3rd Specialty Conference on Material Engineering & Applied Mechanics
3e Conférence spécialisée sur le génie des matériaux et mécanique appliquée

Montréal, Québec
May 29 to June 1, 2013 / *29 mai au 1 juin 2013*

Effectiveness of half-cell potential mapping in corrosion assessment of reinforcement in loaded concrete bridge decks

Parham Chabi[1], O. Burkan Isgor[2,*], Beatriz Martin-Perez[1], Pouria Ghods[2]
[1]Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada
[2]Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada
* Presently at Oregon State University, Corvallis, OR, USA

Abstract: Many of concrete structures that are exposed to aggressive environments suffer from severe durability problems. For instance, the use of chloride-containing de-icing salts on the roads has resulted in extensive steel corrosion in reinforced concrete transportation infrastructure, causing their premature failure. Early detection of corrosion activity in concrete structures before they experience extensive damage is critical for developing effective mitigation, repair and rehabilitation strategies. Half-cell monitoring is a widely-used standardized technique to estimate the probability of reinforcement corrosion in reinforced concrete structures. Despite its extensive use, the accuracy of half-cell potential mapping in detecting corrosion in concrete structures has been a subject of debate for structures under service conditions. In this study, the effectiveness of half-cell potential mapping was evaluated on realistically detailed and loaded slab segments representing bridge decks in service conditions. The experiments were carried out in a controlled laboratory environment, and accuracy of half-cell potential mapping predictions was evaluated in varying degrees of concrete saturation. It was observed that a large number of cases could not be predicted accurately by half-cell potential mapping, and potential measurements needed supplementary data for effective monitoring of corrosion activity in concrete.

Keywords: corrosion, concrete, half-cell potential mapping, monitoring, durability, bridges

1. Introduction

Half-cell potential mapping is a standardized non-destructive method for detecting steel corrosion in concrete structures (ASTM C876-09). In this method, the potential difference between an external electrode located at the surface of concrete and the embedded reinforcement is measured with a high impedance voltmeter. The probability of corrosion is related to the half-cell potential readings on the surface of concrete: the more negative the measured surface potential, the greater the probability of corrosion. Half-cell potential measurements less than -350 mV with respect to the copper/copper sulfate electrode (CSE) (or -276 mV vs. Standard Calomel Electrode, SCE) corresponds to a 90% probability. When the measurement is greater than -200 mV vs. CSE (or -126 mV vs. SCE) the probability of corrosion is less than 10%. When the potential is between -350 mV vs. CSE (or -276 vs. SCE) and -200 mV vs. CSE (or -126 mV vs. SCE), the corrosion state of the rebar cannot be predicted. Figure 1 schematically illustrates the test setup for a typical half-cell potential test on a reinforced concrete element.

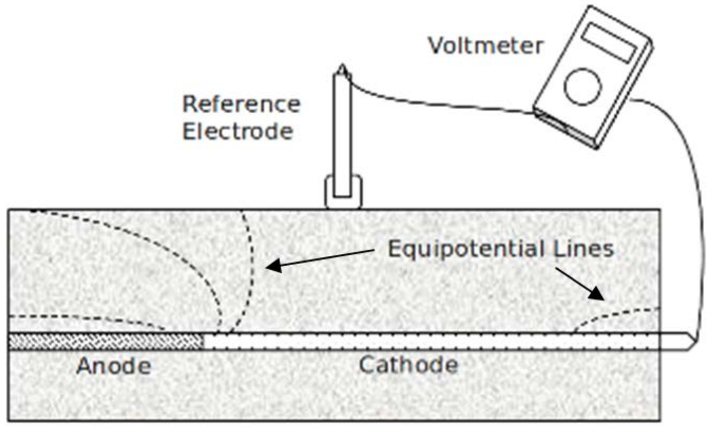

Figure 1 — Typical half-cell potential measurement setup.

The interpretation of the half-cell potential mapping results remains to be a major challenge for engineers. Concrete resistivity, oxygen availability, anode–to-cathode area (A/C) ratio and cover thickness are some of the factors that have been reported to influence the test (Bohni 2005, Elsener 2002, Bertolini et al. 2004). Half-cell potential measurements also depend on the type of corrosion process. In the case of uniform corrosion, the potential readings at the surface of concrete are generally representative of the potential distribution at the interface of steel and concrete (Sagües and Kranc 1992); however, in the case of non-uniform (e.g. local or pitting) corrosion, the measured potentials at the surface of concrete can be substantially different from those of the steel/concrete interface (Pour-Ghaz et al. 2009).

Despite its extensive use, the accuracy of half-cell potential mapping in detecting corrosion in concrete structures has been a subject of debate for structures under service conditions. In this study, the effectiveness of half-cell potential mapping was evaluated on realistically detailed and loaded slab segments representing bridge decks in service conditions. The experiments were carried out in a controlled laboratory environment, and accuracy of half-cell potential mapping predictions was evaluated in varying degrees of concrete saturation.

2. Experimental Setup

The investigation was conducted on a reinforced concrete deck (Figure 2) that was constructed in the laboratory and exposed to chloride-containing salts to initiate corrosion (Deif 2010). This deck had three 0.91-m width reinforced concrete strips, each with a different water-to-cement (w/c) ratio: 0.35, 0.4 and 0.5. The concrete compressive strengths at 28 days for slabs with w/c of 0.35, 0.40 and 0.50 were 62.1 MPa, 51.5 MPa and 44.7 MPa, respectively. The three reinforced concrete slabs were reinforced with eight top and eight bottom #10M steel rebars with a yield strength of 400 MPa. Clear concrete cover to the top and bottom concrete surfaces was 50 mm and 45 mm, respectively.

Each slab was simply supported at two locations: at one end and 1.26 meter from the other end, providing a 2.73-meter long span. The slabs were loaded by means of three threaded steel bars to create service conditions that correspond to 60% of its ultimate moment capacity during the duration of testing. In order to distribute the applied axial load across the width of each strip, the slabs were also reinforced along the transverse direction with four steel bars arranged in two layers, two at the top and two at the bottom. Loads were first applied to the slabs after 200 days of casting; the compressive strengths at the time of loading were 81.0 MPa, 69.4 MPa and 64.5 MPa for slabs with w/c of 0.35, 0.40 and 0.50, respectively. The locations of supports and applied loads were designed to induce both positive and negative bending moment regions along the slab, as well as regions of pure bending and a mix of shear and bending. Details of the applied loads as well as the resulting shear force and bending moment diagrams for a single slab are shown in Figure 3.

The slabs were exposed to de-icing salts and ten wetting/drying cycles to induce corrosion activity prior to the measurements conducted in this research. To simulate chloride exposure conditions in the field, de-icing salt was spread uniformly all over the deck surface. The slabs were then sprayed with water and allowed to dry for 90 days. This wetting-drying cycle was repeated ten times. Further details of the construction and exposure of the test specimen are found in Deif (2010).

The corrosion activity in the reinforced concrete slabs was investigated under three different moisture conditions (dry, partially-saturated and saturated) by measuring half-cell potentials and electrical resistivity of concrete at several locations as illustrated in Figure 4. At selected number of locations polarization resistance was also measured using electrochemical impedance spectroscopy (EIS) to obtain corrosion rates. EIS measurements were obtained by a Gamry Potentiostat/FRA system. Resistivity measurements were taken using a Wenner probe.

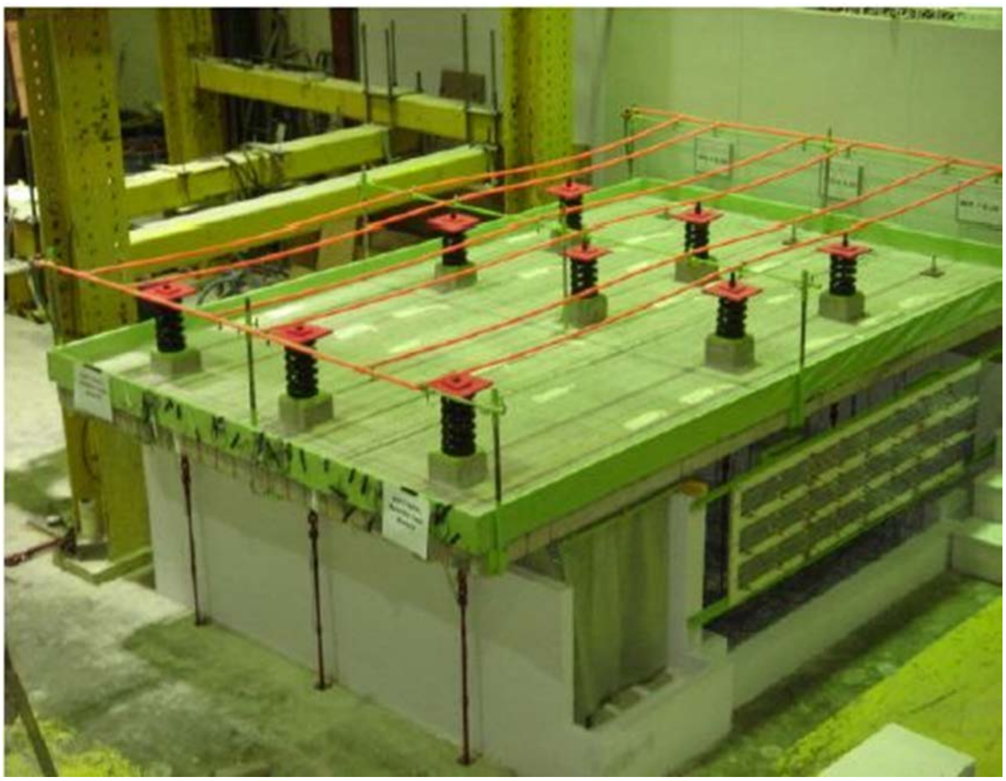

Figure 2 — Reinforced concrete loaded deck used in the investigation.

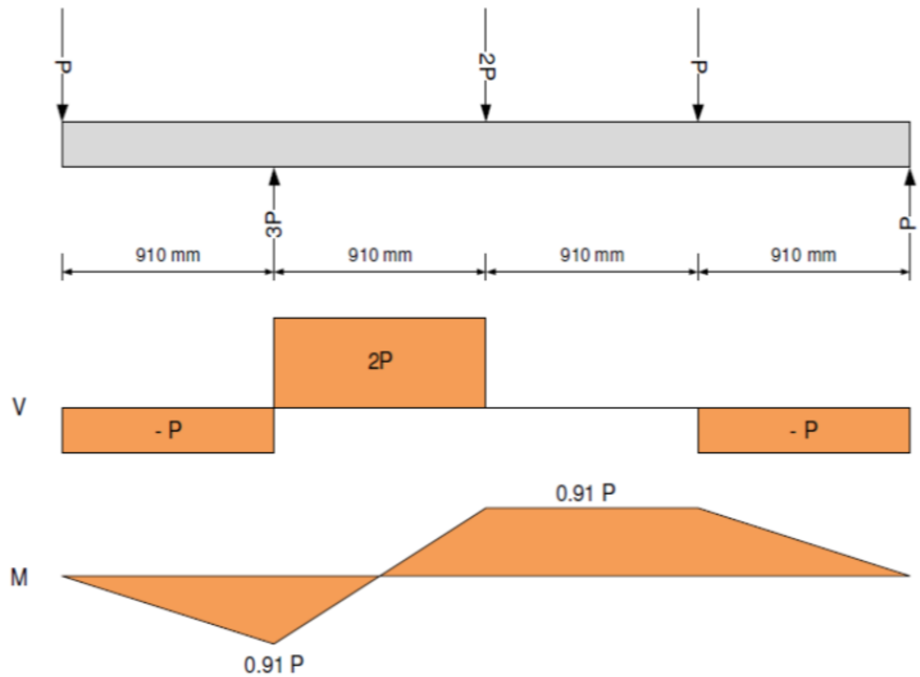

Figure 3 — Applied loads, shear and bending moment diagrams for a single slab (P=27.5 kN).

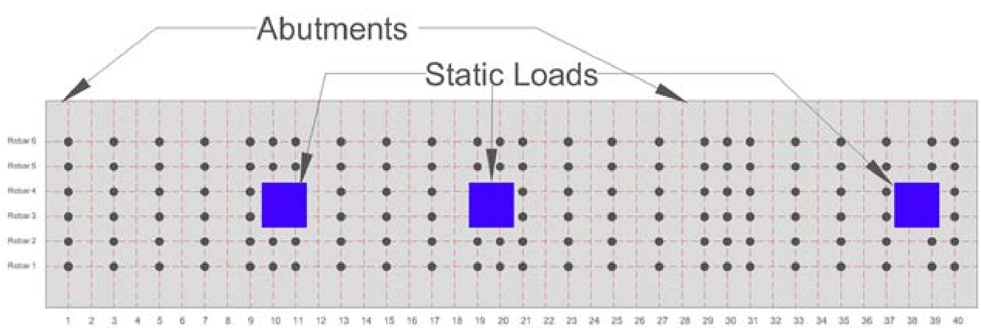

Figure 4 — Locations of half-cell potential measurement points for each slab.

3. Results and Discussion

Half-cell potential measurements on each slab under dry, partially-saturated and saturated conditions are shown in Figure 5. It is clear in this figure that w/c, loading and the degree of saturation of the slabs have significant effects on half-cell potential measurements. Increasing w/c and degree of saturation corresponds to more negative half-cell potential measurements that imply increased corrosion activity. As shown in Figure 5, corrosion activity in the negative moment zones of the slabs, where load-induced cracks openings were on the chloride exposed surface, was considerably higher than that of positive moment zones. Higher corrosion activity with increasing w/c ratio and the degree of saturation were also more pronounced in the negative moment zones.

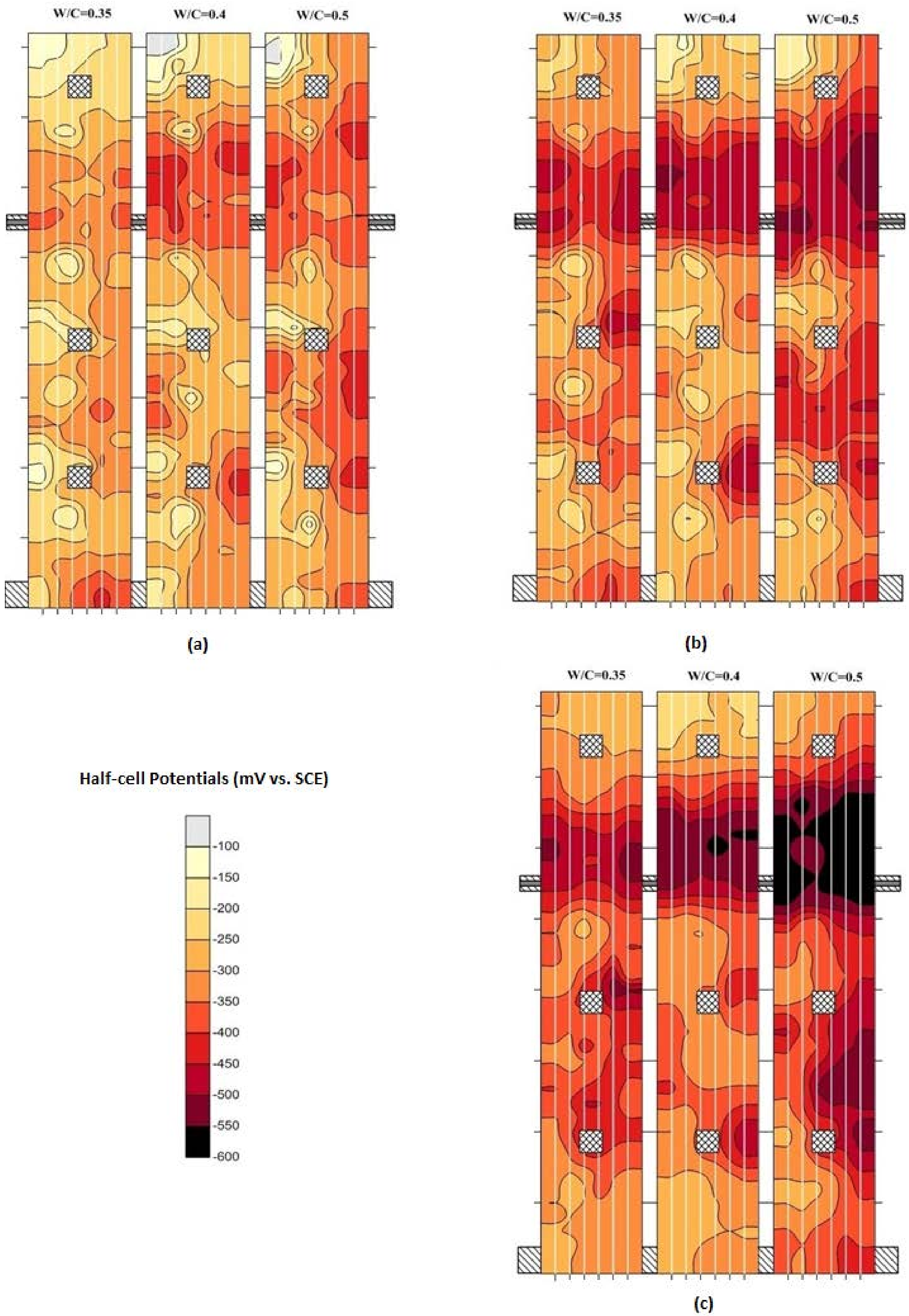

Figure 5 — Half-cell potential measurements **(a)** dry, **(b)** partially-saturated, **(c)** saturated conditions.

The increase in corrosion activity with increasing w/c and degree of saturation can be related to corresponding changes in electrical resistivity of concrete as illustrated in Figure 6. Higher corrosion activity (as represented by more negative half-cell potentials) in Figure 5 correspond well to decreasing concrete resistivity measurements in each slab.

In Figure 7, half-cell pontifical measurements of all slabs under all saturation levels are plotted against polarization resistance (and corresponding corrosion rate as represented by current density) measurements that were obtained from EIS data. This plot clearly shows a correlation among half-cell potential measurements, corrosion rate and the degree of saturation. However, it is also clear in this figure that the guidelines of ASTM C876 fail to provide adequate information about the corrosion state of the steel reinforcement in the slabs. A large number of data points fall in the “uncertain” zone between half-cell potentials of -126 mV (SCE) and -256 mv (SCE). In this zone, the corrosion rates of different measurement points vary considerably from high to relatively low values. Similar variation also exists in the zone predicted with high corrosion probability as per ASTM C876; there are many measurements corresponding to low corrosion rates while half-cell potential mapping results predict high probability of corrosion. It is important to note that corrosion activity was observed at a number of measurement points in the zone predicted with low probability of corrosion as per ASTM C876.

These observations clearly demonstrate the limitations and effectiveness of half-cell potential measurements in realistic scenarios. Although these measurements show promising potential to provide useful and meaningful data for assessing corrosion state of steel in concrete decks, without supplementary data, they remain inadequate, and in some cases, misleading. The supplemental data can clearly be the corrosion rate measurements; however, in the absence of accurate, reliable and practical corrosion rate measurement devices that are specifically developed for field applications, corrosion rates cannot serve this supplementary purpose. EIS technique that provided polarization resistance and corrosion rate data in this investigation is a slow laboratory method; therefore, it is not practical or appropriate for field applications.

Concrete resistivity, on the other hand, can provide the necessary supplementary information to improve the observations of half-cell potential mapping. As illustrated in Figure 6, concrete resistivity measurements are highly correlated with w/c and the degree of saturation, which both affect steel corrosion rates in concrete. Figure 8, which illustrates the relationship between corrosion rate measurements and concrete resistivity, supports this hypothesis. As it can be observed in this figure, concrete resistivity is strongly related to corrosion rates; the lower the resistivity the higher the corrosion rates. Therefore, as a parameter that is easy and quick to measure in the field, concrete resistivity measurements can be used to support the observations of standardized half-cell potential mapping studies to obtain representative and useful conclusions from field assessment studies.

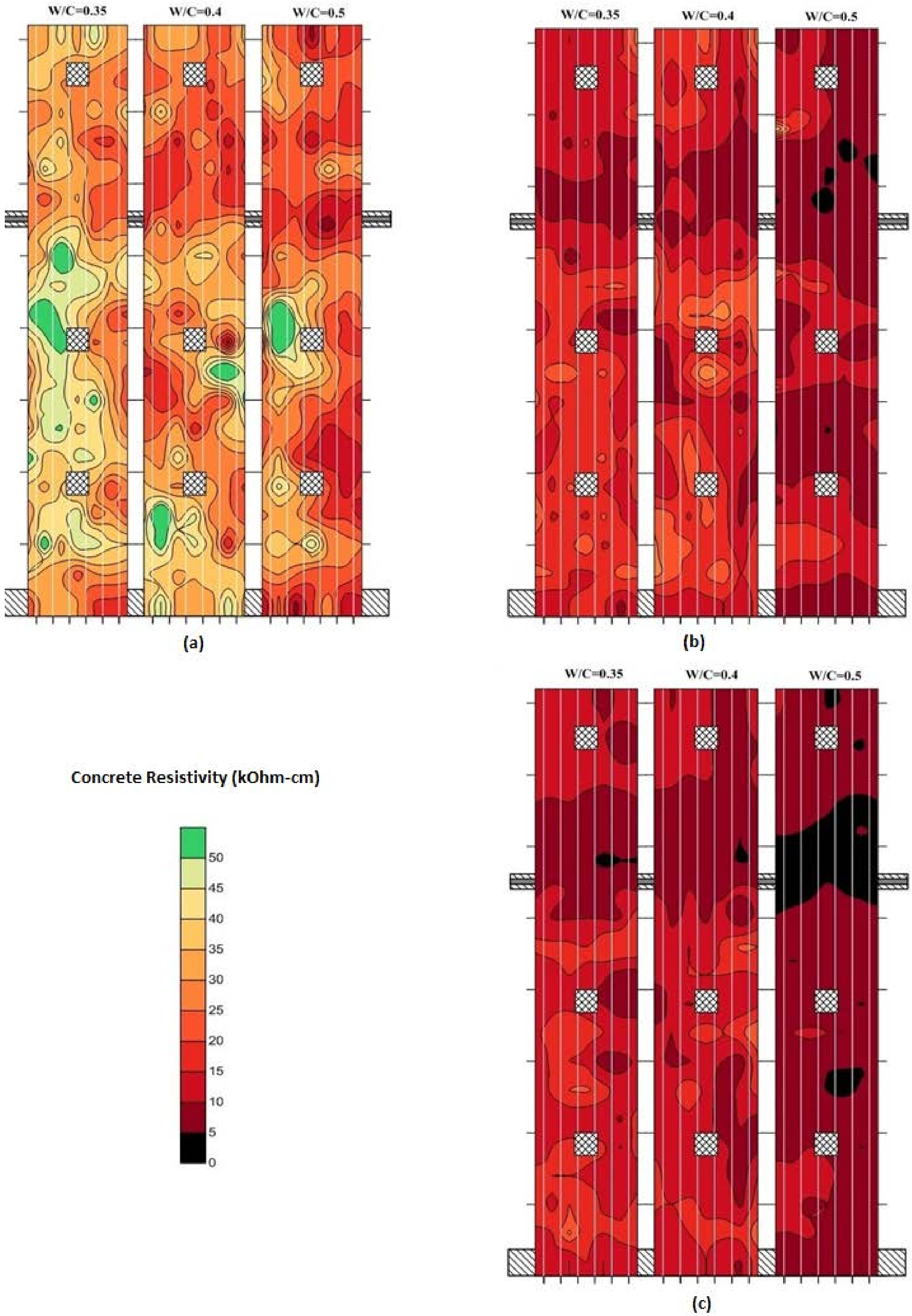

Figure 6 — Resistivity measurements under **(a)** dry, **(b)** partially-saturated, **(c)** saturated conditions.

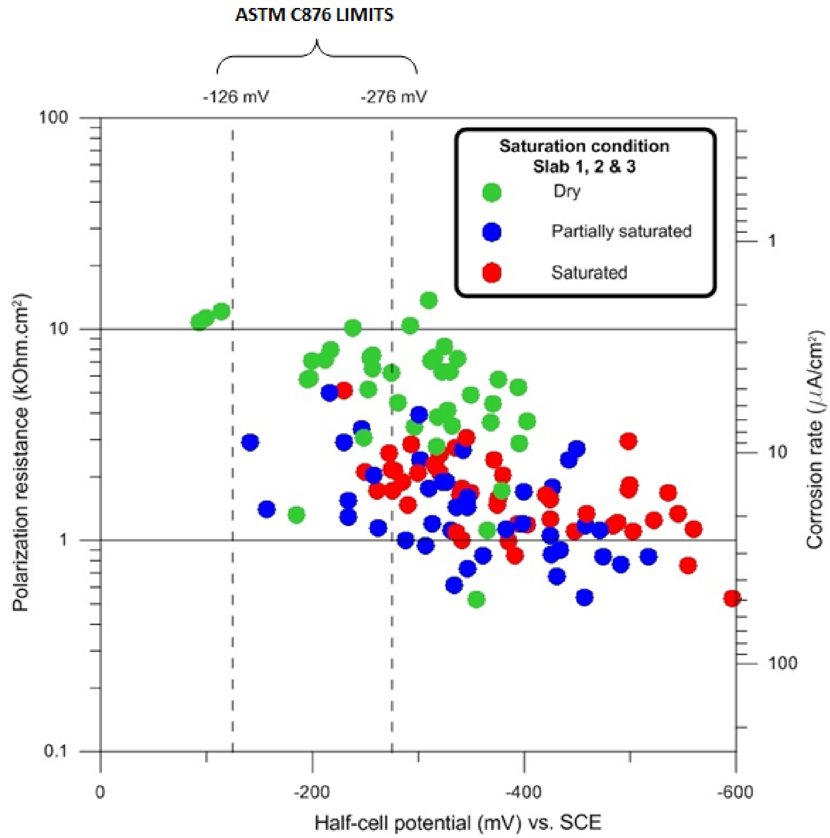

Figure 7 — Half-cell potential vs. polarization resistance measurements.

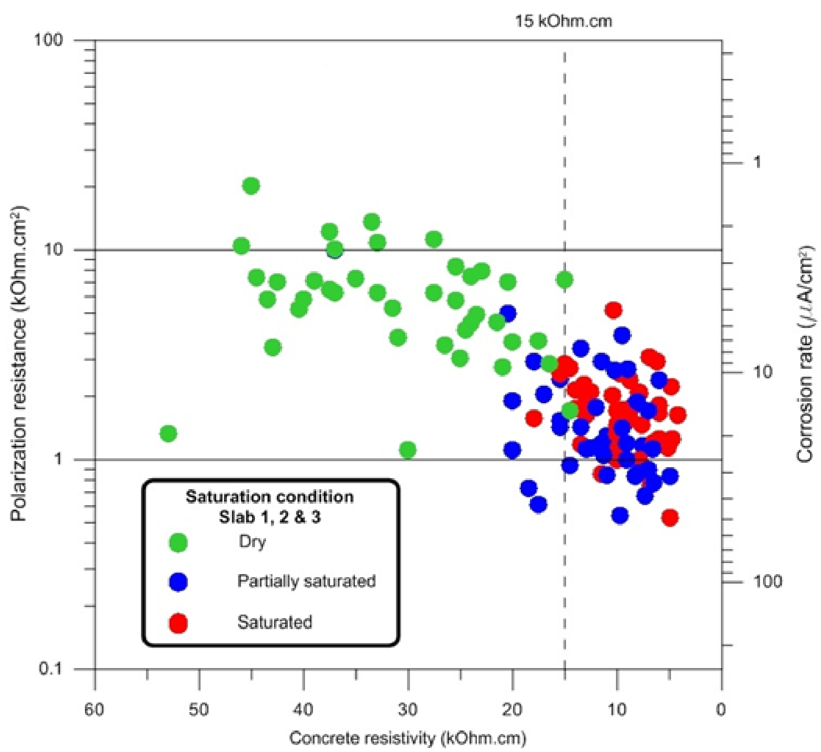

Figure 8 — Concrete electrical resistivity vs. polarization resistance measurements.

4. Conclusions

In the present work, the accuracy of half-cell potential mapping predictions was evaluated on loaded reinforced concrete slabs with varying degrees of saturation. In addition to half-cell potential measurements, the electrical resistivity of concrete and the polarization resistance of reinforcement were determined. From the experimental results, the following conclusions are drawn:

- Hall-cell potential measurements showed higher corrosion activity as the w/c and concrete saturation level increased.
- More negative half-cell potential measurements were recorded on regions under negative bending moment than regions with positive bending moment.
- Large number of cases, with corrosion rates ranging from very high to low, fell into the uncertain corrosion activity zone described by ASTM C876.
- Concrete electrical resistivity measurements correlated well with corrosion rates obtained from polarization resistance. It is therefore suggested that this measurement be used in the field to complement readings from half-cell potential mapping.

5. References

ASTM C876 – 09. 2009. Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. *ASTM International*.

Bertolini, L., Elsener, B., Pedeferri, P., and Polder, R. 2004. *Corrosion of steel in concrete*, Wiley, Weinheim, Germany.

Bohni, H. 2005. *Corrosion in reinforced concrete structures*. Florida, U.S.A.: CRC Press.

Elsener, B. 2002. “Macrocell corrosion of steel in concrete—Implications for corrosion monitoring.” *Cem. Concr. Compos*., 24 (1), 65–72.

Pour-Ghaz, M., Isgor, O. B., and Ghods, P. 2009. “Quantitative Interpretation of Half-cell Potential Measurements in Concrete Structures.” *ASCE Journal of Materials in Civil Engineering*. **21**(9), 467-475.

Deif, A. 2010. Chloride ingress into reinforced concrete sustaining in-service loads. *PhD Thesis Dissertation*, Department of Civil Engineering, University of Ottawa.

Sagües, A. A. and Kranc, S. C. 1992. “On the determination of polarization diagrams of reinforcing steel in concrete.” *Corrosion (Houston)*, **48**(8), 624–633.