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MONITORING CORROSION OF REINFORCEMENT BAR USING CAPACITIVE SENSOR AT DIFFERENT CONCRETE COVER DEPTH

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Abstract: Corrosion of reinforcement is a worldwide problem that affects durability and integrity of reinforced concrete structures. Repairing deteriorated reinforced concrete structures at an advanced stage is very costly and time consuming. It is more advantageous if corrosion can be detected at an earlier stage so that some preventive measures can be carried out. Monitoring of reinforcement corrosion in concrete can be achieved by embedding corrosion sensor within the concrete cover. In this study, an Embedded Capacitor Sensor (ECS) was developed to evaluate corrosion activity in concrete specimen. ECS was embedded in the concrete and its function is to measure the corrosion potential (E_{corr}) of reinforcement. E_{corr} measured by ECS is a result of the accumulated positive and negative charges between the two ECS plates from the corrosion process. For actual testing, ECS was tied to the reinforcement and embedded in concrete specimens. It was then calibrated using standard portable sensor (Ag/AgCl reference electrode) by measuring E_{corr}. The ECS measurement is proven reliable because the reading pattern was similar to what shown by standard portable sensor. For monitoring, the ECS also was tied to the reinforcement and embedded in concrete at two different depths (15 mm and 25 mm). The concrete specimens were contaminated with 5% NaCl by weight of cement and then immersed in 3.5% NaCl solutions at room temperature to speed up the corrosion process. From this research, it was found that E_{corr} for 15 mm concrete cover is higher than 25 mm concrete cover. Thicker cover delay the penetration chloride ion and oxygen to the reinforcement. Eventually, the bars were found corroded from the broken specimens that confirmed the detection of corrosion activities as recorded by the sensors.

Keywords: *Reinforcement corrosion, Capacitor sensor, Concrete cover, Corrosion potential (E_{corr}).*

1.0 Introduction

Corrosion is defined as destruction or degradation of material (mostly metals) due to the chemical reaction of the material with its environment. In the construction, reinforcing bar is corroded due to the carbonation and chloride attack. During the corrosion process, the rust forms and breaks down the passive film when the pH level falls, thus forming of rust reduces tensile strain around the steel as well as cracks in the concrete. Crack followed by spall and causes the loss of durability in structure. This problem if left abandoned, can affect the integrity of the structure (Broomfield, 1997; Veleve *et al*, 2000; Broomfield *et al.*, 2002; Yoo *et al.*, 2003). Due to the problems as mentioned above, it is necessary to conduct studies on the corrosion of the reinforcement. There are many methods that have been tried for the purpose of delaying the corrosion process. Among the methods in the previous studies include improving quality of concrete cover by adding admixture such as volcanic ash, fly ash, ground granulated blast furnace slag and palm oil fuel ash (Mangat *et al.*,1991; Hussain *et al.*, 1994; Thomas *et al.*, 2004; Güneyisi *et al.*, 2005 and Chindaprasirt *et al.*, 2008).

Corrosion can also be delayed by using new material which is designed to resist corrosion such as dual-phase steel, stainless-steel, galvanized-steel and epoxy-coated steel (Ismail *et al.*, 2009; Selvaraj *et al.*, 2009 and Tittarelli *et al.*, 2011). The application of blended cements in concrete or by introducing a new material as reinforcing bar can only delay the corrosion process and increase the service life of a structure. However, the corrosion will still occur no matter preventive measurements had been taken. Therefore, it is also important to conduct a study in corrosion monitoring to predict the quantitative assessment of corrosion, to monitor corrosion risk and to take action in the future (Legat *et al.*, 2004 and Ervin *et al.*, 2009). In this paper, a capacitance-based sensor was developed to evaluate corrosion activity in concrete samples. This sensor in addition to its economic advantage associated with its production, it is strong, durable and reusable. The sensors were tied to the reinforcements during casting and left embedded throughout testing period. Corrosion parameters E_{corr} was measured using 'SRI-CMIII corrosion meter' and the readings were compared with the established half-cell technique.

2.0 Experimental Works

2.1 Reinforced concrete slab specimens

Ordinary Portland Cement (OPC) conforming to **(**BS 12: 1989) was used throughout. Table 1 shows the chemical composition of the cement. Hot rolled mild steel reinforcement with specified characteristic strength, f_y = 250 N/mm^2 was used. The reinforcement has a diameter; 16 mm and length; 330 mm. Epoxy coating is applied to all concrete-reinforcement interfaces. Standard mix from ST4 Table 3 (BS5328-2:1997) was employed for mixing. Reinforced concrete slabs measuring 250 mm x 250 mm x 100 mm thickness were prepared, cured and monitored for corrosion activities. The 28 days concrete compressive strength was 25 N/mm^2. Coarse aggregate of maximum nominal size 20 mm and a water-cement ratio 0.5 were applied. To accelerate corrosion activity of the reinforcement, 5% NaCl by weight of cement was diluted in the mixing water prior to concrete mixing. Figure 1 shows the diagram of slab specimen.

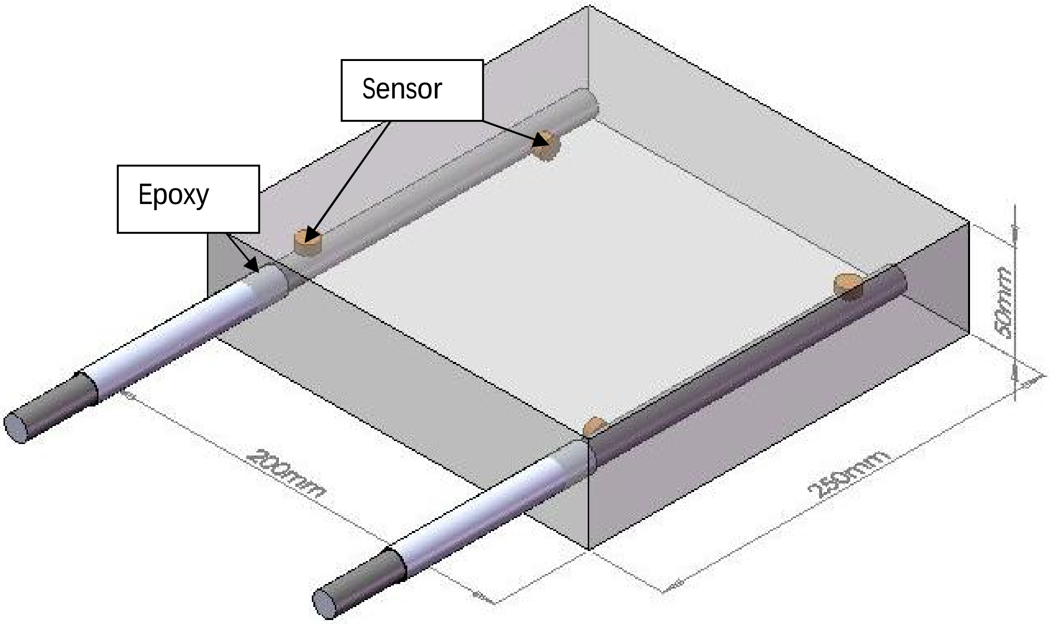

Figure 1: Concrete slab; reinforcement and embedded sensor details

Table 1: Chemical composition of OPC BS 12: 1989

Chemical Composition	**Percentage (%)**
Silicon Dioxide (SiO_2)	20
Aluminium Oxide (Al_2O_3)	6
Ferric Oxide (Fe_2O_3)	3
Calcium Oxide (CaO)	60-63
Magnesium Oxide (MgO)	1.5
Sulphur Trioxide (SO_3)	2.0
Alkalis	1.0
Loss of Ignition (LOI)	2.0-2.7

2.2 Embedded Capacitor Sensor (ECS)

A circular capacitor sensor was designed for corrosion detection. It has a diameter and thickness of 11 mm and 1.6 mm respectively. Atomic percentages of its main compositional materials as identified using field emission scanning electron microscope (FESEM) model Zeiss Supra 35 VPFESEM are copper; 60.23%, nickel; 18.42%, aurum; 12.15% and others 9.2%. The sensor was fabricated on a Flame Retardant 4 (FR-4) Printed Circuit Board (PCB) followed by nickel and gold coats on both front and back surfaces. Figure 2 shows the design of embedded capacitor sensor, where, E= Electrical source, a = radius plate A = 0.25 cm and b = radius plate B = 0.5 cm.

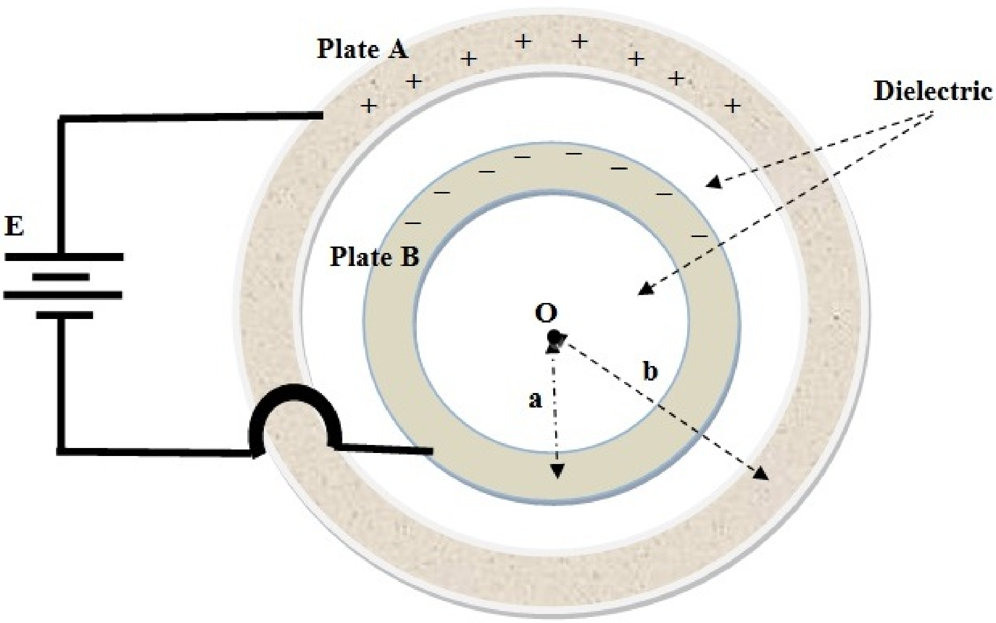

Figure 2: Outer plate (Plate A) and inner plate (Plate B) are separated by an insulating medium (dielectric) in ECS system.

2.3 Portable Sensor (PS)

Figure 3 shows the double counter electrode portable sensor model SRI-CMIII Shikoku Institute with Ag/AgCl as reference electrode. This commercially based sensor is employed in this work for comparative reasons, so that values obtained from the embedded sensor could be correlated.

Figure 3: Portable sensor

2.4 Corrosion measurement

Frequency range of the equipment was set at 10 Hz to 10 mHz and it has an input voltage capacity of 10 mV. Even though, SRI-CMIII meter has the capacity to provide various output data such as corrosion potential (E_{corr}), corrosion current (I_{corr}), concrete resistance ($R_{c'}$), real polarizing resistance (R_{ct}) and apparent polarizing resistance ($R_{ct'}$) (Portable Rebar Corrosion Meter SRI-CMIII Operation Manual, 2007) only measurements of E_{corr} were recorded for comparisons in this work. To accelerate corrosion process, the slab specimens were cyclically dried in laboratory for a week followed by immersion in 5% NaCl solution for another week. The E_{corr} was measured after each complete cycle using SRI-CMIII Shikoku Institute corrosion meter.

3.0 Results and Discussion

3.1 Calibration

The measurement of corrosion potential (E_{corr}) for both sensors were done separately on the same specimen. The E_{corr} for both sensors was taken from the bottom of the specimen at 25 mm concrete cover depth; as shown in Figures 4 and 5. The E_{corr} was measured in the wet phases every 1 month after being exposed to the cycles of wetting and drying in room and in corrosion chamber. In this test, the results of embedded capacitor sensor (ECS) were compared to portable sensor (PS) to observe the pattern of ECS in measuring corrosion potential. Figures 4 and 5 graphically explain the time-related changes in the potential reading of ECS and PS within 100 days. It is apparent that the E_{corr} pattern for both type of sensors are comparable. The measurement by the portable sensor yielded much lower values around -500mV to -550 mV for the whole test duration. However, the E_{corr} measured by ECS are in the range of -400mV to -200mV. Moreover, ECS and PS have different range of measurement in this study. Based on comparison, PS obviously measured a higher range than ECS. This is due to the fact that PS measures against reference electrode, while ECS measure direct to the rebars. Based on the Figures 4 and 5, the E_{corr} of PS ranges between -500mV to -600 mV, while the E_{corr} of ECS lies between -300mV to -400mV. Each of the value measured by ECS has to be added -200mV so that the value equal to the values of standard PS (Ag/AgCl reference electrode).

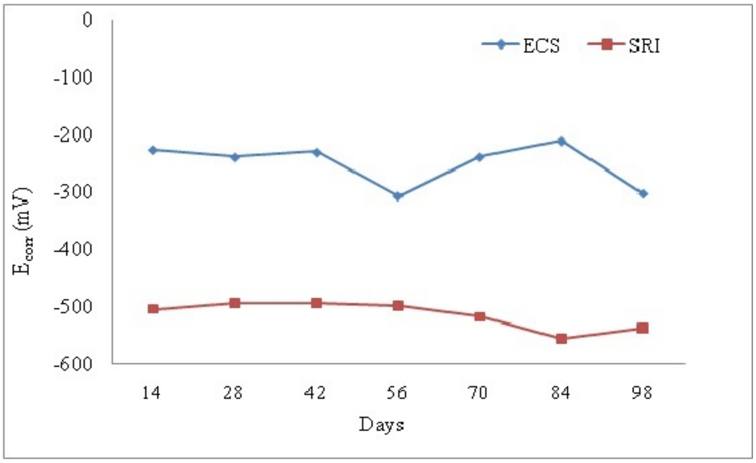

Figure 4: E_{corr} pattern between ECS to SRI-CMIII sensor in room condition

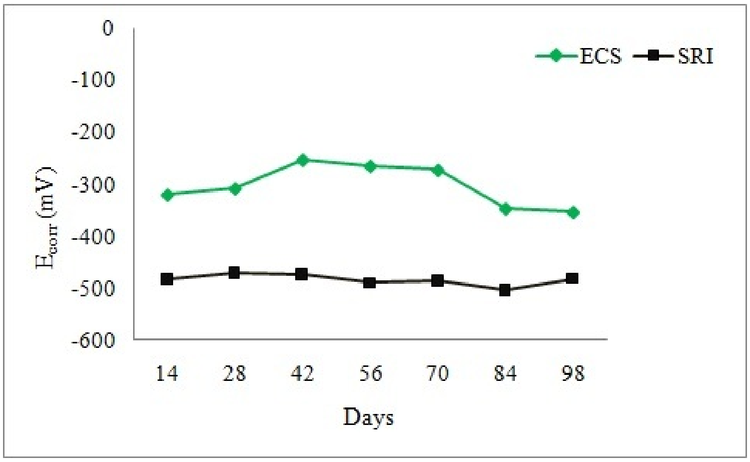

Figure 5: E_{corr} pattern between ECS to SRI-CMIII sensor in corrosion chamber

3.2 Reinforcement corrosion potential

Figures 6 and 7 show the changes of corrosion potential (E_{corr}) versus time obtained from ECS in different concrete cover (15mm and 25 mm) depth. The curves patterns show that the E_{corr} measured by embedded capacitor sensor (ECS) are in the range of -500 mV to -200 mV. Moreover, the E_{corr} of the specimen with 15 mm cover depth has the lowest value as compared to the 25 mm cover depth. According to Table 2 (ASTM C867:1991), the E_{corr} for 15 mm cover depth shows severe corrosion condition as compared to Saturated Calomel Electrode (SCE) and Ag/AgCl electrodes. Nevertheless, the E_{corr} for the sample with 25 mm cover depth for SCE and Ag/AgCl electrodes are almost at the medium corrosion condition. Based on Figures 6 and 7, the qualitative interpretation by the two different electrodes shows that the E_{corr} for sample with 15 mm cover depth were severely corroded. This shows that comparison results to SCE and Ag/AgCl electrodes standard are similar to each other.

As expected from the experiment, the thicker concrete covers result in less corrosion risk. Thus, it is proven that ECS is able to determine the corrosion potential (E_{corr}). The thicker cover depth (25mm) can protect the reinforced concrete because thicker cover could reduce or delay the oxygen and chloride ions penetration from reaching the reinforcing bar. Contrary to the thin concrete cover (15 mm), the reinforcing bars corrode faster because the moisture and chloride ions can attack the steel much faster than thick concrete cover. The results signify that the less concrete cover thickness, the higher the corrosion rate. Furthermore, visual inspection revealed that the reinforcement was corroded as can be seen in Figure 8.

Table 2: Interpretation of potential measurements according to the ASTM C867:1991

Silver/Silver Chloride (mV)	**Saturated Calomel Electrode (mV)**	**Corrosion condition**
> -106	> -126	Low (10% risk of corrosion)
-106 to -256	-126 to -276	Medium
< -256	< -276	High (90% risk of corrosion)
< -406	< -426	Severe corrosion

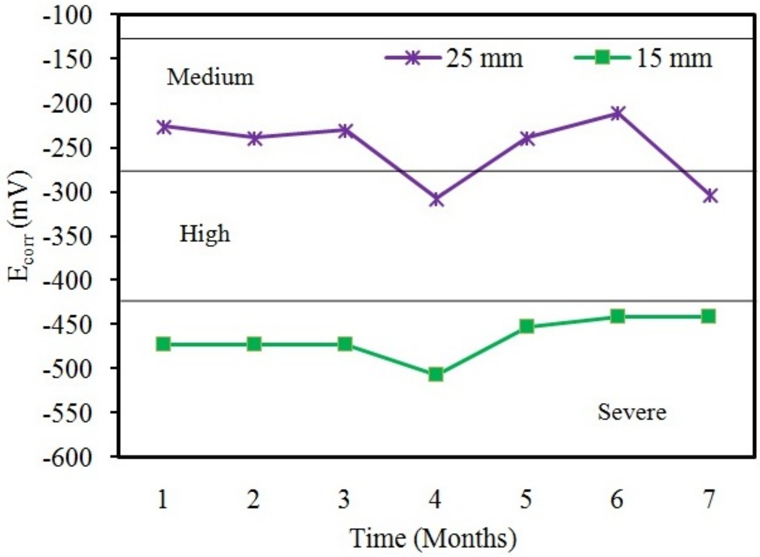

Figure 6: E_{corr} at different concrete cover depth relative to SCE electrode

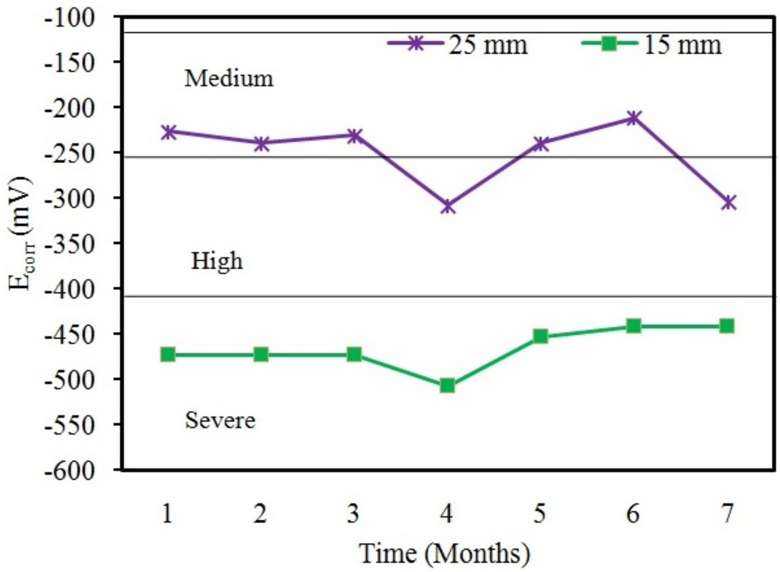

Figure 7: E_{corr} at different concrete cover depth relative to Ag/AgCl electrode

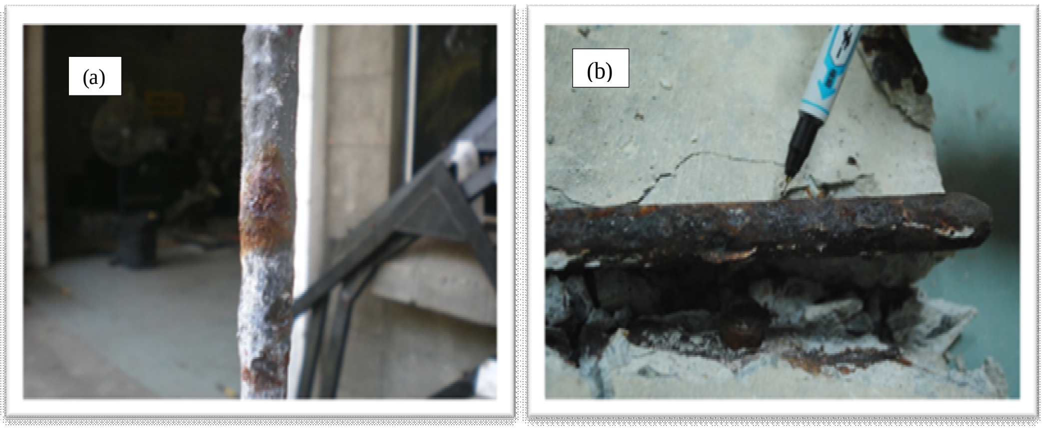

Figure 8: Corroded rebar taken from broken specimen at different concrete cover depth
(a) 15 mm (b) 25 mm

5.0 Conclusion

The conclusions that can be drawn from this study are as follows:

i. Embedded capacitor sensor (ECS) succeeded in measuring the corrosion potential (E_{corr}) towards corrosion reinforced concrete structure either in corrosion chamber or in building room. The ECS measurement is proven reliable through the observation of broken reinforced specimen which was confirmed deteriorated subject to corrosion.

ii. The values measured by ECS are in compliance with ASTM C879:1991 standard. The measured total values are between the ranges as recommended in the standard.

iii. ECS is capable to measure the value of reinforced concrete specimens with different concrete cover depth. The thicker concrete cover gives lower corrosion potential reading compared to thin concrete cover. This is true based on visual observation of the specimen and also findings from previous researches.

iv. Embedded sensor is robust and suitable for installation in reinforced concrete, hence capable of detecting changes in the immediate vicinity of the steel for a longer period.

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