5th International Conference on Durability of Concrete Structures
Jun 30–Jul 1, 2016
Shenzhen University, Shenzhen, Guangdong Province, P.R.China

Influence of Concrete Moisture Condition on Half-Cell Potential Measurement

Sylvia Keßler and Christoph Gehlen
Centre for Building Materials, Technical University of Munich

ABSTRACT

The detection of on-going corrosion is one of the main issues during inspection of reinforced concrete structures. The half-cell potential measurement method is the most common and established non-destructive technique to support this task. But a lot of infrastructures are exposed to rain or seawater, which can cause heterogeneous moisture condition within one component. In turn, this can have influence on the potential mapping results, and as a consequence, the interpretability of the half-cell potential measurement is impaired. This paper focuses on the influence of concrete moisture condition on half-cell potential measurement. Laboratory and practical tests' results are analyzed qualitatively with varying moisture conditions due to natural exposure as well as with different pre-wetting conditions. On the basis of these results, recommendations are made how to evaluate half-cell potential mapping results. If large structures are inspected by half-cell potential measurements, it is advantageous to compare only these parts, which are in a comparable moisture condition by subdivision of the structure.

1. INTRODUCTION

1.1 Background

Chloride-induced corrosion is one of the major deterioration mechanisms for reinforced concrete structures when there are exposed to de-icing salt or seawater. Chlorides penetrate into the concrete and if critical chloride content is reached at the reinforcement level, the corrosion process starts. The depassivation of the rebar is initiated by a local disruption of the protective passive film, the anode is formed. Due to the rebar network, cathodic areas are activated and a short-circuited galvanic element is established. As a consequence of corrosion, local loss of cross-section and subsequent cracking and spalling of the concrete cover could impair the serviceability if no maintenance is executed. Only in this advanced deterioration stage, the reinforcement corrosion can be detected by visual inspection. However, if the corrosion process is in such a progressed stage, cost-intensive maintenance activities are absolutely essential. Before structural damage (cracks and spalling) is reached, the non-destructive half-cell potential measurement method is able to detect on-going corrosion in concrete structures (Grimaldi, Brevet, Pannier, & Raharinaivo, 1986; Elsener & Böhni, 1987; Menzel & Preusker, 1989).

Although the half-cell potential measurement is such a common inspection tool for over 30 years, there are still some open questions concerning the appropriate measurement procedure and interpretation. Which is the proper pre-wetting condition or which is the best time to measure when the structural element is exposed to weather conditions? How the concrete resistivity influences the potential field? Investigations are made with a laboratory and practical test setup. For the practical test setup, 40-year-old naturally corroded reinforced segments from the Olympic Stadium in Munich are available, and potential measurements under different exposure condition were analyzed qualitatively.

1.2 Half-cell potential measurement

The half-cell potential measurement method is a non-destructive inspection method for detecting on-going reinforcement corrosion in concrete structures hand the method has found its way in several standards and guidelines: ASTM C876 – 09 (2009), RILEM (2003), DGZFP Merkblatt B3 (2014), Merkblatt SIA 2006 (2013). Due to corrosion initiation, a potential field is established by the resulting flow of the corrosion current. This potential field can be measured by applying an external reference electrode on the concrete surface and connect the electrode through a high-resistance voltmeter with the reinforcement, see Figure 1.

Information about the corrosion condition state over the whole structural element can be gathered by a grid-like displacement of the reference electrode. The anodic or corroding area (active) and cathodic or non-corroding area (passive) on the reinforcement are different electrodes that vary in free corrosion potential and polarisability, which enable the corrosion detection. Corroding areas can be assumed mostly at the more negative potential values in combination with a pronounced potential gradient. Half-cell potential measurement, also called potential mapping, can only provide information about the current corrosion condition during the measurement. Statements about earlier or future corrosion processes are not permitted.

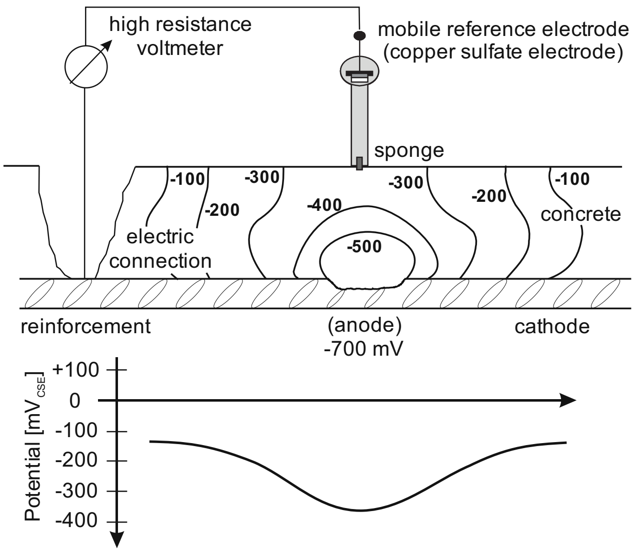

Figure 1. Schema half-cell potential measurement.

A lot of factors, such as anode area, anode to cathode ratio or the concrete cover, are influencing the potential field (Naish, Harker, and Carney (1990); Assouli, Ballivy, and Rivard (2008); Poursaee and Hansson (2009); Pour-Ghaz, Isgor, and Ghods (2009); Schiegg, Büchler, and Brem (2009), ASTM C876 – 09 (2009), RILEM (2003), DGZFP Merkblatt B3 (2014), Merkblatt SIA 2006 (2013)). But one of the major factors is the concrete resistivity. With decreasing concrete resistivity, the resulting macro-cell current, the so-called corrosion rate, increases (Hornbostel, Larsen, and Geiker (2012). One reason for the increasing corrosion rate is that with decreasing resistivity, major cathodic areas can be activated (Beck et al. (2013), and as a consequence, the anode is strongly polarized. Due to the spatially separated anodic and cathodic areas, a potential drop in dependence of the resistivity is formed. The potential drop increases with increasing resistivity, and the resulting difference between the anodic and cathodic corrosion potential is larger. To sum up, high concrete resistivity leads to less cathodically activated areas and a larger potential difference between anode and cathode, which result in steep equipotential lines and a locally restricted potential gradient. In contrast, low concrete resistivity leads to flat equipotential line and a less pronounced potential gradient at the concrete surface.

The concrete resistivity is mainly dominated by the concrete moisture condition (Polder, 2001; Osterminski, Polder, & Schießl, 2012), which can vary with time and within one structural element due to different exposure conditions, e.g., unsheltered against rain. During the half-cell potential measurement procedure, the resistivity in the concrete surface changes as well as a result of the pre-wetting procedure to ensure an electrolytic contact of the reference electrode with the concrete surface. The pre-wetting procedure can consist just in wetting the sponge of the reference electrode or wetting the whole concrete surface. Naish et al. (1990) and Poursaee and Hansson (2009) have shown exemplarily that the pre-wetting of the concrete surface causes a decrease of the concrete resistivity close to the concrete surface, which leads to a potential shift in the negative direction.

2. INVESTIGATIONS

2.1 Setup electrolytic pipe

The electrolytic pipe is a cylindrical Plexiglas pipe (ø: 10 cm and l: 1130 mm) with a cut on the top edge along the *x*-axis to enable the insertion of a moving reference electrode. The reference electrode, calomel electrode (SCE), is connected with a displacement transducer, so that each potential value can be evaluated according to its position. The electrode (ø: 12 mm) is attached centrically into the pipe with a stainless steel being the cathode and a structural steel screwed at the cathode being the anode, Figure 2.

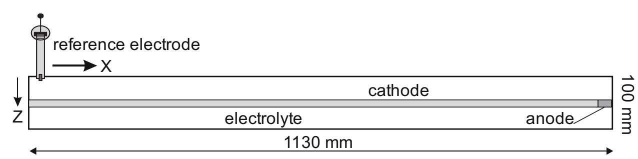

Figure 2. Setup electrolytic pipe.

Within the presented parameter study, the resistivity or the respective conductivity of the used sodium chloride solution is varied to study the influence of the resistivity on the resulting potential field. The chosen values reflect a Portland cement concrete which is wet, outside exposed, or in indoor climate (Polder, 2001). The defined and the measured conductivity are included in Table 1.

Table 1. Variation resistivity – conductivity.

	Condition	Defined resistivity (Ωm)	Defined conductivity (mS/cm)	Measured conductivity (mS/cm)
I	Wet concrete	100	0.1	0.0984
II	Outside exposed concrete	300	0.0333	0.0345
III	Indoor climate concrete	3000	0.0033	0.0036

The respective filling level of the immersion depth (2 cm) as well as the anode area (6.2 cm^2) is kept constant.

2.2 Segments from the Olympic Stadium in Munich

The centre for building materials was provided reinforced concrete segments from the Olympic Stadium in Munich for research. The segments formed the edges of the grandstand of the Olympic Stadium, and the grandstand was exposed to chlorides and changing humidity, so that reinforcement corrosion could be expected over time, see Figure 3.

Figure 3. Grandstand edge of the Olympic Stadium in Munich.

The whole 40-year-old grandstand was demolished due to advanced corrosion deterioration indicated through cracks and spalling. The investigated segments were one of the few elements, which showed neither cracks nor spalling or patch repair, see Figure 4. But it is assumed that due to the comparable exposure condition and material resistance, corrosion is initiated in all elements. The concrete composition and the cement type are unknown due to the age of the structure. The holes in the element were made for the transportation of the reinforced concrete elements.

Figure 4. Segments from the Olympic Stadium in Munich.

The segments enable the study of the development of potential fields on real sized and realistically exposed specimen. The concrete cover depth is beta distributed with mean value 44.3 mm and deviation of 14.4 mm, and the carbonation depth is negligible. Both chloride exposed surfaces are about 2 m × 1.2 m, and the resulting chloride concentrations at the reinforcement depth show values up to 0.4 M-%/cem. The segments are stored outside, and the corresponding information about the daily weather condition, such as precipitation, relative humidity, and temperature, during the investigation period (July 2010 until December 2012) is shown in Figure 5.

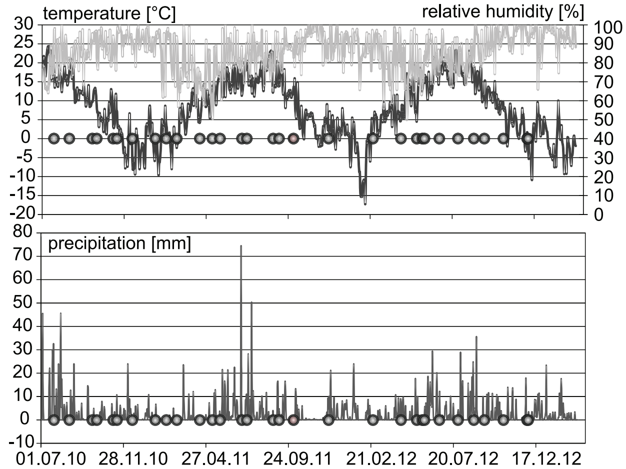

Figure 5. Meteorological data and measurement data (spots): temperature (dark grey), relative humidity (light grey), and precipitation.

The meteorological data (daily average value) within the investigation period reflects well the temperature curve of the seasons. It is notable that in February 2012, the temperatures are extremely low, and during summertime 2011, it rained a lot followed by a long dry period without rain in 6 weeks in autumn 2011. Half-cell potential measurements were executed frequently (spots in Figure 5) after different weather condition, after long rain and dry periods, and at high and low temperatures.

Additionally, different pre-wetting conditions from wetting only the sponge of the reference electrode until pre-wetting the whole surface and measurements after defined waiting times are included into the study. The half-cell potential measurement is executed with a copper–copper sulphate electrode as a reference electrode and with a grid size of 10 cm × 10 cm. Due to the fact that the investigated segments belonged to a former real structure, no instrumentation for measuring the resistivity in depth is included. Therefore, the potential mapping measurements have to be compared qualitatively in regard to concrete resistivity.

3. RESULTS

3.1 Results electrolytic pipe

The diagram in Figure 6 and the probability plot in Figure 7 show the half-cell potential measurement in the electrolyte pipe. Each line represents the measurement in one electrolyte according to Table 1.

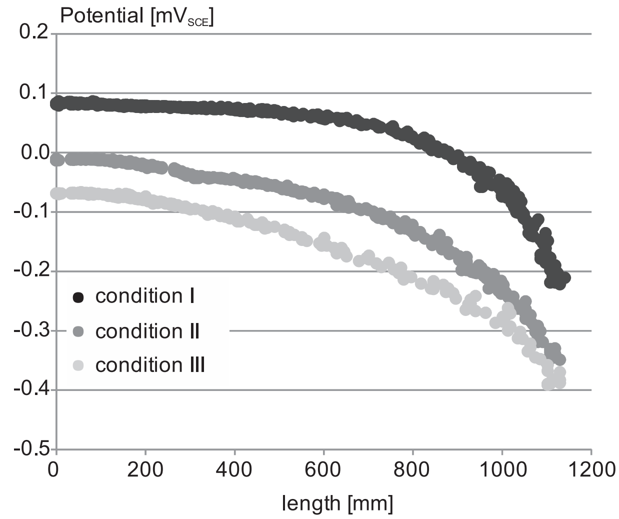

Figure 6. The half-cell potential measurement in the electrolytic pipe under variation of the conductivity.

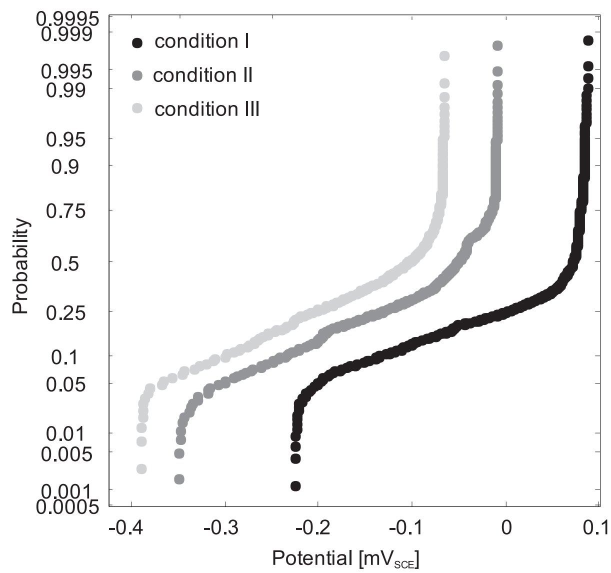

Figure 7. Probability plot of the half-cell potential measurement in the electrolytic pipe under variation of the conductivity.

The probability plot enables the comparison of the probability distribution of each half-cell potential measurement outcome. With decreasing resistivity, the potential values decrease as well, and the influence of the resistivity is characterized by a parallel shift in the probability plot up to 180 mV. The polarized anodic potential shifts as much as the polarized cathodic potential. The half-cell potential is strongly influenced by the resistivity of the electrolyte. In the study of the electrolytic pipe, the solution conductivity is assumed to be totally homogenous in comparison to concrete in an existing structure, e.g., segments from the Olympic Stadium.

In existing outside exposed structures, the concrete resistivity changes due to wetting and drying effects in time, in space as well as in depth followed by a change in the half-cell potential. In order to study the potential development under realistic condition with varying resistivity, half-cell potential measurements are executed frequently on the segments of the Olympic Stadium.

3.2 Results Olympic Stadium segments

3.2.1 Repeatability

Before starting the study about the influence of the resistivity on the half-cell potential in the segments from the Olympic Stadium, the repeatability of the measurement method is tested. The half-cell potential measurement is repeated with the same measurement equipment, the same pre-wetting procedure as well as with the same inspector on the same specimen. The repeat measurements are performed with a time difference of 2 h, see Figure 8. The concrete surface was pre-wetted 20 min before starting each measurement and the used grid size is 10 cm $\times$ 10 cm.

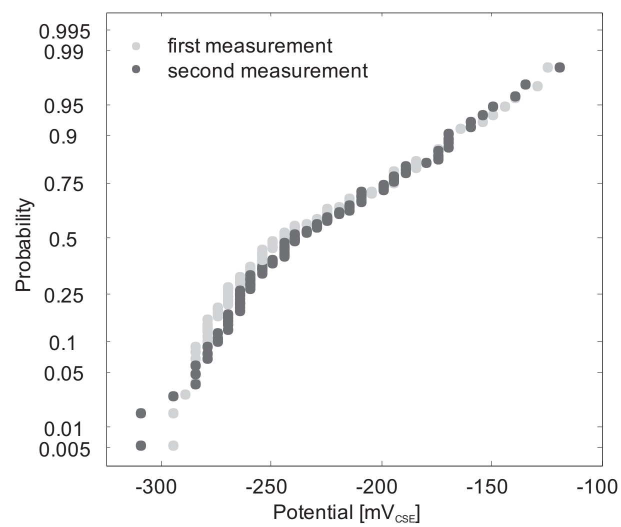

Figure 8. Probability plot of the repeated potential mapping; segments Olympic Stadium.

The probability plot of the repeat measurement is nearly parallel. Some small deviations are only detectable at very low potentials. The reasons for the deviation are drying effects due to the pre-wetting procedure as well as some small displacements of the reference electrode position. But in general, the accordance of both measurements is very good. Due to the fact that the segments dimension is small, the repeatability is tested also on a real existing structure under onsite condition. Half-cell potential measurements on a parking garage ramp was repeated with two measurement equipment, two inspectors (engineering firm and centre for building materials), and with a time difference of 45 min, see Figure 9. The surface was pre-wetted as well, and the grid size is 25 cm $\times$ 25 cm.

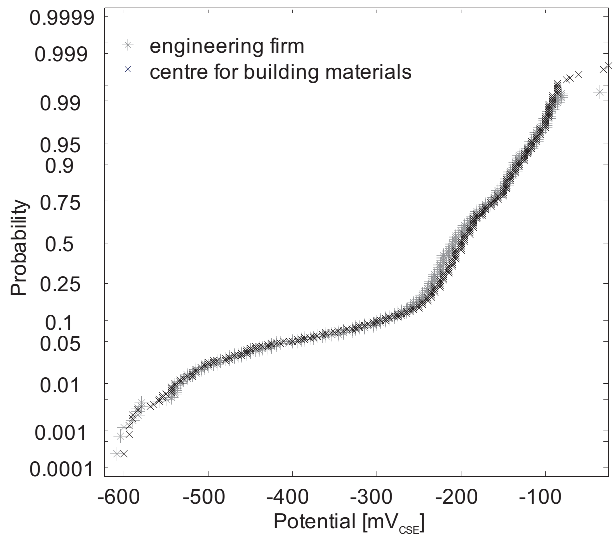

Figure 9. Probability plot of the repeated potential mapping; a ramp of a parking garage.

Also under onsite condition, the repeatability is very good. Both potential distributions are nearly parallel even when the measurements are executed with different equipment and different inspectors. The half-cell potential measurement method is a robust inspection tool. So, it can be assumed that the differences in the potential fields in the following section are caused by the change in the resistivity and not by a natural scatter.

3.2.2 Pre-wetting condition

The pre-wetting of the concrete cover around 20 min before starting the measurement is recommended to ensure the electrolytic contact of the reference electrode with the concrete surface (DGZFP Merkblatt B3, 2014) and to minimize the effect of diffusion potentials (Angst, Vennesland, & Myrdal, 2009). But the pre-wetting procedure changes the resistivity on the cover concrete. Due to the fact that the segments belonged to a real structure, no instrumentation or sensors to monitor the resistivity are installed and so, the following results can only be compared qualitatively. Three different pre-wetting conditions are defined, and it is assumed that the resistivity decreases with more intensive pre-wetting.

- condition A: wetting of the reference sponge just before starting the measurement;
- condition B: pre-wetting of the concrete cover and starting the measurement after 20 min;
- condition C: intensive pre-wetting for 2 h and starting the measurement.

The half-cell potential measurement executed under condition A with a dry concrete surface was difficult to perform. Although the sponge on the reference electrode was wetted, it took a long time until a stable potential could be achieved. The stability of the measured potential can be controlled using a rod electrode, but with a wheel electrode, it is far more difficult and an erroneous measurement is the consequence. Figure 10 shows the equipotential plots under each pre-wetting condition.

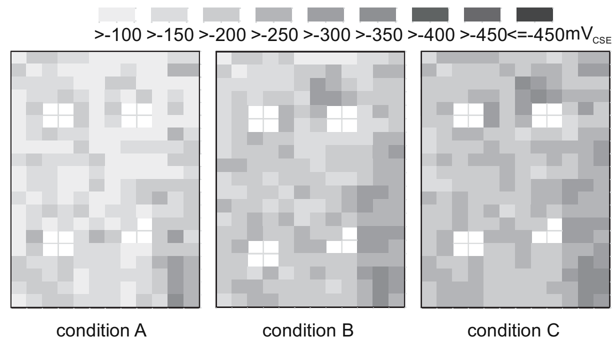

Figure 10. Equipotential plots after different pre-wetting conditions.

With more intense pre-wetting, the resulting potential field is more negative which corresponds to the research of Naish et al. (1990) and Poursaee and Hansson (2009). But the important information is that the values with the most negative potentials and pronounced potential gradients are located in the same position.

Figure 11 presents the results generated under different pre-wetting conditions in a probability plot. The probability plot shifts parallel in negative direction up to 100 mV with more intensive pre-wetting procedure hence with decreasing concrete resistivity. The shift is more pronounced from measurement under condition A to condition B than in between measurement of condition B to condition C.

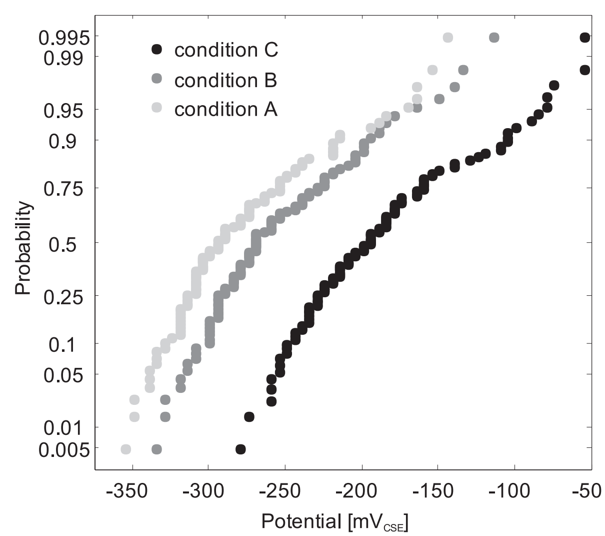

Figure 11. Probability plot under different pre-wetting condition.

The results of the probability plot under varying pre-wetting conditions are comparable to the results of the electrolytic pipe, see Figure 7. Only the absolute potential shift in the electrolytic pipe is larger due to the fact that the range of the resistivity values is also larger in the electrolytic pipe than in the segments. As confirmed by the results, the pre-wetting procedure onsite have an impact on the absolute values of the half-cell potential measurements results. Therefore, using an absolute value, the so-called threshold potential, as a criterion to distinguish between corroding and non-corroding areas is questionable.

3.2.3 Exposure condition

Half-cell potential measurements were executed over a long period of time (July 2010 until December 2012) after different exposure conditions, see Figure 5. The focus was to cover each weather scenario hot and cold temperatures as well as long dry and long rainy periods. In this way, a wide range of different concrete resistivities are included within the study. All half-cell potential measurements captured during the assessment period are summarized in the following probability plot, see Figure 12. The measurement procedure corresponds to condition B, and the used grid size is 10 cm × 10 cm.

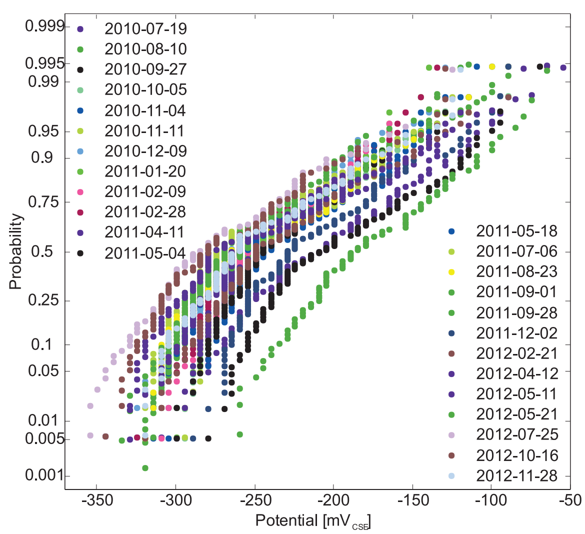

Figure 12. Probability plot of the potential mapping data executed according to pre-wetting condition B.

The potential values are in between –500 mV$_{CSE}$ and –50 mV$_{CSE}$. All measurement results show comparable outcome even comparable gradients, and the values are in a comparable range without any outliers. The absolute potential values scatter in a range of about 100 mV. These results are in accordance with the results achieved under different pre-wetting conditions with a shift as well as about 100 mV. The half-cell potential measurement is just as much influenced by the exposure condition as by the pre-wetting treatment. Whereas Figure 12 presents a full picture, the following figures show selected data from 2011, mainly to get a specific view on interesting findings. The following probability plots show potential mapping data from wintertime and summertime (Figure 13), and during rain and dry periods (Figure 14).

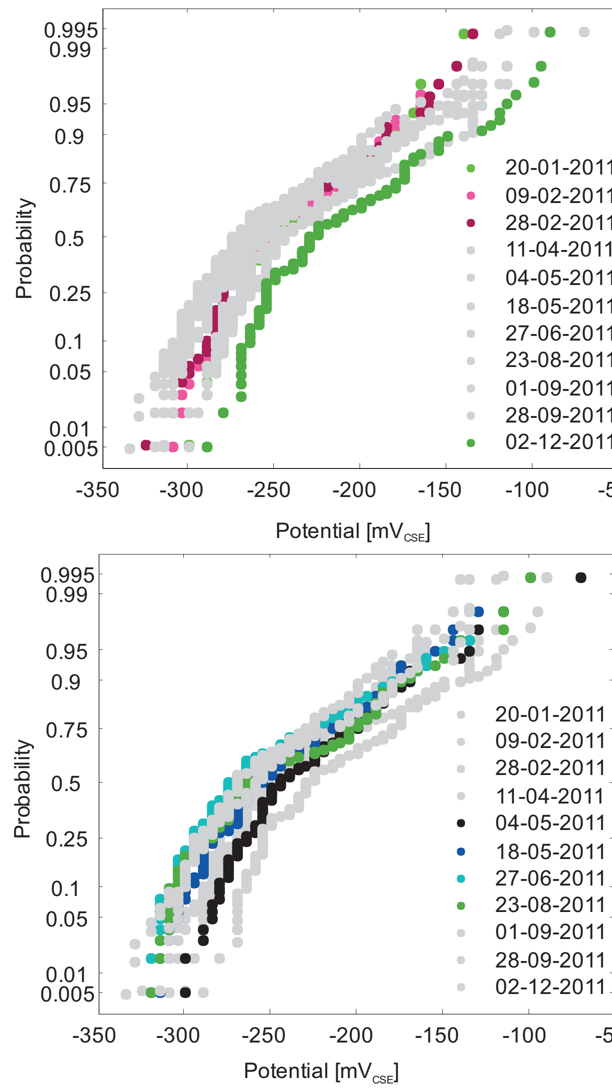

Figure 13. Probability plots of the potential mapping data in wintertime (above) and summertime (below).

The curve with the most positive values is from December 2, 2011. This measurement is characterized by low temperatures and an exceptional long dry period of 6 weeks. High concrete resistivity is expected during the measurement. The curve with the lowest values is from June 27, 2011. Before this measurement, high temperatures were combined with high precipitation. In this case, low concrete resistivity is assumed. The results of both measurements (June 27 and December 2) agree with the results under different pre-wetting conditions.

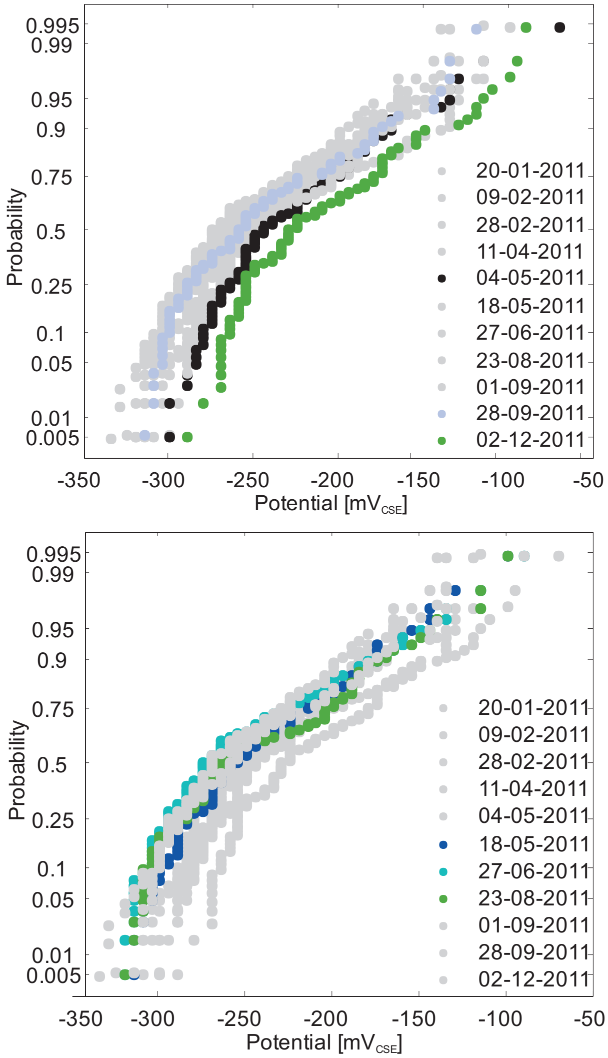

Figure 14. Probability plots of the potential mapping data during rain periods (above) and dry periods (below).

Comparing the probability plots from varying temperatures with those with varying precipitation conditions, it is obvious that moisture content has a higher impact on the potential mapping data than temperature. Accordingly, variation of moisture has a high impact on potential mapping data.

3. CONCLUSION

The half-cell potential measurement method is a robust method to detect on-going corrosion in reinforced concrete structures. Repeated measurements under controlled and under onsite conditions show a very good repeatability. The concrete resistivity has a huge impact on the absolute values of the half-cell potential measurements values. This impact is demonstrated under laboratory condition with an electrolytic pipe and an assumed homogenous resistivity as well as on outside exposed reinforced concrete specimens with heterogeneous distributed resistivity, the segments from the Olympic Stadium in Munich. Half-cell potentials measured after different exposure scenarios as well as under varying pre-wetting condition are compared to each other. With decreasing resistivity, decreases the absolute potential values. Changes in the resistivity lead to a parallel shift of the results in a probability plot. But the areas with the most negative potentials in combination with a pronounced potential gradient remain at the same location.

Considering these results, the question arises if an absolute threshold potential value is suitable to distinguish between corroding and non-corroding areas. The corrosion evaluation of the half-cell potential measurement considering an absolute threshold potential ASTM C876 (2009) could lead to erroneous interpretation. Either a repair is executed although it is not necessary or a wrong all-clear may bring further damages and additional costs in future. Low potentials in combination with a potential gradient are a good indicator for on-going corrosion. Chloride profiles at very low and at high potential areas in combination with selected reinforcement probing can support the assessment on the current corrosion condition state.

In order to evaluate the half-cell potential measurement data of large structures, it is advantageous to compare only these parts which are in a comparable moisture condition by subdivision of the structure, so as to evaluate the potential field in accordance with the structure resistivity. It is recommended to pre-wet the concrete surface once and to start the measurement about 20 min after to ensure stable potentials. Following completion of the investigations at the segments, the concrete cover will be removed to check visually the corrosion condition state of the reinforcement.

REFERENCES

Angst, U., Vennesland, O., & Myrdal, R. (2009). Diffusion potentials as source of error in electrochemical measurements in concrete. *Materials and Structures*, *42*, 365–375.

Assouli, B., Ballivy, G., & Rivard, P. (2008). Influence of environmental parameters on application of standard ASTM C876-91: Half-cell potential measurements. *Corrosion Engineering, Science and Technology*, *43*(1), 93–96.

ASTM C876 – 09 (2009). *Standard test method for corrosion potentials of uncoated reinforcing steel in concrete*.

Beck, M., Bukert, A., Harnisch, J., Isecke, B., Osterminski, K., Raupach, M., … Warkus, J. (2013). Deterioration model and input parameters for reinforcement corrosion. *Structural Concrete – Journal of the Fib*, *13*(3), 145–155.

DGZFP Merkblatt B3 (2014). *Elektrochemische Potentialmessungen zur Detektion von Bewehrungsstahlkorrosion*.

Elsener, B., Andrade, C., Gulikers, J., & Raupach, M. (2003). Half-cell potential measurements – Potential mapping on reinforced concrete structures. RILEM TC 154-EMC. *Materials and Structures*, *36*(261), 461–470.

Elsener, B., & Böhni, H. (1987). Location of corrosion in reinforced concrete: Potential mapping – Possibilities and limitations. *SIA*, *105*, 528–533.

Grimaldi, G., Brevet, P., Pannier, G., & Raharinaivo, A. (1986). Factors influencing electrode potential of steel in concrete. *British Corrosion Journal*, *21*(1), 55–62.

Hornbostel, K., Larsen, C. K., & Geiker, M. R. (2012). Relationship between concrete resistivity and corrosions rate – A literature review. *Proceedings International Conference on Durability of Concrete*, Trondheim, Norway.

Menzel, K., & Preusker, H. (1989). Potentialmessung: Eine Methode zur zerstörungsfreie Feststellung von Korrosion an der Bewehrung. *Bauingenieur*, *64*, 181–186.

Merkblatt SIA 2006 (2013). Planung, Durchführung und Interpretation der Potentialfeldmessung an Stahlbetonbauten. Schweizerischer Ingenieur- und Architekten-Verein (German).

Naish, C. C., Harker, A. H., & Carney, R. F. A. (1990). Concrete inspection – Interpretation of potential and resistivity measurements. *Proceedings 3rd International Symposium on Corrosion of Reinforcement in Concrete Construction*, England, 314–332.

Osterminski, K., Polder, R. B., Schießl, P. (2012). Long term behavior of the resistivity of concrete. *HERON*, Vol. 57 No. 3. Available from: http://heronjournal.nl/57-3/5.pdf

Polder, R. B. (2001). Test methods for on-site measurement of resistivity of concrete – A RILEM TC-154 technical recommendation. *Construction and Building Materials*, *15*, 125–131.

Pour-Ghaz, M., Isgor, O. B., & Ghods, P. (2009). Quantitative interpretation of half-cell potential measurements in concrete structures. *Journal of Materials in Civil Engineering*, *21*, 467–475.

Poursaee, A., & Hansson, C. M. (2009). Potential pitfalls in assessing chloride-induced corrosion of steel in concrete. *Cement and Concrete Research*, *39*, 391–400.

Schiegg, Y., Büchler, M., & Brem, M. (2009). Potential mapping technique for the detection of corrosion in reinforced concrete structures: Investigation of parameters influencing the measurement and determination of the reliability of the method. *Materials and Corrosion*, *60*(2), 79–86.