A SIMPLIFIED METHOD TO ESTIMATE CORROSION RATES – A NEW APPROACH BASED ON INVESTIGATIONS OF MACROCELLS

Method to estimate corrosion rates

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Abstract

A numerical simulation of the corrosion process of steel in concrete based on equivalent electrical circuit models is presented allowing for a quantitative prediction of macrocell action in reinforced concrete. The analysis has been performed for a well-defined geometry with a planparallel and a coplanar arrangement of actively corroding and passive steel. For the planparallel arrangement the conjoint action of microcells and macrocells was investigated for a two-dimensional situation. Furthermore, pitting corrosion on a single rebar was studied for the coplanar arrangement using a transmission line model. The comparison between model-tests and calculations show, that this new numerical model is suitable to estimate corrosion rates of steel in concrete.

Keywords: Steel, Reinforcement, concrete, durability, chloride, corrosion, anode, cathode, macrocell, numerical simulation

1 Introduction

Corrosion of steel in concrete has caused severe durability problems especially at concrete structures exposed to aggressive environments. The repair measures have grown to such an extent, that the operation and repair costs constitute a major part of the current infrastructure.

For durable design and repair of concrete, a basic knowledge of the underlying corrosion mechanisms is needed. Especially the estimation of the corrosion rates of the rebars under different conditions plays an important role.

This paper describes a simplified model based on the electrochemical nature of the corrosion process in order to calculate corrosion rates under well defined assumptions. The model is based on the results from the extensive experimental research of both authors on corrosion of steel in concrete, especially on macrocell action, which has been carried out during the last 10 years.

2 Description of the corrosion process

The mechanism of steel corrosion in concrete is essentially electrochemical in nature, i.e. the corrosion process proceeds by forming spatially separated anodic and cathodic areas on the surface. According to this view a corroding steel surface may be regarded as a composite of anodic and cathodic areas electrically coupled through the body of the steel itself to allow movement of electrons, and electrolytic movement of ions through the electrolyte solution contained within the concrete pore network to permit electromigration and diffusion of ions. With respect to the spatial distribution of anodic and cathodic sites over the steel surface, a distinction has to be made between micro- and macro-corrosion cells [1,2,3].

Uniform corrosion of the reinforcing steel is normally associated with the existence of microcells. These electrochemical cells are characterised by a completely random distribution of anodic and cathodic sites interspersed all over the surface, owing to local chemical or physical differences in or on the steel.

The different exposure conditions throughout the structure and local differences in the concrete properties will undoubtedly promote the development of so-called macrocells. Many factors can set up potential differences between adjacent parts of the steel reinforcement network. Common examples for corrosion of the reinforcement include differential aeration cells and active/passive cells.

The corrosion process induced by the presence of chloride ions at the steel-concrete interface is normally associated with the development of active-passive cells. The local active steel surface predominantly acts as an anodic site whereas the adjacent steel remains passive and consequently acts as a cathodic area. The resulting galvanic action between active and passive steel may have a pronounced effect on the corrosion rate at the anodic site. A macroscopic active/passive corrosion cell can possess both a large driving voltage and a large-cathode/small-anode ratio known to be most detrimental. Under these conditions substantial, strongly localized reductions in the cross sectional area can occur (pitting).

3 Simplified calculation model for macrocells

The electrochemical behaviour of a simple macrocell involving one anodic and one cathodic component can be evaluated by using an appropriate equivalent electrical circuit. A two-component macrocell is considered to comprise a separate anodic and cathodic resistance against polarisation, $R_{p,a}$ and $R_{p,c}$ respectively, linked by an electrolytic concrete resistance, R_{con}, in series. The anodic and cathodic resistances reflect the polarisation behaviour of the steel sections involved. Both interface resistances exhibit a pronounced non-linear current-voltage relationship.

Macrocell action between actively corroding and passive steel can thus be expressed mathematically by the following equation:

$$I_{gal} = \frac{U_C - U_A}{R_{p,C} + R_{con} + R_{p,A}} \qquad \textbf{(1)}$$

The magnitude of the galvanic current, I_{gal}, flowing between the anodic component (actively corroding steel) and the macro-cathode (passive steel) is determined by the ratio of the potential difference between passive (cathodic) and corroding (anodic) areas, (U_C - U_A), and the total resistance of the galvanic circuit. This basic relationship permits the numerical simulation of macrocells for both planparallel and coplanar arrangements of reinforcement steel.

Actively corroding steel may exhibit microcell action in which anodic and cathodic sites are randomly distributed over the exposure surface of the steel electrode giving rise to a uniform corrosion attack. In this condition the polarisation behaviour of corroding steel is described by the following equation relating average current density, i, and potential change (overvoltage), ΔU:

$$i = i_{corr} \cdot \left[\exp\left(\frac{\ln(10) \cdot \Delta U}{b_a} \right) - \exp\left(\frac{-\ln(10) \cdot \Delta U}{b_c} \right) \right] \qquad \textbf{(2)}$$

with ln(10) = 2.303

For the anodic and cathodic Tafel slopes, b_a and b_c, values of 90.7 mV/dec and 176,3 mV/dec, respectively, are introduced introduced which results in a Stern-Geary constant B = 26.0 mV [4]. At the free corrosion potential, E_{corr}, i.e. without any macrocell effects, the steel corrodes uniformly with a corrosion current density of i_{corr} [μA/cm^2]. For the planparallel electrode arrangement, microcell activity is considered for the anodic component with i_{corr} = 1.0 μA/cm^2. If small concentrated anodes are considered, i.e. for the coplanar arrangement, it is assumed that the local anode exhibits no significant resistance against polarisation. In the latter case the macrocell current is equal to the corrosion current of the local anode.

For passive steel it is assumed that anodic reactions can only proceed to a very limited extent. The electrochemical behaviour of passive reinforcing steel under cathodic polarisation is given by:

$$i = \frac{1 - \exp\left(\frac{-\ln(10) \cdot \Delta U}{b_c} \right)}{\frac{1}{i_{corr}} - \frac{\exp\left(\frac{-\ln(10) \cdot \Delta U}{b_c} \right)}{i_{\lim}}} \qquad \textbf{(3)}$$

based on data obtained from experimental investigations [2, 5].

For passive steel values of $1 \cdot 10^{15}$ mV/dec and 176,3 mV/dec for the anodic and cathodic Tafel slopes, b_a and b_c, respectively, were introduced which results in a Stern-Geary constant B = 76.55 mV. The corrosion current density of passive steel at the steady state potential, i_{corr}, is set at 0.01 μA/cm^2 [2]. The influence of oxygen diffusion through the concrete cover on the polarisation behaviour is taken into account by introducing a limiting diffusion current density, i_{lim} [6] It is assumed that oxygen diffusion has a significant effect for coplanar macrocells but not in the case of planparallel arrangements of reinforcing steel [5].

Fig. 1 shows the cathodic polarisation curve of passive reinforcement for different limiting currents according to equation [3].

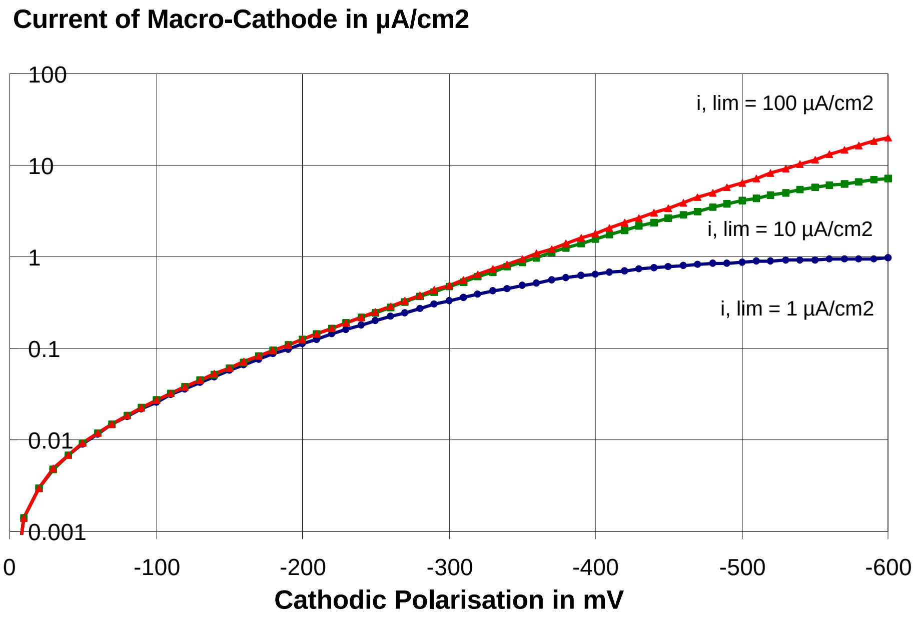

Fig. 1:Cathodic polarisation-curves of passive reinforcement for different limiting currents i, lim

4 Macrocells with planparallel arrangement of corroding steel and macro cathode

For the numerical simulation of a planparallel arrangement, a basic set-up of a macrocell is considered (see figure 2). The macrocell consists of two rebars with a diameter of 16 mm placed in parallel being separated by 200 mm of concrete. This arrangement results in a corroding to passive surface area ratio of 1.0. Both rebars have a cover depth of 32 mm; the width of the specimen amounts to 200 mm whereas a unit length of the rebars of 100 mm is considered resulting in an exposure surface of 50.27 cm^2 for each rebar.

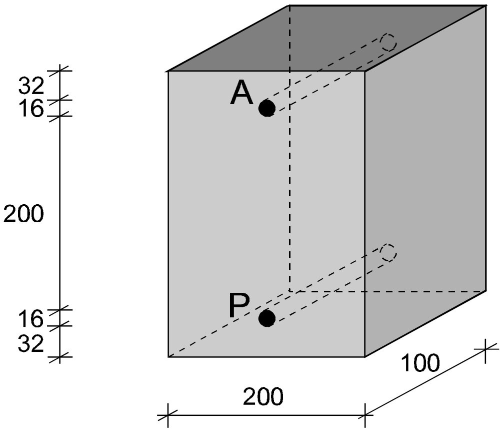

Fig. 2: Cross section of macrocell specimen with planparallel rebar arrangement

The electrochemical behaviour of the steel-concrete interface of each rebar is modelled with 16 discrete equidistant interface elements. The electrical properties of the concrete environment are modelled by pure resistive elements each representing a square cross section of 4×4 mm^2.

As a starting point the corrosion current density for the corroding steel (denoted rebar A) due to microcell action is arbitrarily set at $i_{corr} = 1\ \mu A/cm^2$, resulting in a total corrosion current, $I_{corr} = 50.27\ \mu A$. For the macro-cathode (denoted rebar P) the corrosion current density is set at $i_{corr} = 0.01\ \mu A/cm^2$ reflecting the passive condition of the steel. The concrete resistivity, ρ_{con} [Ω·cm], and the initial potential difference between the passive and the corroding steel, $U_{oc} = (U_C - U_A)$ [mV], are varied within a wide range during the numerical simulation.

5 Corrosion current and resistance control for planparallel rebar arrangement

Due to macrocell action the kinetics of both the anodic and cathodic processes of the corroding rebar are affected. In Figure 3 the resulting change in the corrosion current density, i_{corr}, i.e. self-corrosion rate including macrocell action, is shown as a function of open-circuit voltage U_{oc}, for different practical values of concrete resistivity, ρ_{con}. For $U_{oc} \leq 400$ mV the influence of macrocell action is limited since it does not result in a significant acceleration of the corrosion rate. However, for $U_{oc} \geq 400$ mV the magnitude of i_{corr} is increased from 1.0 $\mu A/cm^2$, i.e. the initial corrosion without macrocell action, to values ranging from 1.23 $\mu A/cm^2$ (400 mV; 50000 Ωcm) to 3.52 $\mu A/cm^2$ (600 mV; 5000 Ωcm). The corresponding potential of the anodic components shifts by +8.0 to +49.5 mV (anodic polarisation) and for the macro-cathode from -268.8 to -436.7 mV (cathodic polarisation).

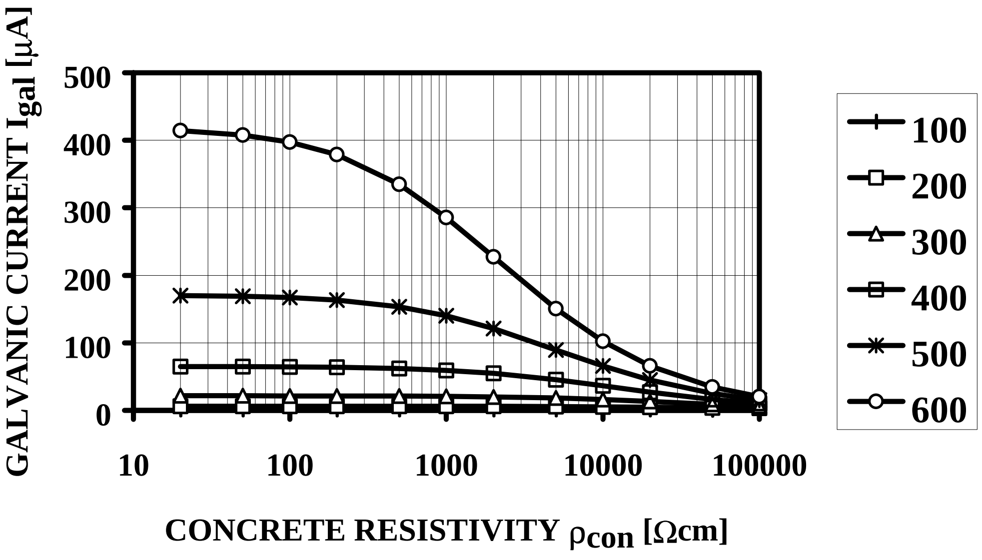

Fig. 3: Macrocell current as a function of concrete resistivity

These potential shifts of the anode and macro-cathode already indicate that the control exerted by the concrete resistance on the macrocell process is significantly lower than the control exerted by the cathodic process of the passive steel. As an example Figure 4 shows the relative resistance control of the three processes involved, i.e. the anodic, cathodic and electrolytic proces, denoted C_a, C_c, C_{el}, respectively, as a function of concrete resistivity for U_{oc} = 400 mV. For the complete range of concrete resistivities investigated the cathodic control, C_c, clearly dominates starting with a value of 93% (20 Ωcm) which gradually decreases to 59% for ρ_{con} = 100000 Ωcm. The increase of concrete resistivity is reflected in a simultaneous rise of the control exerted by the concrete resistance, C_{el}, from 0% to 40%. For U_{oc} = 600 mV and ρ_{con} = 5000 - 50000 Ωcm, the contribution of the concrete resistance to the overall macrocell circuit resistance ranges from 19% to 43% and for U_{oc} = 400 mV from 9% to 31%. Due to the high corrosion rate the relative resistance control of the resistance against polarisation of the actively corroding steel, C_a, is always less than 10%.

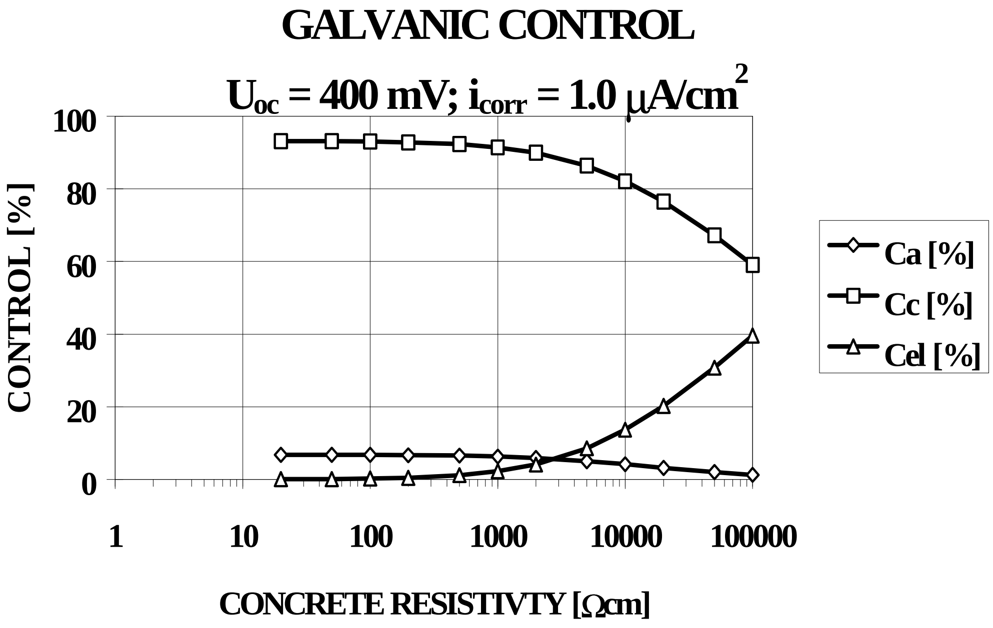

Fig. 4: Relative control of the anodic, cathodic, and electrolytic process on the overall macrocell resistance for planparallel rebar arrangement

6 Macrocells with coplanar arrangement of local anode and macro cathode

A single rebar may exhibit macrocell action when large areas of passive steel are interspersed by small anodic sites. Such a situation may develop when cracks in the concrete cover cross underlying reinforcing bars. The corrosion behaviour of this macrocell may be simulated by a one-dimensional approach using a transmission line model. The passive steel acts as macro-cathode which is subdivided into 50 discrete elements along the rebar, each with a certain potential and current. The individual cathode-elements have a standard length of 10 mm and a diameter of 16 mm.

Between neighbouring elements an ohmic drop over the concrete electrolyte is induced by the flow of ionic current along the rebar. The calculation procedure for macrocells using a transmission model is described in more detail in [2].

Figure 5 depicts the distribution of the cathodic current over the passive steel as a function of the distance from the central corroding zone (ideal anode) for a wide range of driving voltages between corroding and passive zones, U_{oc} = 100-600 mV, using the following assumptions:

- Anode: anodic polarisation resistance = 0 Ω, simulating e.g. extremely high chloride contents; no cathodic reaction on the surface of the anodic component;
- Concrete: longitudinal electrolytic resistance along the rebar: r_{con} = 100 Ω/cm^1;
- Macro-cathode: polarisation behaviour given by eq. [3] with i_{lim} = 100 µA/cm^2.

The first assumption implies that the corrosion current of the anode is given by the overall cathodic current produced by the passive steel area.

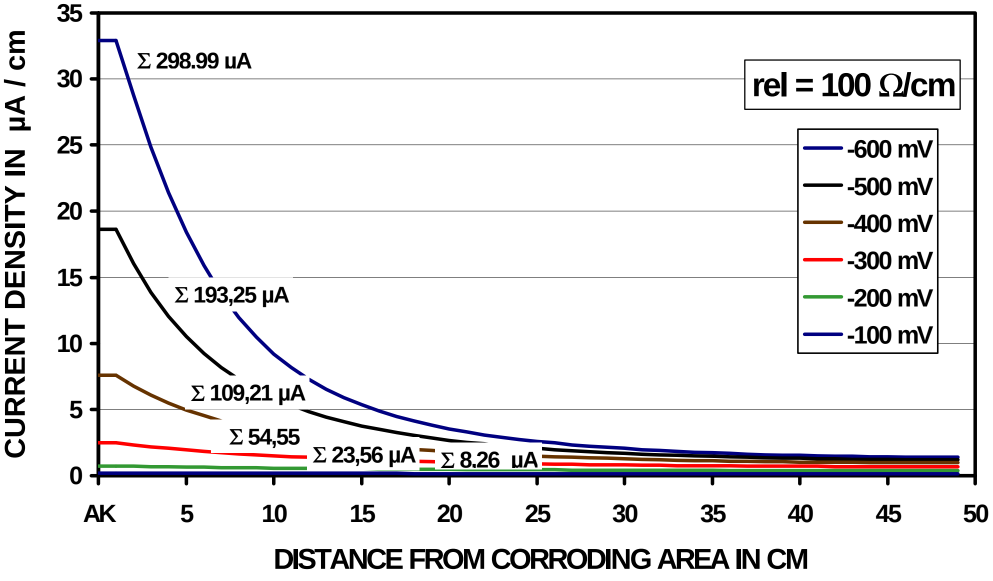

Fig. 5: Cathodic currents for a coplanar macrocell arrangement (example)

As to be expected, the cathodic current density increases considerably with higher driving voltages, and decreases with the distance from the corroding area. However, significant cathodic current densities are not only present within a few cm from the corroding zone, but also at passive steel surfaces more distant from the anode. Especially when high driving voltages are present, passive steel at a distance more than 20 cm still may contribute significantly to the overall cathodic current. The distance of influence may then even amount to several meters in case of low resistivity concrete or in cases with large distance between depassivated and well aerated areas.

6 Investigations to verify the numerical models

Two reinforced concrete beams with a length of 2 m have been produced to study the cathodic current distribution of passive reinforcement within a one-dimensional electrical field to verify the transmission line model. Altogether 20 pieces of reinforcement have been embedded each with a length of 10 cm to simulate one 2 m bar (see Fig. 6). At one side 2 % and 3 % of chlorides / cement have been added to the concrete mix while the remaining 19 segments have been produced using concrete without chloride addition. Connecting an amperemeter between the cables of the rebars it was possible to measure the macrocell currents as shown in Fig. 6. Details are described in [2].

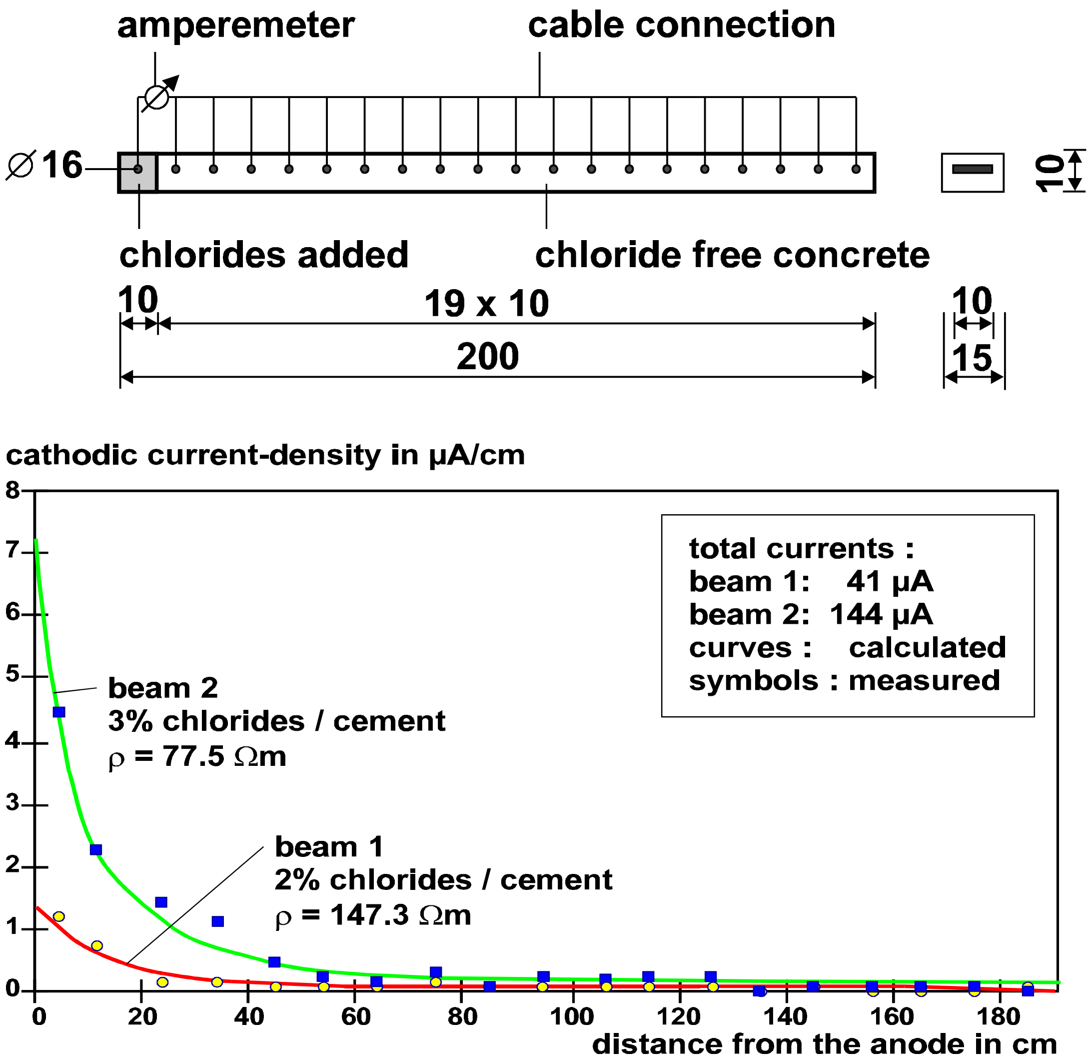

Fig. 6:Test set-up and cathodic current distribution of the passive reinforcement

The test results show a good correlation between measured values and the data calculated using the transmission line model using the formula describing the polarisation behaviour of passive steel (equation [3]). However, for geometrical conditions of macrocells occurring in practise more complex models for the description of the electrical fields have to be used for the numerical simulation.

7 Determination of steel removal rates

The basic relationship between anodic current and steel removal rate is given by Faraday’s law. In Fig. 7 the resulting removal rate [µm/a] due to macrocell action, i.e. due to the current supplied by the macro-cathode, is shown for various anode surface areas, assuming uniform corrosion attack over the exposure surface. In the case of non-uniform corrosion attack, the surface areas showing the highest local corrosion rates are considered of most practical relevance. Therefore an average value for the anode surface may be used as an input for Fig. 6.

For planparallel macrocells the steel removal rates can be approximated as the sum of the initial corrosion current generated by self corrosion and the macrocell current supplied by the macro-cathode. Generally, the macrocell current underestimates the actual rate of attack, since cathodic reactions on the corroding rebar are not completely suppressed.

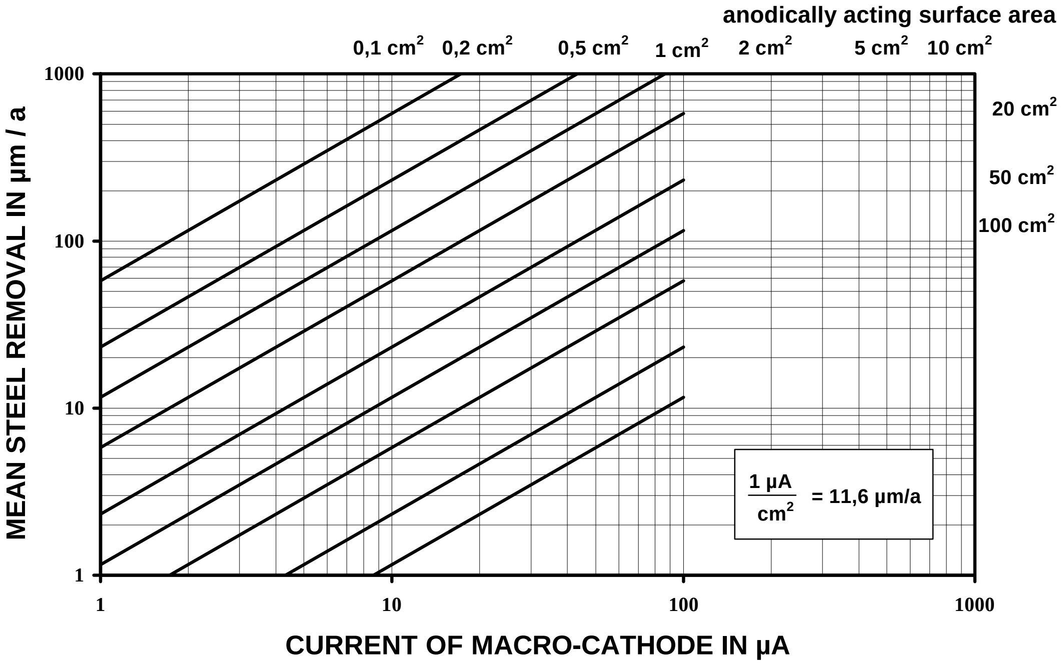

Fig. 7: Relationship between cathodic current and steel removal rate

For the coplanar arrangement the overall cathodic current is equal to the corrosion current of the anode. Hence, the magnitude of the cathodic current can be converted directly into the rate of attack.

8 Concluding remarks

Macrocell action plays an important role in the corrosion process of reinforcement steel. For practical situations this results in complex electrochemical interactions involving all parts of the steel reinforcement network. These effects can be quantified by a numerical analysis which permits a prediction of the current distribution for arbitrary reinforcing steel geometry's, electrochemical characteristics of the steel/concrete interface, and concrete resistivity distributions [5,7].

The magnitude of the macrocell current flowing between the macro-cathode and the anodic component is strongly dependent on the driving voltage, the resistivity of the concrete electrolyte, and the polarisation behaviour of the passive steel. Therefore simplified models based simply on the influence of the electrolytic resistivity on the concrete might be misleading in many cases.

Generally, the rate of attack is determined by the conjoint action of microcells and macrocells. Under adverse conditions the local corrosion rate may be multiplied compared to the initial situation without macrocell action. The situation when the macrocell current equals the corrosion current is approached when the overall anodes of the macrocell system are polarised in the anodic direction by more than approximately 50 mV from their respective initial free corrosion potential.

In general, the highest corrosion rates have to be expected when the corroding area is small compared to the exposure surface of the macro-cathodes. The situation is exacerbated when the concrete has a low resistivity and a high permeability for oxygen. However, restriction of the corrosion rate by oxygen diffusion is not to be expected for most practical situations unless the concrete cover is water saturated during an extended period of time [6].

9 References

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