MD-04-SP107B46

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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

SMART AGGREGATE SENSOR SUITE FOR BRIDGE DECK MEASUREMENTS –PHASE 1

JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORORATORY

SP107B46
FINAL REPORT

MARCH 2004

Technical Report Documentation Page

1. Report No. MD-04-SP107B46	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Smart Aggregate Sensor Suite for Bridge Deck Measurements – Phase 1		5. Report Date July 2003 6. Performing Organization Code
7. Author/s Russ Cain, Bliss Carkhuff, Dr. Pete Pandolfini, Frank Weiskopf		8. Performing Organization Report No. SP107B46
9. Performing Organization Name and Address The Johns Hopkins University, Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SP107B46
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 N. Calvert Street Baltimore, Maryland 21202		13. Type of Report and Period Covered: Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract The Johns Hopkins University/ Applied Physics Laboratory (APL) was funded by the Maryland State Highway Administration (SHA) to develop and perform laboratory and field-testing of a Smart Aggregate (SA) sensor to monitor the corrosive environment of concrete bridge decks and other concrete structures. The SA that was developed includes conductivity and temperature sensors, sensor signal processing, power and communications electronics housed in a small package and a reader head for remote powering and data collection. The SA is designed to be low-cost (in mass production) and have a projected life of over 50 years. The SA was demonstrated in laboratory tests and SAs were installed in two MD SHA bridge decks.		
17. Key Words: Corrosion sensor, corrosion monitor corrosion, conductivity, smart aggregate, embedded sensor, corrosion environment	18. Distribution Statement	
19. Security Classification (of this report) NONE	20. Security Classification (of this page) NONE	21. No. Of Pages 48 / 22. Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

Final Report

Smart Aggregate Sensor Suite for Bridge Deck Measurements
Phase 1

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July 2003

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I Technical Summary

The Johns Hopkins University/ Applied Physics Laboratory (APL) was funded (Ref. 1a, 1b) by the Maryland State Highway Administration (SHA) to develop and perform laboratory and field-testing of a Smart Aggregate (SA) sensor to monitor the corrosive environment of concrete bridge decks and other concrete structures. The intended applications of these sensors is described in Appendix A. The SA that was developed includes conductivity and temperature sensors, sensor signal processing, power and communications electronics housed in a small package and a reader head for remote powering and data collection. The SA is designed to be low-cost (in mass production) and have a projected life of over 50 years. The SA was demonstrated in laboratory tests and SAs were installed in two MD SHA bridge decks.

The long-range goal of the Smart Aggregate development program is to provide an inexpensive, reliable sensing capability to measure the corrosive environment in steel reinforced concrete structures. An adequate description of the corrosive environment of concrete includes: temperature, conductivity, chloride ion concentration, oxygen and pH measurements. Temperature and conductivity were the two sensing capabilities incorporated in this first prototype SA. Conductivity is an indicator of the corrosive environment but not as strong an indicator as chloride ion concentration. Experimental results have shown that concrete (with chloride ion present) with very low conductivity (high resistivity) generally corrodes at a very low rate and as the conductivity increases so does the corrosion rate.

APL modified the well-understood, two-plate conductivity measurement technique to a voltage transient measurement. A small current is applied between two parallel plate electrodes for a brief time and then turned off. The difference in voltage measured across the electrodes while the current is applied and after the circuit is open again is used to determine the cell resistance that is converted to a resistivity using the cell constant. Several electrode geometries were investigated but a simple, parallel-plate geometry was satisfactory. APL used the transient technique and electrodes to measure concrete conductivity for several electrode configurations during the cure process in a laboratory setting. We found that we could reduce the variability of the measurements between sensors dramatically by applying a layer of concrete paste without aggregate to the electrode surface and then apply concrete with aggregate on top.

The Smart Aggregate electronic design precluded the second voltage measurement (i.e. after the circuit is open again). Since the open-circuit-voltage of the conductivity cell changes as the cell ages in the concrete environment, the conductivity measurements depend on the open-circuit voltage. To minimize the open-circuit-voltage, the circuit design shunts the electrodes while the SA is un-powered and shorts the electrodes just before the measurement. This design was validated by comparing measurements of known conductivity solutions made with the Smart Aggregate circuit with measurements from a laboratory grade instrument.

Independent of this effort, APL developed a wireless, embedded sensor platform (WESP) to provide services for the sensing elements. The combination of sensors, integrated with the WESP package, is the Smart Aggregate.

To determine the reliability of SA, APL analyzed the expected lifetime of the WESP package electronics and calculated a means time to failure of several thousand years, primarily because of the very low duty cycle. To demonstrate the reliability of SA, APL fabricated several test specimens and subjected them to thermal cycling. All units are operating at the time of this report.

In addition to reliability tests, APL conducted two separate bridge deck tests in which sensor packages were installed in a MD SHA bridge as part of normal construction operations. The goal of these tests was to demonstrate that the SA could survive the bridge deck installation. In the first test (Johns Hopkins Rd. and US Rte. 29), APL installed 5 SA sensors without conductivity electrodes and 5 dummy packages (no electronics). This deck was poured in November 2001 and the sensors were operating at the last measurement. This test was repeated on a second bridge (Democracy Blvd. & US Rte. I270 South) in September 2002 and the sensors were operating at the last measurement.

The effort to develop a prototype bridge deck monitoring capability that is described herein is viewed as a first step in a continually evolving and improving technology. This development leverages off advances in sensing technology and microelectronics as well as advances in physical modeling of bridge decks based on distributed, long-term measurements made with sensors such as the Smart Aggregate.

MD SHA has identified chloride ion concentration as their primary parameter of interest. The next phase of SA development will investigate a chloride ion sensor based on thick film technology that is compatible with the SA package.

II Background

Among the recent research on automated sensor development for monitoring bridge structures, much work has been focused on mechanical sensing such as stress/strain and pressure. In the late 1990’s automated sensors to monitor corrosion-related degradation did not exist (Refs. 2, 3); however, more recently Virginia Technologies Incorporated has developed a sensor suite for monitoring the condition of concrete and SRI has developed a prototype chloride ion sensor to be embedded in concrete. Chloride and pH are two parameters that are known to influence the corrosion of the rebars; however, the current practices of monitoring them can be either destructive (‘coring’ for conductivity and chloride concentration), semi-destructive (phenolphthalein-spray test for pH) or non destructive. These semi-destructive procedures cannot be used to sample the entire bridge. Coring is often limited to very small areas, and often at locations where it does not lead to structural instabilities. Consequently, corrosion occurring at structurally sensitive locations may never be detected until the corrosion related damage becomes large and visible, at which point the problem makes a transition from maintenance to replacement.

By focusing on measuring the corrosion environment at a large number of locations on a bridge deck, the approach presented herein can detect environmental states that enable corrosion and, coupled with past measurements, indicate the evolution of a particular bridge deck environment with time. Detecting the presence of a corrosion-enabling environment in the early stages enables corrective and/or preventive action to be scheduled and implemented rather than the more costly and time-consuming repair and replacement.

The vision behind this effort is a measurement system that incorporates embedded sensors that are small, rugged, remotely queried, long-lived and inexpensive, so that a large number can be embedded in concrete bridges (refs. 4, 5). A systematically distributed set of sensors that can be interrogated periodically will allow bridge engineers to get the most reliable and continuous update on the health of the element (deck, etc.). Information provided by the system on the internal "health" of an element reduces uncertainty and enables more efficient and effective maintenance management decisions relating to prioritization and scheduling of projects. Perhaps of greatest benefit will be the ability to maintain an historical record of changes and to effectively apply preventative measures in a timely manner, thus minimizing the need for major rehabilitation and associated lengthy disruptions to traffic flow. The state of the art of miniature sensors and wireless communication systems has reached a point that makes such a goal technically feasible and, at the same time, economically attractive in terms of the existing maintenance costs for the Maryland State Highway Administration.

The prototype SA developed in this effort provides conductivity and temperature measurements. The conductivity measurements provide an indication of the corrosive environment of the bridge deck over the life of the deck as discussed below; however, the conductivity value will fluctuate because it is highly dependent on the unbound water in the concrete. Thus conductivity measurements may enable bridge engineers to assess the likelihood of corrosion significantly in advance of when visual inspection and other non-destructive testing techniques indicate corrosion. Point measurements provided by SA will provide the distribution of the conductivity environment over the entire bridge deck surface. Interpolation between the measurements will be left to the judgment of the bridge engineers. This approach to monitoring corrosion is suitable for existing as well as new construction since the smart aggregate sensors can be mounted in the holes after cores have been extracted or placed underneath a deck overlay.

Empirical models have been developed that provide a useful "first-cut" description of the corrosion environment. These models are based on field measurements and include considerable scatter, thus the models are only rough approximations. The model from Ref. 6 (pg 158) expresses the corrosion rate as the product of several terms.

$$I_{corr} = k_\rho / \rho * F_{Cl} * F_{galv} * F_{rust} * F_{O2}$$

"$k_\rho = 2.96*10^4\ \mu A/cm^2/ohm\text{-}cm$ This expression indicates that the corrosion rate depends on the actual concrete resistivity, ρ, modified by: a) F_{Cl} : a factor considering the chloride content, b) F_{galv} : a factor considering how localized the corrosion attack proceeds, c) F_{rust} : a factor depending on the amount of rust previously formed (a kind of age factor due to the rust) and d) F_{O2} : a factor considering the amount of oxygen." This model relates corrosion current to temperature, resistivity and chloride ion concentration. Figure 1 (from Ref. 6) shows the qualitative relation between corrosion current and resistivity. The significance of the figure is that corrosion current is minimal for large values of resistivity; thus if concrete resistivity remains high there is low likelihood of corrosive activity. This hypothesis is corroborated by the work of Broomfield as presented in Table 1 taken from Reference 12.

Table 1: Resistivity Criteria for Steel in Concrete in the Presence of Chlorides or Carbonation

Resistivity kOhm cm	**Corrosion State**
> 100 –200	Low corrosion rate
50 – 100	Low corrosion rate
10 –50	Moderate corrosion rate
< 10	Resistivity is not the controlling factor

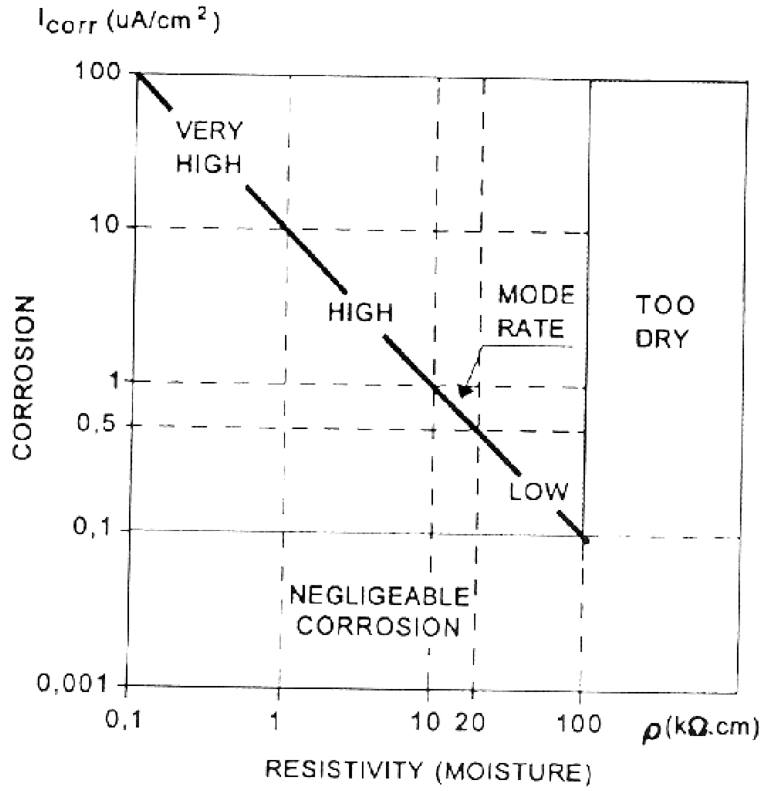


Figure 1: Corrosion Rate Vs Resistivity (Qualitative)

III System Concept

The SA concept consists of a measurement system comprised of sensors, data collection hardware and processing that provides bridge owners the information necessary to operate and maintain a bridge deck in the most cost-effective and reliable manner over the lifetime of the bridge. The concept is shown schematically in Figure 2. The heart of the concept is the SA sensor suite that consists of sensors, sensor signal processing electronics, communications electronics and power conditioning.

In practice, many SA packages would be embedded in the bridge deck when it is built or installed in existing bridge decks. The exact distribution of packages would be selected by bridge engineers. The position of the Smart Aggregate is determined relative to a designated location and recorded with the unit ID. Data would be collected as often as the bridge operators deem appropriate. Data collection would involve moving the reader over the bridge deck and radiating power to the Smart Aggregate beneath it, which, in turn, activates the Smart Aggregate. Ultimately the reader would be mounted to a vehicle that would travel across the deck. During each data collection event, analog data from the sensors is digitized and transmitted to the reader. The reader writes this data to a file for subsequent analysis in addition to the ID of the Smart Aggregate. The anticipated residence time for a query at each location is significantly less than one minute; however, traffic control may be required during data collection. After all of the data is collected and written to files, it is analyzed and, in conjunction with historical results, used to describe the current state of the bridge deck. The results would be presented in the form of a contour map, with the bridge deck as the reference.

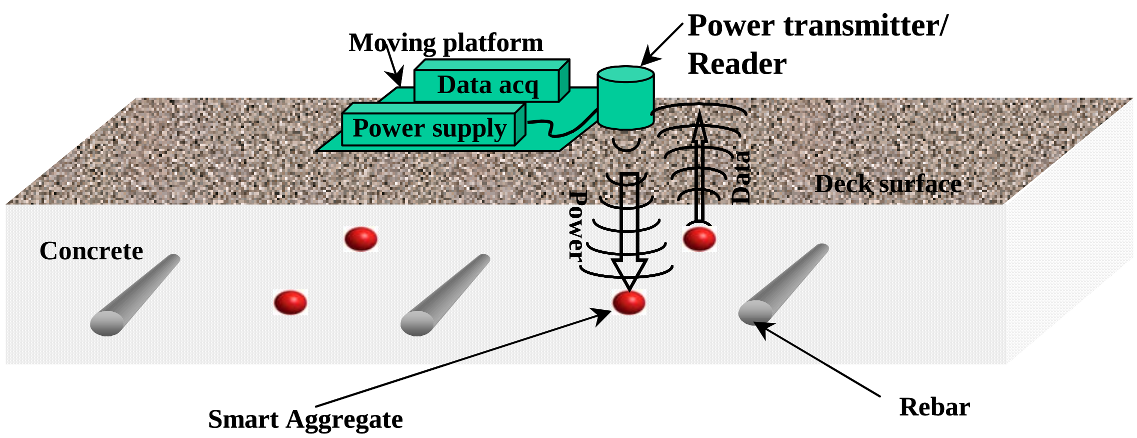


Figure 2: Conceptual Schematic of Smart Aggregate System

IV Conductivity Sensor Requirements

As discussed in Section II, the conductivity of concrete is one indicator (among several) of the corrosivity of the environment. Conductivity was the first measurement integrated in the SA because the sensing technology is well established. The SA implementation measures resistance which is converted to resistivity (inverse of conductivity) with a cell constant. This section addresses conductivity measurement technique, electrode geometries, conductivity measurements and electrode dynamics.

The resistivity of concrete can range from very large numbers (over a hundred thousand ohm-cm) for very dry concrete to relatively low values (a few hundred ohm-cm) for concrete that has lots of moisture and salt. Literature indicates that if the concrete has high resistivity the reinforcement bars (rebar) will not corrode; consequently, APL selected sensor designs that are suitable for measuring resistivities from essentially zero to approximately 100 k ohm-cm since the intent of this measurement system is reasonable resolution of concrete resistivity in a range where the corrosion of the rebar is occurring.

Conductivity Measurement Technique
Investigations into the conductivity measurement technique were made with oceanographic conductivity sensors from another APL program. The sensors had two (platinum coated) gold ring-electrodes; the dimension of each ring was about 1.25-mm ID and 2.0-mm OD. The center-center separation distance between the two rings was 7.5 mm (Figure 3). The cell constant, k = 8.633 cm^{-1} and Resistivity = Resistance/k = (V/I)/k (voltage V and current I). The sensors provided useful response in the resistivity range 1,000-50,000 ohm-cm.

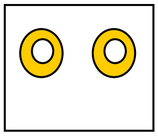


Figure 3: Ring Conductivity Sensor

One of the design goals of Smart Aggregate package was a volume less than 2 cm^3. This limitation on the electronics restricted the conductivity measurement technique to a voltage transient measurement (as compared to impedance spectroscopy); consequently we used a transient technique (voltage vs. time) in these conductivity tests. The tests were conducted with a laboratory instrument - an EG&G PAR Model 270 Potentiostat/Galvanostat - used in the galvanostat mode. A simplified version of the galvanostat is described in Figure 4.

In the voltage transient technique, a constant 10 μA current (I) is applied for 1.2 ms, immediately after closing the circuit. The voltage (V) difference between the two electrodes is measured for a total period of 4 ms, including the time when the current was "on." The maximum difference in the voltage between the time when the current was "on" and "off" is a measure of the resistance of the medium.

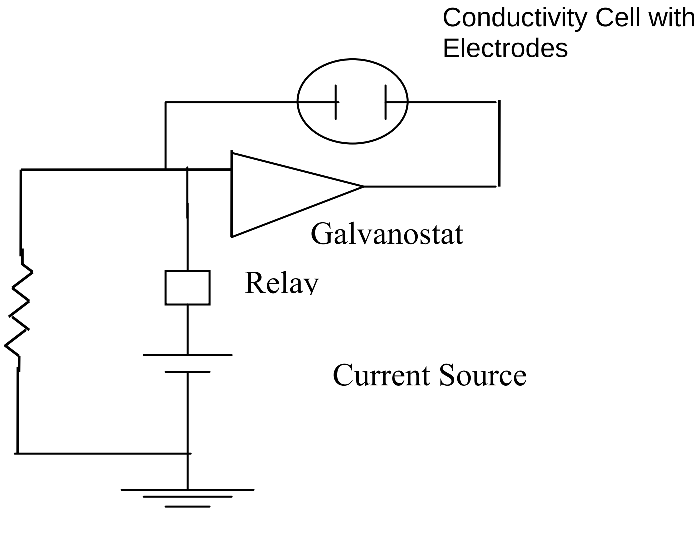


Figure 4: Simplified Galvanostat Schematic

Experimental results, obtained using three standard solutions of 1,000, 8,300 and 50,000 ohm.cm are shown in Figure 5. For the cell constant of, k = 8.633 cm^{-1} for the ring conductivity sensor, the computed value for the conductivity were 50,156 ohm.cm, 8,688 ohm.cm and 1,019 ohm.cm, respectively for the three solutions (actual values given along the left margin of the figures).

These tests gave preliminary estimates for the sensor geometry and measurement technique; in particular, estimates for the following were derived:

1. The separation distance between the electrodes;
2. The electrode area;
3. The current to be injected;
4. The time of current injection;
5. The time of potential measurement; and,
6. The dynamic range for the voltage measurement device.

Further details are provided in Ref. 7.

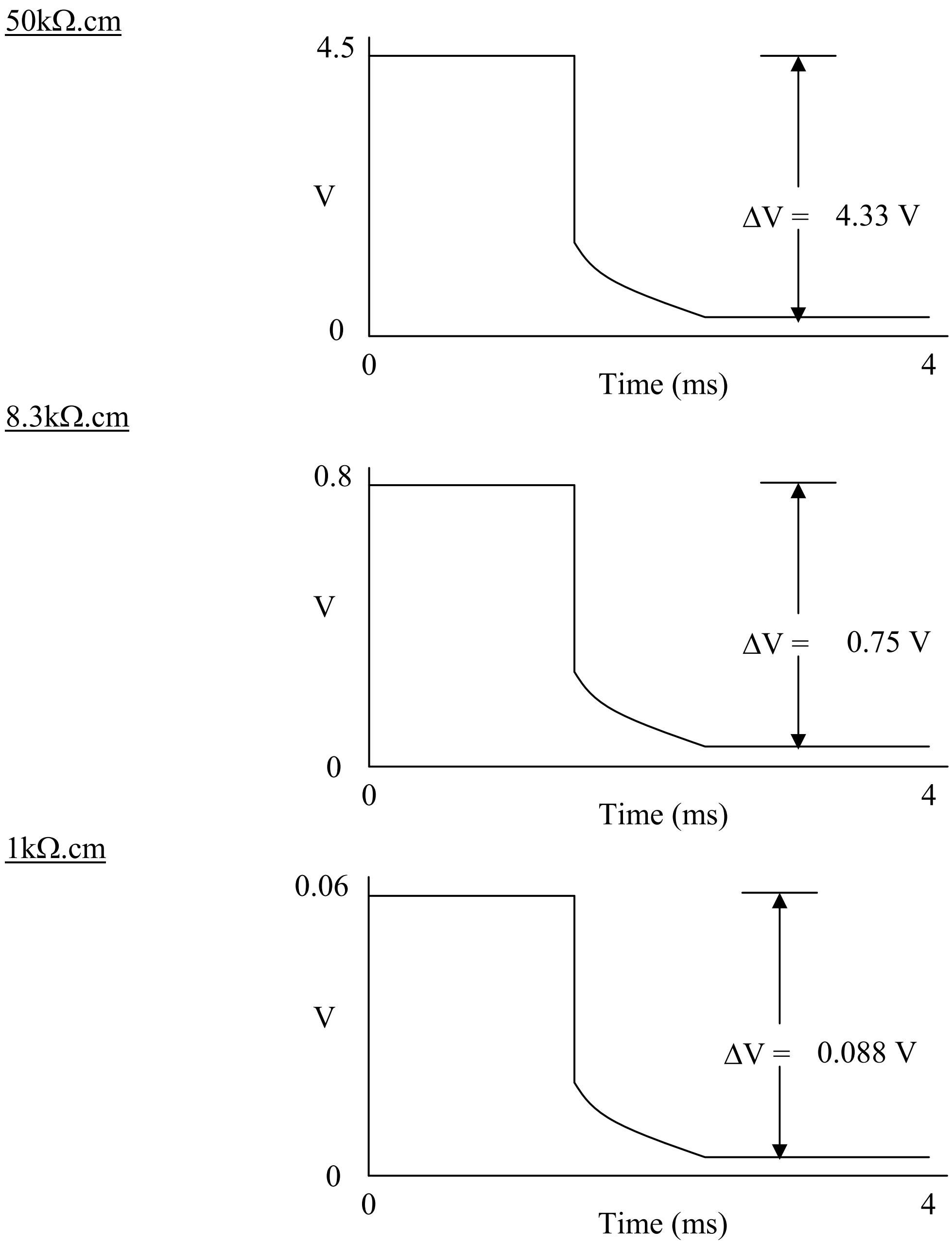
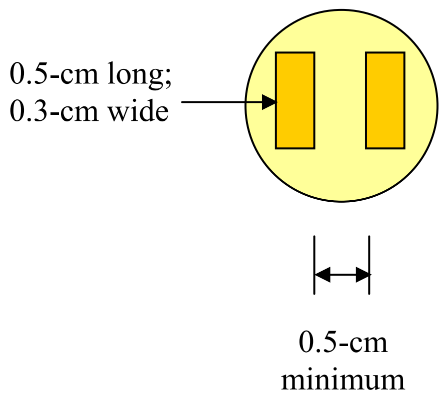


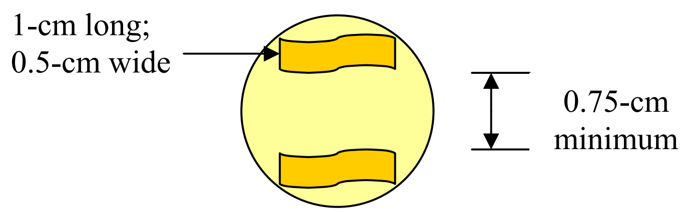
Figure 5: Representative Voltage – Time Histories

Electrode Geometry
APL considered three different designs of electrodes for the conductivity sensor; the initial electrodes were made of gold. The design is based on two factors:
1. The range of resistivity associated with corrosion in concrete (0 to 100k ohm.cm); and
2. The results of the investigations using the oceanographic conductivity sensors discussed above.

Based on preliminary tests with the oceanographic conductivity sensors, APL made estimates on the geometry and the current-voltage-time parameters for measuring conductivity in concrete. One issue that emerged is to ensure contact between the sensor electrodes and the concrete.

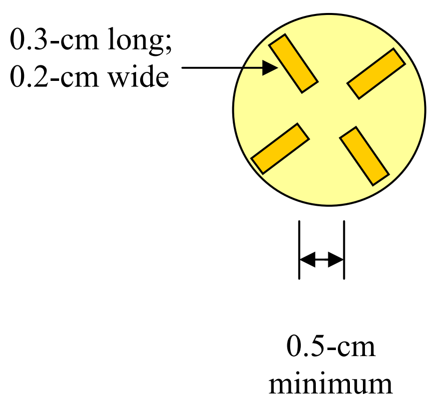
Geometry 1: In the diagram below, the rectangles represent the two electrodes. The suggested dimensions are 0.3x0.5 cm. The separation distance between the two electrodes is 0.5 cm.





Geometry 2: The diagram on the right shows two wiggly electrodes. The suggested dimensions are 1.0x0.5 cm. The separation distance between the two electrodes is 0.75 cm.

Geometry 3: The third arrangement is a spoke geometry with four electrodes.



In all three cases, at least two or three 'via' connections were used for each electrode.

Conductivity Measurements
A series of laboratory investigations were conducted to:

- Select and verify the electrode design

- Gain experience with long-term conductivity measurements in concrete (especially uniformity and repeatability)
- Demonstrate the reliability of the electrodes
- Investigate impact of salt on conductivity

Two sets of each of three electrode designs were provided for evaluation and testing. Initially these electrode designs were evaluated in aqueous solutions of various salt concentrations. All four electrode designs were adequate for these measurements. Based on the success of the aqueous measurements, preparations were made for conductivity measurements in concrete. APL down-selected the electrode designs (to Geometry 1), fabricated several examples and used those sensors to make measurements (with the EG&G PAR Model 270 Potentiostat/Galvanostat) in blocks made from commercially acquired concrete (Home Depot) that APL fabricated. The sensors were attached to wood dowels approximately 2 cm. from the bottom of the block. Data collected over a several week period showed considerable variability. Two possible causes of the variability were hypothesized: poor bonding between the concrete and the gold electrode material; concrete inhomogenities resulting from the aggregate size being comparable to the measurement volume (of the conductivity measurements).

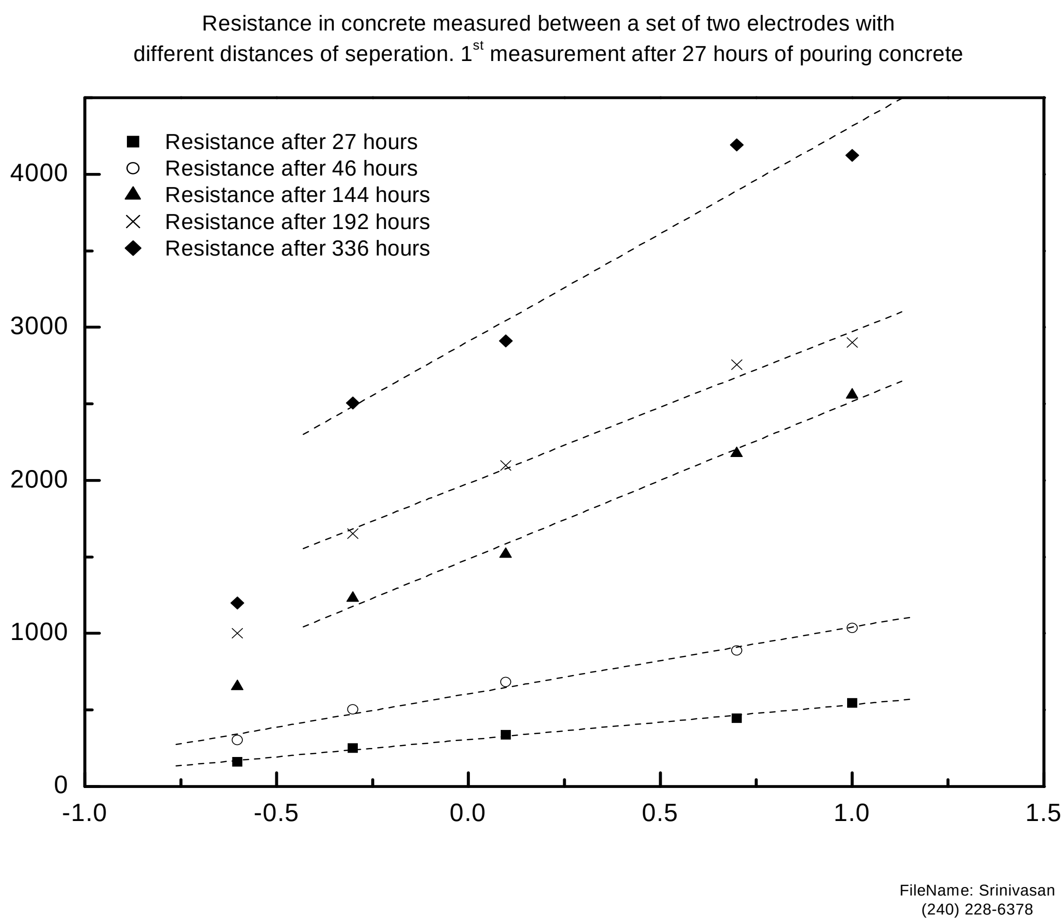


Figure 6: Concrete Resistance (ohms) vs. log (Distance (inches))

A second series of experiments (June 2001) was conceived and prepared to investigate the variability by varying electrode separation and orientation. In the first experiment, the resistance between graphite rods at different separations (Figure 7) was measured (Figure 6). The measurements also showed the expected trend of increasing resistance as the spacing between the electrodes grew (Figure 6). Over a time period of many days, the measurements showed the expected trend of increased resistance with time as the concrete cured but also showed significant variability from point to point in the concrete block.

In the second experiment, the parallel plate electrodes were plated with a Platinum-Palladium-Gold (Pt-Pd-Au) alloy since platinum has better bonding properties with concrete. Two pairs of electrodes mounted back-to-back at two different locations and two different orientations (a total of four sets of electrodes, see Figure 7) – parallel to the large surface area (Sensor 2) and perpendicular (Sensor 1). Data were collected for an extended time period; steady state values at different times are shown in Figure 8. The sensors give expected measurement behavior during concrete drying. The measurements were independent of orientation but still showed considerable variability.

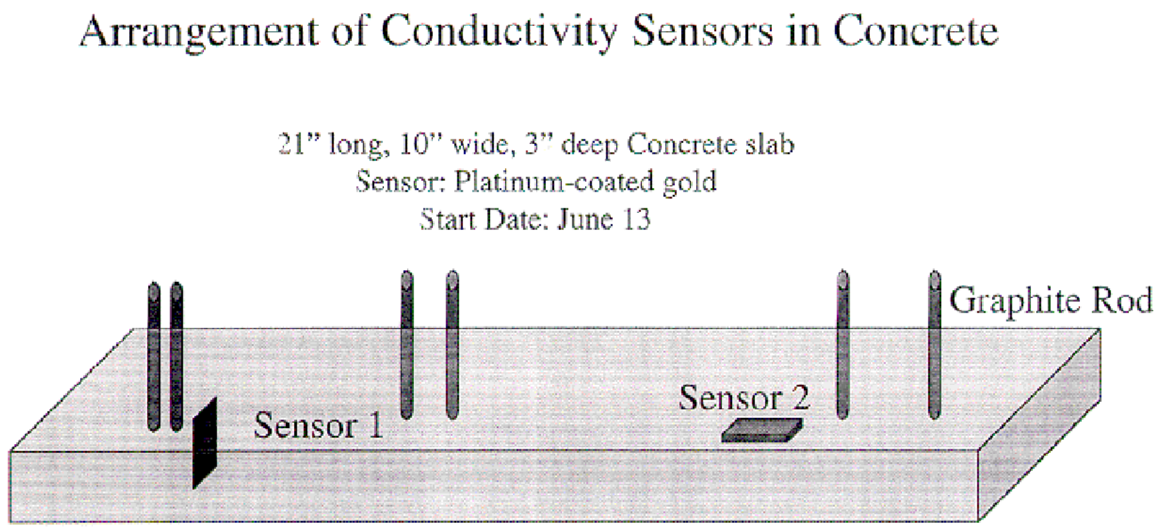


Figure 7: Sensor Arrangement in Concrete Block

The reason for the large range in resistance is hypothesized to be due to variability in the homogeneity of the concrete. A third experiment was initiated (June 2001) in which the effect of the non-homogeneity of the aggregate mix on the measurements was minimized. The sensor orientation is the same as the orientation of the SA in the bridge deck and the electrodes were made of the Pt-Pd-Au alloy (Figure 9). A small quantity of concrete with a minimum amount of aggregate was taken from the dry mix and used to prepare a paste that was smeared over the electrode surface. Once installed in the form, concrete was added to make a complete brick. The resistivity versus time (45 days) indicates very little variability as shown in Figure 10. Although the electrodes are separated by several inches, the numbers are highly repeatable.

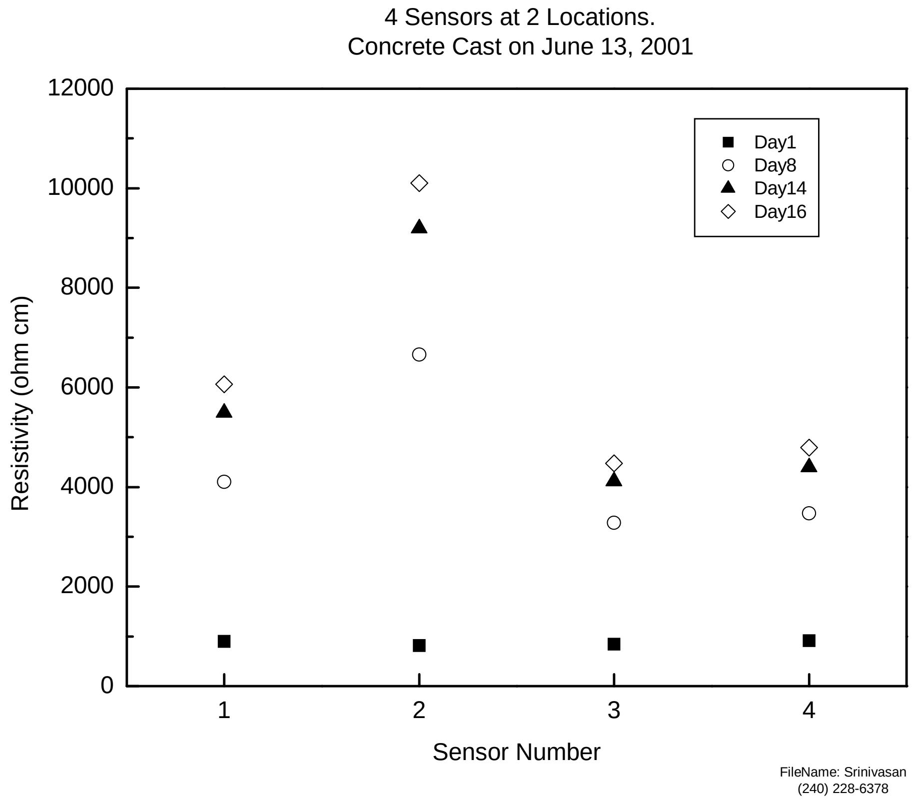


Figure 8: Resistance Vs. Time

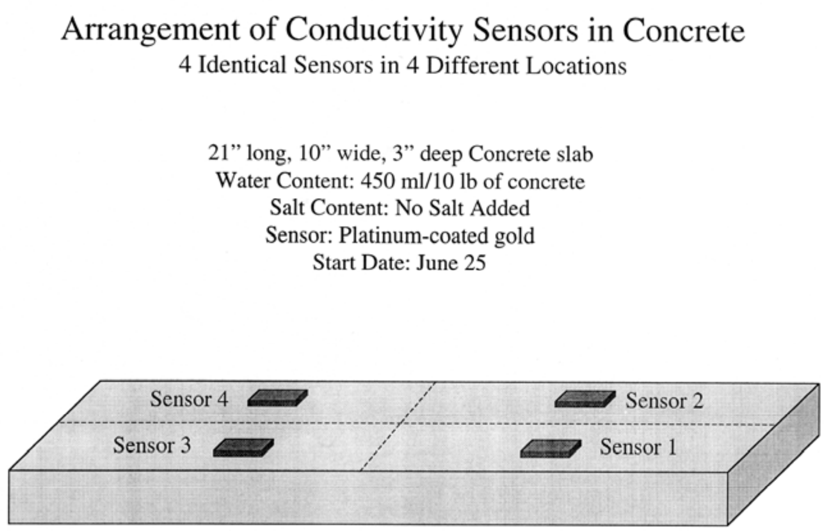


Figure 9: Sensor Arrangement in Concrete Block

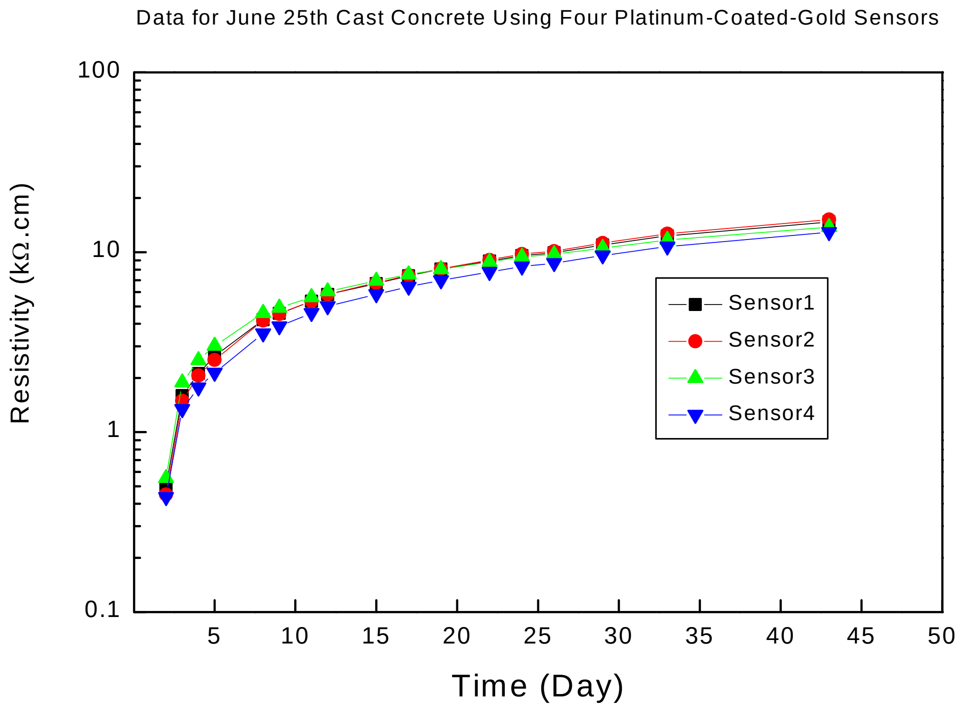


Figure 10: Resistivity Vs. Time for Electrodes with Paste Covering

In a fourth set of measurements, APL investigated the impact of salt on the conductivity measurements. The concrete block was divided into 4 quadrants with different amounts of salt added to each quadrant. The long term behavior was similar to the concrete made without the salt solution and the conductivity decreased approx. linearly with salt concentration; however, the effect was much smaller than hoped for.

In summary, these tests demonstrated that:

- Resistance measurements increase with time between any two fixed electrodes
- Resistance measurements increase with separation between the electrode.
- Individual resistance measurements can vary by as much as a factor of two between any pair of electrodes with the same separation.
- The resistivity value decreased approximately linearly with salt concentration.
- Using the concrete paste over the electrodes significantly reduces conductivity variability.
- Pt-Pd-Au electrodes perform significantly better than Au electrodes.

Electrode Dynamics

All of the measurements discussed above were made with a precision laboratory instrument. As mentioned earlier and discussed in this segment, the SA cannot duplicate the measurement technique used by the instrument. In particular, SA does not measure the Open Circuit Voltage (OCV) between the two electrodes. Over a long time period, in concrete, the OCV can become large (hundreds of millivolts) and the measurement technique must compensate for this.

APL conducted a considerable number of experiments to understand the stability and electrochemical process at the electrodes that form the conductivity sensor. The goal was to better understand the possible sources and magnitudes of error, in particular measurement error introduced by the cell open circuit voltage. Most experiments were conducted with calibrated laboratory solutions of known conductivity.

APL implemented the SA conductivity sensor design in a breadboard and compared performance with a laboratory grade electrometer using the various concrete trays that had been fabricated. The laboratory instrument uses a two-step measurement process: open circuit voltage (OCV) measurement of cell potential; followed by the measurement of voltage across the cell electrodes with a 10 microampere current imposed. The difference in these two voltages is used to calculate the cell resistance which is related to conductivity by a fixed cell constant. The Smart Aggregate (SA) cannot use the two-step process because of limitations on the number of the current microprocessor outputs. Note that newly available electronic components should eliminate this restriction in future designs.

APL explored the difference in the measurement technique between the laboratory grade electrometer and the SA conductivity sensor design through a set of experiments. The difference in the technique is the inability of the prototype SA design to measure the OCV as part of the conductivity measurement protocol. We contrived a "worst case" example were one of the two electrodes (of the conductivity sensor) was poisoned so that a large OCV existed between the two electrodes. The example is "worst case" in the sense that the magnitude of the OCV is considerably larger than the OCVs measured across the electrodes buried in concrete.

Since the SA conductivity electronics cannot measure the OCV, the measurement procedure was modified to short the electrodes, which tends to minimize the OCV, and then impose the current and measure the voltage across the electrodes. Our experience with electrodes buried in concrete indicates that when the electrodes are shorted the peak current is on the order of 10 nanoamperes and has a decay constant on the order of 1 second. For the poisoned electrode, the peak current is on the order of tens of nanoamperes with a similar decay constant. Using the poisoned electrode we found that the OCV measured 0.1 ms after opening the shorted electrodes behaved as follows:

Duration of short	*Peak OCV*
1 sec.	65 milli volts
10 sec	55 mv
60 sec	45 mv

The data show that as the duration of the short increases, the peak OCV decreases. Based on these observations, the SA design was modified so that the cell will have a 110 kOhm load while the sensor is not in operation. This almost permanent load is expected to minimize the OCV of the cell when the measurement is made and consequently minimize the error. In addition, the SA measurement procedure was modified so that the electrodes are shorted for a fixed time interval when power is applied and then a 50 microampere current is applied across the electrodes. The intent was to force the OCV to zero. In summary, the measurement procedure consists of (see Section V for further details):

1. opening the short,
2. applying the current,

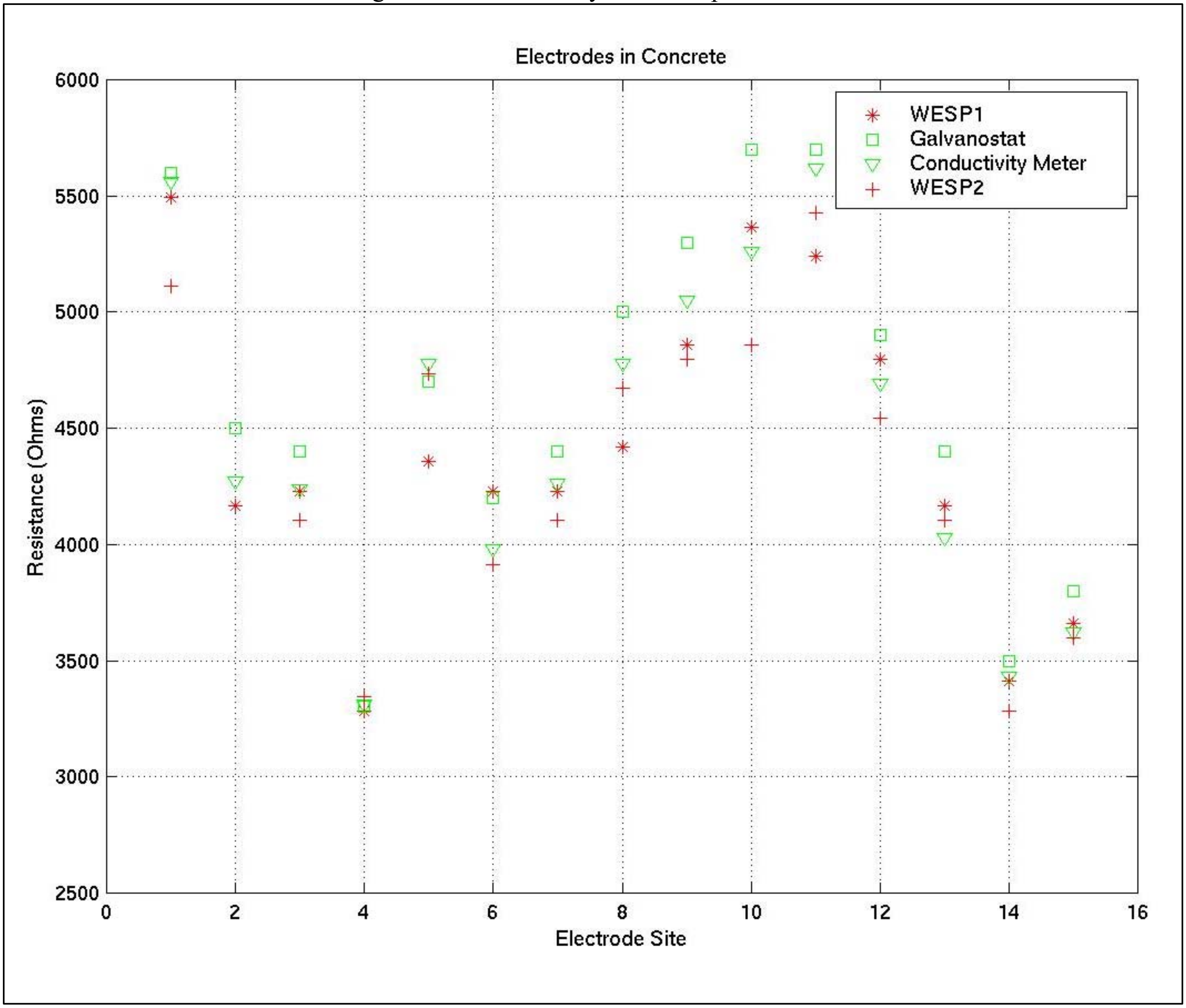
3. measuring the voltage across the electrodes,
4. closing the short, and
5. repeat the process.

The design modifications also included selecting the range of resistance values the sensor will measure as 0.0 to 60 kilo ohms. The upper bound was reduced from 100 kilo ohms to give more resolution in the region of 10 kilo ohms

The SA control software was also modified so that the entire measurement process (short the cell, apply the current and measure the voltage) will be applied repeatedly and only the last few measurements will be used to account for power up transients

In April 2002, these investigations culminated in a direct comparison of conductivity measurements of calibrated conductivity solutions made with a laboratory quality instrument and the Smart Aggregate electronics. The data is shown in Figure 11, WESP1 and WESP2 are two independent measurements made with the SA conductivity circuit. The sequence was WESP1, then measurements with the two laboratory instruments (i.e. Galvanostat, Conductivity Meter) and then WESP2. The measurements compared very favorably (Figure 11) and were generally within the error bars of the instruments. Successful comparison of the data from the two measurements validated the APL conductivity measurement technique.

Figure 11: Conductivity Test Comparisons



V Smart Aggregate Design

WESP

The WESP (Wireless Embedded Sensor Platform) package is described elsewhere (Refs. 8, 9, 10). WESP, developed as part of an APL internal research and development effort, provides the services for sensors that are added to the WESP platform. WESP, in conjunction with the sensors, is called a Smart Aggregate.

The main design considerations of the WESP were small size, easy installation, rugged design, long lifetime (>50 years) and an installed cost of less than $50.

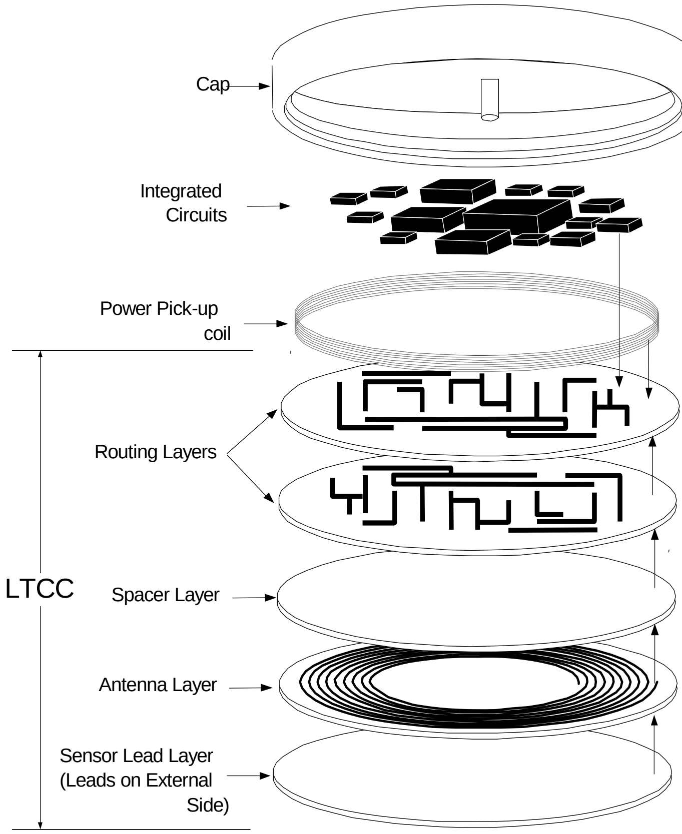


Figure 12 - WESP Assembly

The current WESP package design provides system power and regulation, microprocessor and circuitry for system control, a unique identification number, temperature, sensor signal conditioning, analog to digital conversion, and data transmission. Each WESP is 2.5 cm in diameter and 0.5 cm thick, on the same order as the aggregate typically found in concrete (volume is 2.5 cm^3), and operates on less than 5 mW of power. Power is provided by near field induction operating at 1MHz while data is transmitted via an RF link at 10.5MHz; both power and data are transmitted through the concrete. Successful communications has been achieved through greater than 4" of concrete. Data acquisition provides 8 bits of resolution of the analog sensors. Temperature resolution is 2.5°C over –55 to 130°C. Communications from the WESP is 2400 baud RS232 and incorporates 16 bits of synchronization and 16 bits of unit identification. To minimize cost and maximize reliability, the WESP design incorporated commercial IC packaging, assembly techniques, and materials.

The electronics is on a low temperature co-fired ceramic (LTCC) substrate with the data transmission antenna built on an inner layer with gold vias and plating (Figure 12). The electronics plate is mounted onto a ceramic housing with an epoxy. The housing is green bisque 96% alumina selected for strength, machinability, cost, and close match with the physical properties of the LTCC and the concrete environment. Mechanical analysis indicates the WESP package will withstand the pressures and thermal stresses of the concrete environment and extrapolation of the performance of WESP with current integrated circuit reliability guidelines suggests a mean time to failure of 6000 years. WESP devices have been successfully installed and have been operating in a bridge near JHU/APL for over 18 months and in a second bridge for about 10 months (See VI Field Tests). No alteration in the execution of the bridge assembly was required and the sensors survived the handling and concrete pour intact.

Four first generation WESP units (in holders) were installed into a concrete test block with rebars (Figure 13). The WESP holder is inexpensive injection molded plastic that was used successfully in both bridge pours. The concrete was obtained from a local MD SHA bridge deck pour to insure valid tests. The units are in an-ongoing thermal cycling test (-25°C to 65°C) and have successfully survived 65 cycles. Additional standard microelectronic tests, such as thermal shock, fine and gross hermaticity, and HAST (Highly Accelerated Stress Testing) were performed on the second generation designs. Freeze- thaw cycle tests are planned and additional mechanical testing on the LTCC housing is expected.

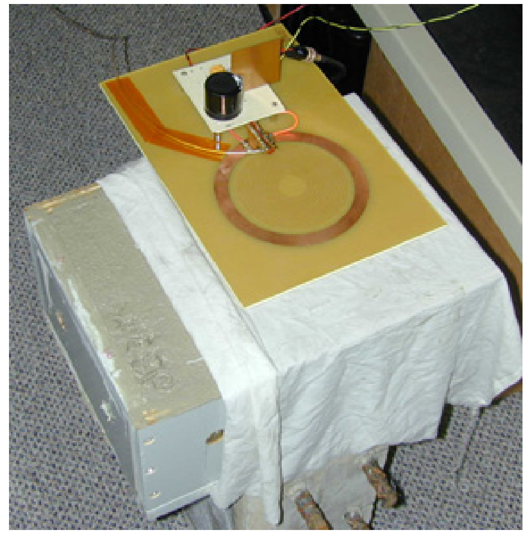


Figure 13 - Pouring Test Block and Measuring Test Block with Reader Head

The initial WESP design was based on a maximum distance for power coupling of about 3 inches. This was later extended to 6 inches to accommodate the first bridge test. This limitation fixed the amount of power available for WESP processing and signal broadcasting. As a consequence, the initial WESP electronic design was based on small and low power consumption components. The processor chosen to satisfy these guidelines was a low capability PIC controller; in particular, the controller had a limited number of inputs and outputs. This imposed limitations on the conductivity measurement technique.

<u>Conductivity Sensor</u>

The initial Smart Aggregate design is a second generation WESP with a conductivity sensor. The conductivity sensor design is a two-electrode miniature galvanostat with additional circuitry to minimize open circuit cell voltages as discussed previously. The electrodes for the galvanostat are processed of Pt-Pd-Au. Prototype versions of this configuration have been fabricated, demonstrated in a laboratory, and demonstrated in a Maryland State Highway Administration (MD SHA) designated bridge (See Section VI Field Tests). Temperature resolution is approximately 1 °C over –55 to 130°C and the resistance resolution is approximately 235 ohms over the 0 to 60 kilo ohms range. Note that Smart Aggregate actually monitors concrete resistance which is related to conductivity through the cell constant.

Standard techniques for measuring conductivity account for the open circuit voltage (OCV) between the electrodes. This is done because the open circuit voltage is a function of a number of uncontrolled environmental parameters and hence highly variable. Because of the hardware limitations mentioned above, it is not possible to measure the OCV, consequently, APL devised a modified conductivity measurement technique and then verified it in a number of experiments culminating in a direct comparison of the modified technique with the analogous laboratory standard technique (see Figure 11).

The complete modified technique used in the Smart Aggregate conductivity measurement is the following:

1. Conductivity electrodes are shunted by 110 kOhms at all times while the SA is unpowered. This is to minimize the possibility of a large open circuit voltage.
2. The electronics are powered up via the external induction field.
3. As the SA power system ramps up, the microprocessor wakes up and goes through a power on reset.
4. After power on reset the microprocessor initializes its output pins and turns off the current source by forcing a short circuit across the conductivity electrodes.
5. This short circuit is held for 250 milliseconds, which has been determined to be of sufficient duration in order to minimize the error in conductivity measurements due to a potentially large OCV.
6. The processor then waits 25 milliseconds. (This wait time is required to set the repeat conductivity measurement time to a minimum of 50 milliseconds)
7. The microprocessor then takes a temperature measurement and stores the data for later transmission.
8. The current source in the conductivity circuit is "turned on" by removing the electrode short circuit.
9. The processor waits 250 microseconds and then takes a measurement of the conductivity circuit output and stores the data.
10. The current through the conductivity electrodes is then "turned off" by re-applying the short circuit to the electrodes.
11. The processor then transmits the data frame to the outside world. The data frame consists of a two byte Barker code (used for data synchronization), a two byte ID number (which is permanently programmed into the microprocessor and is unique for each SA), one byte of temperature data, and then one byte of conductivity data. Data transmission takes 25 milliseconds.
12. The processor then loops back to step 6 and the process repeats until power is removed.

After implementation, the technique was demonstrated with 3 kinds of electrodes in the 12 kOhm standard solution: new electrodes, "aged" electrodes and "very poisoned" electrodes. In all three instances the measurement technique, as outlined above, provides the same answer for the conductivity of the solution. The time constant for the cell's recovery appears to be on the order of seconds not microseconds.

The primary difference between the modified technique and the standard technique is the way the OCV is handled. In steps 4 and 10 of the technique, shortcircuting the two electrodes in the conductivity sensor will reset the potential difference between the two electrodes to zero only when the short is "on." A 110 kΩ bridging resistance is used to minimize the OCV when the short is off and all experimental results indicate that the time constant for the OCV to equilibrate after the short is seconds – much longer than the duration of an individual measurement.

Alternate techniques such as passing a very small current, say 0.1 micro ampere or less, make a voltage measurement, then apply a 50 microampere and make another voltage measurement will be explored. The difference between these two voltages can be used to compute the resistance.

The prototype SA includes a reader head (Figure 13) which radiates power to the individual SA sensors, receives data broadcast from the SA sensor suites and transfers the data to a PC serial port for collection, display and filing. The reader head has gone through 3 design iterations. The original design proved inadequate for the first field test. Although the redesigned (second iteration) reader head was able to successfully read most of the sensors in the first field test (Johns Hopkins Rd bridge over Rt 29), additional stages of gain were added (third iteration) to make the reader head output consistent with an RS232 serial input port for a PC. The 3rd iteration design has been used to monitor the Smart Aggregates in both laboratory and field experiments.

VI Field Tests

The sponsor requested a test to demonstrate that the Smart Aggregate sensor suite would survive a bridge deck pour. As part of this effort, APL planned, equipped, installed and conducted two separate installation tests with the goal of demonstrating that the sensors and holders survive the installation process, maintain the correct sensor location and provide data during and after the concrete curing process. The field tests are summarized in Table 2.

First Field Test

In preparation for the first test APL conducted several visits to the US Rte 29 and Johns Hopkins Road bridge construction site (near the APL campus) to observe a deck installation, develop approaches to sensor localization measurements, plan for the location of sensors and conduct survivability tests with prototype sensor holders.

Over the course of the site visits, APL installed several prototype holders and tested their survivability during the concrete pour, vibrator application and construction crew walking. The initial holder design failed the crew walking but passed the other two criteria. We concluded from this that the WESP package would survive the concrete pour when installed in the holders but that the holder design had to be modified (new design or new material) to withstand a 300 lb. weight. A new holder design was created that made much better use of the rebar as a support. After several design iterations, the holder successfully survived a bridge pour. In many of these tests dummy sensor packages were installed in the holders but none were damaged – just the holders.

As a result of the holder design tests in September, APL redesigned the WESP holder to accomplish three design objectives:

1. Maintain a simple design as in the previous cases to facilitate simple and low cost manufacturing techniques and materials
2. Reduce the projected horizontal area of the design so as to minimize possibility of cavities underneath the holder after the concrete is poured.
3. Significantly increase the load bearing capability of the holder.

The revised design is shown in Figure 14. It is a Y arrangement where the two branches of the top part of the Y straddle the tie wire where two perpendicular rebars in the top mat of reinforcement steel are tied together. The bottom leg of the Y contains a circular cutout for the WESP package that places the top of the WESP package at the same depth as the top of the uppermost rebar. Different size rebars are accommodated with different size cutouts. The bottom and top legs of the

Y clasp the rebar with a snap fit. The holder is put in place by stepping on the top and bottom legs. APL did several fit checks at the bridge site. The installation is extremely easy and produces a fit so tight that it cannot be pulled off with reasonable force.

APL manufactured 11 WESP packages for the first field test. Four sensors were used in a simulated bridge test conducted in the laboratory and five packages were reserved for the bridge test. In addition, APL assembled five dummy packages (no electronics) for the bridge deck pour test.

In preparation for the bridge deck pour installation test, APL investigated two techniques to localize the WESP packages after installation: magnetic field, ultrasound. APL did laboratory measurements that indicated that the WESP package could be readily located in concrete with about 1/4" accuracy when a small magnet was inserted in the package. The sensor system is a low-cost, portable magnetometer; the small magnets (in the WESP) produce an aberration in the uniform earth's magnetic field that effectively locates the WESP package. Laboratory measurements were made with a dummy WESP package (with a magnet) attached to a rebar. The measurements also indicated 1/4" localization accuracy.

In addition, APL explored ultrasound measurements using available ultrasound heads and processing. Exploratory measurements indicated this technique would not work with the available ultrasound head because of excessive reflections from the aggregate and concrete surfaces. More suitable ultrasound heads exist but were not explored because of the associated cost and since the magnetometer approach worked.

Near the end of October 2001, APL conducted a simulated bridge test. A form for a concrete block with four rebar sections was fabricated (see Figure 13). Four WESP holders were installed with WESP platforms. The form was filled with concrete at the bridge site, transported to APL and left to dry for approximately 24 hours. The reader head was laid over the concrete and power applied. The sensors powered up and transmitted data to the reader head. Operability of the WESP packages was periodically checked for the next several days. The concrete block was used for subsequent reliability testing.

On November 5, 2001, APL installed 10 WESP units in the south lane of the bridge being constructed at the intersection of Johns Hopkins Road and US Route 29 (Figure 15). The installation took less than one minute since the holders are simply snapped into place. Five of the WESP units had complete electronics (#5, 6, 7, 8, 9) temperature and pressure sensors and a small magnet to aid in sensor location and five just had the magnet (A, B, C, D, E). The installation of the holders and WESP units went very smoothly.

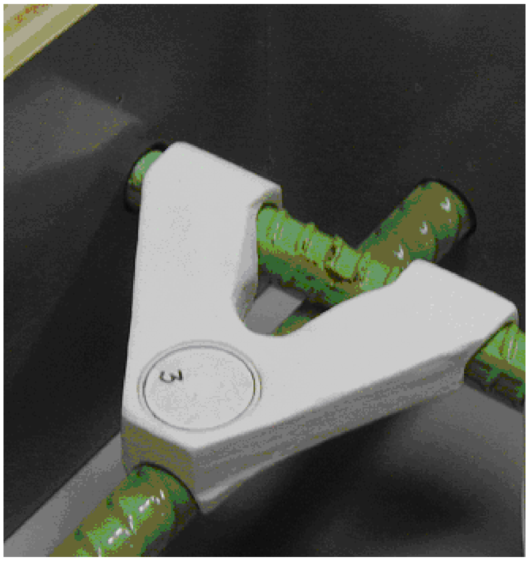


Figure 14: Smart Aggregates Mounted in Holder Installed on Rebar

Figure 15 - Bridge Installation of Smart Aggregate in holders

After the concrete cured for approximately 48 hours, APL returned to the bridge to locate the sensors using a magnetometer based procedure that had been demonstrated in the laboratory and to verify operability of the five WESP units with complete electronics.

Using a Magnetometer that has a sensitivity of 100 mV/nanotesla, we attempted to locate each magnet in the bridge along the X-, Y- and Z-axes. We successfully located the magnets in Sensors 7 to nine and C to E, along the X- and Y-axes. We also estimated their depths (Z-axis), which ranged between 3 and 4 inches. The magnetometer did not locate the magnets in Sensors 4, 5, A and B along any axis. The inability to locate some of the magnets was attributed to variations in the magnetic field caused by the large quantity of rebar and the fact that the WESP units could be deeper than 2.0 inches.

When APL tried to verify operability of the five WESP units with electronics, we were unable to receive data from any of the sensors (#1 - #5). Possible causes of this problem were excess water, failed WESP units, intermittent and inconsistent grounding of the rebar distorting the magnetic field that powers the WESP units and the WESP units being deeper than the 2" penetration range of the reader head. APL conducted laboratory measurements to duplicate the problem under the following conditions:

1) concrete block on the board on the concrete sidewalk
2) concrete block on the concrete sidewalk
3) wet concrete block on the board on the concrete sidewalk
4) wet concrete block on the board on the wet concrete sidewalk
5) concrete block on the metal electrical man-hole cover
6) wet concrete block on the metal wet electrical man-hole cover
7) concrete block on the earth
8) wet concrete block on the wet earth

In all cases, the reader head successfully powered and recorded the WESP sensors buried in the concrete block. Based on these results, the results from the magnetometer test and conversations with the site engineer, APL hypothesized that sensors were more than 3" below the bridge deck surface. An extensive redesign of the reader head (iteration 2) was required to read WESP units that are more than 3" away.

After the reader head was redesigned, APL performed another operability check. The results were very encouraging in that APL got responses from 4 of the 5 WESP units in the bridge that had electronics although one of the units that responded was subsequently overpowered and damaged during the test.

APL has a few overall conclusions based on the Hopkins Rd. bridge test:

a. The sensors are installed between approx. 3.5 and 4 inches below the road surface in the Hopkins Rd. bridge. This conclusion led to iteration 3 of the reader head design in order to accommodate a wider range of sensor package depths.
b. The WESP units have demonstrated the ability to survive the installation process and the concrete cure cycle.
c. There is no evidence the WESP units moved during the installation; consequently the current holder design should be adequate for subsequent tests.
d. Over voltage protection should be included in subsequent redesigns of WESP.

Second Field Test

A second installation test was conducted because of the difficulties with the first test. SHA personnel identified the test bridge as Democracy Blvd. where it passes over the West leg of I-270. The test was conducted in November of 2002.

This test used some of the Smart Aggregate sensors discussed in Section VII. A total of 10 sensors were installed using the same general procedure developed in the first installation test (See Figure 16). Five of the SAs are constructed with a resistance range of 0 Ω to 60kΩ, four have a resistance range of 0 Ω to 120kΩ and one has a range of 0 Ω to 240 kΩ.

As part of this test, APL investigated the use of ultrasound to image the Smart Aggregate holders embedded in the concrete. Although the technical literature was encouraging, laboratory experiments were not. For these measurements, two 500 kHz transducers were purchased. APL was able to use these two transducers in a pitch-catch configuration (one for generation of the ultrasonic waves and one for detection) through 5" of concrete with the measured ultrasonic arrival time very close to the predicted 34.5 micro seconds. However, this measurement was very sensitive to the placement (coupling) of the transducer to the concrete. We then tried to use only a single transducer to both transmit and receive the ultrasound through the 5" piece of concrete and measure the backwall reflection. This didn't work because of ringing in the transducer. One can remove the ringing by decreasing the pulse power, but then there is not enough reflected energy for the transducer to detect. The problem is that much of the ultrasonic energy is being scattered by the concrete aggregates. One could try lower frequency transducers to lessen aggregate scattering, but then the spatial resolution of the transducer decreases as well limiting your ability to adequately resolve the embedded sensor.

APL returned to the installation site several times (day 8, day 15, day 22) to collect SA data for comparison with the pre-pour data (Figure 17). In general, the temperature measurements behave as expected. Post installation temperature measurements are shown in Figure 18. The pre-pour measurements show some scatter which is associated with the electronic design. Day 8 measurements show some warming of the deck consistent with the curing process but the measurements after that tend to track the ambient temperature.

The initial conductivity measurements also behaved as expected. The pre-pour measurements show maximum possible values that the sensors can measure since there is no concrete path between the electrodes. The day 8 and day 15 values show a trend of increasing resistance; however, the day 22 values show 8 of the 10 resistance measurements have reached the maximum value. Subsequent measurements indicate that all 10 of the SA packages have reached the maximum value (Figure 19).

APL makes the following observations on this topic:
1. We have made a large number of measurements with concrete dried for 3 months or more where the resistance was much larger than 100 kΩ.
2. In order to affect conductivity, the water trapped in the concrete has to be free and not bound.

There is some uncertainty as to whether the conductivity measurements should have nominal values in the several 10's of kΩ range after a long cure time due to residual water trapped in the concrete pours. The APL measurements indicate the concrete in the Democracy Road bridge, after 22 days of pour, dried to the same extent as the concrete in the laboratory after 90 days of drying.

Site	Installed	Configuration	Status
Hopkins Rd. Bridge	November 2001	5 WESP packages (temp & pressure sensors) 5 dummy packages	3 of 5 packages operating as of June 2003 - 1 overpowered at 1st reading - 1 carrier freq. out of tolerance - last reading Jan. 2003
Democracy Blvd. Bridge	September 2002	10 Smart Aggregates (resistance meas. ranges: 5 at 0 to 60 k ohm 4 at 0 to 120 k ohm 1 at 0 to 240 k ohm)	All units operating as of Jan. 2003 (last measurement date)

Table 2: Field Test Summary

Figure 16: Second Field Test Installation and Deck Pour

Figure 17: Post Deck Pour Smart Aggregate Localization

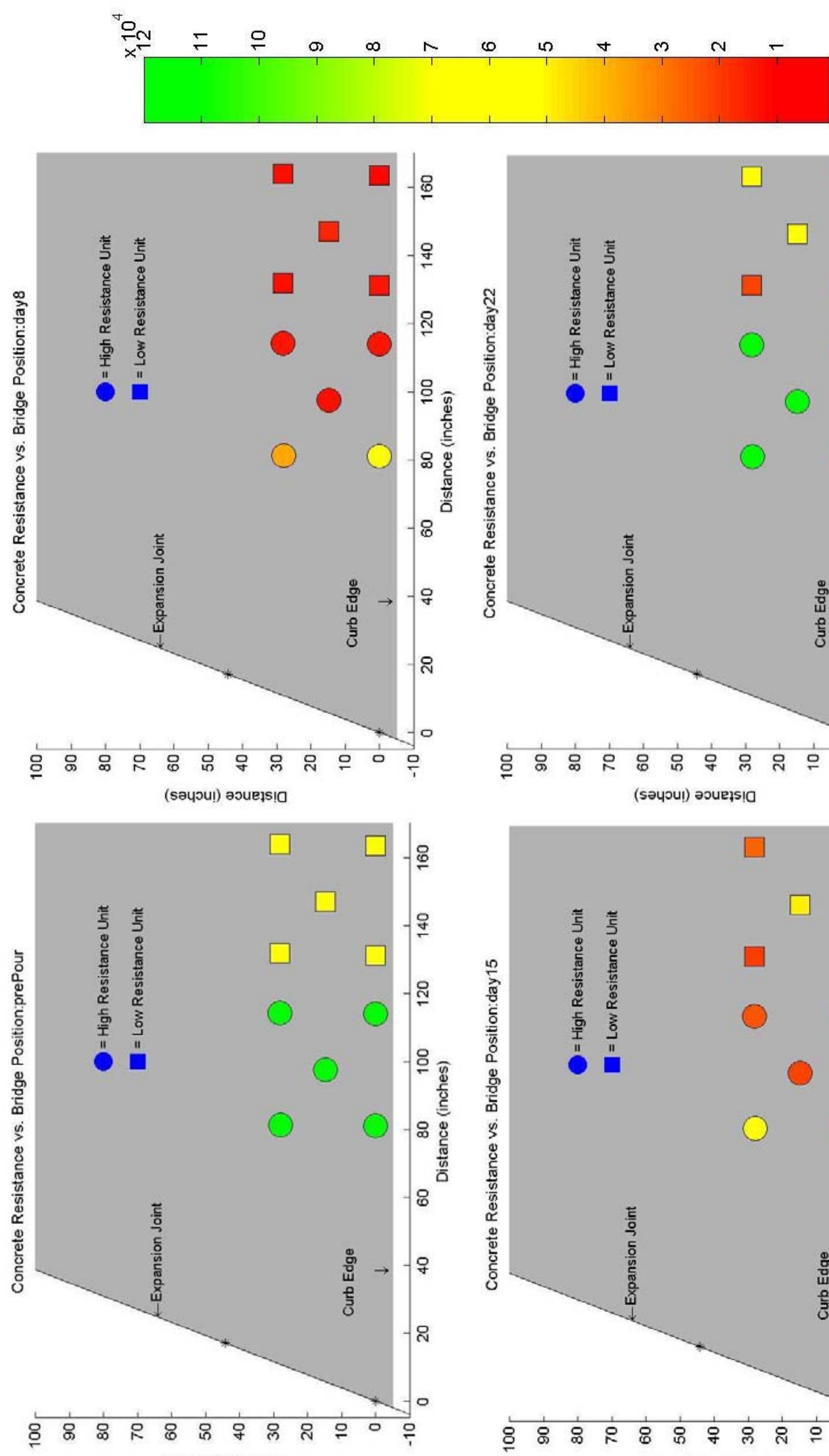


Figure 18: Post Installation Resistance Measurements (kΩ)

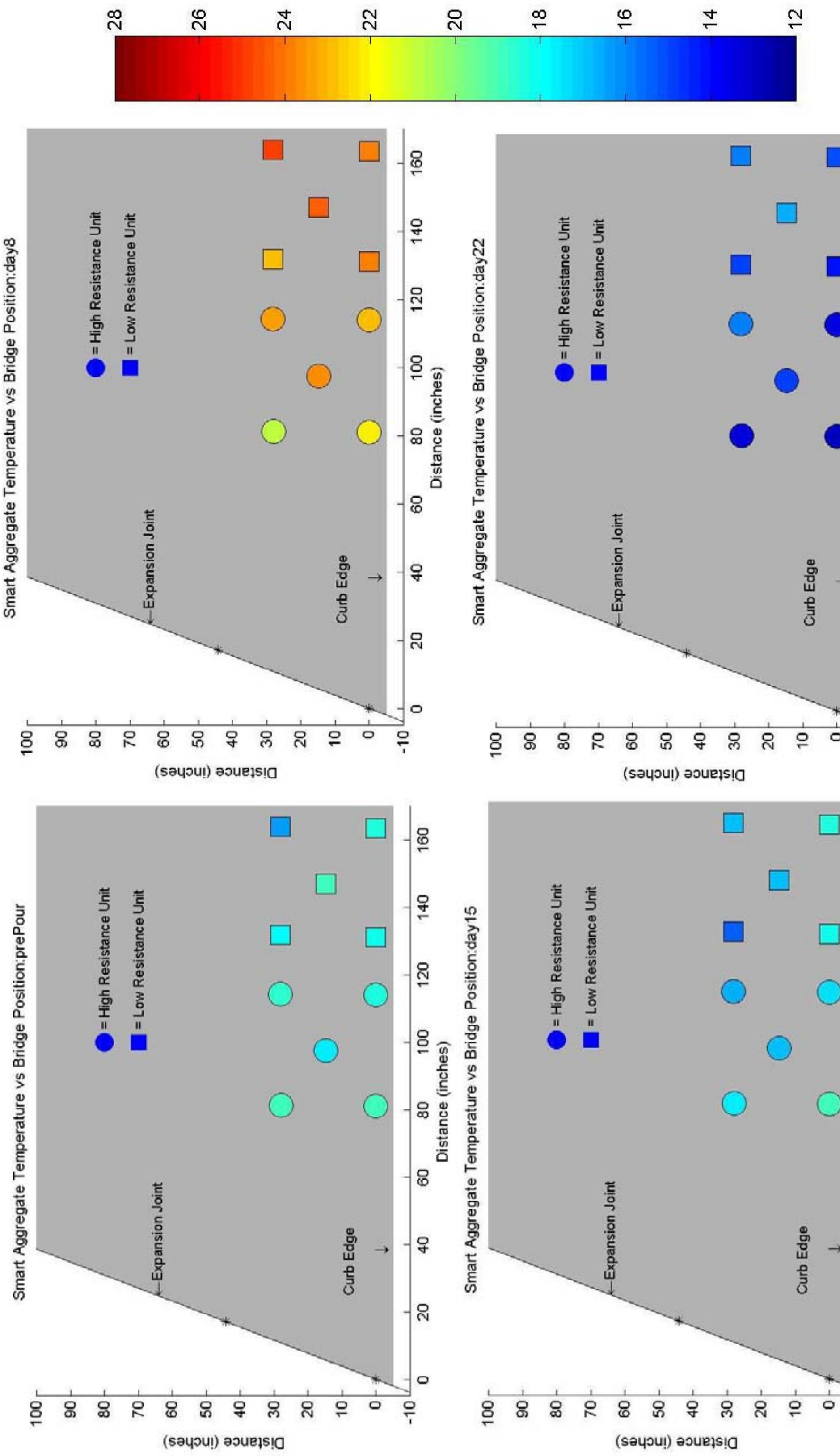


Figure 19: Post Installation Temperature Measurements (ºC)

VII Fabricate Smart Aggregates

The development, design and testing of the conductivity circuit is discussed in Section IV and the integration of the conductivity sensor with WESP is discussed in Section V. In preparation for fabrication, a Smart Aggregate design review was held (9 May 2002). The review included the Smart Aggregate development team, representatives from the MD SHA, APL program managers active in sensor development, and APL design engineers not involved in Smart Aggregate/WESP development. The participants identified several recommended design modifications but did not identify any design flaws. The Smart Aggregate team implemented the relevant design changes and started fabrication of approximately 15 Smart Aggregate units. Ten of these units were used for bridge testing and five for laboratory testing.

The prototype Smart Aggregate fabrication was divided into 3 stages:

stage 1 : Power system - receiving coil and power conditioners;
stage 2 : PIC (i.e. the processor) and sensor electronics; and,
stage 3 : Transmitter

A single unit was built to demonstrate the fabrication process. The product of each stage was tested in the laboratory before the next stage was done. Several problem areas were identified and addressed. Once the problems had been resolved, the remaining units were built and tested in the same 3 stages.

During fabrication, several kinds of testing were done on the Smart Aggregate units

a. Visual inspection of LTCC during coil placement
b. Power pick-up trim testing and corrections
c. Operability test of fully assembled (but not encapsulated) units at two temperatures and two conductivities. The result is an accept/reject decision with rejects sent for rework
e. Final operability check-out test after encapsulation

A major program goal is 50 year lifetime for Smart Aggregate packages. The time to failure of the electronic components has been estimated as much greater than the 50 year design goal. To insure the reliability of the packaging, dummy (no electronics) Smart Aggregate units were tested. These tests focused on package integrity and included: fine and gross leak tests and highly accelerated stress test (HAST).

At the end of fabrication, APL had 10 Smart Aggregates and holders ready for a bridge test and 5 additional units that will be used for laboratory testing at APL.

A unit cost in mass production for Smart Aggregates of under $50 is a program goal. The first generation WESP devices were very expensive (approx. $1500). The unit cost for the Smart Aggregates fabricated in this phase (Phase 1 development) is approximately $450 even though the Smart Aggregate is more complicated than WESP. Estimated cost for SA in the proposed Phase 2 development is approx. $150. These cost reductions were the result of design and process improvements; although most of the fabrication steps were still manual. Significant cost reductions will be achieved for future generations of WESP/Smart Aggregate by adopting commercial manufacturing techniques rather than the manual fabrication used to date. Final assembly costs in a mass produced version are expected to be approximately $40 each. Several patents have been filed under these programs and significant interest has been generated in the industry.

IX CONCLUSION

JHU/APL has successfully designed, developed, implemented and tested Smart Aggregate sensor suites for monitoring resistance (and resistivity) in concrete structures, particularly bridge decks. The system is a distributed, low cost (projected as less than a few percent of bridge cost in mass production), extremely rugged, highly reliable, and redundant to insure survivability to over 50 years.

The sensor suites have been tested in the laboratory and the results compared with laboratory grade instruments. Most of the major program goals (small size, long lifetime, under $50 cost) have been met. The sensor size is a disk of approximately ¾" diameter and ¼" thick. The lifetime limiting facet of Smart Aggregate is likely to be package integrity. Steps to insure package integrity include package testing at fabrication, on-going reliability (thermal cycling) tests and field tests in two MD SHA designated bridges. The field tests have demonstrated the prototype Smart Aggregate holder, ease of installation, durability of the SA during the deck pour process and the ease of collecting data. The field test measurements of temperature have behaved as expected but the resistance measurements have reached levels approaching very dry concrete. These values have been questioned by technical authorities and APL is still working to determine the correct values.

Although engineering prototype versions of the Smart Aggregate are very expensive, final assembly costs in a mass produced version are projected to be approximately $50 each. Several patents have been filed.

In future efforts APL will extend the Smart Aggregate sensor suite to include chloride ion concentration as well as concrete resistivity and temperature.

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Appendix A: Smart Aggregate Applications Provided by Maryland State Highway Administration

by E. S. Freedman

January 12, 2004

NEW BRIDGE SUPERSTRUCTURES:

- FOR STRUCTURES WITH SEPARATED GIRDERS AND CONCRETE CONSTRUCTION WHERE DECK IS POURED IN ONE ELEMENT AND FINISHED DECK IS RIDING SURFACE

  Since we believe the life of a structure is 80 years; and under the present cycling we believe the decks we are now constructing have a life of 40 years before total replacement is necessary, overlaying can play a key role. We know that a new overlay on a deck at a critical stage can extend the life by about 15 to 20 years. Therefore, it is possible if the initial life of a salvageable deck could be, say 30 years, it may be possible to place three overlays, one at age 30 years, one at 50 years and one at 65 years, and never have to totally replace the deck. If the overlays do a better job than predicted, then the three overlays listed above could be reduced to two. This can only be accomplished by getting good data on the chloride content within the deck so as to overlay the surface at the optimum time, which will be the role of the sensor attached to the top rebar mat of deck. This timing is critical and must be when it is not necessary to remove more than 2 ½" of concrete surface so as to minimize the potential for the need to remove portions of the deck below the top layer of rebars. The savings for this effort is not only monetary but in minimizing the disruption to traffic during the lifetime of a structure.

- FOR STRUCTURES WITH SEPARATED GIRDERS AND CONCRETE DECK CONSTRUCTION WHERE DECK IS POURED, AND THEN AN OVERLAY IS PLACED THEREON TO BECOME THE RIDING SURFACE, ALL DURING INITIAL CONSTRUCTION

  For this scenario the chloride sensors would be placed on top of the deck pour before placing the as built overlay. This will allow the engineers to know when chlorides have reached this critical level, (i.e. top of the main concrete members). This will then trigger the need to remove the original sacrificial concrete overlay and replace it with a new concrete overlay so that the life of the deck can easily be prolonged for the life of the structure. The savings in this case is a total replacement of the entire deck as opposed to only periodically replacing the concrete overlay as indicated for conventional construction.

- FOR STRUCTURES WHERE THE TOP SLAB IS THE MAIN SUPPORT MECHANISM, SUCH AS IN A CONCRETE BOX SUPERSTRUCTURE OR WHERE THE SUPERSTRUCTURE IS COMPOSED OF CONCRETE SLABS

IN FULL CONTACT WITH EACH OTHER; AND A PROTECTIVE OVERLAY IS PLACED THEREON

We do not want chloride intrusion to reach and affect these main structural elements at all. Therefore, during initial construction, sensors can be placed on top of the main concrete elements before placing the overlay, all during initial construction. This will allow the engineers to know when chlorides have reached this critical level, (i.e. top of the main concrete members). This will then trigger the need to remove the original sacrificial concrete overlay and replace it with a new concrete overlay – so that the life of the main superstructure can easily be prolonged for the life of the structure. The savings in this case is a total replacement of the entire superstructure as opposed to only periodically replacing the concrete overlay as indicated for conventional construction; a savings in time, money and disruption to traffic.

EXISTING BRIDGE SUPERSTRUCTURE

For existing structures for elements we believe are salvageable, which are many in number – the placement of sensors in the existing decks for a separated girder system or on top of the main concrete elements where it is the main support mechanism, etc. , has significant merit. It will allow utilizing the considerations indicated above for new structures to prolong the life of many of these older decks and/or main superstructure members; thereby maximizing the effects of overlaying and deck replacement in a timely fashion. The number, location and cost of supplying and installing these sensors – and most important, their ability to give reliable readings – will indicate when a deck and/or main concrete elements are salvageable and if so, when is the optimum time to remove and replace either an overlay or the upper portion of the deck proper.

OTHER STRUCTURAL ELEMENTS IN BRIDGE STRUCTURES NEW AND/OR EXISTING SUBSTRUCTURE ELEMENTS

Many substructure elements, especially pier caps and abutment bridge seat areas, can be attacked by chlorides when they are under superstructure expansion joints. As the chloride sensor suites are developed and we become adept at having devices that can easily read them, this will open the door for use in the substructure elements, not only in new but in existing elements as well.

OVERALL COST SAVINGS AND BENEFITS

At the present time the only means of determining the chloride contents of key elements is mostly a destructive and costly process. Traffic needs to be restricted and then an evaluation of the conductivity of the rebars can be made – indicating major and minor corrosion taking place, plus the actual coring of elements and then having a laboratory evaluation of these cores for their chloride content.

If the chloride sensor suite reaches our ultimate goal the units will be economical, easily installable, reliable in their information, with the reading of the data easily done, all with minimum disruption to traffic, and no need for concrete cores – and most important, provide a quick readout on conditions with minimum additional efforts.