ACCELERATED ARTIFICIAL CORROSION MONITORING OF REINFORCED CONCRETE SLABS USING THE HALF-CELL POTENTIAL METHOD

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ABSTRACT

Corrosion of ferrous materials is the most expensive problem in maintaining America's civil infrastructure. Detecting and monitoring corrosion using nondestructive testing (NDT) methods is preferred, due to its noninvasive nature to avoid interrupting the operation of structures while in service. Half-cell potential (HCP) method (ASTM C876) is one of the most widely used NDT methods in civil engineering. In this paper, we report our experimental work of an accelerated artificial corrosion test on reinforced concrete (RC) slabs, using the HCP method to monitor corrosion activity. Four RC slabs were designed with #4 rebars embedded at various concrete covers (1.5", 2.0", and 2.5"). A water-to-cement (w/c) ratio of 0.52 was used in concrete. An accelerated artificial corrosion test was proposed, in which a weekly ponding-drying procedure was followed for fifty-two weeks. A saline solution of 15% concentration level was used in ponding three RC slabs, while one slab was left unponded for comparison. From the result, time-dependent progression of rebar corrosion in concrete was experimentally simulated. Spatial distribution of HCP data at various concrete covers was also measured during the course of the experiment.

INTRODUCTION

Managing aging civil infrastructure is one of the greatest challenges faced by the U.S. While destructive testing methods are impractical and typically result in the need to repair, non-destructive testing (NDT) methods offer civil engineers an option to inspect and monitor structures of different types and materials (e.g., concrete, steel, timber) for various purposes (preliminary or detailed). Among the widely seen damages in concrete structures (reinforced and prestressed), corrosion of ferrous reinforcement stands a critical problem to the sustainability of structures and a challenge to inspect and repair. The half-cell potential (HCP) method is an accepted and widely used approach to determine the level of corrosion of ferrous reinforcement in concrete (ASTM C876 *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete*). From the HCP result, presence and level of corrosion can be empirically determined.

While the HCP method offers an effective tool for locating corroded steel rebars in concrete and for evaluating their condition, its measurement and interpretation can be affected by temperature, relative humidity, concrete resistivity, moisture content in concrete, and concrete carbonation (1). To better describe the time-dependent process of rebar corrosion in concrete, long-term experiments are needed. Meanwhile, HCP measurements along each rebar indicate the condition of concrete cover at different locations. Spatial distribution of HCP can be used to describe the propagation of corrosion and to provide insightful information for repair.

Many previous researchers reported the validity of using HCP to determine the level of corrosion in RC structures such as beams (2, 3). Yuan et al. (3) reported that an artificial environment (e.g. consistently high temperatures and relative humidity) can accurately simulate rebar corrosion. Other accelerated artificial corrosion tests were also reported, such as the modified Southern Exposure Test (4). Leelalerkeit et al. (5) found that HCP may give false positive results and suggested a visual inspection to confirm the results. Poupard et al. (6) demonstrated that HCP could be used in assessing the condition of RC structure in marine environments. Li and Melchers (8) proposed a relationship between HCP and time, while their experiment work was conducted on RC beams. Otieno et al. (9) suggested the use of other NDT methods to assist HCP in result interpretation. From literature review, little has been reported regarding the spatial and time-dependent distribution of HCP on RC slabs.

The objective of this paper is to report our experimental work on an accelerated artificial corrosion test of reinforced concrete (RC) slabs, their corrosion monitoring using the HCP method, and the modeling of HCP measurements. Standard #4 steel rebars were buried at various concrete covers inside four RC slabs and subjected to a weekly ponding-drying cycle for fifty-two weeks in a controlled environment (temperature and relative humidity) to investigate the spatial and temporal development of HCP. This accelerated artificial corrosion test simulates the corrosion process in reinforced/prestressed concrete bridge decks and parking garages in cold regions where deicers containing chloride ions are used in winter. Details of our experimental work and modeling results will be presented in the following sections. Finally, findings are summarized in the conclusions.

ACCELERATED ARTIFICIAL CORROSION TEST

Corrosion in steel rebar depends on several factors including concrete cover, temperature, relative humidity, and the salinity of the solution. To investigate the spatial and temporal distribution of HCP data on RC slabs, an accelerated artificial corrosion test was designed and used to develop HCP data for fifty-two weeks. Four RC slabs were cast with same dimensions of 40”(width)-by-72”(length)-by-7”(depth). Fig. 1 and 2 describe the RC slabs.

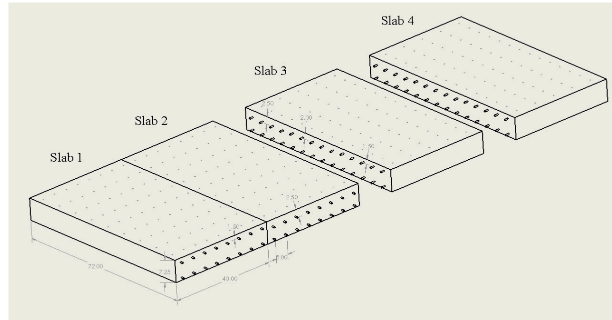

Fig. 1 Four RC slabs and their rebar orientation schemes

Fig. 2 Four slabs inside a plastic tarp

The RC slabs were cast on a wooden base that remained throughout the length of the experiment to keep them off the floor and safe from accidental leakage elsewhere in the Concrete Laboratory at UML. The water-to-cement ratio of the concrete was approximately 0.52. The wooden formwork on slabs 1~3 was removed after the curing process was complete; the forms were left on slab 4 because it was not ponded. After formwork was removed, the exposed ends of the bars were coated with epoxy to prevent accidental alt spillage from corroding the rebars. Insulated wires were welded to one end of the rebars in order to provide a place to connect one end of the voltmeter. Wires were attached to only one end of the bars. In slabs 1 and 2, sixteen rebars were installed in two layers per slab, while twenty-eight rebars were used in two layers per slab in slabs 3 and 4. The concrete cover in slabs 1 and 2 were 1.5” and 2.0”, respectively. Three concrete covers (1.5”, 2.0”, 2.5”) were used in slabs 3 and 4. In slabs 3 and 4, five rebars were buried at 1.5” concrete cover, five at 2.0”, and four at 2.5”.

Three-inch height dams were built from acrylic sheets to keep the saline solution on the slab. The pieces of acrylic were attached to the top of the slabs with silicone rubber; the pieces were also attached to each other. Silicone was also placed in between slabs 1 and 2 to eliminate water transfer between the sides of the slabs.

Three RC slabs were subjected to an accelerated corrosion test while the fourth slab remained as a control. The accelerated corrosion test consists of a weekly ponding-and-drying cycle in which sodium chloride solution of 15% concentration was used. In each cycle, ponding period takes four days and drying period three days. Slabs 1 and 2 were cast adjacent to each other and the saline solution allowed to flow from one surface to another. Slabs 3 and 4 are separated from each other (Fig. 1).

The saline concentration (15%), relative humidity (50%), and temperature (100°F in drying, 73°F in ponding) were kept constant to create a controlled environment for accelerated corrosion. HCP measurements were taken at the end of the drying period. Climate control (temperature and relative humidity) was achieved using two heaters and a humidifier placed under a plastic tarp. The tarp was suspended from six wooden posts attached to a wooded base of the slabs. Temperature and relative humidity were monitored throughout the experiment using two wireless thermo-humidity sensors at a sampling rate of 15 minutes. Fig. 2 shows the plastic tarp and the RC slabs in the Concrete Laboratory at UML.

HCP DATA COLLECTION

HCP measurements were collected every week using a silver/silver chloride (Ag/AgCl) electrode. When collecting HCP data, the slabs were pre-wetted several hours before the measurements were taken to ensure sufficient conductivity at the surface of concrete and a damp cloth was placed between the electrode and the concrete surface. All HCP measurements were taken directly over the rebars every eight inches along the rebars. This ensures the least amount of resistivity by the concrete. The steel rebars in slabs 1 and 2 were placed in the longitudinal direction along the length of the slab. The rebars in slabs 3 and 4 were placed in the lateral direction (Fig. 2). Along each steel rebar, HCP measurements were collected every eight inches, resulting in nine points per rebar in slabs 1 and 2 and five points per rebar in slabs 3 and 4. To ensure the RC slabs had developed its mechanical strength, no HCP measurements were taken during the first 28 days. In slabs 1 and 2, nine HCP points were collected per rebar, while five HCP points were collected per rebar in slabs 3 and 4. There were 72 HCP points on slabs 1 and 2, and 70 HCP points on slabs 3 and 4. Fig. 1 shows the points where HCP measurements were taken.

The Ag/AgCl HCP measurements were converted to copper/copper sulfate ($Cu/CuSO_4$) values for data interpretation, according to ASTM C876. The HCP measurements lower than the threshold HCP (-350 mV) indicate high potential of corrosion.

RESULTS

Time-dependent average and minimum HCP curves of all four RC slabs are provided in Fig. 3. In Fig. 3, it is observed that the slab 4 HCP curve is well above -350 mV, indicating no corrosion activities inside the slab. Until the fifty-second week of the experiment, based on the average HCP measurements collected from all RC slabs, slab 1 shows most severe corrosion (average HCP lower than -380 mV), while slab 2 and 3 shows an average HCP around -140 mV and -240 mV, respectively. This result is evident and in good agreement with visual inspection. Fig. 4 shows two major locations on slab 1 with spreading rust on the surface of slab 1. Fig. 5 is the close-up of the rust location on the left of slab 1, while Fig. 6 is the close-up of the rust location on the lower right of slab 1.

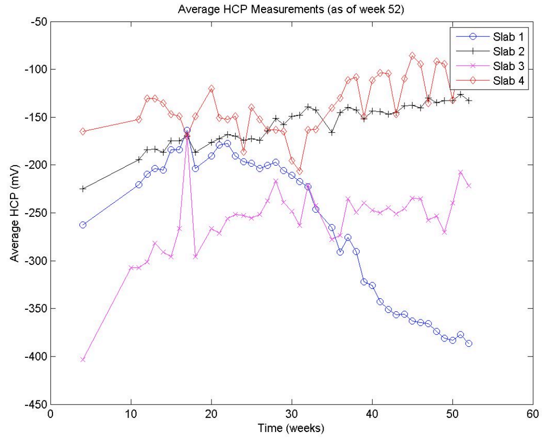

Fig. 3 Average HCP measurements (52 wks)

Fig. 4 Surface rust locations on slab 1

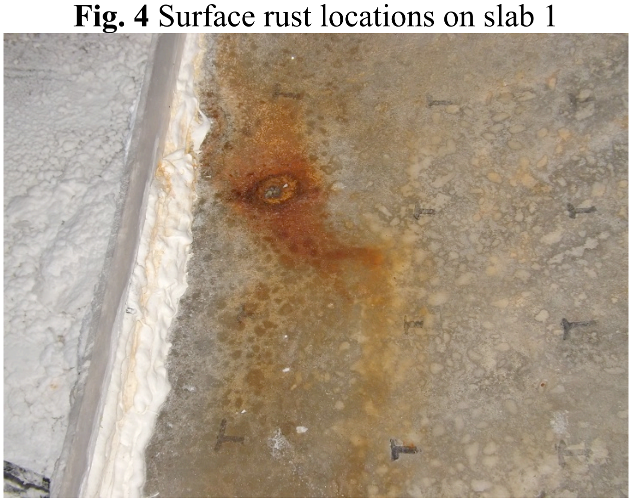

Fig. 5 Close-up surface rust location on the left of slab 1

In the analysis of minimum HCP measurements, the locations with minimum HCP measurements on each slab at the fifty-second week were used to develop the time-dependent HCP curves. Fig. 7 shows the minimum HCP curves

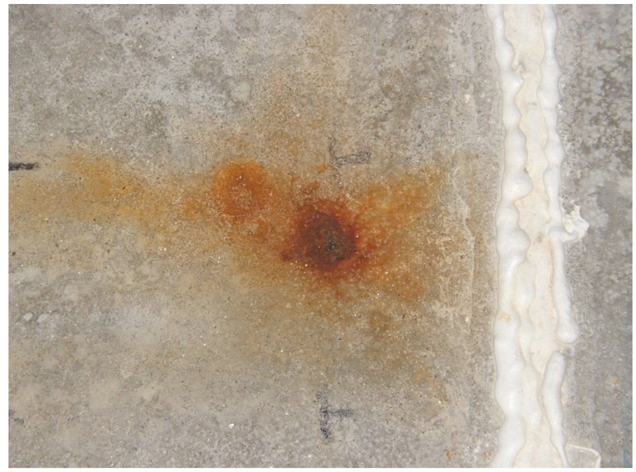

Fig. 6 Close-up surface rust location on the lower right of slab 1

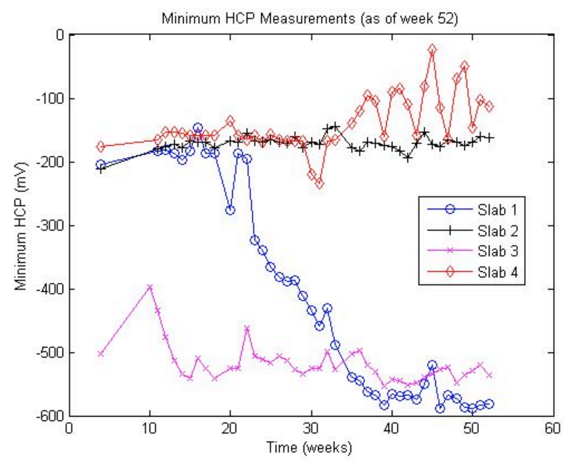

Fig. 7 Minimum HCP measurements (52 wks)

In Fig. 7, the minimum HCP location on slab 1 shows a steady descending trend for fifty-two weeks. Slab 3 also demonstrates a descending trend, while minimum HCP locations on slabs 2 and 4 show little or no corrosion activities. Note that the "minimum HCP location" on each slab was determined based on the HCP data at the fifty-second week; the minimum HCP location could change from one week to another, depending on the corrosion rate and level of activities within each slab. Slab 1 HCP curve was as expected with the HCP steadily decreasing until it reached a minimum of about -580 mV. Slab 2 HCP curve decreased dramatically in the first few weeks, but then rose slightly and settled at about -180 mV through the rest of the experiment. Slab 3 HCP curve took a sharp dip at the beginning, but stayed at about -550 mV with no significant variation after week 10. Slab 4 HCP curve is the control slab; its data remained fairly constant until about week 30 but fluctuated widely for the final weeks about -120 mV.

In the modeling of time-dependent HCP curves, 4^{th}-order polynomial models were chosen to develop model parameters. All curve-fitting models were obtained with a 95% confidence level. Residuals (R^2 value) in these models were also calculated to evaluate the performance of each model. Eq. (1) presents the form and parameter definition of the 4^{th}-order polynomial model.

$$HCP(t) = P_1t^4 + P_2t^3 + P_3t^2 + P_4t + P_5 \quad (1)$$

where HCP is the half-cell potential measurement (mV), t the measurement time (week), P_1, P_2, P_3, P_4, and P_5 model parameters. Table 1 lists the model parameters for the minimum HCP curves of four slabs, while Table 2 lists the model parameters for the average HCO curves.

Table 1. Model parameters for minimum HCP

slab	1	2	3	4
P_1	-3.722e-4	1.575e-5	1.860e-5	-5.037e-4
P_2	6.16e-2	9.032e-4	-2.116e-3	5.574e-2
P_3	-3.21	-0.1928	0.1145	-1.988
P_4	49.05	6.771	-4.405	26.21
P_5	-377.8	-234.4	-451.9	-261.5
R^2	0.97	0.46	0.31	0.51

Table 2. Model parameters for average HCP

slab	1	2	3	4
P_1	3.399e-4	-3.614e-5	-4.226e-5	-3.736e-4
P_2	-3.102e-2	4.985e-3	1.138e-2	4.444e-2
P_3	0.6127	-0.2572	-0.8518	-1.725
P_4	2.375	7.219	24.43	25.23
P_5	-280.2	-247.3	-485.4	-263
R^2	0.98	0.91	0.66	0.56

In this time-dependent modeling of HCP, the 4^{th} order term (P_1) was required to achieve a better fit. Linear parameter (P_5) can be used to preliminarily indicate the level of corrosion, while the nonlinearity of HCP curves must be recognized. Figs 8~11 provide the minimum HCP data and fitted curves of all RC slabs. 95% prediction bounds are also illustrated in these graphs. Also, note that the scale in each graph is different.

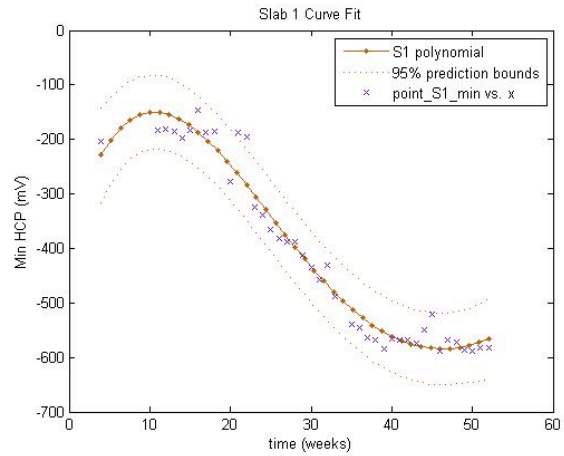

Fig. 8 Data and fitted model of minimum HCP curve on slab 1

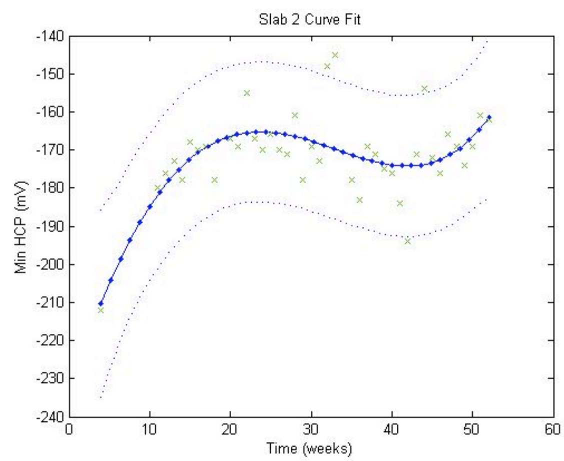

Fig. 9 Data and fitted model of minimum HCP curve on slab 2

Regarding the spatial distribution of HCP measurements, contour maps of HCP data at week 52 were generated. Figs. 12~15 show the HCP contour of all slabs. In Fig. 12, high corrosion activities are found at the lower edges of the slab. This is in good agreement with the visual images on slab 1 (Fig. 4). Comparing Fig.

12 with Fig. 13, it is evident that the increase of concrete cover significantly reduces the corrosion potential.

In slabs 1 and 2, since the rebars are

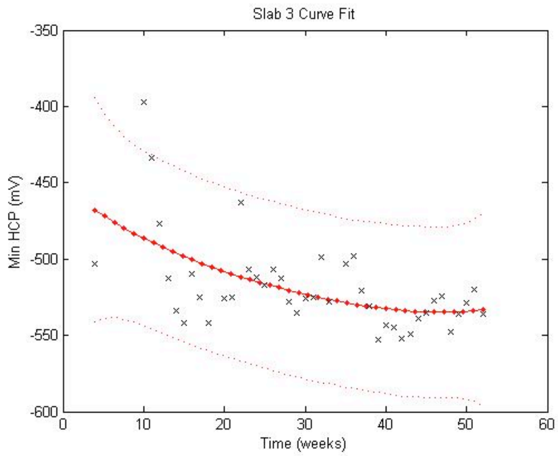

Fig. 10 Data and fitted model of minimum HCP curve on slab 3

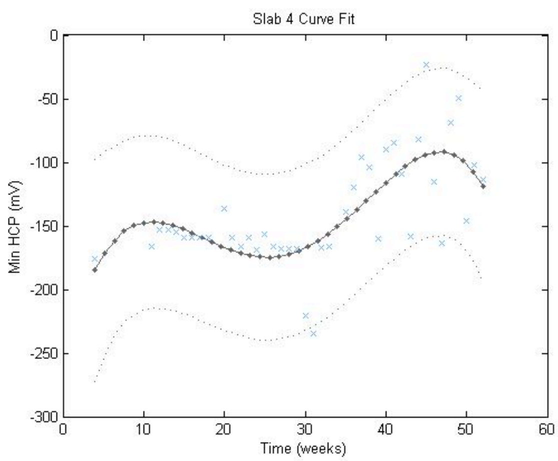

Fig. 11 Data and fitted model of minimum HCP curve on slab 4

In Fig. 14, the spatial distribution of HCP on slab 3 illustrates a general ascending trend along the length direction of the slab, except for the HCP data over one rebar at coordinate 33.5. This ascending trend coincides with the increase of concrete cover from 1.5” to 2” to 2.5”. As for the control slab 4, spatial variation of HCP is within -100 mV throughout the slab in week 52. This information can be used to indicate the background noise from concrete in HCP measurements.

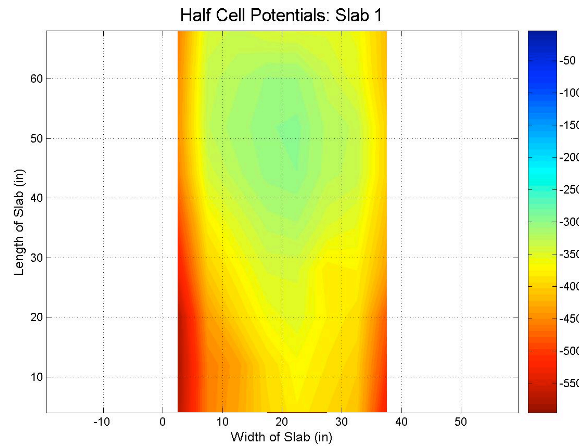

Fig. 12 HCP contour map of slab 1

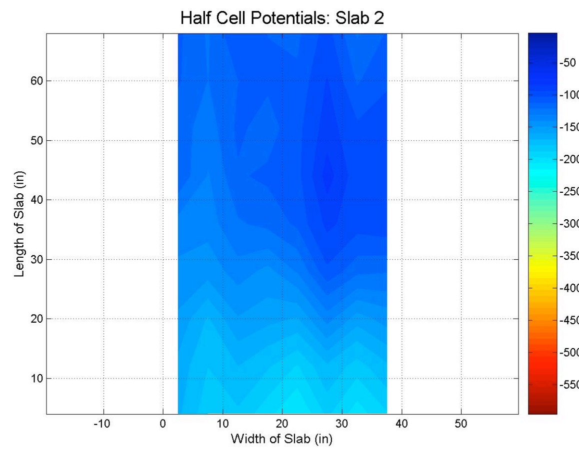

Fig. 13 HCP contour map of slab 2

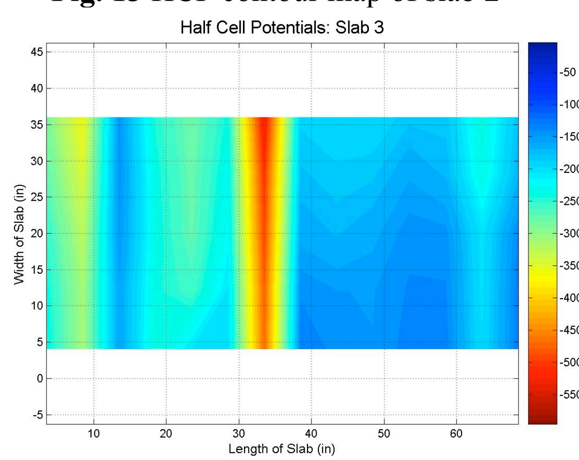

Fig. 14 HCP contour map of slab 3

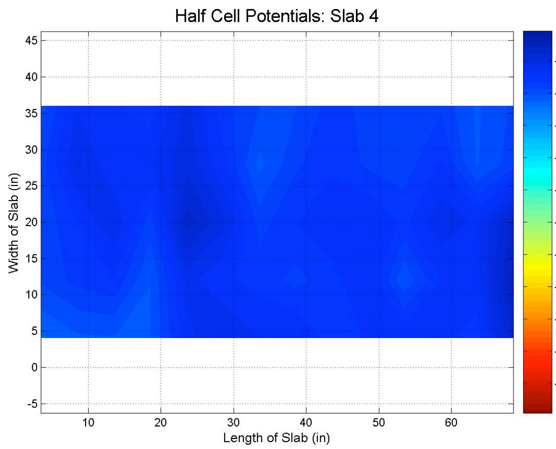

Fig. 15 HCP contour map of slab 4

Figs. 16~19 provides the three-dimensional (3D) illustrations of HCP data of Figs. 13~15.

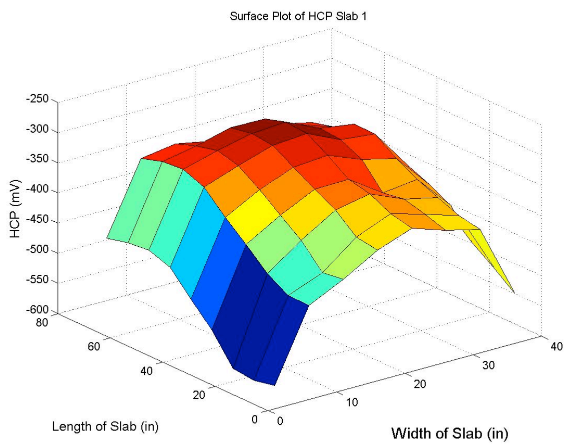

Fig. 16 3D HCP contour map of slab 1

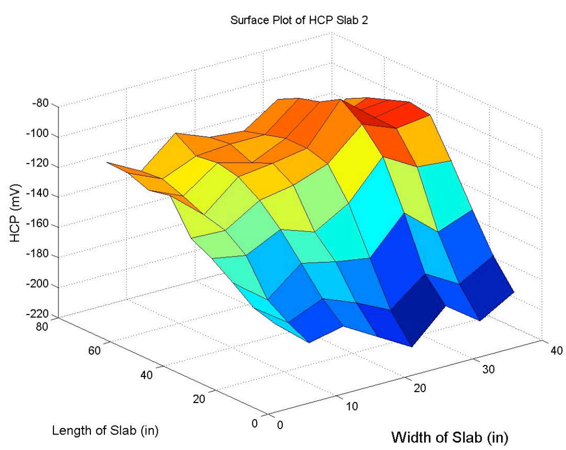

Fig. 17 3D HCP contour map of slab 2

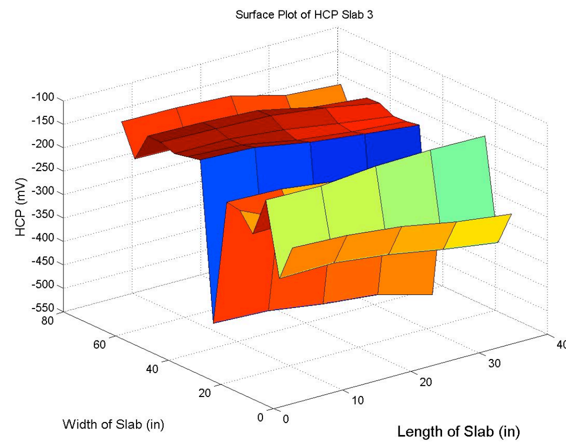

Fig. 18 3D HCP contour map of slab 3

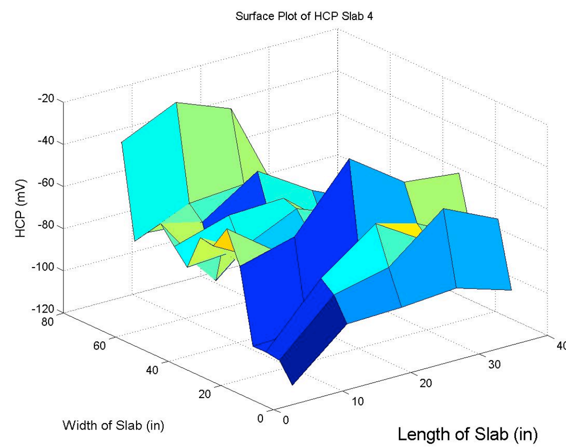

Fig. 19 3D HCP contour map of slab 4

CONCLUSIONS

In this paper, an accelerated artificial corrosion test of four reinforced concrete (RC) slabs, their corrosion monitoring using the HCP method, and the modeling of HCP measurements are reported. After fifty-two weeks of weekly ponding and drying cycles and collecting HCP data almost every week, the spatial and temporal distributions of HCP measurement on RC slabs with three different concrete covers (1.5”, 2.0”, and 2.5”) were developed. Findings are summarized in the following:

- From our experimental result, it is validated that the increase of concrete cover results in the decrease of corrosion activities or higher HCP measurements (Figs. 12 and 13).

- Comparing measured HCP data with visual inspection on the slabs, spreading surface rusts were found at the locations with very low HCP values (<-500mV) (Figs. 4 and 12). This observation will be used to predict the onset of surface rust on the slabs in the future.
- Although the quality of concrete was carefully controlled, from the HCP data collected on unponded slab 4, certain level of fluctuation was observed in the HCP data. This information can be used to indicate the level of HCP background noise and used to de-noise HCP data.

Furthermore, our results also show the minimum HCP value can be used to approximate the corrosion activity of the entire slab with reasonable accuracy. Ongoing research work includes improving prediction models and continuing the accelerated artificial corrosion test.

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