ABSTRACT: Subproject A2 of this joint research project investigates macrocell formation with the main emphasis on geometrical influences. Another important aspect that will be investigated within the next years is the time dependence of the anodic activity and the macrocell current. Hence, this subproject provides key data for the final design model. The investigations on macrocells were carried out by laboratory experiments and additionally by numerical analyses to increase the available database especially with respect to geometrical influences. Thereby all specimens were designed to represent practical conditions, i.e. slabs or beams with a localised depassivation. Based on these results, it is possible to model the macrocell current under steady-state conditions. Chloride induced corrosion at real structures, however, is influenced by many time-dependent factors, i.e. temperature and polarisation behaviour of depassivated reinforcement parts. In order to implement the time dependence into the probabilistic design model extensive laboratory tests on about 110 macrocell corrosion specimens are actually carried out. During a time span of two years, electrochemical measurements and visual inspections are conducted on the test specimens to investigate especially the time-dependent behaviour of the anodically acting parts. The determination of the characteristic corrosion patterns and metal removal of the anodic areas is achieved by a unique three-dimensional optical technique using high-resolution digital cameras.

1 INTRODUCTION

The corrosion process—especially in case of macrocell formation—depends on a lot of different boundary conditions which have to be considered to develop a design model for the remaining lifetime after depassivation. A major issue is given by different geometrical arrangements of diverse structural members like beams or slabs. Furthermore a structure can be affected by chloride attack in different manners, e.g. as a result of local damages of surface coatings or a local exposure to splash water, leading to different arrangements of active and passive reinforcement bars.

As it is almost impossible to cover this wide range of geometrical varieties by a laboratory test programme a different approach was chosen. Recent research results show (Brem 2004, Warkus 2006) that macroelement formation in concrete members can be successfully investigated by applying numerical methods. One advantage of this approach is the possibility to substitute laboratory experiments by computer simulations and to study the effects of diversified boundary conditions. Especially geometrical influences can easily be investigated.

First specimens representing basic practical conditions and geometrical arrangements were produced and laboratory measurements were carried out. Then numerical simulations of the laboratory specimens were performed. After a successful calibration of the calculations by the measurement results parameter studies were carried out.

A numerical simulation allows to study galvanic systems under constant steady-state conditions, but for a damage model one has to consider the time dependence of the corrosion process. Especially the anodic polarisation behaviour is time-dependent because corrosion pits at the surface of depassivated steel bars can change their quantity and size. New pits can occur and existing pits can repassivate. In terms of a time-dependent damage model these issues will be investigated in a comprehensive testing series.

2 MACROCELL CORROSION AND GEOMETRICAL EFFECTS

2.1 Laboratory experiments

2.1.1 General

As the focus is directed on geometrical effects the concrete composition and exposure conditions are kept constant for all specimen. The concrete composition is
conform to the standard composition of the research group and the exposure conditions were chosen at 20°C and 95% RH to prevent the specimens from desiccation. To investigate the effects of different cement types, specimens with ordinary Portland cement (OPC) and blast furnace slag cement (BFS) were fabricated.

In order to create macrocells, all specimens were cast in two steps and during the first step chlorides were added to the mixing water to depassivate the reinforcing steel. After two days the second part of each specimen was concreted without chlorides to generate cathodically acting reinforcement bars. The time period of two days was chosen to delay the diffusion of chloride ions into the chloride free concrete. Furthermore all passive reinforcement bars were placed in a minimum distance of 3 cm to the chloride containing concrete. By this measures an unintended depassivation can be prevented for several years.

The macrocell current of all specimens was almost continuously measured. Furthermore, simple instant-off measurements were performed to measure the polarisation of the electrodes.

2.1.2 Specimens
To cover a wide range of different structural members, specimens with different geometries were fabricated. The test series varies from simple specimens with two parallel reinforcement bars to more complex slab-like specimens or girders with three layers of reinforcement and additional stirrups (figures 1–4).

First basic geometrical arrangements were investigated. The most elementary geometry is given by two parallel reinforcement bars (CP, figure 1). This configuration represents concrete structures with one passive and one active layer of reinforcement. The second geometrical arrangement is a one-dimensional
configuration with one depassivated reinforcement bar in the centre of the specimen and five cathodically acting reinforcement bars on each side (figure 2). This configuration is a very simple example for a localised depassivation.

The next test series serves to investigate more complex slab-like specimens with different arrangements of active and passive steel bars. (figures 3 and 4). Both types have a length and width of 140 cm, a thickness of 20 cm and two layers of reinforcement. Parts of the upper layer are depassivated by chloride admixture. Chlorides were added in a single corner of the specimen (SP, fig. 3) or along the centreline (SL, fig. 4).

Finally two different types of specimens with more than two layers of reinforcement and additional stirrups were fabricated (figure 4): One with a depassivation in a single corner (BC) and one with a chloride contamination of a complete reinforcement layer (BL).

2.2 Simulations

2.2.1 General

All simulations were carried out with a boundary element programme called BEASY CP. It is capable to solve the Laplace-equation and Ohms law inside an electrolyte and to apply the following boundary conditions to describe the polarisation behaviour of the metal electrodes (Raupach 2006):

- constant potential
- constant current density
- linear or non-linear relation between current density and potential (polarisation curve).

2.2.2 Assumptions

Two basic input parameters are necessary. The concrete resistivity has to be known and was taken from sensor readings. Furthermore, appropriate polarisation curves for both electrodes must be considered:

1. Cathodically acting reinforcement

The polarisation curve of the passive reinforcement was assumed according to the Butler-Volmer equation (eq. 1).

\[ i = i_{\text{corr}} \left[ \exp \left( \frac{\ln(10) \cdot \Delta \Phi}{b_a} \right) - \exp \left( - \frac{\ln(10) \cdot \Delta \Phi}{b_c} \right) \right] \]  \hspace{1cm} (1)

where \( i = \) current density; \( i_{\text{corr}} = \) corrosion current density; \( \Delta \Phi = \) over-potential; \( b_a = \) anodic Tafel constant; \( b_c = \) cathodic Tafel constant.

2. Anodically acting reinforcement

The anodically acting reinforcement was considered by using an integral polarisation resistance \( R_a \). This linearisation and simplification is an assumption and it has to be checked whether it leads to reasonable results.

The necessary parameters (Tafel-slope, anodic polarisation resistance, etc.) were calculated by regression analysis from instant-off measurements.

2.2.3 Results

1. Potential distributions

As one result the potential distribution can be visualised for all geometrical arrangements (figures 6–9). The symmetry of the specimens was considered at simulating.

2. Macrocell current

For an estimation of corrosion rates and the remaining lifetime the macrocell current is of main concern.

Figure 6. Calculated potential distribution of the specimen with two parallel arranged reinforcement bars (PP, symmetry).

Figure 7. Calculated potential distribution of the specimen with coplanar arranged reinforcement bars (CP, symmetry).

Figure 8. Calculated potential distributions of the slab-like specimens (SP, SL, symmetry).
Table 1 shows a comparison of the measured and calculated values. The simulation of the third series (BC and BL) is still part of the actual research work and therefore not presented.

The difference between calculated and measured macrocell current is in most cases less than ±10%, indicating that the galvanic systems were simulated correctly by use of the selected assumptions.

2.2.4 Parameter study

2.2.4.1 General

Based on these results it becomes possible to study macrocells under different boundary conditions to derive necessary parameters for the engineering model of the research group. Subsequently, a brief example for the slab-like geometries is presented.

Table 2. Parameter study.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>SP</th>
<th>SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>[Ωm]</td>
<td>100, 500, 1000, 10000</td>
</tr>
<tr>
<td>Driving voltage</td>
<td>[mV]</td>
<td>300, 400, 500</td>
</tr>
<tr>
<td>Cathode/anode surface area ratios</td>
<td>–</td>
<td>53:1, 96:1, 18:1, 36:1, 192:1, 54:1</td>
</tr>
<tr>
<td>Anodic polarisation resistance</td>
<td>[Ωm²]</td>
<td>2</td>
</tr>
</tbody>
</table>

Resistivities between 100 and 500 Ωm represent wet concrete structures, e.g. in marine environments, values above 10,000 Ωm usually occur in dry concrete members. The given cathode to anode surface area ratios were calculated by taking reinforcement amounts into account which occur under practical conditions, e.g. at parking decks.

The cathodic polarisation curve for all calculations was assumed according to the Butler-Volmer-equation (eq. 1). The constant anodic polarisation resistance of $R_a = 2 \text{Ωm}^2$ corresponds to the measured mean value of all OPC specimens.

2.2.4.3 Results

Subsequently the calculated influence of single parameter on the macrocell current is presented and briefly discussed. Finally the results were used to calculate necessary parameters for the working hypothesis of the research group.

1. Concrete resistivity

The figure 10 shows the macrocell current as a function of resistivity (log-scale) for different driving voltages. As expected the results show a strong influence of the concrete resistivity on the macrocell current, because beyond a resistivity of 1000 Ωm the current decreases significantly. This corresponds to results of on-site observations.

However, it has to be noted that no other limiting factors were considered. Figure 11 shows the derived controlling factors for the calculation of the SL-specimen. At low resistivity cathodic control can become dominant. Hence, the macrocell current can be decreased, if a lack of oxygen appears. But this scenario will be investigated by future simulations.

2. Cathode to anode surface area ratio

The influence of the cathode to anode surface area ratio was investigated by changing the amount of cathodically acting reinforcement. The other input parameters were kept constant. The results in terms of the calculated macrocell current-density for different surface area ratios and concrete resistivities are shown on figure 12.
3. Modelling and cell factors

Subsequently the working hypothesis of the research group is briefly repeated. Following Ohm’s law the macrocell current can be controlled by three different resistances: the polarisation resistances at the surface of the anode $r_a$ and cathode $r_c$ and the electrolytic resistance in-between:

$$I_{macro} = \frac{U}{r_x + \frac{1}{A_x} + r_e \cdot \rho_e}$$  

(2)

where $I_{macro}$ = macrocell current; $U$ = driving voltage; $r_x$ = specific polarisation resistance; $A_x$ = electrode surface area; $k_e$ = cell factor; $\rho_e$ = concrete resistivity.

As mentioned above the objective of this sub-project is on the influence of different geometrical arrangements. Hence, the cell factors $k_e$ is of great concern. In order to calculate it the total electrolytic resistance $R_e$ must be derived from the simulation output files (Brem 2004). Afterwards it becomes possible to calculate the cell factors of all performed simulations:

$$k_e = \frac{R_e}{\rho_e}$$  

(3)

On figure 13 the results are shown for both slab-like geometries and different cathode to anode surface area ratios.

The dependence of the cell factors on the resistivity and the cathode to anode surface area ratio is comparably weak. In case of high corrosion rates beneath a concrete resistivity of 1000 $\Omega \text{m}$ the macrocell current can be estimated on the safe side using equation 2 with a cell factor of 0.4 m$^{-1}$ for the specimen with a chloride contamination along the centerline (SL) and 3.0 m$^{-1}$ for the specimen with a chloride contamination in one corner (SP). The different cell
factors show clearly the strong influence of the geometry of the galvanic system on the resulting macrocell current.

This is an example, how numerical analyses can help to derive necessary input parameters for the working hypothesis of the joint research group. As the presented results are only valid for two specific geometries, further research work will focus on simulations of other practical geometries.

3 TIME-DEPENDENT EFFECTS

3.1 General

As explained above it is possible to investigate macroelement formation in concrete members by laboratory experiments and in addition by numerical analysis for steady-state conditions. But in terms of a lifetime assessment the time-dependent changes of a galvanic system must be considered. Derived from the deterioration models for the-time dependent corrosion current \(i_{\text{corr}}(t)\) and depth of the corrosion damage \(x_{\text{corr}}(t)\) the primary objective of this subtask during the second phase consists of the investigation of the time-dependent system parameters under relevant boundary conditions:

\[
i_{\text{corr}}(t) = \frac{U(t)}{\frac{r_a(t)}{A_a(t)} + \frac{r_c(t)}{A_c(t)}} + i_{\text{self}}(t) \tag{4}
\]

and:

\[
x_{\text{corr}}(t) = \alpha(t) \cdot \frac{11.6}{A_a(t)} \cdot i_{\text{corr}}(t) \tag{5}
\]

- the driving voltage \(U(t)\)
- the anode (specific integral polarization resistances \(r_a(t)\) and actual corroding surface \(A_a(t)\))
- the cathode (specific integral polarization resistances \(r_c(t)\) and cathodically active surface area \(A_c(t)\))
- the specific type of corrosion damages in the anodic areas \(\Delta A(t)\) (i.e. distribution of pits, pit depths, pitting factor \(\alpha(t)\)).

In order to achieve this an extensive laboratory test series has been initiated. Based on a defined reference case selected boundary conditions such as temperature, cement type, water application and chloride content will be varied. The influences on the above mentioned time-dependent model parameters will then be studied by continuous and periodical electrochemical and destructive investigations. Due to the probabilistic approach of the design model the number of test specimens is chosen to be sufficient for a statistical analysis of the respective model parameter. Like this the dependency of these parameters on the varying boundary conditions shall be quantified and subsequently integrated into the design model.

3.2 Programme

The work programme for the second phase of this subproject reads as follows:

- continuous and periodical survey of relevant corrosion parameters by means of electrochemical investigation methods
- destructive investigation of test specimens in selected time intervals with a subsequent analysis of corrosion damages in the anodic areas of the corrosion cell as well as supplementary determination of relevant parameters such as the total chloride content.

3.2.1 Test specimens and test series

All in all 7 different laboratory test series will be conducted, which allow a detailed investigation of the time dependent macrocell action under selected boundary conditions. For each series up to 18 test specimens are prepared resulting in a total number of about 120 specimens. In defined time intervals (i.e. 12, 18 and 24 month) between 3 and 6 test specimens of each series will be investigated in a destructive manner taking into account the typical scatter of corrosion test results of steel in concrete (see figure 14). In order to create immediate macrocell corrosion activity the concrete surrounding the anode contains 3 M.\%/c chlorides. This measure is necessary in order to investigate the time-dependent development of the macro cell corrosion process within the given project schedule (i.e. 2 years). All electrochemical tests will be conducted using a MnO2-reference electrode which is embedded in each test specimen. Furthermore the specimens are equipped with a watertight basin in order to ensure the different kinds of applications for the anticipated test series. For the set-up a minimum ratio between cathodic and “anodic” surface areas of 45:1 is provided. Due to the fact that chloride induced corrosion is a rather local phenomenon, the ratio between the cathodic surface area and the actively corroding anodic surface areas will be far higher. This is to be shown by means of the surface analyses of the anodic bar. In order to avoid any boundary effects, the lateral surfaces of the test specimens are coated with an epoxy resin.
3.2.2 Methodology
To gather all necessary information to describe the time dependent behaviour of the respective parameters of the deterioration model the following methodology will be used, see figure 14.

3.2.3 3D surface analyses
The detailed surface analysis of the dismounted anode bars will be achieved by means of a high resolution 3-D camera technology. The created data set of the scanned anode surface will then be analyzed using suitable software packages with respect to total mass loss, pit distributions and pit depths, see figure 15. Like this corrosion damage categories will be established and in combination with other test results (i.e. macro cell current measurements) a differentiation between macro cell and micro cell corrosion action shall become possible with respect to their time dependency. In addition to that comparing studies between the analyzed damage type and electrochemical characteristics such as the specific polarization resistance shall be conducted in order to establish possible correlations. Finally, the surface analysis shall clarify whether the present corrosion type results in crack inducing corrosion products or not.

4 CONCLUSIONS
To investigate macrocell formation in concrete members laboratory tests and numerical simulations were carried out. In a first step the numerical models were successfully calibrated by measurements. Based on this a parameter study was performed to identify the influence of selected parameters. The results show a strong impact of the concrete resistivity and thereby of the moisture content on the resulting macrocell current. Furthermore, the influence of different amounts of cathodically acting reinforcement was investigated. The results show clearly, that an increase of passive reinforcement bars within a practical range has only an under-proportional influence on the macrocell current. Afterwards the results were used to derive suitable input parameters for the working model of the research group.

Further investigations of the anodes will be accomplished involving different exposure conditions and time-dependent effects. The anodes will be examined by electrochemical measurements and by destructive testing with an subsequent, optical analysis of the corrosion damages.

REFERENCES