Concrete Structures

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## **1 INTRODUCTION**

The major part of the European infrastructure has reached an age where capital costs have decreased. But inspection and maintenance costs have grown such extensively, that they constitute the major part of the current costs.

During a Brite/Euram Project several European partners develop and produce an integrated monitoring system. So the inspection and maintenance costs and the traffic impairments can be reduced. Additionally the operator of the structures will be able to take protective actions before damaging processes start.

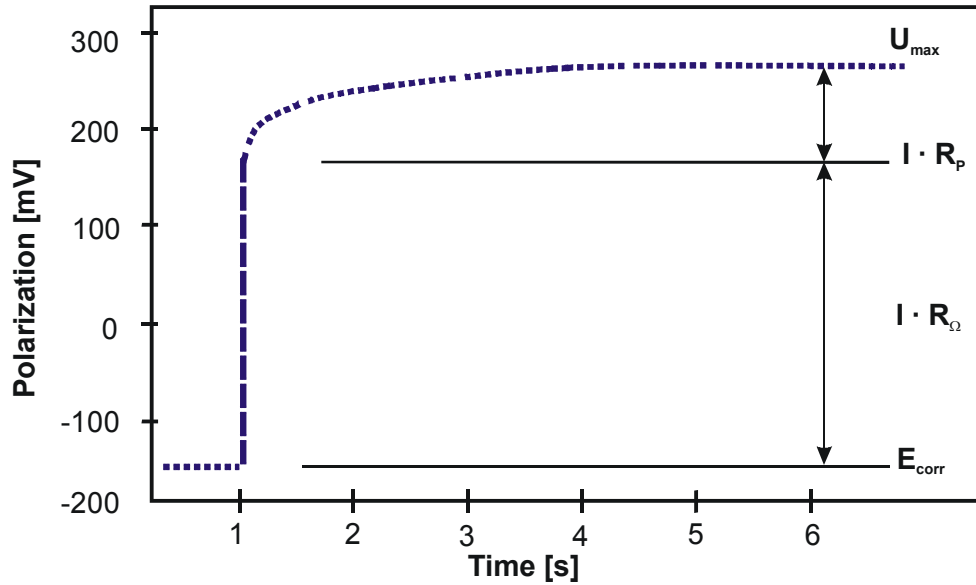
One major part of this project is the determination of the corrosion state at the rebars in new and existing structures depending on the deterioration of the concrete. In addition to evaluation of different types of sensors new developed portable equipment using galvanostatic pulse technique was tested under laboratory conditions. The objective of laboratory tests is testing suitability of portable monitoring equipment for non-destructive and unambiguous determination of reinforcement corrosion. Comparing achieved results regarding their accordance to real conditions shall provide background information for on-site situations.

## **2 BACKGROUND**

The galvanostatic pulse technique has been introduced for field application in 1988 to overcome problems with interpretation of corrosion risk of reinforcement occurring when half cell potential readings are applied in wet, dense or polymer-modified concrete, where access of oxygen is limited. Since introduction of this technique development work is conducted in order to allow quantitative evaluation of the ongoing reinforcement corrosion [1, 2].

Galvanostatic pulse method is a rapid non-destructive polarization technique which has been used for evaluation of reinforcement corrosion both in laboratory and on site.

A short time anodic current pulse is impressed galvanostatically to reinforcement from a counter electrode placed on concrete surface together with a reference electrode. The applied current is normally in the range of 5 to 400  $\mu\text{A}$  and the typical pulse duration is up to 10 seconds. The small anodic current results in change of reinforcement potential which is recorded as a function of polarization time. Reinforcement is polarized in anodic direction compared to its free corrosion potential. Typical potential transient response is shown in figure 1.



**Figure 1:** Typical polarization pattern

When the constant current  $I_{app}$  is applied to the system, the polarized potential of reinforcement  $U_t$ , at given time  $t$  can be expressed as :

$$U_t = I_{app} \cdot \left[ R_p \cdot \left( 1 - e^{-\frac{t}{R_p \cdot C_{dl}}} \right) + R_{\Omega} \right] \quad (1)$$

where:

$R_p$  = polarization resistance

$C_{dl}$  = double layer capacitance

$R_{\Omega}$  = ohmic resistance

In order to obtain values of  $R_p$  and  $C_{dl}$  separate from the ohmic resistance  $R_{\Omega}$  this equation can be transferred to linear form :

$$\ln (U_{max} - U_t) = \ln (I_{app} R_p) - \frac{t}{R_p \cdot C_{dl}} \quad (2)$$

where  $U_{max}$  is the final steady potential value.

Extrapolation of this straight line to  $t = 0$ , using least square linear regression analysis yields an intercept corresponding to  $\ln (I_{app} R_p)$  with slope of  $(R_p C_{dl})^{-1}$ .

The remaining overpotential corresponds to  $I_{app} R_{\Omega}$  which is the ohmic voltage drop. After the polarization resistance  $R_p$  is determined by means of this analysis, the corrosion current  $I_{corr}$  can be calculated from Stern Geary equation (3) :

$$I_{corr} = \frac{B}{R_p} \quad (3)$$

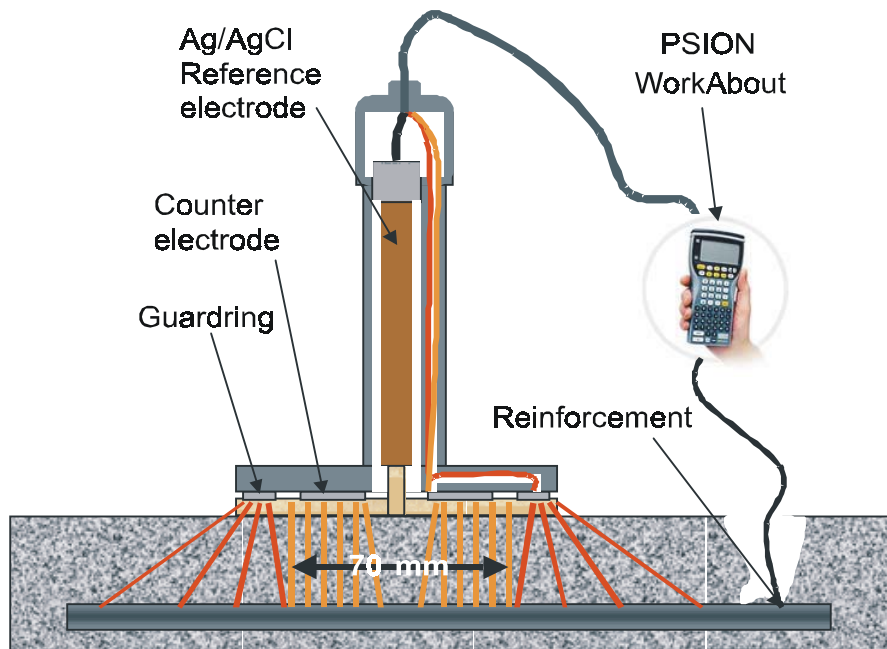
where B is an empirical constant determined to be 25 mV for actively corroding steel and 50 mV for passive steel.

The DC polarization resistance technique with calculation of the instantaneous corrosion current ( $I_{corr}$ ) from Stern Geary equation, has been applied extensively since 1970.

The problem is, that in real structures the area of counter electrode is much smaller than that of the working electrode (reinforcement) and the electrical signal tends to vanish with increasing distance.

As a result, the measured effective polarization resistance can not be converted to a corrosion rate.

To overcome this problem a second concentric counter electrode (Guardring) is used to confine the current to the area of the central counter electrode (figure 2).



**Figure 2:** Conditions on Pulse-head

When the diameter of the reinforcement and the exposed length of the reinforcement (counter electrode diameter) are known the instantaneous corrosion rate can be calculated. It is important to emphasize that the obtained corrosion rate is an instantaneous average rate for the confined area that strictly apply to the measuring conditions. Exposure conditions, especially temperature and concrete humidity can alter  $I_{corr}$  by a factor of 10 or more. Experimental data from onsite measurements have shown that average corrosion rates determined from  $R_p$  measurements in the case of chloride induced localized corrosion underestimates the real corrosion rate by a factor of 5 - 10 or even more. From an

engineering point of view such local reduction of reinforcement cross section is dangerous for the safety of structures especially in zones with high tensile or shear forces.

It is obvious that wrong estimation of the amount of reinforcement for bars parallel or crossing make the average corrosion rate to high but also cracks and delamination are often the reason for wrong corrosion rate estimates.

For life time predictions a more detailed knowledge of the daily and seasonal changes of corrosion rate is required in order to obtain meaningful values. It is essential to combine the corrosion rate measurements with post mounted corrosion and chloride sensors or a number of other non destructive evaluation methods to determine the concrete integrity and penetration rates.

### 3 EXPERIMENTAL SETUP



**Figure 3:** Specimen with parallel rebars and crossing



**Figure 4:** Specimen with rebars in different depths

Different types of specimens (figure 3 and 4) made of poor concrete (water cement ratio = 0,6) were exposed at laboratory atmosphere (20 -25 °C, 70 % RH)

Thereby chloride free specimen and specimen with mixed in chloride (2 weight% to mass of cement) were used.

After curing in regular time intervals the following values were measured :

- Corrosion potential by means of galvanostatic pulse device,
- Corrosion rate by means of galvanostatic pulse device and

Reliable verification of the corrosion rate measurements is only possible by gravimetric determination of the weight loss. Therefore, after certain time intervals complete specimens were crashed and rebar weight loss was determined.

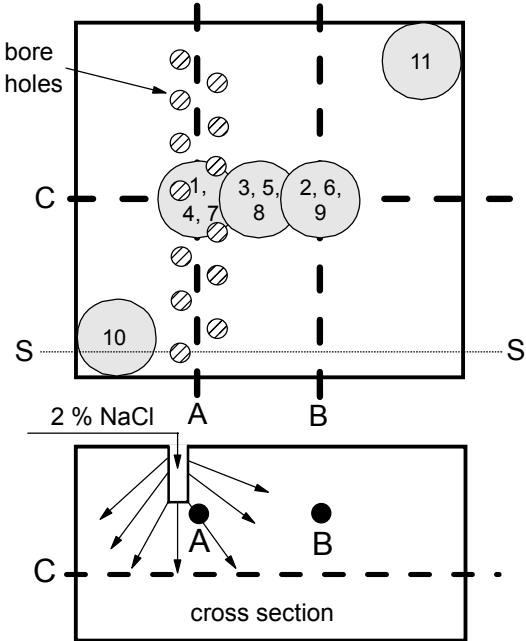
**4 MEASUREMENTS AND DISCUSSION**

**4.1 Conditions**

All measurements were performed on specimen as shown in figure 5. Directly before the measurement the surface and the contact sponge were wetted. The sponge was cleaned (squeezed in fresh tap water) after every specimen (max. 11 readings). Pulse value was 14  $\mu$ A for all measurements, if no other values are described. Potential was measured versus Ag/AgCl-gel-electrode (inside the measurement head) with  $207 \pm 1$  mV versus standard-H-electrode.

**4.2 Perforated specimen**

**4.2.1 Design and NaCl-injection**



**Figure 5:** Perforated specimen with visible wetness mark

**Figure 6:** Perforated specimen with measurement locations and cross section

On a part of specimens holes were drilled above rebar A (figure 6). Holes were kept filled with NaCl solution. After some days of exposure humidity distributed inside the specimen. Marks were observed on specimen and confirmed, that aggressive environment reached the rebar (figure 5).

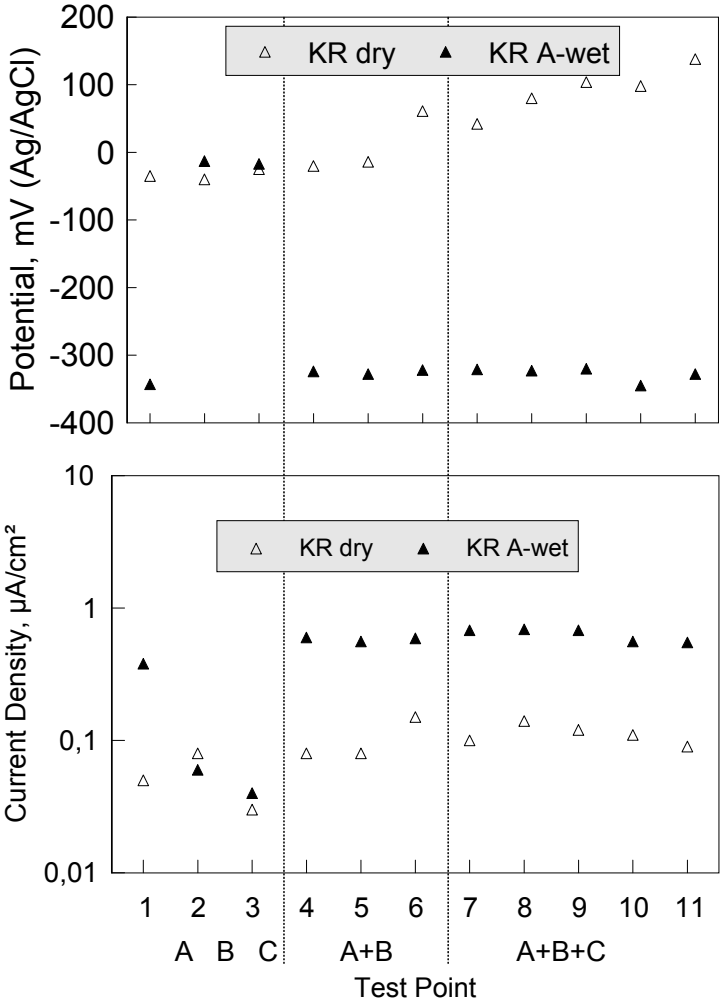
**4.2.2 Influence of surface area on partly active reinforcement**

After achieving stable values measurements were performed at already described (figure 6) locations and compared to readings obtained at dry conditions (i. e. before NaCl-injection).

As well potential as current density readings show activity on rebar A, where NaCl was injected (figure 7).

On dry (passive) specimens no significant difference at current density could be observed. The slight increase of potential might be caused by polarization effects due to the pulse of the previous measurement.

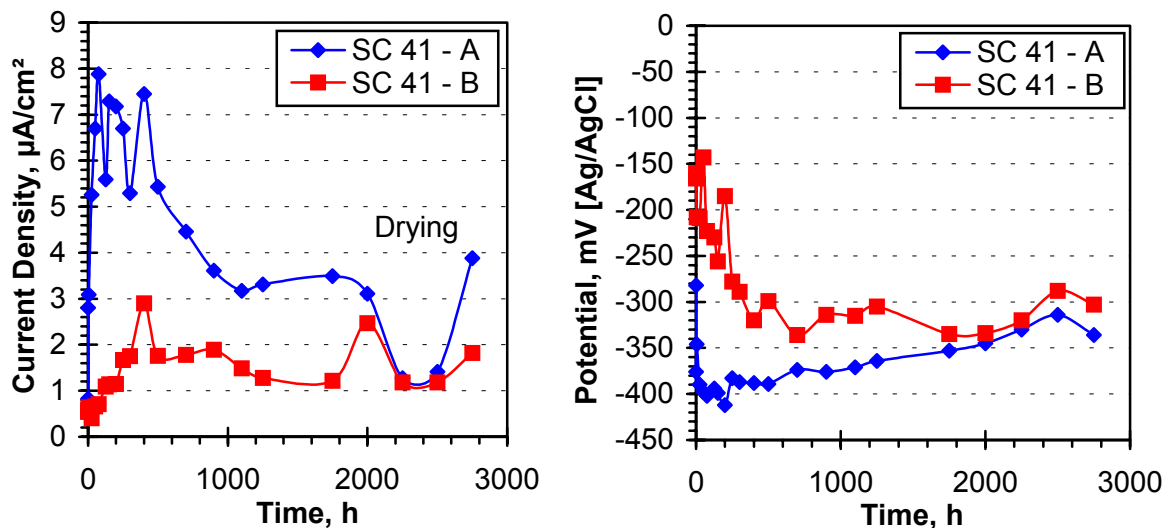
On wet specimens both diagrams clearly show active stage on rebar A whilst B and C remained passive (separated bars). Connecting active and passive rebars does not show any surface area effects. All values are dominated by the active partner. This leads to the problem, that the current density value shows activity but does not mean anything in terms of calculating corrosion rate if surface area is not known.



**Figure 7:** Potential and current readings at different locations and various rebar configurations

### 4.2.3 Long term exposure of perforated specimen

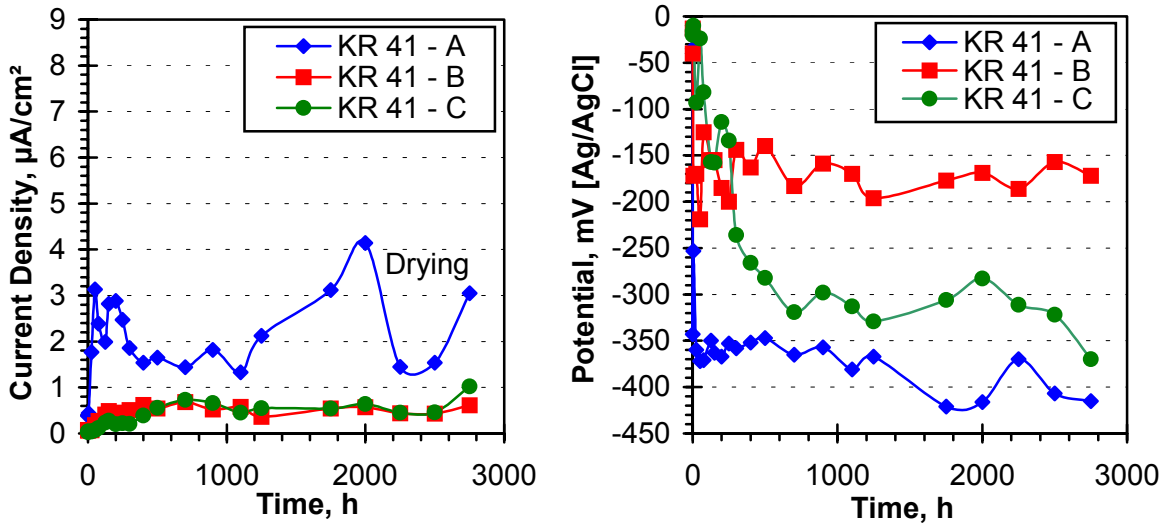
7 specimens, perforated to accelerate corrosion processes, were observed for a longer time period by periodic pulse measurements. Hereby significant difference between specimen containing chloride from the beginning (cast in) and chloride free specimen was detected. So, for instance, directly chloride exposed rebar A of specimen SC41 showed during the first 14 days a more quickly increase of current density values from below  $1 \mu\text{A}/\text{cm}^2$  up to  $10 \mu\text{A}/\text{cm}^2$ . Meanwhile potential dropped within few hours from  $-275 \text{ mV}$  to  $-400 \text{ mV}$  (vs. AgCl). Afterwards current density values tendentiously returned and varied around a low level. This return is accompanied by a potential increase to values in the range around  $-350 \text{ mV}$ . Variations are mainly caused by discontinual ponding of rebars with NaCl-solution (temporarily drying out). After 200 h ponding was reduced, whereby current density significantly decreased. On only indirectly effected bar (SC41-B) current density increased time-delayed and only by a small amount of  $3 \mu\text{A}/\text{m}^2$ . Potential also decreased time delayed and reached not before 500 h values below  $-300 \text{ mV}$  (figure 8).



**Figure 8:** *Current density (a) and potential (b) values on rebars of specimen SC41 with perforated concrete cover and chloride ponding on rebar A*

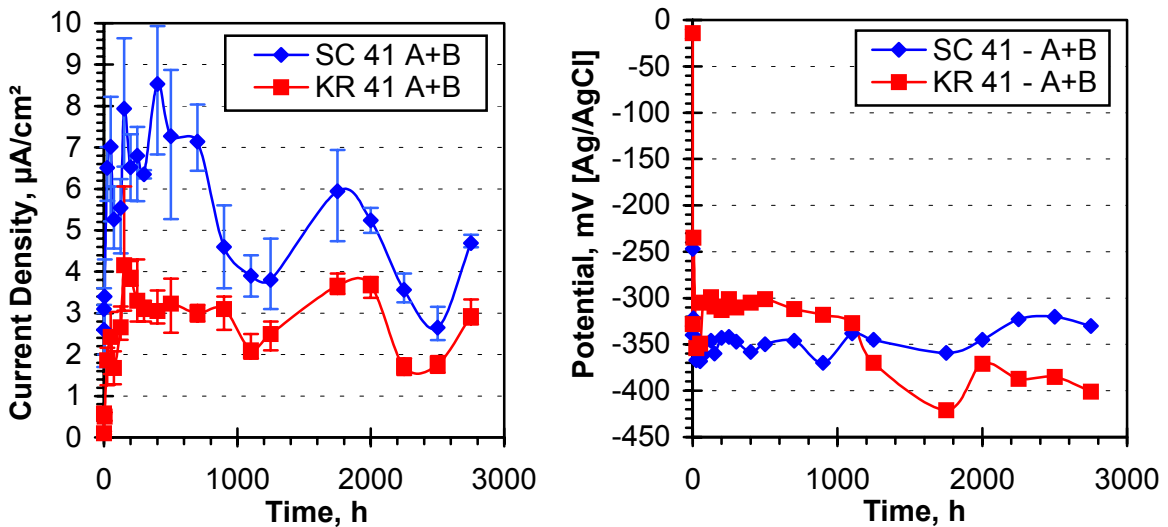
On specimen KR41 (figure 9) on directly exposed rebar A also a quick increase of current density to values up to  $3 \mu\text{A}/\text{cm}^2$  was observed. But current densities returned to  $1,5 \mu\text{A}/\text{cm}^2$  already after 400 h. After 1250 h a slow increase of current density to  $4 \mu\text{A}/\text{cm}^2$  was observed, which was finished after 2000 h by a temporarily drying out caused by interruption of NaCl-addition. This drying out effect correlated to behavior, also observed on other specimens. Rebars KR41-B and KR41-C, only indirectly effected, showed only a slight increase of current density to values around  $0,5 \mu\text{A}/\text{cm}^2$  within the first 500 h. Values remained in that range until 2500 h. On rebar KR-C a increase to  $1 \mu\text{A}/\text{cm}^2$  was measured.





**Figure 9:** Current density (a) and potential (b) values on rebars of specimen KR41 with perforated concrete cover and chloride ponding on rebar A

During exposure rebar A and B were permanently connected. Pulse measurements at these conditions showed essentially the same behavior of current density and potential as on directly exposed rebars A.



**Figure 10:** Current density (a) and potential (b) values on rebars of specimen SC41 with perforated concrete cover and chloride ponding on rebar A, rebar A and B connected

Corresponding curves are shown in figure 10. Beside the average value, the spread of 3 measurements is displayed. Also have the different behavior of specimen SC41 and KR41 is obvious.

By integration of current course considering polarized area change amount ( $Q$ ), transferred during experiment time, can be obtained. Dividing that charge amount by exposure time  $t_A$  an average corrosion current  $i_m$  can be calculated. By division of that amount by surface area of the rebar ( $A = 31,4 \text{ cm}^2$ ), average current density  $i_m$  is obtained, which would cause the same charge transfer by integration over time.

For such comparison after 4 months block SC has been destroyed, and weight loss at the rebars was determined by pickling off the corrosion product. From obtained weight loss and exposure time corrosion current density  $i_{\text{corr}}$  was calculated by Faraday's law.

Comparison of current densities obtained by pulse measurement and by integrated weight loss rate is shown in table 1. Values show a relatively good correspondence.

**Table 1:** *Current density values calculated from weight loss and obtained from GPM-measurements*

SC 41	weight loss whole bar	current density from weight loss	mean current density calculated from GPM over 4 months
Description	$\Delta m$ [g]	$i_{\text{corr}}$ [ $\mu\text{A}/\text{cm}^2$ ]	$i_m$ [ $\mu\text{A}/\text{cm}^2$ ]
bar A (2 cm depth)	1,30	4,8	3,6
bar B (3 cm depth)	1,36	5,0	1,5
bar A + B (center)	2,66	4,9	5,0
exposed / polarized surface		95 $\text{cm}^2$	31 $\text{cm}^2$

## 5 DISCUSSION

Investigations on specimen at laboratory conditions clearly show, that galvanostatic pulse method (GPM) is suitable to evaluate real corrosion stage of reinforcement in concrete. Active and passive conditions can be detected exactly. In addition influence of corrosion stimulation by ponding with NaCl-solution was proven. Influence of discontinued wetting (temporarily drying phases) on corrosion behavior of reinforcing steel could be detected by periodic GPM-measurements. So GPM is an important supplementation to corrosion potential measurements.

Even if special separate investigations at laboratory conditions partially showed a relative good correlation of current densities calculated from weight loss and obtained by GPM, it needs to be assessed, that determination of corrosion current density by GPM is only a semi-quantitative method.

Tendentiously it can be distinguished between areas of strong, medium, or low respectively no corrosion. But corrosion current, respectively area related current density derived from polarization resistance, and a lifetime estimation based on these values is effected by a lot of influences leading to wrong interpretations. Especially it shall be pointed to necessary assumption to size of polarized area (field distribution, position of measurement head) respectively really corroded area (localized or partial corrosion attack). Furthermore an interaction of active and passive areas needs to be assumed, which could not be simulated at laboratory measurements and separated conditions. Additionally it needs to be considered, that GPM-measurements only provide a momentary value of actual corrosion stage, which significantly depends on actual concrete conditions (for instance humidity content, pH-value, chloride content).

Also on one hand corrosion rate can be reduced by formation of corrosion product on surface (diffusion barrier). On the other hand formation of thick corrosion product layers can accelerate corrosion (crack formation, detaching of concrete, hygroscopic salt effects). Described systematic and random influence factors can cause miscalculations of corrosion current up to one decade, which make a lifetime estimation not really suggestive. At these basic considerations within those investigations it has not to be overlooked, that influence of discussed parameters will be much lower at on-site conditions, because a separate consideration of active and passive areas can only be made on larger dimensions. Therefore interaction of different areas (as obtained on laboratory experiments) will be significantly smaller. In addition to that in practice an uniform corrosion attack contrary to laboratory tests is observed. On the other hand at on-site conditions a lot of other parameters complicate estimation of corrosion stage comparing to defined laboratory conditions.

Pulse measurements do not provide information about past as well as future corrosion conditions and evolution. These are mainly depending on changing conditions in surrounding concrete, which are subjected to statistical, random deviations. Only current status information are available. That's why only long time observation combined with periodical pulse measurements provide information about tendency of corrosion stage and evolution (e.g. steady, in- or decreasing).

A semiquantitative estimation of actual corrosion rate based on GPM-measurements is only possible, considering further parameters like reinforcement potential and concrete humidity etc.

## **6 CONCLUSIONS**

New developed hand held easily to handle portable equipment using Galvanostatic Pulse Method was tested on several materials and at different environmental conditions to provide quick information of actual corrosion stage. Key parameters were concrete material, rebar conditions, humidity, temperature. Special attention was paid on the comparability of instrument readings to real behavior. Various combinations were tested. The response of the instrument under various circumstances was compared to the real materials loss of the evaluated rebars.

At laboratory conditions actual corrosion stage could be detected. Evaluation of results obtained during long-term investigations showed a very good correlation to real corrosion stage and enables users to estimate corrosion behavior of reinforcement. However exact life time estimations using only GPM-results are only semi successful and needs a lot of further considerations because measurement conditions (moisture content, temperature, unknown active area etc.) mainly infect obtained values.

## **7 OUTLOOK**

Described exposure is being continued. Especially investigations to determine area influence on life-time prediction are now running. Comparison of observed behavior at laboratory test will be compared to on-site investigations. Results will be available within the next years and will be presented in future papers.

These results combined with other results, like deformation and vibration probes, obtained during this BRITE/EURAM-project will contribute to develop an integrated corrosion monitoring system so that end-users become able to optimize their maintenance management systems and therefore costs and traffic impairments can be reduced.

## **ACKNOWLEDGEMENTS**

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