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Compact passive wireless reinforced concrete corrosion initiation sensor that can be installed in existing steel

Khalada Perveen, Greg. E. Bridges, Sharmistha Bhadra and Douglas J. Thomson

Dept. of Electrical and Computer Engineering, University Of Manitoba, Winnipeg, Canada
umpervvee@myumanitoba.ca , bridges@ee.umanitoba.ca , umbhadra@cc.umanitoba.ca and
Douglas.Thomson@ad.umanitoba.ca

Abstract: It is important to detect corrosion at the initiation stage for effective intervention to minimize the impact of corrosion. In this paper, we present a passive inductively coupled coil sensor that can detect corrosion potential with respect to a reference electrode. The sensor has a sensitivity of 0.13 kHz/mV. Several experiment results of different geometry of this sensor show that it can measure corrosion potentials with a resolution of less than 10 mV. The sensor is 25 mm in diameter and is intended to be installed by drilling a 25 mm or greater hole into existing concrete. The bottom of the hole is filled with mortar and the sensing electrodes are embedded within the mortar. Chlorides from the concrete diffuse into the mortar eventually reaching the electrodes leading to rise in the corrosion potential. This corrosion potential can be used indicate the level of chlorides within the concrete. The generated potential is a measure of the transfer of electron charge between the metal and its environment; here between the steel and the concrete. This is a property of the steel/concrete interface and not of the metal itself. Thus, it is impossible to determine the absolute value of this electrochemical potential and it is necessary to have a reference electrode to measure the potential difference of steel with respect to this reference electrode. The presented sensor can be fabricated at very low cost and is suitable for corrosion monitoring of existing structures.

Keywords: *Corrosion potential sensor, Resonant frequency, Inductive coupling, RFID coil, Interrogator*

1. Introduction:

Durability and safety of reinforced concrete structures and the corrosion of steel reinforcing has received great attention in recent years. One of the main reasons for corrosion initiation of reinforcement steel is Cl^- ingress from the de-icing salts used extensively to clear snow and ice in winter [1].

Corrosion monitoring is necessary for safety and infrastructure management but most of the sensing technologies use a wired connection. The large installation costs of the wired connection from the sensors to the data acquisition system make it impractical especially for installation in existing structures. These costs make its economic value of wired sensors unattractive [2].

Initially, the reinforced concrete maintains a very high pH which passivates the steel reinforcement by forming a thin layer of oxide film on the steel. However, Cl^- ingress lowers the pH in the concrete and causes the passivation layer to become compromised. Below a threshold pH level the reinforcement becomes active and corrosion is initiated [3]. Several techniques have been introduced to measure the corrosion but they are not reliable predictors of corrosion initiation [4].

In this paper, the embedded coupled coil sensor detects the corrosion potential with respect to a reference electrode which is also embedded in the concrete [5-8]. As the sensor is passive, so it can be monitored wirelessly by a portable interrogation system over the life time of infrastructure. The presented sensor is designed on a one-sided printed circuit board (PCB), which small size allows the unimpeded transport of reactants from surroundings media to the electrodes.

2. Inductively coupled coil sensor theory

I. Operating principle of the corrosion initiation sensor

The sensor is simple in design and attractive for mass manufacturing making it suitable for large scale deployment. A block diagram of coupled coil sensor is shown in fig. 1 where sensor is embedded inside concrete block. The sensor coil along with the sensing circuit forms a LC resonator.

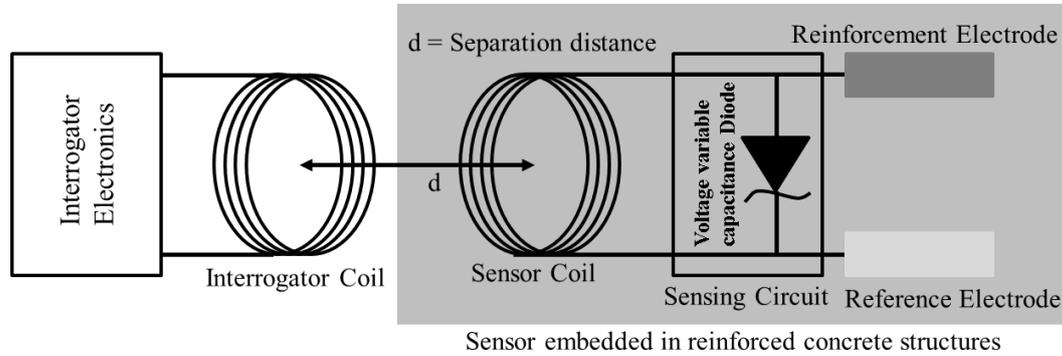


Figure 1: Block diagram of coupled coil sensor

One terminal of the sensing circuit is connected with two electrodes and other terminal is ended with the sensor coil. Concrete is an electrolyte. When two different metals come to a contact with an electrolyte it forms a galvanic cell. Once corrosion process initiates it generates a potential between the two electrodes changes the junction capacitance of the varactor diode. This junction capacitance change of the varactor diode changes the sensor resonant frequency. An external reader coil is used to track the sensor resonant frequency [7, 8].

The corrosion potential generated from two electrodes changes the junction capacitance of the varactor diode as shown in eqn. 1.

$$C_j(V_C) = C_0(1 - V_C/\phi)^{-\gamma} \quad (1)$$

Where C_0 is the junction capacitance at zero bias, V_C is the voltage across the varactor, ϕ is the junction built in potential (~ 0.5 volts for Si) and γ is the doping profile (0.5 for an abrupt junction and 2 for hyper-abrupt junction) factor.

The sensor resonant frequency is defined as

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi \sqrt{L_2 C_j(V_C)}} \quad (2)$$

Where f_0 is the resonant frequency, L_2 is the sensor coil inductance. Therefore, by measuring the sensor resonant frequency, we can determine the corrosion potential using a measured frequency to voltage conversion [6].

II. Circuit modelling of the sensor and the Interrogator

Figure 2 shows a SPICE model for coupled coil sensor. The interrogator or reader circuit consists of a transient or continuous voltage source whose amplitude and timing are chosen to avoid the nonlinearity of the varactor diode [7-9]. In the transient mode the interrogator works by first exciting the sensor coil then switching to a receive state. In the receive state the interrogator amplifies the signal emitted by the sensor coil. The signal is then analyzed to determine the sensor coil resonant frequency. The model is shown in figure 2; V_{cell} is produced by two electrodes embedded in the concrete as a simple galvanic cell, whereas concrete acts as an electrolyte.

The circuit paramters were determined by fitting the results to the model or by direct measurement using an impedance analyzer (Agilent 4294A). In the above circuit modeling, $R1 = 50\Omega$,

parasitic capacitance of interrogator coil $C1 = 1.2$ pf, series resistance of interrogator coil $R1 = 0.474\Omega$, interrogator coil inductance $L1 = 3.32\mu\text{H}$, similarly for sensor coil $L2 = 2.53\text{mH}$, $R2 = 176\Omega$, and $C3 = 3.384\text{pf}$. The other components are physical circuit elements $C4 = 1\text{nf}$, Varactor diode (NXP - BB202), $R4 = 10\text{G}\Omega$, $R3 = 1\text{M}\Omega$ and $C5 = 100\text{pf}$. Moreover, $R3$ and $C5$ acts as a protection circuit for varactor diode from the static charge when the sensing circuit is not connected with coil and electrodes and $R4$ is the leakage path of the varactor diode.

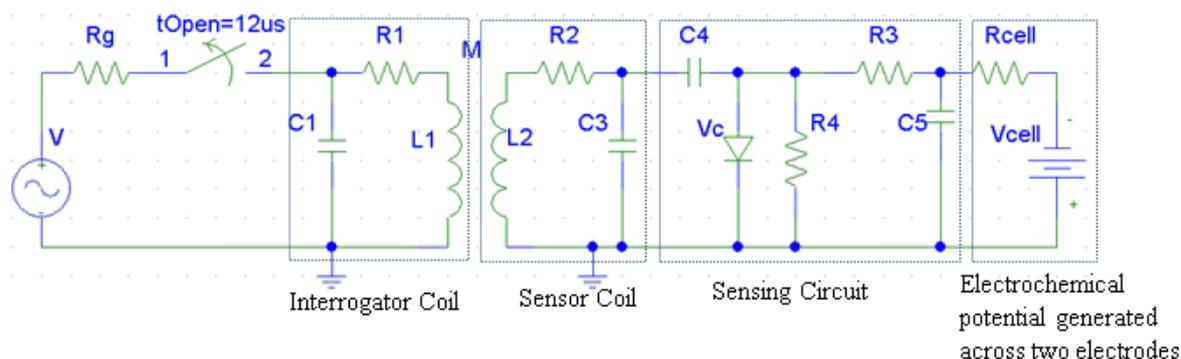


Figure 2: Equivalent circuit of corrosion initiated sensor coupled with Interrogator

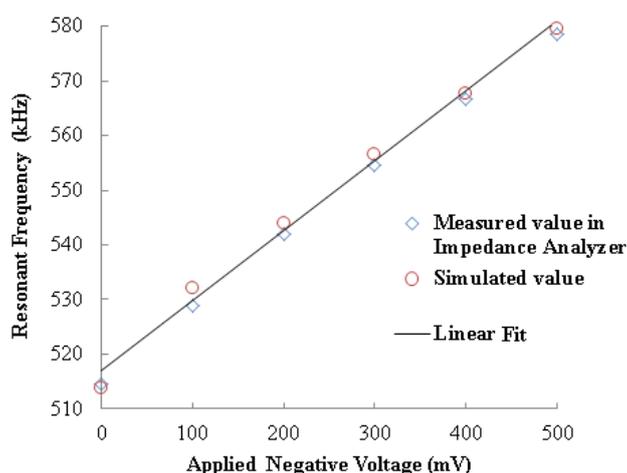


Figure 3: Results of simulated and measured value of the corrosion initiating sensor

Using this circuit, model SPICE simulations of the change in resonant frequency were estimated. These were compared between simulated and measured values in an impedance analyzer (Agilent 4294A). The results of these are shown in figure 3 and are in close agreement.

3. Simulated corrosion voltage test

An applied controlled DC voltage using a precision power supply (HP 6115A having a resolution less than 5mV) test was done on the sensor for calibration purposes.

The source voltage was varied from 0 mV to 500 mV negatively. Fig. 4 shows the test set up and the calibration results which is a linear fit.

A resonant frequency shift of $\sim 0.13\text{kHz/mV}$ is observed. Using this calibration the corrosion voltage can be related to resonant frequency shift and can be extracted using equation 3 for corrosion initiating PCB sensor.

$$V(\text{mV}) = 8.036 \times f_0(\text{kHz}) - 4148.8 \quad (3)$$

It is important to limit the coupling between two coils to avoid the nonlinearity of the varactor diode.

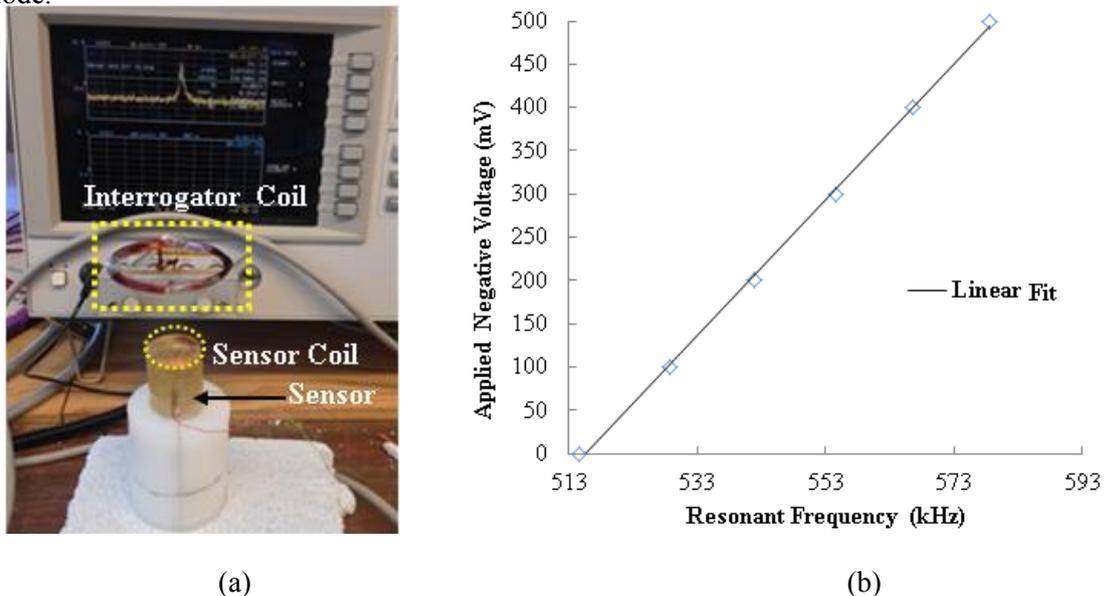


Figure 4: (a) Prototype DC test set up (b) Calibration of the sensor using negative DC potentials

4. Sensor performance with interrogation distance

The sensor performance was measured with different interrogation distance to determine the corrosion potential error that comes from the changing separation distance between interrogator and sensor coil. Figure 5 shows the sensor performance with separation distance between the sensor and the interrogator coil.

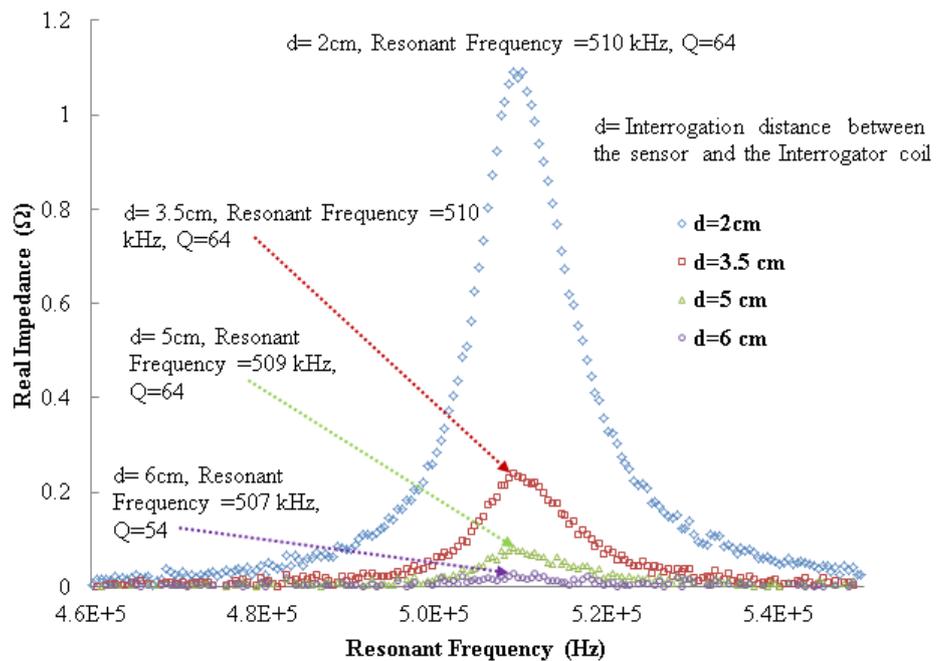


Figure 5: Sensor performance with separation distance

Table 1: Introduced equivalent potential error and SNR with separation distance for corrosion initiation sensor

Separation Distance d=cm	Resonant Frequency f ₀ =kHz	Sensitivity = kHz/mV	Equivalent potential error= mV	SNR(dB)
2	510	0.13	NIL	45.9
3.5	510		NIL	32.3
5	509		7.69	21.9
6	507		23.08	9.13

An obtainable resonant peak was detected with a maximum separation distance of 5 cm. A quadratic curve fitting algorithm was used to estimate the sensor resonance peak but the increasing separation distance imposes surrounding noise giving a maximum, 0.196% measurement error of sensor resonant frequency for an interrogation distance of 5cm [10]. This translates to a potential error of 7.69 mV. The table 1 demonstrates the signal to noise ratio and the equivalent voltage error of the sensor with increasing separation distance.

5. Integration and Encapsulation of sensor

The encapsulation of the sensor is required to protect from the hermetic environment inside of concrete. We have enclosed our sensor in several steps. A printed circuit board design is shown in figure 6(a). The dimension of the PCB is 30 mm×25 mm. A simple RFID coil with a 23 mm diameter is used as a sensor coil. It is glued at the top of the PCB by non-conductive epoxy (NHP 112 0807 Industrial grade). As reference and reinforcement electrodes, 316-grade stainless steel and 1018- grade mild steel are being used respectively.

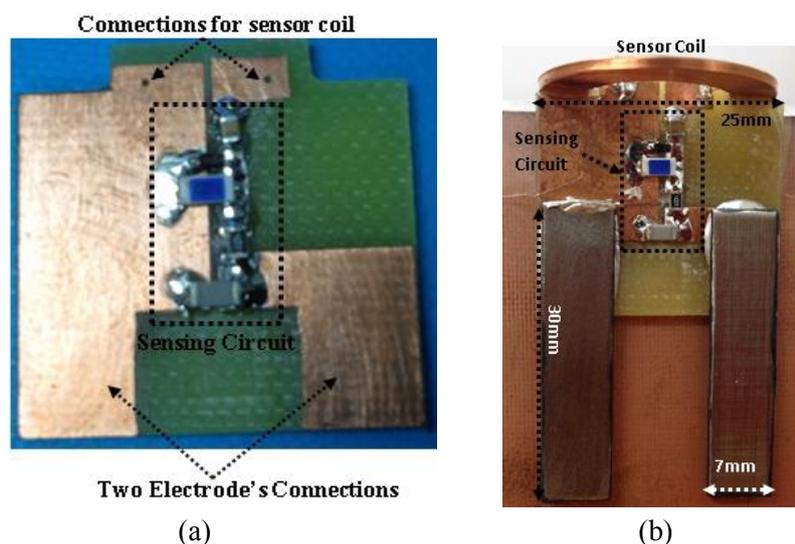


Figure 6: (a) Sensing circuit on PCB (b) PCB sensor without electrical wire connections

The electrode size is 7 mm × 15 mm. The electrodes are bonded with the sensing circuit using MG Chemicals 8331 conductive silver epoxy [7, 8]. The edge of the electrodes is coated using nail polish (Sally Hansen Hard as Nails Xtreme Wear) to avoid the crevice corrosion [7, 8] which is shown in figure 6(b). Two electrical wire connections are made from two electrodes for direct measurement of the corrosion voltage which is being compared with the wireless measurement.

Figure 7(a) shows a fully enclosed sensor including wire connections which is ready to be embedded. From figure 7, roughly the sensor size is 2 inches × 1 inch.

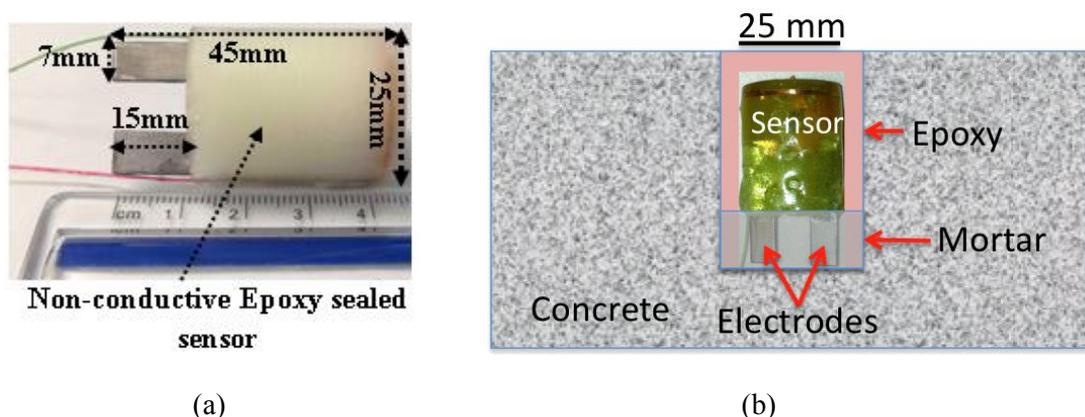


Figure 7: (a) Sealed sensor which is ready to be embedded (b) Sensor is ~25mm in diameter and is intended to be embedded into mortar placed in the bottom of a hole drilled into the concrete. Chlorides diffuse into the mortar leading to a rise in the corrosion potential. The potential can be measured using external coils. The potential can be read with 10 mV resolution.

6. Accelerated Corrosion test results

Results of tests using DC potentials, see figure 4, show the linear response with potential resolution of less than 10 mV. Using the same electrodes, but a different geometry sensor, with accelerated corrosion test was carried out using cement based mortar samples. The specimen block is made by Quickrete mason mix (type S mortar, no. 1136). A diffusion test on one of the mortar blocks (water/mortar ratio 0.155) using a water absorption technique was carried out under 100% relative humidity. The moisture diffusivity of the mortar block was estimated to be $D_w = 5.4 \times 10^{-11} \text{ m}^2\text{s}^{-1}$ [8]. The moisture diffusivity of concrete is typically in the range of $10^{-14} \text{ m}^2/\text{s}$, which is almost 600 times lower than mortar used in this work. The electrodes produce a 250 mV corrosion potential with 2% NaCl by weight of water [8]. This level of chloride will cause the initiation of corrosion [11]. From the image taken after the sample was broken away from the electrodes it can be seen that little visible corrosion is present, even though the chloride concentration has exceeded that required to initiate corrosion [8] as shown in figure 8. This demonstrates this sensor is capable of detecting conditions for initiation well before visible corrosion has occurred.

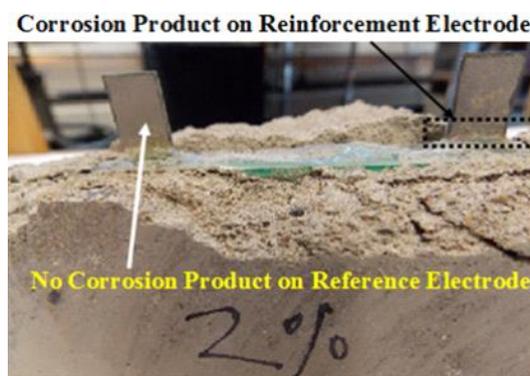


Figure 8. In an accelerated corrosion test with 2% by weight added NaCl compared to added water a corrosion potential exceeded that required for initiation, but no visible corrosion is present.

At present we are carrying out more extensive tests of the diffusion of chlorides within the mortar. The specimen is made by Quickrete mason mix (type S mortar, no. 1136). We made four different percentages 0.4, 0.8, 1, and 1.2 chlorides mixed specimen in which 0.8, 1 and 1.2 are equivalent to 1, 2 and 3 % NaCl mixed mortar specimen respectively in [8]. Each mortar sample has 3 different heights 1cm, 2cm and 3cm. In each height level we cast 3 pairs of reference and reinforcement electrodes which are shown in figure 9. We prepared 36 pairs of electrodes for these experiments. Each electrode is sandblasted to avoid the contamination. Edges and a small portion of each electrode is coated with nail polish (Sally Hansen Hard as Nails Xtreme Wear) to avoid the crevice corrosion [7, 8, 12]. The electrode size is 30 mm × 10 mm same as [8].

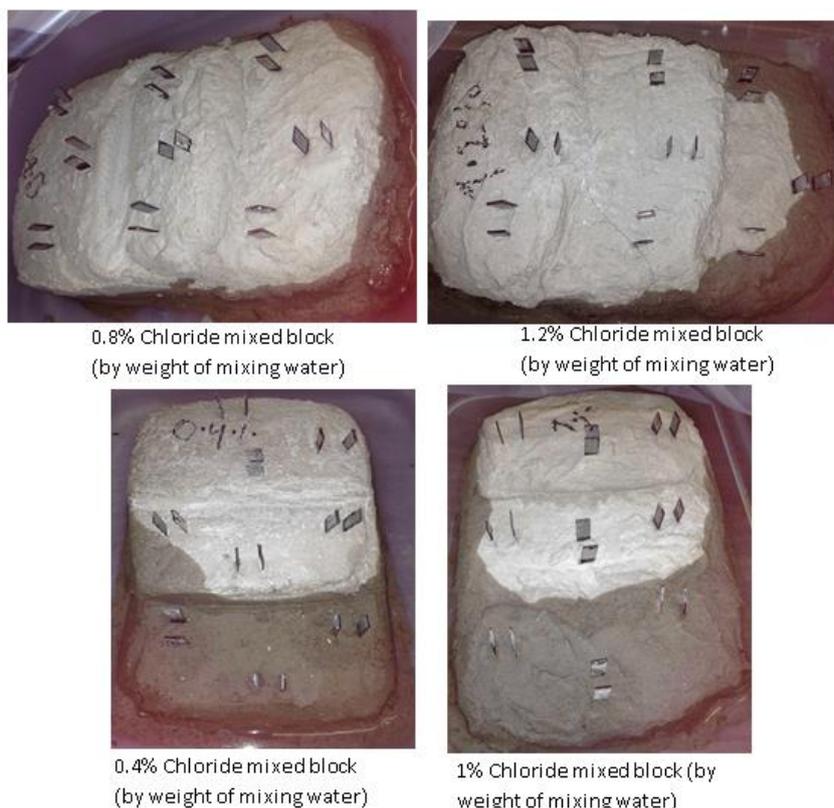


Figure 9: Different percentage chlorides mixed mortar specimen under tests for measuring the diffusion of chlorides

The electrodes are embedded at the same time of making mortar samples. Then it is left 25 days for curing. After 25 days, then it is submerged in DI water which contains almost zero corrosion causing substances. These tests are still in process. The mortar specimens are kept in 100% relative humidity. At the end of these tests we would be able to show the reproducibility of the sensor electrodes, chlorides diffusion rate with distance, and chloride concentration level in existing structures extracted from the generated potential across two electrodes.

7. Conclusion

In conclusion, the sensor is passive and simple in design makes it battery less option for long term monitoring. The sensor is very small in size, which can be produced commercially in large scale for bridge decks corrosion monitoring. Previous accelerated corrosion tests and an applied DC voltage test show that we are able to detect corrosion rate by tracking sensor resonant frequency with less than 10 mv potential change across two electrodes. The accelerated corrosion tests from [7, 8, 11]

show that this sensor can detect the corrosion initiation of the new civil structures. From [8] we have successfully determined the chloride concentration level in existing structures. However, the on-going tests results will determine the chloride concentration level in existing civil structures, the reproducibility of the sensor and the chloride diffusion rate with distance in large extent.

8. Acknowledgement

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