Agronomy Research **17**(S1), 1053–1061, 2019
https://doi.org/10.15159/AR.19.100

Half-cell potential mapping for corrosion risk evaluation of prestressed concrete ribbed panels from agricultural building after 20 years of service

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Abstract. Corrosion of steel is a significant problem in prestressed concrete structures as it decreases structural capacity and performance. In this research the 20-year-old prestressed concrete ribbed ceiling panels (of type PNS-12) with dimensions of 6 m (length) by 1.5 m (width) from an existing Estonian agricultural building (pigsty) are studied. The objective is to evaluate the corrosion risk of steel reinforcement of ribbed panels by means of a indirect (non-destructive) method and compare the results with a direct method.
The methodology consists of a) non-destructive measurements of half-cell potential and b) comparision with actual condition of steel reinforcement after concrete removal (demolition). Non-destructive measurements were performed on the 10 longitudinal ribs of 5 ribbed panels, respectively. Steel half-cell potential maps were developed based on 900 measurement points recorded by half-cell (Great Dane).
After destructive tests the ribbed panels including their longitudinal ribs were demolished and the concrete was carefully removed. The position and condition of steel details was photographed (direct method), which enabled the comparison with potential maps (indirect method).
The results demonstrated that in general, half-cell potential maps give a rather good indication on the condition of corroding steel rebars with respect to intact details. Also, half-cell potential maps were found relatively useful in estimating the corrosion risk in the studied precast ribbed panels.

Key words: half-cell, potential mapping, corrosion risk, ribbed panels.

INTRODUCTION

Corrosion of steel is a significant problem in reinforced concrete structures as it decreases structural capacity and performance. The decrease of structural capacity is due to the reduction of bond strength between steel bar and concrete and the reduction of steel cross section. The decrease of performance is due to the cracking of concrete cover and the increase of deflection.

During recent decades the expense of repair and rehabilitation of existing reinforced concrete structures has increased due to corrosion deterioration, which can also be considered as significant economic problem. It is estimated that approximately

50% of the expenditure in the construction industry is spent on repair, rehabilitation and maintenance of existing reinforced concrete structures (Long et al., 2001).

A half-cell is a section of metal in a solution of its own ions (such as copper in copper sulphate, silver in silver chloride etc.). If it is connected to another metal in a solution of its own ions (such as iron in ferrous hydroxide, $Fe(OH)_2$) there will be a potential difference between the two "half-cells". It is a simplified battery or an electrical single cell. It will generate a voltage because of the different positions of the two metals in the electrochemical series and due to the difference in the solutions (Broomfield 2007).

Half-cell potential mapping has provided a very useful, non-destructive method to locate areas of corrosion for monitoring and condition assessment of reinforced concrete structures as well as in determining the effectiveness of repair work (Schiegg, 1995; Bertolini et al., 2004). As an early-warning system, corrosion is detected long before it becomes visible at the concrete surface. Based on potential mapping, destructive and laboratory analysis (e.g. concrete cores) and corrosion-rate measurements can be performed more rationally (SIA, 2006). In addition, the amount of concrete removal in repair works can be minimized because the corrosion sites can be located. Today potential mapping is the most widely recognized and standardised non-destructive method for assessing the corrosion state of rebars in concrete structures. In addition to the Americal Standard (C876 -15) and RILEM recommendation (RILEM TC 154-EMC, 2003), several national guidelines (e.g. Concrete Society TR60 2004 in UK, SIA 2006 in Switzerland) describe the use and interpretation of half-cell potential measurements.

Corrosion of steel in concrete follows the well-established electrochemical mechanism of corrosion of a metal in an electrolyte (Page & Treadaway, 1982; RILEM TC 60 CSC, 1988). Corrosion of a metal implies separate anodic and cathodic processes occurring simultaneously on the same metal surface. At the anodes, iron dissolves and iron ions diffuse into the concrete, leaving behind electrons. At the cathodic sites, the iron ions combine with water and oxygen to form an expansive corrosion product, i.e., rust. Corrosion is controlled by how easily the iron ions can move through the concrete from the anodes to the cathodes and it depends on the availability of oxygen and moisture at the cathodes.

The corrosion potential E_{corr} (half-cell rebar /concrete) is measured as a potential difference (or voltage) against a reference electrode (half-cell). The numerical value of the measured potential potential difference between the steel in concrete and the reference electrode will depend on the type of the reference electrode used and on thecorrosion condition of the steel in concrete. In addition, half-cell potential of steel in concrete cannot be measured directly at the interface concrete / rebar due to the presence of the concrete cover (Fig. 1), the potentials are thus influenced by iR drop in the cover, by macrocell current and possibly by junction potentials (RILEM TC 60 CSC, 1988).

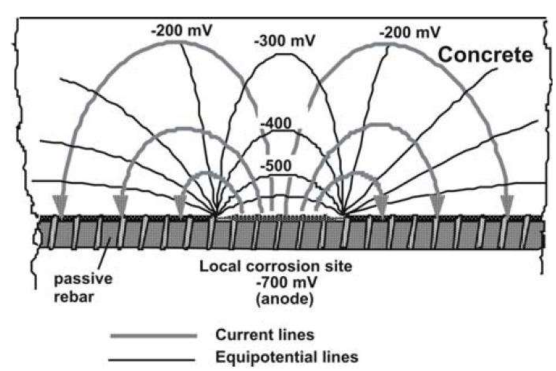

Figure 1. Schematic view of the electric field and current flow in an active / passive macrocell on steel in concrete (RILEM TC 154-EMC, 2003).

Depending on the spatial distribution of anodic and cathodic reactions on the surface of the steel and the conductivity of the medium, two types of corrosion (uniform and macro-cell or localized corrosion) can take place. Half-cell potential measurements allow the location to be determined of areas of corroding rebars (anodic processes) being the most negative zones in a potential field. However, the interpretation of the half-call readings is not straightforward because the concrete cover and its resistivity influence the readings at the concrete surfaces (Bertolini et al., 2004), represented in the discussion section of the current paper.

In Estonian industrial and agricultural buildings there exist a lot of precast concrete load-bearing structures, which were manufactured in the 1970's and 80's during the mass-industrialization and production of reinforced and prestressed concrete structures. By now, due to corrosion deterioration, many of these structures are near to reaching their designed service life. In this research the 20-year-old prestressed concrete ribbed ceiling panels with dimensions of 6 m (length) by 1.5 m (width) from an existing agricultural building (pigsty) are studied. The objective of this study is to evaluate the corrosion risk of steel rebars in ribbed panels by means of indirect (non-destructive) methods and compare the results with a direct method.

MATERIALS AND METHODS

Five 20 years old prestressed concrete ribbed ceiling panels of type PNS-12 from an existing agricultural building (pigsty) are the subject of the current study. The top view, longitudinal and transverse section of a ribbed panel PNS-12 is shown in Fig. 2. The prestressing and reinforcing steel rebars of a ribbed panel PNS-12 are shown in Fig. 3.

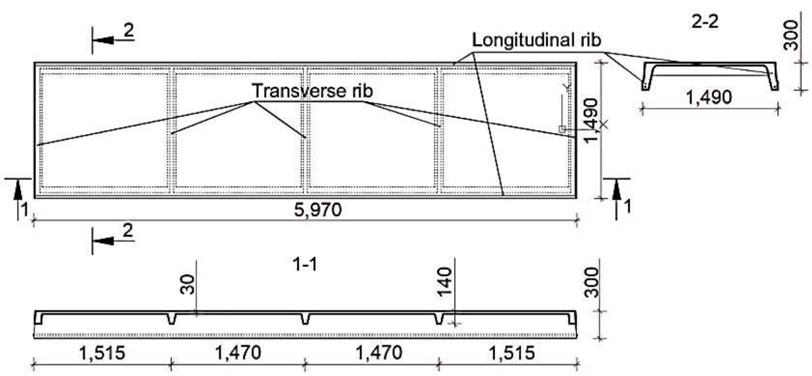

Figure 2. Top view, longitudinal and transverse section of a ribbed panel PNS-12 (PK-01-111, 1961 *Dimensions are in mm.*

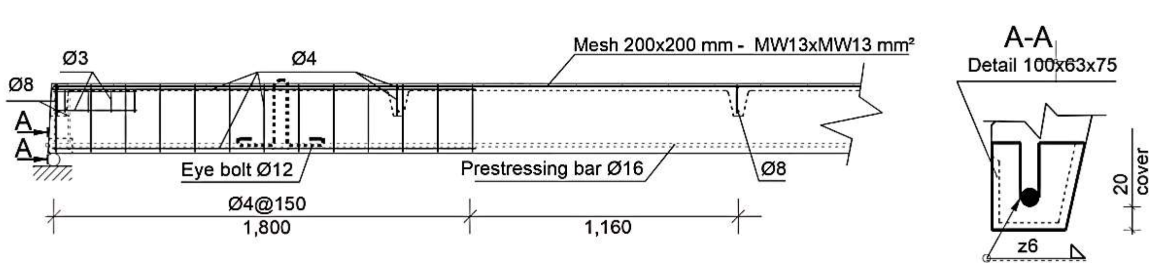

Figure 3. Reinforcement and anchorage of the ribbed panel PNS-12 (PK-01-111, 1961). *Dimensions are in mm.*

The study methodology in general consists of a) non-destructive measurements by half-cell potential of a longitudinal rib (of a ribbed panel PNS-12) and b) comparision with actual condition of steel rebars after removal of concrete (demolition of longitudinal ribs of ribbed panels PNS-12).

The procedure for measuring half-cell potentials is presented as follows (Fig. 4).

A sound electrical connection is made to the rebar, namely prestressing bar ø16mm in the current study. An external reference electrode is placed on a wet sponge on the concrete surface and potential readings are taken with a high impedance voltmeter (> 10 MΩ) on a regular grid on the free concrete surface. Good electrolytic contact is essential to get stable readings, the point of measurement should be clean and wetted with a water-soaked sponge on the surface.

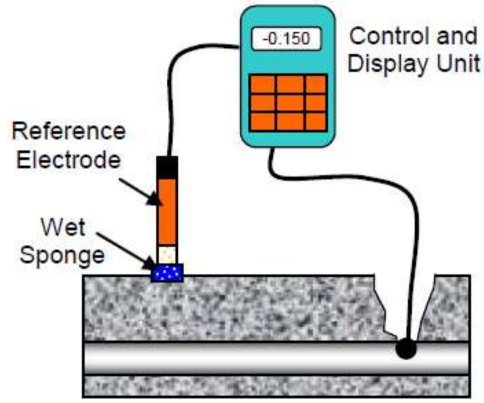

Figure 4. Principle and main components of half-cell potential measurements: reference electrode, high impedance voltmeter, connection to the rebar.

The mapping of the corrosion potential of steel was performed with a German Instruments GD-2000 Mini Great Dane system (Fig. 5) The Mini Great Dane measures the surface potentials relative to an Ag/AgCl/1M KCl reference electrode and the electrical resistance of the cover concrete between the electrode and the reinforcement. The indicated potential, E_{corr}, is in terms of a $Cu/CuSO_4$ electrode (CSE), which are -110 mV lower in value than for the Ag/AgCl/1M KCl electrode.

Half-cell potential measurements were performed on the 10 longitudinal ribs of 5 ribbed panels, respectively. Four horizontal and 30 vertical gridlines were marked in each longitudinal rib, with measuring points formed at the crossing of the gridlines. In this way, 30 (horizontally) x 4 (vertically) grid of 120 measurement points per longitudinal rib was formed. Altogether 120 (measurement points per longitudinal rib) x 2 (ribs) x 5 (ribbed panels) = 1,200 measurement points were recorded for steel potential. Representation of half-cell potential data was performed by developing colour plots of the measurement points (potential maps).

Figure 5. The Great Dane corrosion mapping system.

After the non-destructive tests, the ribbed panels including their longitudinal ribs were demolished and concrete was carefully removed. The actual position and condition of the steel (main prestressing bar, reinforcing wire meshes (acting for shear) and eye bolt (for lifting ribbed panels)) was photographed (direct method), which enabled the comparison with the potential map (indirect non-destructive method).

RESULTS AND DISCUSSION

Half-cell potential measurements allow the location to be determined of areas of corroding rebars, being the most negative zones in a potential field, but not showing the corrosion rate. The interpretation of the potential readings is not straightforward because the concrete cover and its resistivity in addition to the corrosion potential of the steel influence the readings at the concrete surface. The resistivity itself varies with temperature, with concrete moisture and chloride content or carbonation (Bertolini et al. 2004).

According to atmospherically exposed reinforced concrete the potential of passive steel is between +170 and -80 mV derived for the Ag/AgCl/1M KCl electrode (SSE) as applied in the current study (+ 50 to -200 mV CSE). If corrosion is ongoing the potential becomes more negative: chloride-induced pitting corrosion typically results in values from -280 to -580 mV SSE (-400 to -700 mV CSE), corrosion due to carbonation usually results in values from -80 to 380 mV SSE (-200 to -500 mV CSE), strongly depending on the presence of moisture (Bertolini et al. 2004).

The ASTM C876-91 provides one possibility for interpretation of half-cell potential readings (Table 1). This interpretation was devised empirically from chloride-induced corrosion of cast in place bridge decks in the USA, thus not fully applicable to the current study.

Table 1. ASTM C876-91 criteria for corrosion of steel in concrete for Ag/AgCl/1M KCl standard reference electrode

Silver/silver chloride/ 1.0M KCl	Corrosion condition
> - 100 mV	Low (10%) risk of corrosion
- 100 to -250 mV	Uncertain corrosion risk
< - 250 mV	High (> 90%) risk of corrosion
< - 400 mV	Severe corrosion (or low oxygen/water saturation)

The results from Halgma & Linnus, 2007 show that uniform corrosion was detected in some of the steel prestressing bars during visual inspection. In some ribbed panels the prestressing bars were found to be non-corroded referring to passive steel. No signs of chloride-induced localised (or pitting) corrosion were detected during visual inspection.

The results of half-cell potential measurements are shown in Table 2. Also, average concrete carbonation and cover depth data are presented as background information in Table 2. As the areas of corroding rebars are the most negative, the minimum potential values are considered as important. Also, the maximum values are given in Table 2 to indicate the range of potential measurements.

The carbonation depth versus cover depth ratio in Table 2 indicates that at least one third of the cover (Fig. 3) of all studied ribbed panels PNS-12 is carbonated. According to theory of steel corrosion in concrete, the active corrosion starts, in the presence of moisture, when the concrete cover is fully carbonated. In two cases (P8 longitudinal rib D-C and P12/A-B, respectively) almost the full cover is carbonated in average. The corresponding minimum potentials (-210 mV in P8/D-C and -225 mV in P12/A-B), however, correspond to an uncertain corrosion risk in Table 2.

Table 2. Results of half-cell potential, carbonation and cover depth measurements at the studied longitudinal ribs of ribbed panels. Values in bold indicate significant results, which are further discussed in the text

Ribbed panel /	Potential, mV vs. Ag/AgCl		Average concrete carbonation/
Longitudinal rib	min	max	cover depth, mm
P7/A-B	-121	121	7.0 / 23.6
P7/ D-C	-216	55	7.4 / 24.2
P8/A-B	-218	-1	**27.0 / 24.4**
P8/ D-C	-210	95	*22.3 / 24.3*
P9/A-B	-166	70	8.4 / 25.0
P9/ D-C	**-297**	4	8.4 / 24.2
P10/A-B	**-361**	98	9.9 / 25.6
P10/D-C	-160	46	9.4 / 27.7
P11/A-B	-91	47	8.1 / 24.3
P11/D-C	-228	130	9.1 / 24.6
P12/A-B	-225	11	*14.4 / 18.1*
P12/D-C	-151	1	9.1 / 21.3

In one case (P8 longitudinal rib A-B, marked as bold in Table 2) the cover is fully carbonated on average (average carbonation depth is more than average cover depth). The corresponding minimum potential (-218 mV in P8/A-B), also corresponds to uncertain corrosion risk in Table 2. It should be noted that carbonation depth measurement locations did not correspond to the half-cell potential grid in ribbed panels, because it was not possible to perform the carbonation measurements at the exactly same location. The carbonation depth was measured in 10 locations per one concrete core, drilled from the longitudinal rib. Five cores were drilled from each longitudinal rib of a ribbed panel. Therefore, each average carbonation depth value, in Table 2, is based on 50 measurements.

The largest negative potentials were found in ribbed panel longitudinal rib A-B (P10/A-B) and P9/D-C (-361 and -297 mV versus Ag/AgCl/KCl reference electrode, respectively in Table 2)). According to ASTM C876-91 criteria, both of these values exceed the high (>90%) risk of corrosion condition (< -250 mV versus Ag/AgCl/KCl reference electrode). However, only approximately one third of the cover was carbonated in both of those cases (9.9/25.6 for P10/A-B and 8.4/24.2 for P9/D-C in Table 2), indicating that the corrosion should not have yet started.

The half-cell potential map of P10/A-B shows the most negative potentials in the lower right corner of the Fig. 6. The position and condition of steel details of P10/A-B was also photographed (direct method, in Fig. 7), which enabled the comparison with half-cell potential map (indirect, non-destructive method). Fig. 7 shows that that the steel prestressing bar (initial ø16 mm in Fig. 3), reinforcements (ø3 and 4 mm), eye bolt (ø12 mm) and other details of P10/A-B had relatively large visually distinguishable corrosion deterioration. It should be mentioned that large negative potential readings of half-cell have also other causes such as water saturation and pressure of galvanised components.

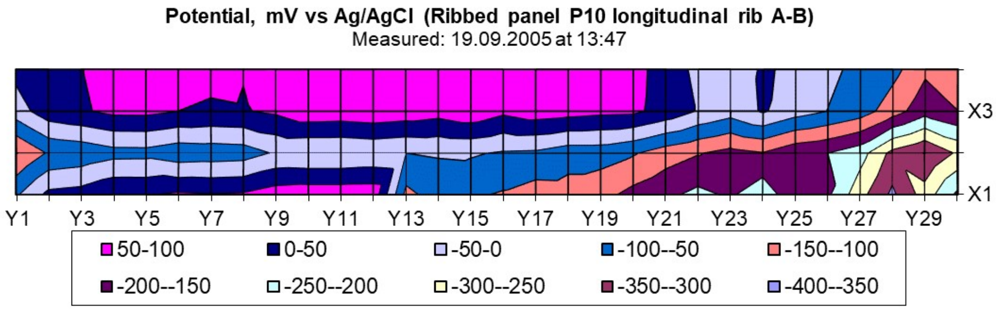

Figure 6. Half-cell potential map of the longitudinal rib with the largest negative potential (P10/A-B).

Figure 7. Photograph of the steel prestressing bar, reinforcements and eye bolt details of the longitudinal rib A-B of ribbed panel P10 (P10/A-B) after demolition.

For comparison purposes the half-cell potential map of the ribbed panel with the smallest negative potential difference (P11/A-B) was chosen (Fig.8). The position and condition of steel details of P11/A-B was also photographed (Fig. 9)

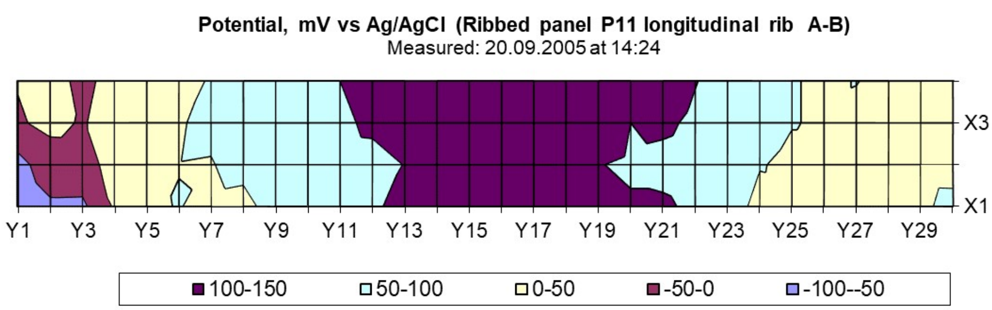

Figure 8. Half-cell potential map of the longitudinal rib with the lowest negative potential (P11/A-B).

Figure 9. Photograph of the steel prestressing bar, reinforcements and eye bolt details of the longitudinal rib A-B of ribbed panel P11 (P11/A-B) after demolition.

Fig. 9 shows that the steel prestressing bar (initial ø16 mm in Fig. 3), reinforcements (ø3 and 4 mm) and eye bolt (ø12 mm) of P11/A-B details are relatively intact in visual observation. This corresponds rather well with the half-cell potential map (Fig. 8) of the same member (P11/A-b). Therefore, good correlation between half-cell measurements and visual observation was found in the current study.

CONCLUSIONS

Half-cell potential mapping offers a possibility to quantitatively evaluate the corrosion risk in the studied precast concrete structures (ribbed panels PNS-12) with a non-destructive technique, which is a major step forward in comparison with visual inspection.

Despite the difficulties in interpreting the half-cell potential maps reported in the literature, the proposed ASTM criteria correlated well with the results of the current study. However, the most severe corrosion conditions according to ASTM criteria were not recorded in the current study. This should be addressed in the further research.

The current study also confirmed that half-cell only indicates a risk of corrosion, not the rate, so it is common for areas to be discovered with negative potentials and no corrosion.

ACKNOWLEDGEMENTS. The support of the loan of the equipment by Olav Sammal (ETUI Beton Test OÜ) is greatly acknowledged.

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