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Short Communication

Effectively Analysis of Concrete Bridge Deck Corrosion using Electrochemical Impedance Spectroscopy

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Corrosion condition measurement of steel reinforcement in concrete is important in concrete constructions. Electrochemical impedance spectroscopy (EIS) is one of the effective technique for measuring corrosion condition based on the electrical impedance value. In this contribution, the reinforcing steel corrosion conditions in concrete bridge decks were studied. Several effects of parameters including the presence of a sealant, temperature and moisture content were investigated. Results suggest the EIS is a valuable tool for non-destructive bridge deck condition assessment. The best frequency range used for measurement is 100 Hz to 1 kHz.

Keywords: Electrochemical impedance spectroscopy; Concrete bridge deck; Corrosion potential; Chloride concentration;

1. INTRODUCTION

Corrosion assessment is an important aspect for evaluating the safety of the concrete constructions. For concrete bridge specifically, the damage of the bridge can be affected by the corrosion of the embedded reinforcing steel. Raining, automobile exhaust and deicing salts can result in the chloride infiltration for concrete bridge can consequently trigger the corrosion process [1, 2]. In order to evaluation of the chloride infiltration effect, different techniques were developed for corrosion potential measurement such as modulated confinement of the applied current method [3, 4], multiple electrode method [5] and galvanostatic pulse method [6-9]. For traditional methods, the resistance of concrete to chloride penetration cannot be directly measured. For concrete bridge deck specifically, he measurement cannot provide the information of the depth of penetration unless the bare deck has been accessed. Moreover, use of traditional method such as two-pronged probe can subject to operator error.

Besides the traditional ways, the emerging application of electrochemical impedance spectroscopy (EIS) is an alternative way for corrosion potential measurement [10-21]. EIS measurement is performed by applying alternating potentials of varying frequencies between the embedded reinforcing steel. For this particular technique, electrical impedance value was measured and then used for evaluating the corrosion potential of steel reinforcement in concrete [22-26]. Commonly, current is injected vertically into the concrete bridge deck between the surface and the embedded reinforcing steel, usually the top mat, to evaluate the degree to which the reinforcing steel is protected from chloride infiltration by the entire bridge deck system. That is, the vertical nature of EIS testing allows full penetration of the current through all layers from the deck surface down to the reinforcing steel, which, unlike typical resistivity testing, allows evaluation of the protection against chlorides provided by any deck surface treatments, the full depth of the concrete cover, and any rebar coatings [27-30]. This method could interrogate all materials between the two electrodes. Sánchez and co-workers identified the different processes in the passive layer growth over steel rebar surface using EIS method [31-33]. Vedalakshmi and Palaniswamy investigated the rebar–concrete interface electrochemical phenomenon using EIS method [34]. However, the drawbacks of the EIS method is its complex process, time-consuming measurement, which hardly to be applied for on-site measurement. Therefore, development of a simple EIS based method for field testing of bridge decks corrosion potential is essential. In this contribution, we investigated the sensitivity of EIS measurement by changing the frequencies according to the properties of the deck. The optimized frequency range was proposed for various levels of corrosion conditions. Moreover, several effects of parameters including the presence of a sealant, temperature and moisture content were investigated as well.

2. EXPERIMENTS

2.1 Electrochemical impedance spectroscopy measurement

Electrochemical impedance spectroscopy (EIS) measurement was carried out at an Agilent 33250A function/arbitrary waveform generator. A 6-in.-diameter circular probe consisted of an acrylic base, a foam interface and an aluminum foil electrode was used for testing concrete slabs. The concrete slabs were prepared at size of 50 cm × 45 cm × 14 cm and containing a length of #5 reinforcing steel. For concrete slab preparation, Type I/II portland cement and Class F fly ash were mixed at a weight ratio of 80/20. The water to cementitious materials ratio was 0.42.

In order to evaluate the influence of chloride infiltration, the different quantities of sodium chloride was used during the concrete preparation. Concrete slabs containing 0.9 kg, 2.2 kg and 14.5 kg of chloride per cubic yard of concrete were prepared for analysis.

In order to evaluate the EIS change by the presence of the sealant, lithium silicate sealant and silane were successively sprayed on the prepared concrete slab. Another concrete slab was only sprayed by the lithium silicate sealant. EIS measurement was carried out three months after the sealant coating process.

The effect of the sensitivity on temperature was carried out by EIS testing prepared concrete slabs at specific temperature environment. The prepared concrete slabs samples were moved to the target temperature 24 h before EIS measurement. In this study, temperature of 10, 25, and 40°C were investigated.

For moisture effect study, different immersion time treatments were carried out. We prepared concrete slabs were dried at oven first and an EIS measurement was recorded before the moisture content addition. Then, a wet towel was placed over the top surfaces of the slabs. The EIS measurement was carried out at soaking times of 0.5, 1, 2, 6, 12, and 24 h.

Three decommissioned concrete bridge deck slabs from Qiqihar (denoted as B-1, B-2 and B-3) were used as real samples for EIS testing. Three concrete bridge deck slabs were constructed in 1991, 2002 and 2012 with asphalt coverage. The asphalt was removed before the EIS testing

2.2 Statistical Analysis

Effect of temperature on the impedance performance of the concrete slab was analyzed statistically. An analysis of variance (ANOVA) was performed for p value analysis. The null hypothesis for each ANOVA was that the impedance values for the levels were the same, while the alternative hypothesis was that the impedance values for at least two levels were different. Replicate impedance values collected on the same slab, or impedance values collected on replicate slabs when replicate slabs were available, were averaged by frequency, such that a single impedance value was computed for each frequency at each level. Each level was then represented in the ANOVA by a range of impedance values spanning the range in frequency. Each ANOVA produced a *p*-value that was used for evaluating differences between the levels; a *p*-value less than or equal to 0.05 indicated that the difference between at least two levels was statistically significant.

3. RESULTS AND DISCUSSION

The effect of chloride concentration on slabs corrosion was firstly studied. The results confirmed that the concrete impedance can be affected by the chloride concentration. As depicted in Figure 1A, the impedance spectrum of the sample slab without mixed with sodium chloride showed the highest impedance. After an addition of sodium chloride, the impedance showed a clear decline. The impedance spectrum of the slab contains 0.9 kg of chloride per cubic yard showed the second-highest impedance, while the slab with 4.5 kg of chloride per cubic yard showed the lowest impedance. Impedance measurement could be reflected the corrosion potentials of the reinforcing steel because the corrosion process could affect the impedance. An inverse relationship was observed between the impedance and the corrosion rate. It can be explained as the high impedance could restrict the corrosive ions movement, which suppresses the corrosion process. Therefore, the high impedance value implies the less corrosion process.

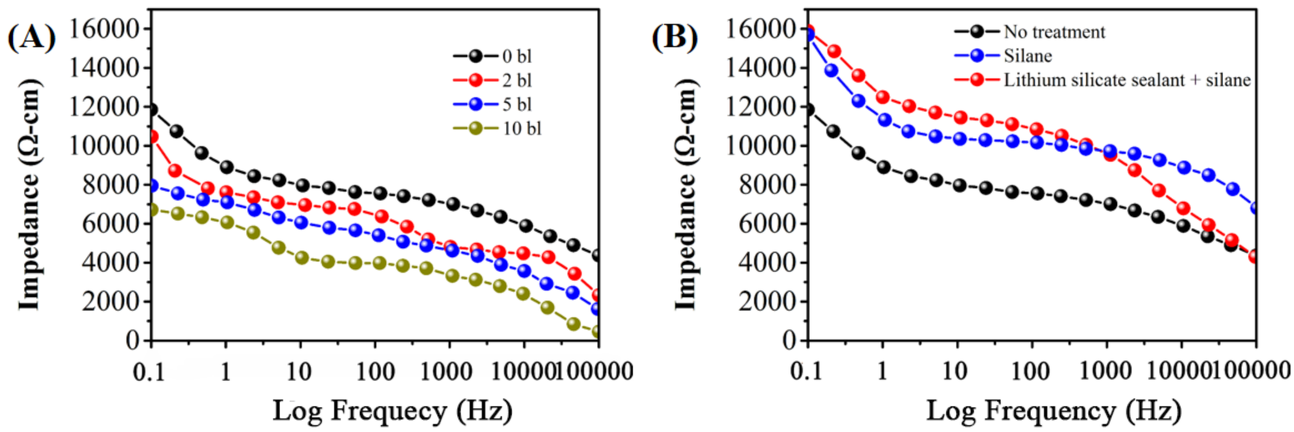

Figure 1. (A) Impedance spectra of concrete slabs contain different concentrations of chloride. (B) Impedance spectra of concrete slabs in the presence of lithium silicate sealant and lithium silicate sealant + silane.

The effect of the presence of sealant was then investigated. Figure 1B shows the impedance spectra of concrete slabs in the presence of lithium silicate sealant, lithium silicate sealant + silane and without any sealant. It can be seen that the presence of the sealant have a significant effect on the impedance performance. Clear enhancements of the impedance values were observed when apply both sealant. The addition of silane slightly enhanced the impedance value of lithium silicate sealant treated concrete slab. Based on this study, the application of sealant could effectively protect the embedded reinforcing steel.

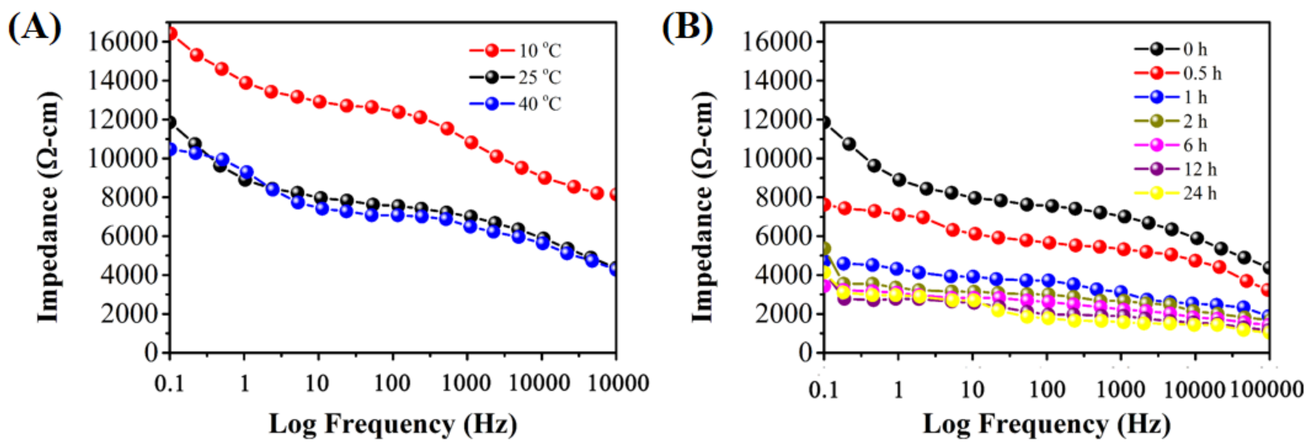

Figure 2. (A) Impedance spectra of concrete slabs measured at different temperature. (B) Impedance spectra of concrete slabs at different immersion time.

Temperature also could affect the impedance performance of the concrete slab. Figure 2A shows the impedance spectra of concrete slabs measured at 10, 25, and 40°C. It can be seen that the highest impedance value was obtained at 10°C while the lowest impedance value was obtained at 40°C, suggesting the increasing of temperature could accelerate the corrosion process and result a low impedance performance. Analysis of variance was used for analysing the sensitivity of impedance to the temperature. Both p-value were less than 0.05, suggesting the temperature had a statistically significant effect in the concrete corrosion process.

Moisture content is a well-known factor could affect the corrosion rate of the reinforced steel. Figure 2B shows the impedance spectra of concrete slabs at different soaking periods. It can be seen that the impedance value dramatically decreased after contact to the moisture. After 2 hours, the impedance spectra started to exhibit a slowly decreasing. Based on the result, lower moisture environment could effectively prevent the corrosion process.

In order to find out the optimum frequency range for measurement of corrosion status of the reinforcing steel in concrete bridge decks, t-test and analysis of variance were used. Figure 3 shows the relationship of the impedance values with the p-value. p-value equal or less than 0.05 suggests the target parameter has the statistically significant effect in the concrete corrosion process. Therefore, the choice of the frequency range requires the deck properties could results a p-value less than 0.05. As shown in the figure, the area below the dot line was considered as the most interest area. Based on the observation, the frequency range between 100 Hz to 1000 Hz presented the maximum of the low p-value. In order to avoid the power grid noise harmonics (the electric power grid operates frequency is 50 Hz in China), 190 Hz was used for the following real bridge deck slab sample measurement. For comparison, Argyle [35] claimed the impedance testing in the frequency range of approximately 100 Hz to 1 kHz would be expected to provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system. He used a single frequency of 200 Hz for impedance testing of the decommissioned bridge deck slabs, because the electric power grid operates on a frequency of 60 Hz in U.S.

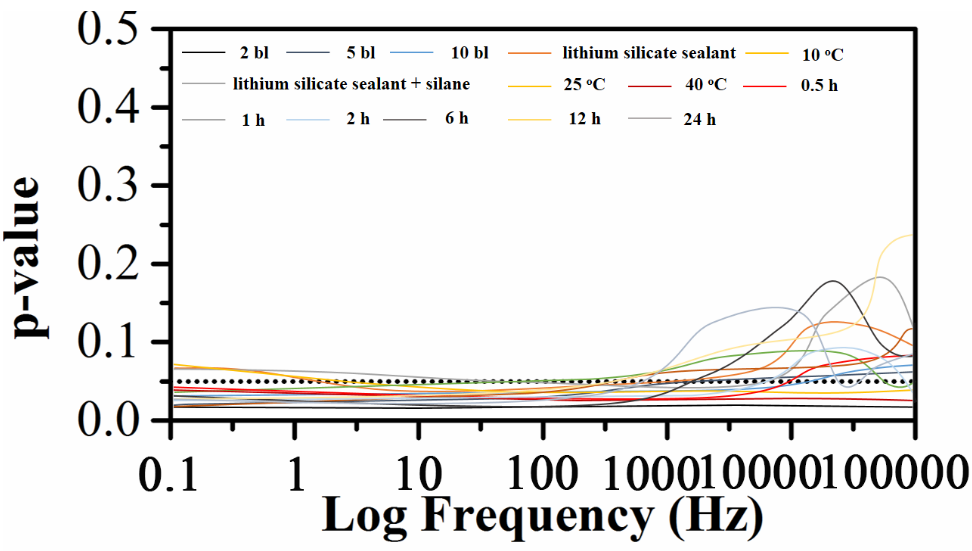

Figure 3. p-values of the above measured impedance data.

Three decommissioned concrete bridge deck slabs from Qiqihar were then used as real samples for chloride concentration testing and impedance testing. The chloride concentration testing was carried out at 3 cm depth of each concrete bridge deck slab. The impedance testing was carried out using a guard ring system described in the experimental section. The embedded rebar was connected with a steel screw at the saw-cut edges for electrode connection. Figure 4A-C show the contour plots of chloride concentration as obtained from the vertical impedance instrument at 190 Hz.

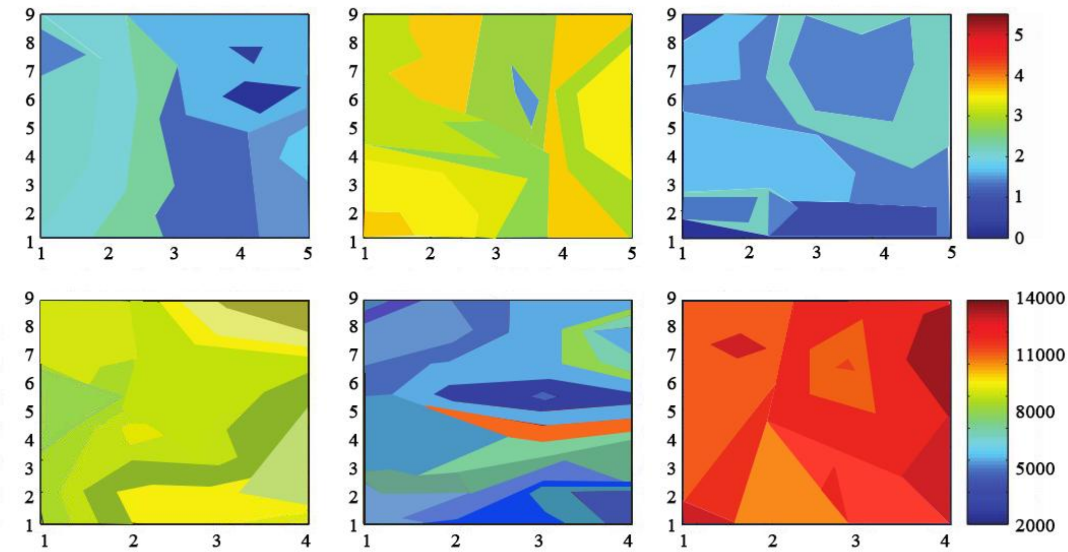

Figure 4. Contour plots of chloride concentration for (A) B-1, (B) B-2 and (C) B-3. Contour plots of impedance for (A) B-1, (B) B-2 and (C) B-3.

As shown in the figure, the B-2 bridge deck slab had the highest average at 2.37 kg of chloride per cubic yard of concrete, while B-3 bridge deck slab had the lowest average at 0.47 kg of chloride per cubic yard of concrete. The average chloride concentration of the B-1 bridge deck slab was 1.02 kg of chloride per cubic yard of concrete. Therefore, the B-3 bridge deck slab showed the best chloride filtration condition, which is consisted with the observed condition. Figure 4D-F show the contour plots of impedance as obtained from the vertical impedance instrument at 190 Hz. It can be seen that the B-3 bridge deck slab showed the highest impedance value, suggesting the best corrosion condition, while the B-2 bridge deck slab showed the second highest impedance value. In contrast, the B-1 bridge deck slab showed the lowest impedance value, suggesting the worst corrosion status. Based on above tests, the B-3 bridge deck slab showed the lowest average chloride concentration and exhibited the highest impedance value. The above measurements well agreed with the statement proposed by Bartholomew et al. [27] The vertical impedance measurements proved useful to bridge engineers and managers seeking to optimize applications of maintenance and rehabilitation treatments through improved assessments of deck protection systems.

4. CONCLUSIONS

The sensitivity of EIS characterization towards bridge deck slab was investigated at various frequencies. The influence of the presence of a sealant, temperature and moisture content for EIS measurement results were studied in detail. Based on the t-test and analysis of variance, the particular frequency range from 100 to 1000 Hz was used for analysis. For real bridge deck slab measurement, 190 Hz was chosen as the measurement frequency. The chloride concentration testing and impedance testing were carried out. The results were represented as contour plots for observation. Sample B-3 showed the lowest corrosion condition.

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