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RILEM TC 154-EMC: 'Electrochemical Techniques for Measuring Metallic Corrosion'

Recommendations

Half-cell potential measurements – Potential mapping on reinforced concrete structures

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The text presented hereafter is a draft for general consideration. Comments should be sent to the TC Chairlady: Dr. Carmen Andrade, CSIC - Instituto de Ciencias de la Construccion "Eduardo Torroja", Serrano Galvache s/n - Aptdo 19.002, 28033 Madrid, Spain; Tel.: +34 1 302 04 40; Fax: +34 1 302 07 00; Email: andrade@ietcc.csic.es, by 31 December 2003.

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1. PREFACE

Corrosion of steel in concrete is one of the major problems with respect to the durability of reinforced concrete structures. The majority of concrete structures perform well even after a long period of use in normal environments. However, there are various reinforced concrete structures important for our infrastructure, especially bridges and buildings, which exhibit premature damage due to environmental actions (EN 206). In contrast to mechanical actions (as load, wind, etc.) the environmental actions are not reversible and accumulate hazardous components (as *e.g.* chloride ions) in the concrete. A high percentage of the damages is caused by insufficient planning, wrong estimation of the severity of environmental actions and by bad workmanship and thus many of these structures need to be repaired after a short service life. In most industrial countries, repair and restoration of reinforced concrete structures today is nearly as important as new constructions.

Due to the importance of the problem, RILEM set up an initial committee on reinforcing steel corrosion in 1960. A second committee related to the problem, TC 60-CSC 'Corrosion of Steel in Concrete', was established in 1980, presenting a state-of-the-art report in 1988 on the generally agreed knowledge about the processes causing corrosion and the corrosion mechanism themselves. RILEM TC-124 on Strategies for the Repair of Concrete Structures Damaged by Steel Corrosion published a draft recommendation in 1994, where the importance of condition assessment has been pointed out as the first step in the repair process. To ensure a sound decision on the type of repair work, it is essential to get first of all a thorough assessment of the condition of the structure, including the evaluation of:

- cause of damage or loss of protection
- degree and amount of damage
- expected progress of damage with time
- effect of damage on structural behaviour and serviceability.

The acquisition of reliable information on level and rate of deterioration is done during regular main inspections relying on visual examination of the whole structure. If no reliable conclusion on the state of the structure or part of it can be obtained, an additional inspection (verification) including non-destructive testing has to be performed until the cause of damage is clearly identified.

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Following the work of TC-124, RILEM set up a Technical Committee 154-EMC on Electrochemical Techniques for Measuring Corrosion of steel in concrete. During the first meeting of the committee it was decided to prepare RILEM Technical Recommendations on

- Half cell potential measurements
- Test methods for on-site corrosion rate measurements of reinforcement by means of the polarization resistance
- Test methods for on-site measurement of resistivity of concrete
- Embedded Probes for Corrosion monitoring

These documents are presently prepared for publication. This Draft RILEM Technical Recommendation on Half-Cell potential measurements intends to give a general description of half-cell potential measurements for assessing the corrosion risk of an existing structure (inspection), for locating precisely corroding rebars prior to and during repair work and for evaluating the effectiveness and durability of the repair work. Special attention will be paid to factors influencing potential measurements and to the interpretation of potential readings.

2. SCOPE

This RILEM Technical Recommendation intends to provide the background, a description of the application and guidelines for the interpretation of half-cell potential measurements on reinforced concrete structures. It covers both: point measurements (mostly used during inspection, thus in the project phase of a restoration) and potential mapping.

3. SIGNIFICANCE AND USE

Half-cell potential measurements as described in this document can be performed on structures with ordinary or stainless steel reinforcement. Corrosion of prestressing steel in concrete can be assessed in the same way. Prestressing steel in the ducts of posttensioned cables can not be assessed: metallic ducts shield the strands from the concrete surface, plastic ducts isolate the strands. Epoxy coated steel is not treated in this recommendation because EP coated bars usually are electrically isolated from each other and thus cannot be measured. Galvanized steel can be measured in the same way but different criteria applied.

Half-cell potential measurements are suitable mainly on reinforced concrete structures exposed to the atmosphere. The method (measurement and interpretation) can be applied regardless of the depth of concrete cover and the rebar size and detailing. Half-cell potential measurements will indicate corroding rebars not only in the most external layers of reinforcement facing the reference electrode but also in greater depth.

The method can be used at any time during the life of a structure and in any kind of climate providing the temperature is higher than +2°C. Half-cell potential measurements should be taken only on a free concrete surface, the presence of isolating layers (asphalt, organic coatings or paints etc.) may make measurements erroneous or impossible.

Half-cell potential measurements are recommended and may be used for one of the following main purposes:

1 Locate corroding rebars and thus assess the present corrosion condition of the reinforcement during inspection and condition assessment of a RC structure

2 Define the position for further destructive analysis (cores for chloride analysis, inspection windows to visually examine the corrosion state of the rebars etc.) and of embedded sensors for further monitoring on the basis of the results of potential measurements

3 Evaluate the corrosion state of the rebars after repair work and thus evaluate the efficiency and durability of repair work

4 Design an anode layout of cathodic protection systems or electrochemical restoration techniques

Half-cell potential measurements do not provide quantitative information on the actual corrosion rate of the rebars. They should be interpreted in the context of complementary data from the concrete structure (chloride content, carbonation, porosity etc.) by specialists or skilled engineers experienced in the field of corrosion testing and structural evaluation.

4. DEFINITIONS

The definitions and terminology used in this recommendation are in agreement with ISO 8044 (1999) third edition.

5. THEORETICAL BACKGROUND OF HALF-CELL POTENTIAL MEASUREMENTS

5.1 The electrochemistry of corrosion of steel in concrete

Corrosion of steel in concrete follows the electrochemical mechanism of corrosion of a metal in an electrolyte [1, 2]. Chemical thermodynamics determine whether a particular metal tends to corrode in a particular environment. According to the equilibrium potential / pH diagram (or Pourbaix diagram), ordinary reinforcing steel in the highly alkaline environment of concrete is protected by a thin oxide film (the passive film) from further corrosion. This protective passive film may be destroyed by chlorides penetrating through the concrete cover to the steel surface and / or by carbonation of the concrete, thus the loss of alkalinity due to the reaction with CO_2 from the atmosphere - the steel is then depassivated. Active corrosion will take place when the steel is depassivated and both oxygen and humidity, are present at the steel surface.

Corrosion of a metal implies separate anodic and cathodic processes occuring simultaneously on the same metal surface. Corroding steel in concrete acts as a mixed electrode with coupled anodic and cathodic reactions taking place simultaneously on its surface [1, 2]. At the corroding site (the anode), iron is dissolved and oxidized to iron ions leaving electrons in the steel: $Fe \rightarrow Fe^{2+} + 2\,e^-$. Due to the condition of electroneutrality, these electrons have to be consumed by the cathodic reaction at the steel surface, where oxygen is reduced and hydroxyl ions are produced: $O_2 + 2H_2O + 4e^- \rightarrow 4\,OH^-$.

Depending on the spatial distribution of anodic and cathodic reactions on the surface of the steel and the conductivity of the medium, two different types of corrosion can take place:

5.1.1 Uniform corrosion

The simplest form of a corrosion process is one in which anodic and cathodic reations are coupled to form numerous micro-cells on the steel surface and occur on the same areas. This type of corrosion can be represented by the Evans diagram (Fig. 1a) showing the polarization curves for the separate anodic and cathodic reactions intersecting at a point P where the mean anodic and cathodic current densities are equal and represent the corrosion rate i_{corr}. The electrode potential of this couple at this point is termed the corrosion potential E_{corr}. It is constant over the whole surface of the corroding zone. For steel in concrete, uniform corrosion is normally encountered when the steel has lost its passive state due to carbonation or very high chloride concentration, and humidity and oxygen are present in sufficient amounts to sustain the cathodic reaction.

A special case of uniform corrosion is the state of active, low potential corrosion. In environments where the availability of oxygen is very limited, as is sometimes the case for fully submerged or buried reinforced concrete, the cathodic current density may be too low to maintain the passive film on the steel. Under these circumstances the metal behaves actively, the corrosion potential is depressed to very negative values in the range of ca. -0.9 to -1.0 V SCE. The rate of metal dissolution is very low owing to the very low cathodic current density [1].

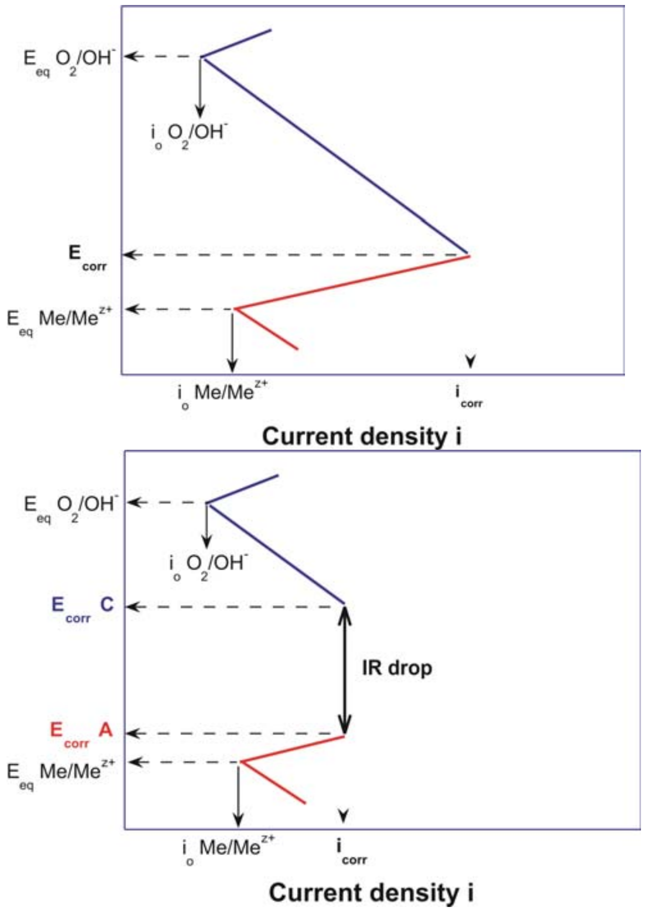

Fig. 1 - Evans diagram for uniform corrosion (a) and for a corrosion couple with ohmic drop (b). E_{corr} = corrosion potential, E_{eq} = equilibrium potential, i_{corr} = corrosion current density.

5.1.2 Macro-cell corrosion

In macro-cell or localized corrosion, the anodic and cathodic areas of the corrosion process are separated in space. Under these circumstances, a significant amount of ohmic potential drop (IR-drop) separates the potential of the anodic and the cathodic area and the Evans diagram is modified (Fig. 1b). The corrosion potential varies with position between the limits of E_{corr} (anode) and E_{corr} (cathode). The positions of local anodes are indicated by regions of more negative corrosion potentials - thus surveys of corrosion potential can be used to locate sites of active corrosion.

For steel in concrete, macro-cell corrosion is occurring in the case of localized corrosion attack due to the action of significant levels of chlorides in the concrete. The corrosion takes the shape of corrosion pits, concentrated anodic areas, surrounded by relatively large areas of passive steel (acting as cathode).

5.2 Half-cell potentials

The corrosion potential E_{corr} (half-cell rebar / concrete) is measured as potential difference (or voltage) against a reference electrode (half-cell). As a corrosion detection technique this was first used by Stratful [3]. The numerical value of the measured potential difference between the steel in concrete and the reference electrode will depend on the type of reference electrode used and on the corrosion condition of the steel in concrete. In addition, half-cell potentials of steel in concrete cannot be measured directly at the interface concrete / rebar due to the presence of the concrete cover (Fig. 2), the potentials are thus influenced by iR drop in the cover, by macrocell current and possibly by junction potentials.

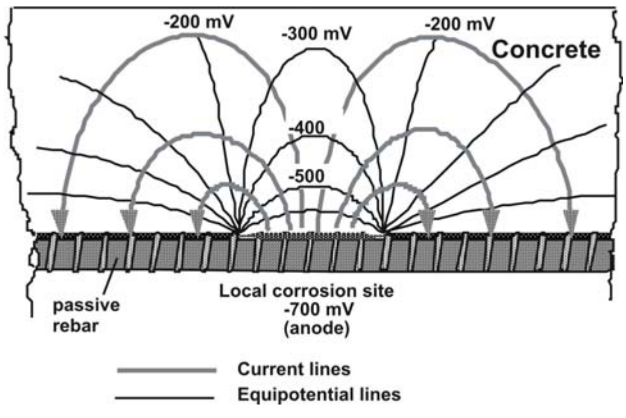

Fig. 2 - Schematic view of the electric field and current flow in an active / passive macrocell on steel in concrete.

5.2.1 Reference electrodes

It is essential to quote always the reference electrode being used for half-cell potential measurements. In practice the following reference electrodes with a defined, constant and reproducible potential versus the standard hydrogen electrode (SHE) are used:

Copper / copper sulfate sat	CSE	+ 0.318 V SHE
Calomel (Hg / Hg2Cl2) KCl sat.	SCE	+ 0.241 V SHE
Silver chloride (Ag / AgCl) KCl sat.	SSCE	+ 0.199 V SHE

For on site work, the saturated copper-copper sulfate electrode is most robust and is sufficiently accurate, although errors may arise due to contamination of the concrete surface with copper sulphate [4]. Calomel and silver chloride electrodes are used more in laboratory work. The base potential of the reference electrodes depends on the concentration of the electrolyte, thus care has to be taken to operate in saturated conditions. The temperature dependence of the reference electrodes has no practical influence on the readings on site.

5.2.2 Corrosion state of steel in concrete (uniform corrosion)

Half-cell potentials measure the corrosion potential E_{corr} which is related to the corrosion state of steel in concrete. As is shown in subsequent paragraphs, the measured values are influenced by concrete cover, concrete resistivity (moisture content) and oxygen availability. Some typical ranges of potentials of steel in concrete for different conditions are given in Table 1.

Table 1 - Typical ranges of potentials of normal steel in concrete (Volts CSE)

water saturated concrete without oxygen	-0.9 .... -1.0 V
wet, chloride contaminated concrete	-0.4 .... -0.6 V
humid, chloride free concrete	+0.1 .... -0.2 V
humid, carbonated concrete	+0.1 .... -0.4 V
dry, carbonated concrete	+0.2 .... 0 V
dry concrete	+0.2 .... 0 V

The low potential active conditions (see § 5.1.1) result in very negative potentials (ca. -1.0 V CSE). Corroding steel in chloride contaminated concrete shows potentials ranging from -0.6 V to -0.4 V CSE. Passive steel in concrete reacts as an oxygen electrode on variations in pH of the concrete pore solutions, thus the corrosion potential depends with dE/dpH = -0.06 V (at 25°C) on the pH. This means that potentials in carbonated concrete are more positive. The corrosion potential of passive steel in concrete further depends on the oxygen availability (moisture content) and can vary over a wide range of potentials. Passive stainless steels show similar potentials to ordinary passive steel.

Influence of concrete resistivity (moisture content)

A major influence on the potential readings is the condition of the surface layer of the concrete (wet or dry). Changes in the moisture content (*e.g.* by wetting of the concrete surface) shift the potential values in the wetted areas to more negative values [4], but the potential gradients and location of local potential minima (corroding spots) do not change. Inhomogeneous moisture distribution (*e.g.* dry/passive and wet/corroding) enhances the potential differences between the corroding and passive zones. The moisture content of the concrete can be checked with resistivity measurements (RILEM Technical Recommendation "Test methods for on-site measurements of resistivity of concrete"). Rusted rebars in very dry concrete may not be well detected.

Influence of pH

No systematic trends are found with respect to the influence of pH when using different cement types or additions of microsilica. From experience it is known that the potentials of steel in concrete containing slag cements are more negative compared to OPC concretes.

5.2.3 Macrocell and localized corrosion

In the case of macrocell corrosion and localized corrosion attack the reference electrode placed on the concrete surface does not measure the "true" corrosion potentials of anode and cathode but a mixed value which depends on the position of the electrode and the concrete resistivity. The most negative values of the half-cell potentials always locate the local anode. The absolute values of the potentials measured are influenced by the cover depth and the resistivity of the concrete:

o *Cover depth*

The potential difference between the position above the anode and a distant cathode becomes smaller with increasing cover depth - thus the location of a small corroding spot becomes more difficult with high cover depth (Fig. 3) [5]. On the other side, these potential gradients can indicate if a corroding area is located near the surface or at rebars deep in the concrete.

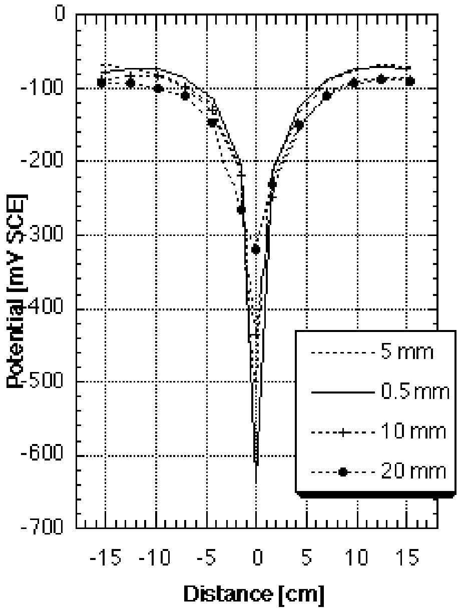

Fig. 3 - Influence of cover depth (distance from the steel surface) on half cell potentials over an active / passive macrocell [15]. Resistivity 1300 Ωm, total length 30 cm, anode 0.5 cm.

o *Concrete resistivity*

The macrocell current affects the potentials of the cathode (passive steel): the anode is polarizing the passive rebars in the vicinity of the corroding spot to more negative potentials (Fig. 4). This shift of potentials to more negative values is

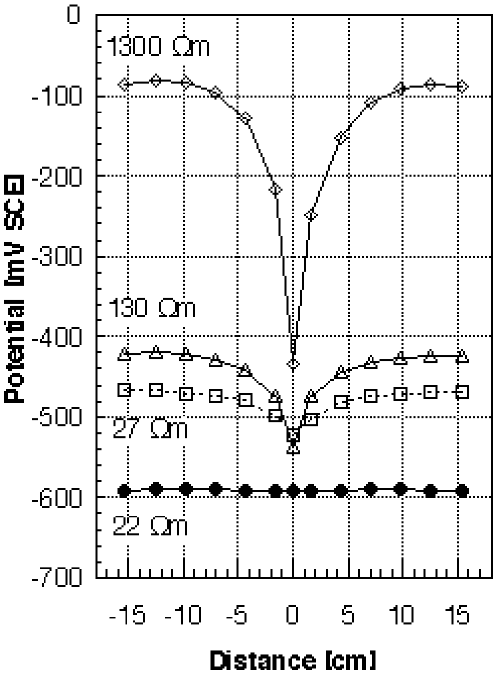

Fig. 4 - Influence of electrolyte resistivity on half cell potential distribution measured on an active / passive model macrocell [15]. Cover depth 20 mm, total length 30 cm, anode 0.5 cm. Open symbols in aqueous electrolyte, closed symbols in very wet, chloride containing mortar.

pronounced in low resistive concrete (wet, chloride contaminated) and it helps to detect even very small corrosion spots with a comparatively large grid size (*e.g.* 0.15 m) [5, 6]. In high resistive concrete (dry, carbonated structures) the most pronounced differences between anode and cathode are found, but only a very small area of passive rebars is polarized and the detection of small corroding spots becomes more difficult.

Further factors influencing the distance of macrocell action are the availability of oxygen at the cathode (cathodic current density) and the amount of passive rebar surface around the anode.

- *Contact with buried or submerged parts of RC structure*s

Buried or submerged parts of RC structures show very low potentials due to the restricted oxygen availability (see 5.2.1). The potential of passive rebars near the buried or submerged ones is polarized to low values, which should not be misinterpreted as corroding steel [6, 7].

5.2.4 Junction potentials

At interfaces between solutions of different composition (chloride content, pH etc.) junction potentials can be created due to the different transport numbers (product of concentration and ion mobility) of ions present. The electrolytic connection between the reference electrode on the surface and the concrete occurs by ionic flow, thus junction potentials might in principle arise. Differences can be expected due to changes in surface pH or different chloride concentrations in the concrete. The magnitude of such junction potentials and their significance is under discussion. For practical purposes their influence on half-cell potential measurements is negligible.

6. PRACTICAL EXECUTION OF MEASUREMENTS

6.1 Measurement arrangement

The measurement of half-cell potentials is based on the electrical and electrolytic continuity between rebars in concrete, reference electrode on the concrete surface and voltmeter (Fig. 5).

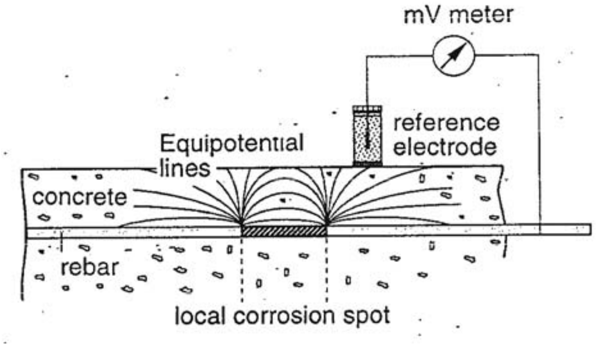

Fig. 5 - Principle and main components of half-cell potential measurements: Reference electrode, high impedance voltmeter, connection to the rebar.

6.1.1 Voltmeter

The voltmeter should have a high input impedance so that the current flowing through the reference electrode does not disturb the stability of the reference electrode potential. In general the current should not exceed about 10 pA. For measurements on normal outdoor concrete the minimum acceptable input impedance is 10 MΩ.

The connections to the voltmeter should be made as follows: the reference electrode is connected to the negative terminal, the reinforcing steel to the positive terminal of the voltmeter. In this arrangement half-cell potential readings generally will be negative. The occurrence of positive potentials is possible on passive rebars in dry concrete.

6.1.2 Electrolytic contact to the concrete surface

Electrical conduction between the reference electrode and the concrete is established by the transport of ions. This can be effected by placing a conductive bridge between the reference electrode and the concrete. In practice, frequently a wet sponge is placed between the reference electrode and the concrete surface. The sponge has to be wetted periodically with a diluted solution of detergent. This conductive bridge lowers the resistance between the reference electrode and the concrete and reduces the liquid junction potential between the electrolyte in the reference electrode and concrete. It is important that the sponge is not allowed to dry out and it should be cleaned or replaced regularly to prevent contamination of the reference electrode.

If potential wheels or multiple electrode devices with wheels are used (*e.g.* Fig. 6), the contact to the concrete shall be established in a similar way. The wheels shall provide good electrolytical contact to the concrete surface. On dry concrete, during warm periods etc. more water is needed to establish the electrolytic contact. Excessive prewetting of the concrete surface changes the "natural" conditions, and a potential shift to more negative values

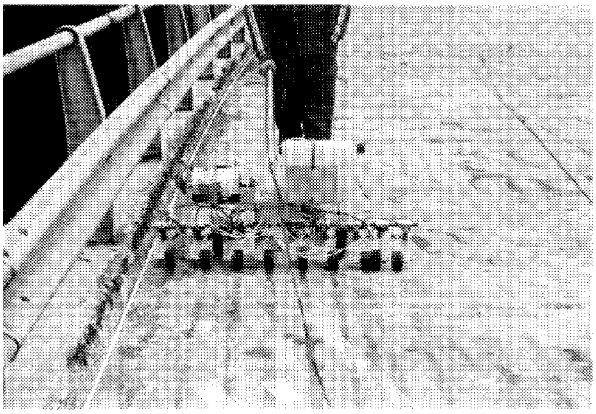

Fig. 6 - Multiple wheel electrode half-cell potential measuring instrument with computer assisted data acquisition [5, 10]. Note the slight wetting of the concrete surface at the wheels in order to achieve a good electrolytic contact between reference electrode and concrete.

will result (see 5.2.2). In conditions of very dry, carbonated concrete corrosion could be activated. However, this might be done intentionally in order to be able to locate corroding steel. It should not be misinterpreted in terms of high corrosion risk.

6.1.3 Electric contact to the reinforcement

The electrical connection to the rebars requires a metallic, electrically sound contact. If crocodile clips are used the rebars have to be cleaned from rust. A secure connection can be obtained by drilling a 25 mm hole into the concrete above the rebar, then drill a 4 mm hole into the rebar and insert a self tapping screw with attached lead into the hole in the steel. Sometimes it may be convenient to make the electrical connection to an external metallic feature of the structure such as a pipe or parapet. In such a case it is essential to check that there is electrical continuity with the reinforcement.

6.1.4 Reinforcement continuity

In all cases, the electrical continuity of the reinforcement has to be checked prior to perform half-cell potential measurements. On large structures like bridge decks, on structures with different construction intervals or on very old structures, continuity may not be present overall or locally. The resistance determined with AC measurements between remote points on a structure should be < 1 Ohm (without resistance of the connecting cable) in order to get reliable measurements. If the resistance values are higher, multiple electrical contacts shall be made to the reinforcement. Note: on structures with epoxy coated reinforcement (not welded), the individual bars are isolated and the electrical continuity necessary to measure half-cell potentials is not given.

6.2 Calibration and standardization

The reference electrode(s) used for half-cell potential measurements have to be checked against a standard (*e.g.* laboratory Calomel electrode) in the lab or on site before starting to take measurements. The difference should be less than 10 mV.

6.3 Coordinate system

The primary goal of potential measurements on reinforced structures is to locate areas of corroding reinforcement. Thus before starting to take measurements a coordinate system has to be put onto the structure in order to be able to relate readings with the point on the structure where they were taken. The coordinate system may be oriented towards characteristic features (appearing equidistant on the structure) or consist of equidistant lines marked onto the concrete surface. During automatic measurements with a potential wheel that measures also the distance the agreement with the coordinate system on the structure has to be checked frequently.

6.4 Procedure

Potential measurements can be performed with a single electrode (point measurements) or with one or several wheel electrodes (potential mapping).

Inhomogeneous surface conditions as *e.g.* wet and dry areas or not embedded rebars that are encountered should be located on a sketch in order to facilitate the interpretation of potential readings.

For a statistical evaluation of the data (cumulative probability plot, histogram) the grid spacing must be kept constant.

6.4.1 Point measurements

Measurements with a single electrode will usually be performed with a large grid size (0.5 m up to 2 m) *e.g.* in the project phase of a restoration or condition assessment (in order to get a rapid and cost effective overview on the corrosion state of a structure) or on comparatively small objects. These measurements can be made on vertical, on top or bottom horizontal surfaces or any other orientation. When measuring horizontal surfaces from the bottom, care has to be taken that the reference electrode is filled with sufficient electrolyte solution.

6.4.2 Potential mapping

Potential mapping is usually performed with a multiple wheel arrangement and a small grid size of ca. 0.15 m on large surfaces (bridge decks, walls, parking decks etc). With single or multiple electrode instruments and computer assisted data acquisition (Fig. 6) several 100 m^2 per hour can be measured. About 30-50 single measurements are taken per square meter of concrete surface. For this reason the precision of the individual reading is less important, a higher drift (see below) can be accepted.

Potential mapping is most easy when measuring horizontal surfaces (bridge decks, parking decks). Vertical surfaces or horizontal surfaces from the underside can be measured with the same experimental arrangement, provided a suitable construction that presses the (multiple) wheels onto the concrete surface is available.

6.5 Source of errors in measurements

The requirements for stability of a single half-cell potential reading are higher for point measurements with a large grid size than for potential mapping because every point is representative of a large area.

o *Drift of half-cell potential readings*

If the half-cell potential reading shows a systematic change over time (called drift), this may be due to water entering into dry concrete changing the moisture content (and resistivity) at the point of measurement. Rates of drift of less than 20 mV per minute can be ignored. On some commercial instruments the drift tolerance can be selected and an acoustic signal indicates the operator when readings are stable and are taken by the instrument.

o *Randomly fluctuating readings*

If the half-cell potential readings are not stable but fluctuating randomly, a loss of electrical continuity is usually the cause. This can be due to air bubbles or lack of enough electrolyte in the reference electrode, sponge being dried out, bad electrical connections to the rebars or to the voltmeter. Not yet detected concrete delaminations may result in similar effects. Fluctuations may be induced also by the presence of stray currents (DC rail- or tramway, CP systems etc.).

6.6 Data presentation

The way of representing half-cell potential measurements may vary according to the number of readings taken: if a large grid size was used or only a few readings were taken, the half-cell potential values may be given as table or be written directly into the plan view. A large number of data can be presented as potential map and / or in a statistical representation.

6.6.1 Half-cell potential map (potential field)

Representation of half-cell potential data in order to locate areas with different potential can be performed by colour plots, equipotential contour plots, 3D plots or others. In a colour plot (Fig. 7) each individual data point is represented without smoothing or interpolation by a coloured square of adequate size on a suitably scaled plan view. The colour is related to the potential interval (*e.g.* red = -0.4 - -0.35 V CSE). The maximum potential interval associated to a colour shall usually not exceed 0.05 V. Colour plots allow to identify erroneous readings or potential shifts in one electrode when multiple wheel electrodes are used. Erroneous readings (*e.g.* electrode occasionally not well contacted) are visible but do not influence the map as a whole.

In an equipotential contour plot (Fig. 7) lines of constant potential are calculated and plotted through points of equal or interpolated equal values. Contour plots react very sensitive on single erroneous readings (*e.g.* very negative potentials) because fictitious contour lines are plotted around the erroneous point. The maximum contour interval should be 50 mV.

3D plots represent the potential readings on the z axis versus the x/y position. This representation usually is of limited value when the measured potential maps are very inhomogeneous.

6.6.2 Statistical representation of the data

The data to be represented and treated statistically (histogram, frequency distribution or cumulative probability plot) have to be measured and recorded on a regular grid size (a smaller grid size *e.g.* in areas with corrosion would erroneously increase the percentage of corroding reinforcement on the structure). In the statistical representations the information on position of the reading is lost.

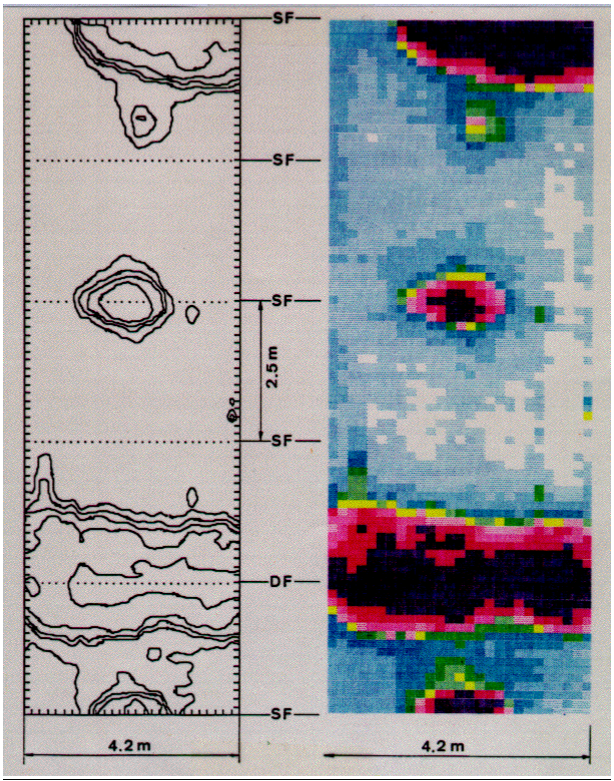

Fig. 7 - Examples of half-cell potential maps (Riding deck in the Tunnel San Bernardino) [5, 6]. Data representation: colour plot (right) and equicontour line plot (left). DF: dilatation joint (every 25 m).

Histograms or frequency distributions are obtained when all potential readings are grouped in intervals of potential and the number of readings in each group are counted. If the intervals chosen are quite large (*e.g.* 50 mV), a histogram of potential readings is obtained. A frequency distribution (Fig. 8) is obtained when the group interval is

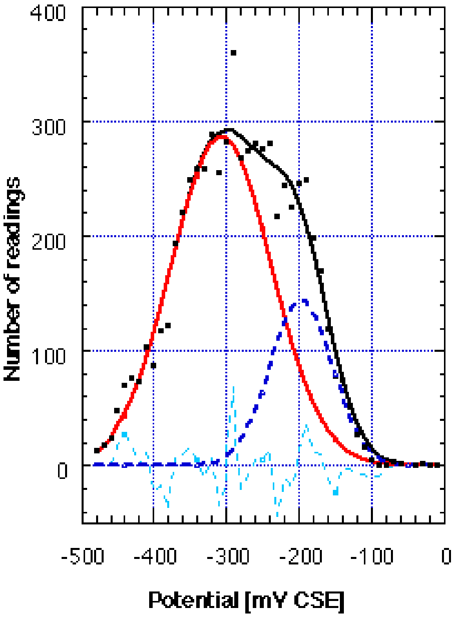

Fig. 8 - Frequency distribution of half cell potential data (retaining wall at Rofla, alpine highway N13 in Switzerland). Original data ▲, curve fitted assuming gaussian distribution for active and passive potentials [22].

small (5 mV or 10 mV, according to the total number of readings) and the number of readings N(E) is plotted versus the potential E. The frequency distribution gives a first impression on mean value of potential, distribution and skewness. It may be used to compare different parts of a structure (*e.g.* two lanes of a bridge deck, different oriented facades etc.). From the frequency distribution the presence and percentage of actively corroding and passive rebars can be estimated.

Cumulative frequency distributions are obtained by summing up the frequency distribution and plotting the values Σ N(E) versus the potential E on a probability plot (Fig. 9). A single gaussian distribution would appear as one straight line. Usually, two or three straight lines with different slopes are obtained indicating the passive and active distribution of potentials. Due to the (usually) much higher number of readings of passive potentials, this distribution is defined better. From the cumulative probability plot the border value of potential (90% or 95% passive) can be determined.

7. INTERPRETATION AND USE OF HALF-CELL POTENTIAL DATA

7.1 Interpretation of half-cell potential data

7.1.1 Potential range indicating active and passive state

Half-cell potential measurements taken from the concrete surface are influenced not only by the corrosion state of the rebars (active or passive) but - as has been shown in chapter 5 - by the concrete cover and the resistivity of the concrete. The resistivity itself varies with temperature, with concrete moisture and chloride content or carbonation. Thus the surface state and moisture content of concrete affect the numerical value of potential readings as is documented by a lot of research work [4-9] and practical application of potential mapping [10-12] where the corrosion state of rebars (corroding, passive) has been related to the potential measured at the concrete surface (Fig. 10). Very different potential ranges indicate corroding steel on different bridge decks or substructures. The values of potential known as van Daveer Criteria [13] and used also in the ASTM Standard C876 (under revision) should not be used as absolute criteria to determine the condition of steel in concrete.

7.1.2 Half-cell potentials and concrete resistivity (moisture content)

Changes in the moisture content (*e.g.* by wetting of the concrete surface) lead to a shift of the whole potential field to more negative values, *e.g.* a shift of ca. 100 mV was found on a bridge deck measured in dry and wet conditions after rainfall. The potential gradients and location of potential minima did not change, differences were found only in the magnitude of potential readings. This further indicates that the potential gradient rather than the absolute value of potential is an indicator of corroding rebars.

In structures with chloride induced corrosion, corroding areas usually coincide with low resisitivity areas (Fig. 11) as has been found on a part of a bridge deck where both potential and resistivity mapping have been performed [14, 15]. This is

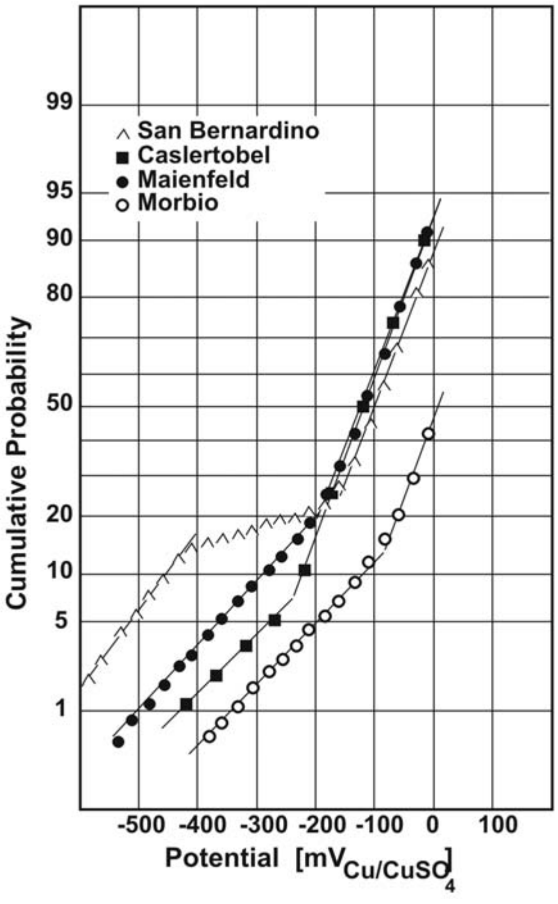

Fig. 9 - Cumulative frequency distribution (probability plot) of half-cell potentials measured on different bridge decks [6, 10, 15]. Note the curve “San Bernardino”: due to the abrupt change in concrete humidity (corroding = wet, passive = dry) the distribution curves of active and passive potentials are shiftet by ca. 150 mV.

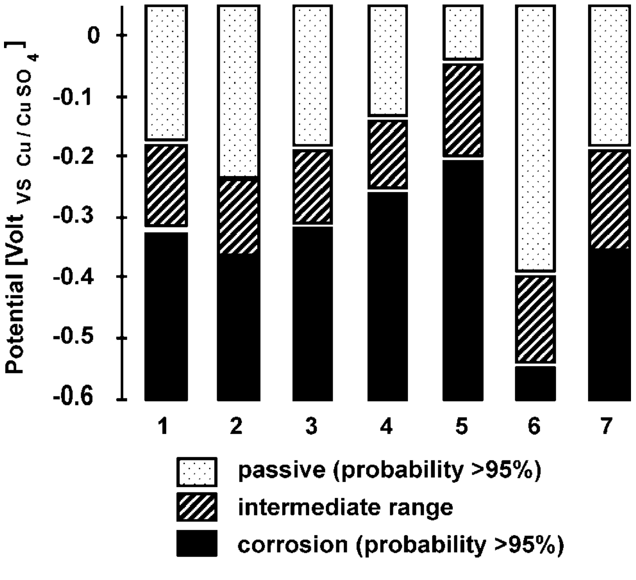

Fig. 10 - Experimentally determined potential range indicating active corrosion on different bridge decks compared to the ASTM C876 standard [6, 10, 15].

1 Cugnertobel, 2 San Bernardino, 3 Rhinebridge Tamins, 4 Caslertobelbrücke, 5 Morbio bridge, 6 Column in seawater, 7 ASTM C876 Standard.

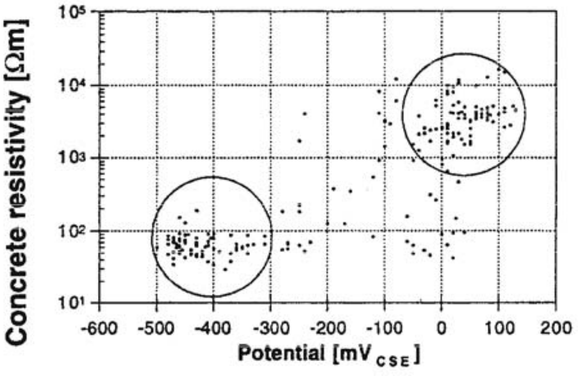

Fig. 11 - Relation between half-cell potential and concrete resistivity measured at the underside of a chloride contaminated bridge deck [14, 15].

due to the fact that chlorides are transported more easily into concrete with a lower resistivity (more open pore structure), high chloride concentrations depassivate the rebars and active potentials are measured. Points with low resistivity but passive potentials (Fig. 11) can be interpreted as areas with a high corrosion risk for the future. Areas with high concrete resistivity and potentials in the passive range are not affected by chloride ingress.

The moisture content of the concrete may vary from one part of the structure to another, an example is given from the carriageway in an alpine tunnel (Fig. 7). The dilatation joints are all leaking, thus the concrete in the vicinity of the joints is wet, highly chloride contaminated and the reinforcement is actively corroding. Further away from the dilatation joints the concrete is very dry, no chlorides penetrate and the rebars are passive. Inhomogeneous moisture distribution enhances the potential differences between the corroding and passive zones.

As shown above, half-cell potential and resistance data may be combined to give an overview of various factors relevant to corrosion risk. However, interpretation requires taking into account particular features of the structure under study and cannot be considered straight forward.

The influence of carbonation is twofold: due to the loss of the concentrated alkaline pore solution the pH of the pore solution is much lower and carbonated concrete, often sheltered from rain, shows high resistivity. This influences both the absolute values of the potentials measured from the concrete surface and the possibility of locating small corroding areas. In high resistive media as carbonated concrete, the location of small corroding areas will be more difficult. Half-cell potential measurements taken on concrete structures with high resistive surface layers due to carbonation show more positive potentials of both, passive and corroding rebars.

As mentioned before, high resistive surface layers may make correct interpretation very difficult.

7.2 Use of half-cell potential data

7.2.1 Locate corroding rebars

The primary purpose of half-cell potential measurements is to locate corroding rebars in a concrete structure during condition assessment or repair work [10-12]. It has been outlined in the paragraph above, that the surface state and moisture content of concrete affect the numerical value of potential readings (Fig. 10), therefore very different potential values may indicate corroding steel on different RC structures.

Locating areas of actively corroding steel is best achieved by considering the spatial variation of potential (local minima, gradients in the potential field, Fig. 7) and not the absolute values of the potentials. Rigidly using fixed boundary limits of potentials to distinguish active and passive zones (*e.g.* -0.35 V CSE as proposed in ASTM C876-91) can be misleading.

Due to the easy polarization of passive rebars close to the actively corroding spot in low resistive concrete the location of very small corroding spots is much easier in cases of chloride induced corrosion than in carbonated concrete [10, 12].

7.2.2 Define position for further destructive analysis

The half-cell potentials measured have to be interpreted in the context of additional information as *e.g.* corrosion state of the rebars (visual examination, loss of cross section), chloride content at the rebar, resistivity of the concrete, cover depth etc. This requires further non-destructive or destructive analyses. The location of the most significant points of analyses can be determined in a rational, cost effective way based on the potential field.

o Inspection windows to determine the state of corrosion

Half-cell potential measurements allow to locate corroding rebars on concrete structures when corrosion is ongoing. In a first interpretation no direct information on the state of corrosion of the rebars (reduction in cross section) can be obtained. At selected areas where large gradients $\Delta E/\Delta x$ in potential exist, the rebars can be inspected visually after concrete removal [10, 16]. The inspection window should preferably be about 0.3 - 0.5 m large and extend in length from completely passive zones to heavily corroding zones (Fig. 7). The boundary limit of active respectively passive potentials are determined by associating the rebar state with the measured half-cell potential values (Fig. 10).

With the information from the inspection windows, a rough relation between the corrosion state of the rebar and the measured half-cell potential at the concrete surface can be obtained for a specific concrete structure [10]. This relation is not universal and changes from one structure to another.

o Position of cores for chloride analysis

The position where cores for chloride analysis have to be taken can be determined in a more rational way based on the potential field: cores shall be taken in selected areas with uniform potential, covering the centre of actively corroding zones, passive zones and in the transition region. In a number of chloride contaminated reinforced structures [10, 16, 17] a relation between potential and chloride content at different depth has been found. This allows to interpret the potential field at least qualitatively and for the specific structure as “chloride distribution map”, thus a more complete picture of the chloride contamination can be obtained with only few cores.

Potential mapping results can be combined in a useful way with other types of “quick and cheap” non-destructive measurements such as resistivity mapping. Potential maps can be used to select areas for further analysis using more elaborated non-destructive testing (*e.g.* corrosion rate measurements based on polarization resistance, RILEM TC

154-EMC) or for sample locations for destructive analyses. Finally, they can be used to select the positions for embedding sensors . In all cases, the number of measurements or sensors can be minimised and the results integrated in a rational way into the overall picture of the structure.

7.2.3 Control the effectiveness and durability of a restoration work

There are different repair options for corroding reinforced concrete structures. Some of them intend to bring the steel in a non-corroding or passive condition. Thus half-cell potential measurements can be used in principle to evaluate the effectiveness and the durability of the repair work. Usually this requires a potential survey on the same areas as performed during inspection (prior to repair). The interpretation of the overall success of the repair work can be evaluated best on the basis of the cumulative probability plot; plotting the potential map made after repair will show areas where steel is still corroding.

o Traditional repair: replace chloride contaminated concrete

Half-cell potential mapping can be used to evaluate the effectiveness of repair works on bridge decks [18]. Potential readings taken on the repaired bridge deck some months after repair (but before the membrane and the asphalt will be applied) have to be compared to the potential map recorded prior to repair. If the potential values in repaired and old concrete (with passive rebars) are similar, the repair strategy chosen (removal of all chloride contaminated concrete in the areas where corroding rebars were found) was successful [18, 21].

o Electrochemical Chloride Removal

Electrochemical chloride removal was used as a non-destructive restoration technique on a heavily chloride contaminated bridge abutment, where corrosion of the rebars just started. The inspection prior to the repair work as well as the evaluation of the efficiency of the chloride removal was done with half-cell potential mapping on the abutment [19]. After the first chloride removal, the potential values became more positive by about 80 - 100 mV indicating the repassivation of the rebars. Some areas with too high chloride contents after the first chloride extraction were treated a second time after several month, the half-cell potentials became more positive again. An evaluation five years after completion of the repair work showed that no corrosion had initiated and the potential field became more homogeneous (Fig. 12). In contrast to some isolated chloride analysis, half-cell potential measurements allow to evaluate the whole surface of the abutment and they provide clear information on the repassivation of the rebars [19-21].

o Electrochemical realkalization

Half-cell potential measurements can be used to evaluate the corrosion state of the rebars after electrochemical realkalization. The results on a test site [20, 21] have shown that the potential values after the treatment (after waiting three months in order to allow depolarization) were shifted by about 0.2 V to more negative values. Any straightforward, simple interpretation “more positive potentials = repassivation” fails. The decrease in potentials is due to two effects: after the realkalization treatment, the concrete resistivity is much lower due to the presence of a quite concentrated sodium (bi)carbonate solution in the pores and the alkalinity around the rebars has strongly increased (from about pH 9 to 13). The success of the treatment in stopping corrosion should therefore be related to the establishment of a uniform potential field.

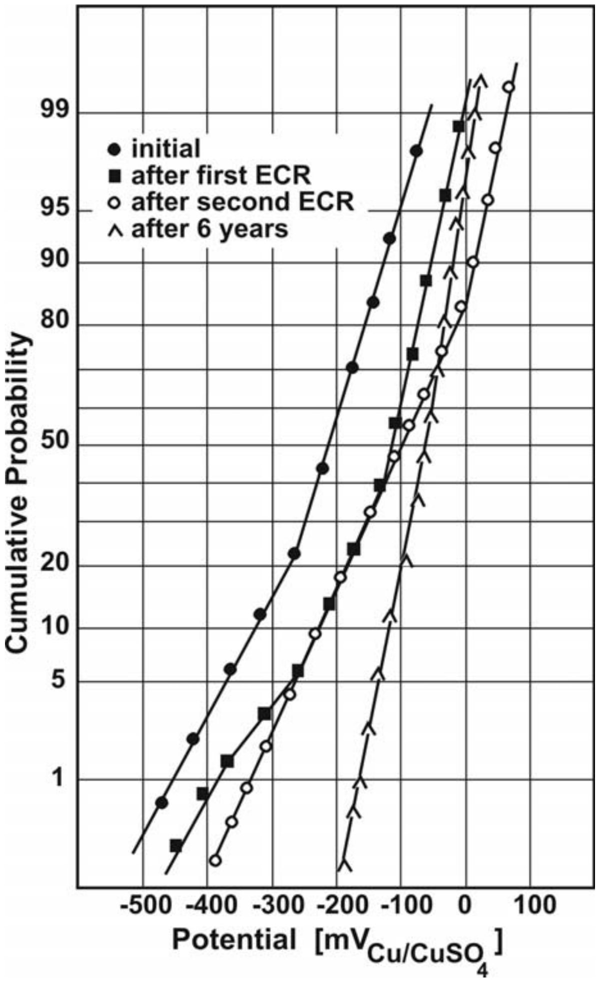

Fig. 12 - Cumulative frequency distribution (probability plot) of half-cell potential data before, after first and second chloride removal treatment and control after five years [15, 20, 21].

o Inhibitors

Testing the efficiency of inhibitors penetrated from the concrete surface with half-cell potential measurements is difficult [21]. Changes in the pore water composition and thus the concrete resistivity as well as different possible mechanisms of the inhibitor action (anodic, cathodic, mixed, blocking...) can lead to shifts of the half-cell potential measured from the concrete surface that cannot be interpreted straight forward. More research is needed before potential mapping may allow unambiguous evaluation of inhibitor treatment.

In consequence, the following points should be taken into account when assessing the efficiency and durability of repair work with half-cell potential measurements:

o Time of measurement

The waiting time prior to perform measurements after repair work has to be defined according to the type of repair: electrochemical restoration techniques (ECR, ER) lead to a strong cathodic polarization of the rebars, the time to depolarize can be between one and several months according to the oxygen access to the rebars. New concrete or repair mortar instead require time to hydrate and dry out partially.

o *Shift in potential*

The shift in potential (before and after repair) depends on the type of repair technique applied and its mechanistic action. Half-cell potential mapping can be used to evaluate the effectiveness and durability of repair works with the "normal" interpretation only when the concrete resistivity is not changed too much by the treatment.

o *Homogeneity of potential field*

More important than the change in the absolute value of the potential is that after a successful repair a uniform potential field without hot spots shall be obtained.

7.2.4 Design of anode layout of CP or electrochemical repair systems

The distribution of current from a homogeneous anode on the concrete surface is governed by the concrete resistivity and the corrosion state of the rebars:

o *Corrosion state*

Corroding areas of the structure require more protection current than areas with passive steel, due to the lower polarization resistance the current will flow preferentially in the corroding regions.

o *Concrete resistivity*

The protection current will follow the low resistive pathways, thus in areas with very humid or wet concrete will flow more current.

Based on half-cell potential maps the corroding zones can be identified and the layout of the anodes can be optimized: critical areas can be protected by isolated anodes and connected separately to the rectifier or the amount of anode material (two or three layers of anode mesh) can be increased in order to comply with the high current density expected. The final draft version of European Standard EN12696 states that potential mapping must be carried out on representative areas, in particular for locating spots for reference electrodes to be placed.

8. REPORT

A report on half-cell potential measurements should contain:

- date of testing, weather conditions (temperature, humidity) at the time of testing and preferably over a few days before testing
- description of the structure, any visual observations at the concrete surface (spalling, rust staining, exposed rebars etc.)
- reference electrode used and calibration data
- measuring grid used
- results of half-cell potential measurements (preferably in form of potential map with clear and scaled relation to the structure)
- chloride or carbonation analysis (if available).

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