

EMBEDDED CAPACITOR SENSOR FOR MONITORING CORROSION OF REINFORCEMENT IN CONCRETE

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Abstract

Corrosion of reinforcement can affect durability and integrity of reinforced concrete structures. Repair cost for a badly corroded structure can be very costly and time consuming. In this paper, several capacitor sensors were developed to monitor corrosion potential of reinforcement in concrete. The impedance capacitive of sensors was tested in various acid and alkali solutions using Agilent 4284A Precision LCR meter. The other sensors were tied to reinforcements and embedded in concrete specimen contaminated with 5% chloride to measure corrosion potential. The specimens were exposed to the corrosion chamber and indoor environments. From the research, it was found that the sensor can measure the impedance capacitive at different frequencies in the aggressive solutions. Besides, it was observed that the patterns of corrosion potential shown by the embedded sensors were similar to the SRI sensor. The output values from embedded sensor are in a range of recommendation by the ASTM-C876. Eventually, the bars were found corroded from the broken specimens that confirmed the detection of corrosion activities as recorded by the sensors.

Keywords: Corrosion of reinforcement, Corrosion testing, Embedded sensor, Chloride.

1. Introduction

Corrosion is defined as the destruction or degradation of a material (mostly metals) due to a chemical reaction of the material with the environment. In the construction sector, steel reinforcing bars are used as load-carriers to strengthen concrete structures.

Nomenclatures

C	Capacitance, F
E_{corr}	Corrosion potential
f	Frequency, Hz
X_c	Impedance capacitive, ohm

Nevertheless, the steel can corrode overtime and corrosion of reinforcement is a major problem to the construction industry worldwide. Initially, embedded steel bar in concrete develops a passive iron oxide film that makes it highly resistant to corrosion. However, the aggressiveness of an environment tends to corrode the steel either due to carbonation or chloride attack. Carbonation is a process of reaction between carbon dioxide (in environment) and calcium hydroxide (in concrete) to forms calcium carbonate that reduces concrete pH and weakens the passive layer of rebars. Meanwhile, with sufficient high concentration of chloride attacks and destroys the passive layer of rebars [1-5]. Due to these problems, it is necessary to conduct a study on the corrosion of reinforcement in order to maintain the durability and reliability of reinforced concrete structures.

There are a few options has been tried to address corrosion problems. Corrosion can be delayed by using new material which is designed to resist corrosion. Ismail et al. [6] used dual-phase steel as rebar to replace ordinary mild steel. Dual-phase steel has high corrosion resistance compared to conventional steel bar due to the low measurement of corrosion rate in ordinary and aggressive environment. Hossain et al. [7] replace cement with volcanic ash as a corrosion resistance in mortars. Volcanic ash reduces the quantity of calcium hydroxide hence delaying the onset of reinforcement corrosion. Nevertheless, it also important to study the assessment method in testing and monitoring corrosion processes in concrete. Thus, corrosion monitoring is the best way to provide quantitative assessment of corrosion. Song et al. [8] and Bjegovic et al. [9] gave an overview of the existing sensor technology and its efficiency.

However, the interest on non electrochemical embedded sensor was scarcely found in literature. Lee et al. [10] developed the corrosion sensor to monitor carbon dioxide and chloride permeation through the changes in the resistance value due to corrosion. The responses of the sensors were evaluated through the changes in resistance with different chloride concentration of NaCl solution. The red rust was found on half of the sensor after two cycles. Leung et al. [11] and Mohammad et al. [12] developed the optical fibre sensor based on the light reflection concepts. The fibre optic sensor can be embedded in the existing and new concrete structure for monitoring purposes. Fragility of fibre optic makes it difficult to work with. Magnetostrictive sensors were proposed by National Institute of Standards and Technology in Boulder, Colo. The sensor technique was based on the changes that occur in the physical dimensions of ferromagnetic materials due to the changing in magnetic field [13]. In this study, a capacitor sensor was developed to evaluate corrosion activity in concrete specimen. This sensor has the economic advantage associated with its production because it is strong, durable and reusable. Therefore, when the sensor was tied up closely to the rebars the corrosion parameter can be measured to provide quantitative data.

2. Embedded Capacitor Sensor (ECS)

2.1. Capacitor sensor design

ECS is an electrical capacitor sensor. It was developed using existing Printed Circuit Board (PCB) fabrication technology and was plated using Electroless Nickel/Immersion Gold (ENIG) process. ECS was designed with a circular shape with the dimension of 11mm in diameter and 1.6 mm in height. ECS is placed at a depth of 1 mm inside an acrylic casing as presented in Fig. 1(a). This is to prevent sensor surface from scratch. ECS has two plates which are separated by a medium known as the FR-4 as shown in Fig. 1(b). The back surface of ECS connected to the front by the through-holes. To connect the ECS to corrosion meter, the wires were soldered at the back of the surface. Figure 2(a) and (b) shows the photos of ECS.

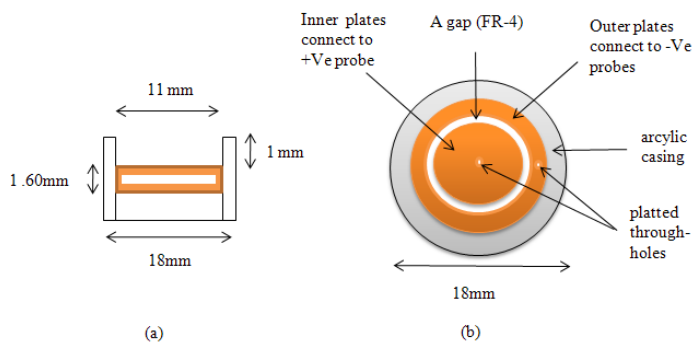


Fig. 1. (a) Side View of ECS. (b) Plan View of ECS.

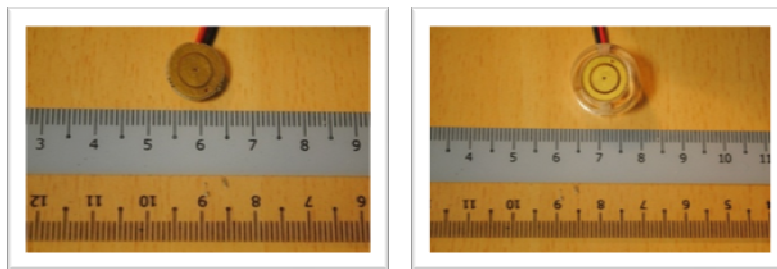


Fig. 2. Photos of the ECS. (a) Front View of the ECS, (b) Front View of the Soldered ECS with Casing.

2.2. Working principle of ECS in reinforced concrete

To detect corrosion process, the ECS was attached to the steel bar which was embedded in concrete prisms as shown in Fig. 3. In this research, the concrete acts as an insulator. It will not allow the flow of electric current. The steel bar which was embedded with ECS is a conductor. ECS has two plates which are the positive and negative sides. The existence of the changes in ions denotes the impedance of ECS. By referring to Fig. 4, during the oxidation process, H^+ or Fe^{2+} allows positive charge to increase. This implicates the upsurge of negative

charge to counterbalance the circuit. As a result, the resistances between the plates will increase. The increase in resistance denotes the commencement of the corrosion activity. Thus, by monitoring the voltage and current values from the systems, corrosion activity can be predicted with constant condition of voltages and frequencies applied.

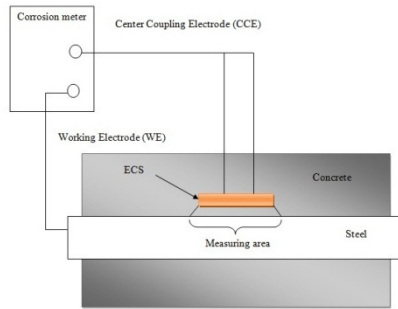


Fig. 3. Measuring Area of ECS.

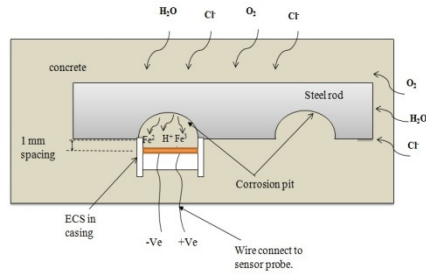


Fig. 4. Illustration of the ECS Working Principle in Reinforced Concrete.

3. Methods

3.1. Impedance capacitive testing

To test the feasibility and stability of ECS, the sensors were immersed in corrosive solutions. The sensor's impedance capacitive was measured from 20 Hz to 1 kHz in parallel mode using Agilent 4284A Precision LCR meter at 10 mV DC volt. The impedance capacitive testing of ECS used was of bare sensors (without mortar on surface) and sensors with 1mm layer mortar-filled. The impedance capacitive test begins with a bare sensor immersed in a test tube containing solutions. Five tests were carried out using different chemicals; each contained 10 ml and 1 M of sulfuric acid (H₂SO₄), acetic acid (CH₃COOH), sodium hydroxide (NaOH), ferric chloride (FeCl₃) and sodium chloride (NaCl). The tests then were repeated using sensors with mortar-filled. Figure 5 shows the experimental set up of the impedance capacitive test. Impedance capacitive in relationship with frequencies and capacitance is given by the Eq. (1), where X_c is impedance capacitive, f is frequency and C is capacitance [14]

$$X_c = \frac{1}{2\pi f C} \tag{1}$$

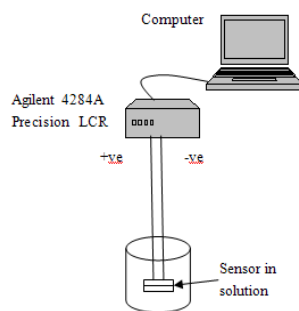


Fig. 5. Experimental Setup for Capacitance Testing.

3.2. Impedance capacitive testing

To test the effectiveness of ECS in signalling corrosion, ECS was attached to the rebars embedded in the concrete as shown in Fig. 6. Ordinary Portland Cement (OPC) was used in this work in compliance with BS 12: 1989 [15]. Concrete prism sizes (250×200×100) mm were cast with an embedded steel bar size 12 mm in diameters and 150mm of exposure length. The concrete prisms were designed with 20 Mpa strengths (at 28 days) using the aggregate size of 10 mm. The steel rods were cleaned using sand paper (800 grades) and coated by epoxy except for the portion of measurement area to avoid the corrosion at air-concrete interface. To accelerate the corrosion activity of the reinforcement in the concrete, 5% of NaCl by weight of cement was diluted in water and mixed with the concrete.

Figure 7 shows the physical condition in corrosion chamber and indoor environments. The relative humidity (RH) in corrosion chamber was 95% RH with temperature $35\pm 2^\circ\text{C}$ while the indoor was 50% RH with $25\pm 2^\circ\text{C}$. The specimens were exposed to both conditions for 98 days. E_{corr} were measured in the wetting phases every two weeks after being exposed to the cycles of wetting and drying in indoor environment and in corrosion chamber environment. The hypothesis for this observation is; the specimen exposed to the corrosion chamber shall give higher E_{corr} because in the chamber, the humidity and temperature level are higher. Moreover, the specimens were sprayed with salt water according to ASTM B117 AS1580 [16] simulating aggressive corrosion environment. In this test, the results of ECS were compared to SRI sensor.

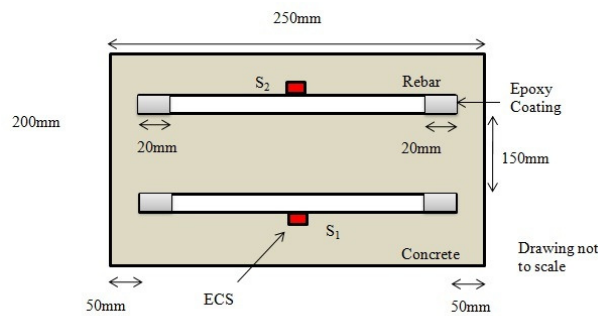


Fig. 6. Concrete Prism with ECS Attachments.

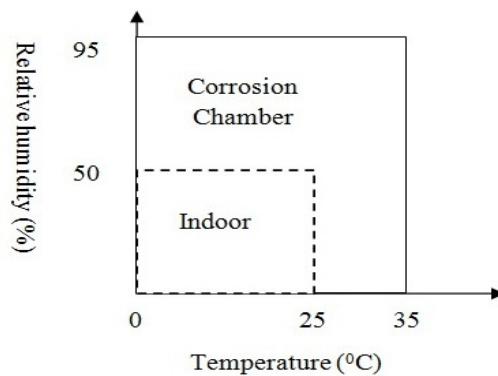


Fig. 7. Environmental Exposure Conditions.

4. Results and Discussion

4.1. Impedance capacitive test in solutions

Figures 8 and 9 exhibit the impedance capacitive measurements of a bare and a mortar-filled sensor respectively immersed in chemical solutions. The presence of mortar as a resistance to the sensor indicates higher impedance capacitive value compared to the sensor without mortar. These chemical solutions are electrolytes and contain free ions. Acids were chosen to simulate an acidic environment which reduces cement alkalinity. In addition, sodium hydroxide simulates an alkaline environment to prevent rebar from corroding. Ferric chloride and sodium chloride were selected since it contains chloride ions contributing to steel bar corrosion [17]. From the figures it was explicitly found that the impedance capacitive in different medium (acids, alkaline and neutral) decreases steadily and almost close to zero towards higher frequency. Therefore, it can be concluded that the ECS is principally working and coherent with the theory, refer to Eq. (1), when tested in different solutions.

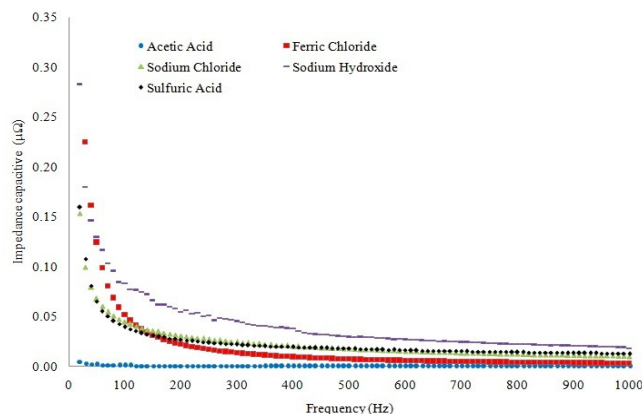


Fig. 8. The Impedance Capacitive of a Bare Sensor Immersed in Different Solutions.

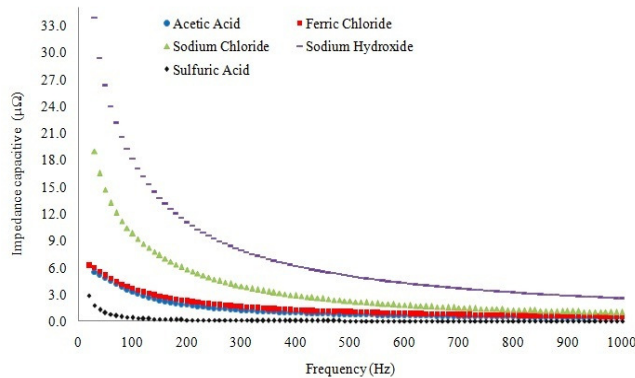


Fig. 9. The Impedance Capacitive of a Mortar-Filled Sensor Immersed in Different Solutions.

4.2. Corrosion potential (E_{corr}) of reinforcement

Figures 10 and 11 graphically explain the time-related changes in the potential reading of ECS and SRI sensor within 98 days. It is obvious that the E_{corr} patterns for both types of sensors are similar. The measurement recorded by SRI sensor yields are at a much lower value of -500mV to -550 mV for the whole test duration. E_{corr} measured by ECS which ranging from -300mV to -200mV for indoor environment and -400mV to -200mV for corrosion chamber environment. ECS reading indicates high corrosion level while SRI sensors yield a more extreme result with severe corrosion level according to Table 1 [18]. Silver/Silver Chloride reference electrode was used in the SRI sensor.

Table 1. Interpretation of Potential Measurements according to the ASTM C876 [18].

Silver/Silver Chloride (mV)	Corrosion condition
> -106	Low (10% risk of corrosion)
-106 to -256	Medium
< -256	High (90% risk of corrosion)
< -406	Severe corrosion

However, the main purpose of this test is to find out whether or not the potential measurement of ECS is in the acceptable range. According to Broomfield [5], the corrosion potential gives negative reading because in half-cell system, the positive terminal is connected to the steel and the negative terminal is connected to the half-cell sensor. A very negative potential can be measured with half-cell. However, the very negative potential reading can be found in saturated conditions with little oxygen. Thus it is supposed that there is no corrosion without any supply of oxygen. Therefore, in regards to the findings, the measurement of ECS is satisfactory since the measurement by ECS did not give a positive reading (half-cell terminal connection) and also did not measure a very negative reading. Perhaps the accuracy of ECS is greater and more sensitive than SRI because of its closer distant to the reinforcement.

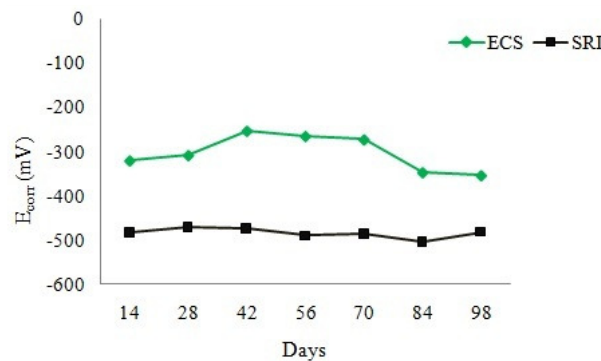


Fig. 10. E_{corr} Pattern between ECS to SRI Sensors for the Specimen in Corrosion Chamber Environment.

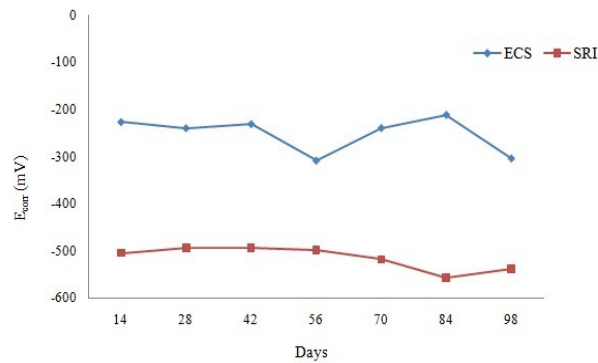


Fig. 11. E_{corr} Pattern between ECS to SRI Sensor for the Specimen in Ordinary Environment.

Corrosion chamber provides the corrosive environment to accelerate the corrosion process compared to indoor environment. The aggressive conditions are due to the higher relative humidity as well as the temperature. This finding is compatible to the predicted hypothesis, whereby the specimen has a higher risk of corrosion level tested in aggressive condition compare to indoor condition. Eventually, the bars were found corroded from the broken specimens to confirm the detection of corrosion activities as recorded by the sensors as shown in Fig. 12. Balafas et al. [19] reported that at high temperature, ions become mobile and salts become soluble due to the lack of water content in the environment. Thus mechanism of corrosion keeps on going because the ions are mobile to complete the oxidation and reduction process [5].



Fig. 12. Visual Inspection of Corroded Rebar: (a) Specimen Exposed to Indoor Environment. (b) Specimen Exposed to Corrosion Chamber.

5. Conclusions

Some concluding observations from the investigation are given below.

- ECS principally can work in different types of mediums (acids, alkaline and natural) in term of impedance capacitive measurement. The sensor yields different measurement values of impedance capacitive according to the types of chemical used.

- ECS can also provide a good and robust performance in measuring corrosion potential (E_{corr}) of reinforced concrete structures. The measurement result was confirmed by half-cell potential techniques comply with the ASTM C876 standard.
- In corrosion chamber, corrosive environment is made up so that the specimen here will corrode faster as compared to in a room condition. The evidence is exhibited by higher measurement of corrosion potential by ECS for specimen exposed inside corrosion chamber (corrode faster) as compared to specimen in indoor environment.
- ECS can be practically used to measure corrosion potential at a specific point only where the sensor is placed. Outlying zone may not be covered by the sensor, hence limiting the comprehensive assessment on the wider surface of reinforcement bar.

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References

1. Page, C.L. (1975). Mechanism of corrosion protection in reinforced concrete marine structures. *Nature*, 258(5535), 514-515.
2. Andrade, C.; and Martinez, I. (2006). Corrosion rate monitoring of deteriorated and repaired structures through on-site linear polarization measurements using surface or embedded sensors. In the *2nd International RILEM Symposium on Advances in Concrete through Science and Engineering*, Quebec City, Canada.
3. Ann, K.Y.; Ahn, J.H.; and Ryou, J.S. (2009). The importance of chloride content at the concrete surface in assessing the time to corrosion of steel in concrete structures. *Construction and Building Materials*, 23(1), 239-245.
4. Sohahngpurwala, A.A. (2006). *NCHRP Report 558: Manual on service life of corrosion-damaged reinforced concrete bridge superstructure elements*. National Cooperative Highway Research Program: Washington, D.C., USA, 13-15.
5. Broomfield, J.P. (1997). *Corrosion of steel in concrete: Understanding, investigation and repair*. E & FN Spon: London, UK.
6. Ismail, M.; Hamzah, E.; Guan, G.C.; and Rahman, I.A. (2010). Corrosion performance of dual-phase steel embedded in concrete. *The Arabian journal for science and engineering*, 35(2B), 81-90.
7. Hossain, K.M.A; and Lachemi, M. (2004). Corrosion resistance and chloride diffusivity of volcanic ash blended cement mortar. *Cement and Concrete Research*, 34(4), 695-702.
8. Song, H.W.; and Saraswathy, V. (2007). Corrosion monitoring of reinforced concrete structures - A review. *International Journal of Electrochemical Science*, 2(1), 1-28.

9. Bjegovic, D.; Meyer, J.J.; Mikulic, D.; and Sekulic, D. (2003). Corrosion measurement in concrete utilizing different sensor technologies. *NACE International*, Paper No. 03435.
10. Lee, H.S.; Shin, S.W.; Ahn, J.M.; Kim, Y.C.; and Kho, Y.T. (2003). Development of corrosion sensor for monitoring steel-corroding agents in reinforced concrete structures. *Materials and Corrosion*, 54(4), 229-234.
11. Leung, C.K.; Wan, K.T.; and Chen, L. (2008). A novel optical fiber sensor for steel corrosion in concrete structures. *Sensors*, 8(3), 1960-1976.
12. Ismail, M.; Dina, E.; Rosly, A.; and Ikhsan, S. (2005). Observation of corrosion process of reinforcing steel. *Jurnal Kejuru-teraan Awam*, 17(1), 13-22.
13. Bartels, K.A., Kwun, H.; and Hanley J.J. (1996). Magnetostrictive sensors for the characterization of corrosion in rebar and prestressing strands. In *SPIE Proceedings on non-destructive Evaluation of Bridges and Highways*, 2946, 40-50.
14. Stanley W. (1973). *Guide to electronic measurements and laboratory practice*. Prentice-Hall, Englewood Cliffs, New Jersey.
15. British Standards Institute, 1996. BS 12: 1989, Specification for Portland cement.
16. ASTM B117 AS1580 (2007). Standard Salt Spray (Fog) Apparatus. American Society for Testing and Materials.
17. Kyung, J.W.; Yokota, M.; Leelalerkiet, V.; and Ohtsu, M. (2004). Practical use of half-cell potential method for NDE of corrosion of reinforced concrete structure. *Key Engineering Materials*, 270/273, Part 2, 1638-1644.
18. ASTM C876 (1991). *Standard test method for half-cell potential of reinforcing steel in concrete*. American Society for Testing and Materials.
19. Balafas, I.; and Burgoyne, C.J. (2010). Environmental effects on cover cracking due to corrosion. *Cement and Concrete Research*, 40(9), 1429-1440.