A Wireless Sensor for Monitoring Chloride Ingress in Concrete

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Rengaswamy (Srini) Srinivasan

Contact rengaswamy.srinivasan@jhuapl.edu
(240) 228-6378
(443) 841-8825 (mobile)

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Team and Acknowledgement

Bliss Carkhuff, Johns Hopkins University
Terry Phillips, Johns Hopkins University
Hassan M. Saffarian, Corrosion Sensors, LLC

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MDSHA Chief of Research: Allison R. Hardt
Miniature Wireless *Smart Aggregates* Embedded in Bridge Decks

1” Diameter; Totally Wireless
Embeddable Sensor Overview

• Background

• Chloride Sensor

• Corrosion Sensor
  1. Corrosion rate
  2. Coating health monitor
  3. Water corrosivity

Note: This slide describes various wireless sensors that has been made and tested.

Among the corrosion sensors, there are three types: corrosion rate; coating health monitor; and water corrosivity.
Overview of Corrosion in Concrete

Note: This slide describes the various physical and chemical parameters that influence corrosion of rebar.

- Temperature
- Chloride
- Water
- CO₂
- O₂
- CP/stray current

A.C. Impedance Measurement

Conductivity/Temperature to Corrosion Rate Algorithm

“Parametric” Algorithm to determine Corrosion Rate

Impedance to Corrosion Rate Algorithm

Estimated Corrosion Rate

Actual Corrosion Rate

Surrogate Corrosion Rate

Concrete and Rebar Structure

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Threshold Limits of Chloride in Concrete

- Allowed limit in concrete*
  - 0.05 %wt. (by mass of concrete) or 1.89 lb/cu. yd.
  - 0.4 %wt. (by mass of cement)
    - 0.85 g of salt (max) allowed in 1 L (or 1.7 kg) of concrete

- Limit of chloride when steel begins to corrode†
  - Steel corrodes when the chloride content is 0.6 times the concentration of [OH\(^-\)]
  - If the pH = 12.9, [OH\(^-\)] = 1x10\(^{-1.1}\) M; and [Cl\(^-\)] = 48 mM

* Missouri Department of Transportation (MoDOT) Report No. RDT-03-004, March 2003, p. 10.
Composition of Concrete

Composition of concrete in a volume of 1m$^3$:

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>350 kg</td>
</tr>
<tr>
<td>Lightweight coarse aggregate</td>
<td>473 kg</td>
</tr>
<tr>
<td>Lightweight fine aggregate</td>
<td>168 kg</td>
</tr>
<tr>
<td>Normal weight fine aggregate</td>
<td>550 kg</td>
</tr>
<tr>
<td>Water required for desired slump</td>
<td>180 kg</td>
</tr>
<tr>
<td>Density</td>
<td>1676 kg/m$^3$</td>
</tr>
</tbody>
</table>

3750 lb/cu. yd.
139 lb/cu. ft.
**Sensing Chloride:**

**Steel-Based Chloride Sensor**

- Sensing elements
  - Carbon Steel and Stainless
- Driving force
  - Difference in the galvanic potential
- Parameter monitored
  - Time traces of the potential difference
  - Time traces of the galvanic current

**Technique Name:** Electrochemical Noise

- Zero Resistance Ammeter (or) Voltmeter
- Mortar Seal
- Current Collector
- Steel Sensor
- Chloride
Steel-Based Chloride Sensor

Open

Zero Resistance Ammeter (or) Voltmeter

Cl

Mortar Seal

Current Collector

Steel Sensor

Time (second)

EN Signal

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Steel-Based Chloride Sensor

Zero Resistance Ammeter (or) Voltmeter

Chloride

Mortar Seal

Current Collector

Steel Sensor

EN Signal vs. Time (second)
Note: This data was collected on a freshly poured concrete that was first cured for one month. Next, water with various amounts of salt (as indicated in the graph) was added to the top surface of the concrete. At the time of the measurement, there was 0.5-inch of water with salt “standing” on the top surface of the concrete. The amplitude of the current that we registered (200-1600 nA) were unusually large for the 10-50 mM salt water that was standing on the concrete surface. This made us to suspect that the concrete might have been contaminated with salt water (when it was poured) or its pH was too low (<12). Therefore we repeated this test using concrete from a different pour; the results are compared in the next several slides.
Note: This data helps to understand the data in the last slide. The data shown in this slide were collected in aqueous medium, not concrete. The pH of the medium was controlled using Ca(OH)$_2$ and NaOH. The current at pH 12.2 is high, demonstrating the effect of low pH on the current (increased rate of corrosion of rebar). We suspected the pH of the concrete (in the last slide) was low.
Testing in Concrete, Round #1 (Site #1)

Data: Average of 4 sensors at each chloride concentration

Average EN Signal (nA)

- 0 mM Chloride
- 50 mM Chloride
- 30 mM Chloride
- 10 mM Chloride

Was pH <12.0?
Did concrete mix had salt?

Concrete had cracks
Testing in Concrete, Round #2 (Site #2)

Concrete Pour: 9/27/07; Cure Time: 31 days; Chloride test start: 10/29/07

300 hours after exposure

Note: this is the second attempt mentioned earlier. Note, the amplitude of currents are much lower.

![Graph showing currents over time with different concentrations of chloride solution.](image)
Testing in Concrete, Round #2 (Site #2)

Concrete Pour: 9/27/07; Cure Time: 31 days; Chloride test start: 10/29/07

Note: The amplitude of currents did not go up further, even as we increased the chloride concentration, because the pH of the concrete was perhaps >12.
Testing in Concrete, Round #2 (Site #2)
Concrete Pour: 9/27/07; Cure Time: 31 days; Chloride test start: 10/29/07

Note: Overall, the concrete at the second site did show little sign of chloride induced activity. This was possible, only if its pH was high, say >12.
Site #1 versus Site #2

Site #2

- 0 mM Chloride
- 10 mM Chloride
- 30 mM Chloride
- 50 mM Chloride

Site #1

- 50 mM Chloride
- 30 mM Chloride
- 10 mM Chloride
- 0 mM Chloride

Time (second)

Current (nA)
Site #1 versus Site #2

- Pore-free, crack-free concrete seal
- Allows chloride to percolate slowly

Site #2: Free of Pores
Site #1: w/ pores/cracks
Test Results from Coring Concrete from Bridge Decks

Site #1 versus Site #2

Site #1: Salt is too high; pH is too low

Site #1

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CHLORIDE CONTENT LBS/CU. YD.</th>
<th>pH</th>
<th>DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 in.</td>
<td>2 in.</td>
<td>5 in.</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.9</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Site #2

Salt is low; pH is high; Density is high

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CHLORIDE CONTENT LBS/CU. YD.</th>
<th>pH</th>
<th>DENSITY</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1 in.</td>
<td>2 in.</td>
<td>5 in.</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Allowed Limits
Salt: 1.89 lb/cu. yd.
pH: ~12
Density: 140 lb/cu. ft.
Chloride Sensors Summary

• The sensor predicted
  – Problems at Site #1
  – Found Site #2 concrete was good
Embeddable Wireless Corrosion Rate Meter for Concrete

(TEDCO)
Results from the
**Embeddable Wireless Corrosion Rate Meter for Concrete**

![Graph showing corrosion rate over time with different chloride concentrations.](image)

- **Closed Symbols** ➢ Concrete is wet
- **Open Symbols** ➢ Concrete is dry or drying

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Sensor Instrumentation: EIS and EN

Schematic

- R.f. Transmitter
- Voltage Buffer or Transimpedance Amplifier
- Antenna
- Power and Clock Management
- Surrogate Rebar Electrode
- Inductive Pickup Coil (or) Battery
- μController
- A/D Analog Switch

EIS: Impedance
EN: Electrochemical Noise
Miniature Wireless Instrument Embedded in Bridge Decks
Status of the Embeddable Sensor for Concrete

• **Monitors chloride ingress**
  – Technique used: Electrochemical Noise

• **Measures corrosion rate**
  – Technique used: Full Spectrum Electrochemical Impedance Spectroscopy

• **Monitors coating health**
  – Technique used: Full Spectrum Electrochemical Impedance Spectroscopy

• **Small, and communication and power are wireless**
  – Therefore fully embeddable