KKU Engineering Journal

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Monitoring corrosion levels of fly ash concrete reinforcement using electromagnetic method

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Received January 2012

Accepted August 2012

Abstract

This research aims to study the monitoring of corrosion levels in steel reinforcement bars in fly ash concrete by using the electromagnetic method. This method is proposed as a new non-destructive methodology for corrosion level inspection of steel bars immersed in fly ash concrete. An alternating current with a frequency of 100 kHz is applied to generate changing magnetic flux. This method is also used to generate a magnetic flux in the excitation coil and the root mean square voltage (E_{rms}) depends on the total magnetic reluctance of the sensing coil touching the fly ash concrete. In this research, the first specimen group of fly ash concrete is mixed with various aggregate levels of 0%, 20% and 40% of fly ash weight, respectively without rebar. The second specimen group of fly ash concrete is mixed with various aggregate levels of 0%, 20% and 40% of fly ash weight, respectively, with rebar. Each subgroup is composed of 12 specimens. All specimens are immersed in water for 90 days and then dried for 7 days. In addition, the second specimen subgroup is divided into 4 groups which are normal, low, medium, and high times of corrosion determined by the length of time the specimens are immersed in NaCl 5% solution with electric current used to accelerate the corrosion level. An electric current density of 400 $\mu A/cm^2$ is applied for 0 hours, 48 hours, 96 hours, and 144 hours, respectively. Each group includes three pieces. The results of the electromagnetic method for identifying types of fly ash concrete for various aggregate levels used in this research are 0%, 20% and 40% of fly ash weight, respectively without rebar. The values of the fly ash concrete are found to be 2.80V, 2.79V and 2.75V, respectively. This method could identify the corrosion levels of the second group with rebar at medium to high levels of fly ash concrete, which are 0% and 20%. The E_{rms} values of the steel rebars are 2.920V, 2.890V 2.923V, and 2.897V, respectively. The average steel loss are 1.94%, 3.09% 1.81%, and 2.75%, respectively. The corrosion levels of the 40% fly ash concrete could only be measured at the high corrosion level, and thevalues of this fly ash concrete is 2.950V. The average steel loss is 1.46%.

Keywords : Electromagnetic, Reinforcing, Magnetic reluctance, Concrete, Corrosion

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1. Introduction

In the past, most of the design studies in the literature and research in reinforced concrete assumed that the durability of reinforced concrete structures could be taken for granted. However, it becomes obvious that many reinforced concrete structures are exposed to environmental stress during their lifetime and this could deteriorate the concrete or steel reinforcement. The reinforced steel bars are considered the biggest problem faced by structural engineers over the last decade. Non-destructive test (NDT) techniques have been used to evaluate the general conditions of reinforced concrete [1]. Additionally, these techniques rely on elastic wave based techniques [2] and electromagnetic-based techniques. Electromagnetic-based techniques can be divided into the induced eddy current-based technique [3], ground penetrating radar (GPR) [4], and X-ray techniques [5]. Each of these techniques has its advantages and disadvantages, as well as limitations. Techniques based upon elastic waves present inaccuracy when used to detect anomalies or in the presence of objects of small dimensions, due to the large wavelength of this kind of wave. Furthermore, high frequency electromagnetic waves enable identification of the size and position of the reinforced concrete owing to the concrete's magnetic properties. Electromagnetic based techniques have interference effects on the frequency range. Finally, the ionizing radiation techniques (X-ray and gamma rays) may cause serious risks to the workers' health and to the environment [6]. In conclusion, this work suggests a new methodology for the corrosion level inspection of steel bars immersed in fly ash concrete structures by using an electromagnetic method [6]. In comparision to other conventional methods, our methodology is more cost efficient and offers an additional advantage of safety.

2. Theory

2.1 The corrosion process

Generally, when the passive layer of a steel bar breaks down, rust will appear instantly on its surface. These chemical reactions are similar to carbonation or chloride attack. When corrosion of the reinforced steel bars occurs in concrete, the rust dissolves in any void that contains water. The electrons will accumulate according to the following equation (1), which presents the anodic reaction.

$$Fe \rightarrow Fe^{+2} + 2e^{-} \quad (1)$$

If the electrons which accumulate on the steel reinforcement do not outnumber the electrodes in the oxygen and the water, the cathodic reaction can be adapted in the following equation (2)

$$2e^{-} + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^{-} \quad (2)$$

This equation shows that the presence of OH^- results from the cathodic reaction. Moreover, the hydroxide ions slightly increase the alkalinity and reduce effect of carbonates or chlorides. From Equation 3, it is noted that water and oxygen are the main factors for the corrosion process.

$$2Fe(OH)_3 \rightarrow Fe_2O_3 \cdot H_2O + 2H_2O \quad (3)$$

The preceding chemical reactions show the transformation of steel from ferrous hydroxides ($Fe(OH)_2$), which react with oxygen and water to produce ferric hydroxides ($Fe(OH)_3$), and the last component which is the hydrate ferric oxide (rust). In other words, its chemical formula is $Fe_2O_3.H_2O$.[7]

Ferric hydroxide is very effective in the deterioration and spalling of concrete cover since the volume of the rust increases the original volume of the steel bar, while the cross-sectional areas of the steel bars decrease.

2.2 Fly ash

Fly ash, a by-product of burning pulverized coal in thermal generating stations, is a finely divided, amorphous alumino-silicate that reacts at normal temperature with calcium hydroxide to produce calcium-silicate hydrates (C-S-H) with cementitious properties; i.e. it is a pozzolanic material. As such, fly ash is a valuable resource to the construction industry as it can be used together with Portland cement to produce concrete. Fly ash will react with the calcium hydroxide (Ca(OH)2) liberated by the normal hydration of Portland cement producing additional cementitious material in the hardened concrete [8]. It is not a good conductor of magnetic flux. It is a high magnetic reluctance. A magnetic reluctance is evident since the voltage in the coil induced by the magnetic flux is decreasing as the density of the fly ash in the aggregate is increasing

2.3 Probe head

Figure 1 shows the schematic of the probe head. The probe structure is a U-core which is capable of well-controlled and directional field distribution. The probe material is ferrite, used for its high permeability and low core loss. It is energised by using AC frequency in the excitation coil by equation (5) and the coupled signal to a sensing coil connected to a monitor. The magnetic flux induces the sensing coil which can result in a current in the coil. The magnetic flux can be calculated from equation (6). Hence, the magnetic flux depends on magnetic reluctance in the core as shown in equation (7) [9]. The magnetic reluctance is used to detect the corrosion level of the reinforcing steel bar in concrete as showed in Figure 2.

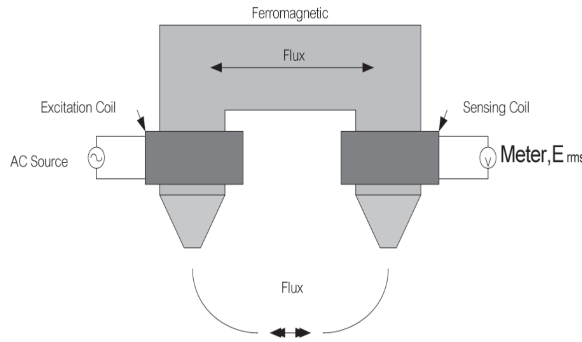

Figure 1 The schematic of probe head

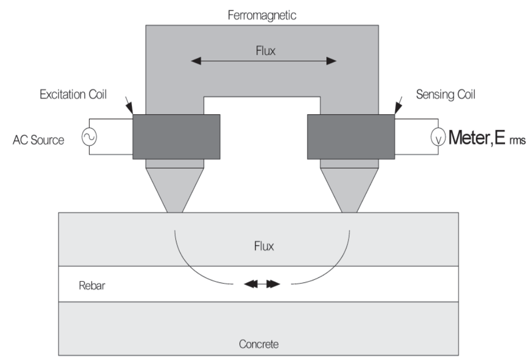

Figure 2 Conceptual sketch of the electromagnetic field measurement

In AC electric machines as well as many other applications, the voltage and fluxes vary sinusoidally with time. Assume that the core flux Ψ(t) varies sinusoidally with time by Faraday law, the voltage induced in the N-ture coil is:

$$e(t) = N\left(\frac{d\Psi}{dt}\right) \quad (4)$$

The root-mean-square (rms) value of the induced voltage is [9]:

$$E_{rms} = 4.44Nf\Psi \quad (5)$$

E_{rms} is the root-mean-square (rms) value of the induced voltage

N is the turn of coil

f is the frequency

Ψ is the net flux linking the loop

$$\Psi = \frac{\Im}{\Re} \qquad (6)$$

$\Im$ is the magneto motive force

Ψ is the net flux linking the loop

$\Re$ is the total reluctance of core of the loop

$$\Re = \frac{l}{\mu_0 \mu_r S} \qquad (7)$$

$\Re$ is the magnetic reluctance

l is the length

S is the cross-sectional area

μ_0 is the permeability of free space and is $4\pi \times 10^{-7}$ Henry/Meter

μ_r is the relative permeability of the medium

3. Methodology and Materials

3.1 Methodology

The procedure for measuring the corrosion level of steel bars in a reinforced concrete structure is shown in Figure 3.

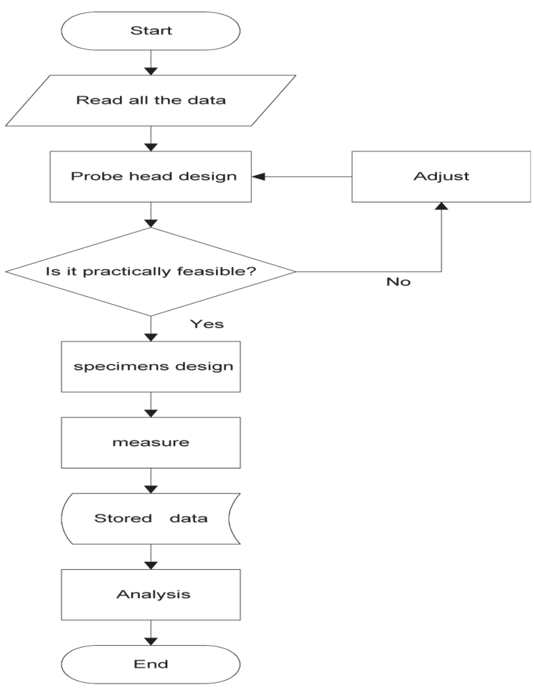

Figure 3 Flow chart of procedure for measuring corrosion level of steel bars in reinforced concrete structure

3.2 Materials

As shown in Figure 4 the size of the specimens is 100x100x100 mm. The reinforced concrete is made by using portland cement concrete (PCC) with ASTM C150 standard compound of 0%, 20% and 40% of fly ash weight respectively. The dimension of each specimen of the reinforcement is 9 mm diameter and 100 mm length. The steel bar is immersed in the center of the concrete. The specimens of the first group of fly ash concrete at different aggregate levels used in this research were 0%, 20% and 40% of fly ash weight, respectively, without rebar. The second specimens group of fly ash concrete for various aggregate levels used in this research are 0%, 20% and 40% of fly ash weight, respectively with rebar. Each subgroup is composed of 12 specimens. The total specimens were immersed in water for 90 days and then dried for 7 days [8]. In addition, the specimens of the second subgroup were divided into 4 subgroups which were normal, low, medium, and high times of corrosion determined by the specimens immersed in NaCl 5% solution with an electric current used to accelerate the corrosion level. A current density of 400$\mu A/cm^2$ was applied for 0 hour, 48 hours, 96 hours, and 144 hours, respectively as shown in Figure 5. Each group included three pieces.

3.3 Measurement set-up

The schematic of the NDT installation arrangement can be seen in Figure 6 and the characteristic input signal in Table 1 produced by a function generator (Tektronix model AFG310) with excitation coil at a frequency of 100 kHz. This frequency is appropriate for a ferrite core [10]. Its output voltage is approximately 10Vp-p (maxium output voltage of Tektronix model AFG310). The probe head is controlled by a dc motor and the output voltage is measured by an oscilloscope (Tektronix model TDS3054B) and computed at the sensing coil. In Figure 6, the probe head is installed in the middle of the specimen to measure the electromagnetic field. The corrosion level of the steel bars in reinforced concrete structure is determined.

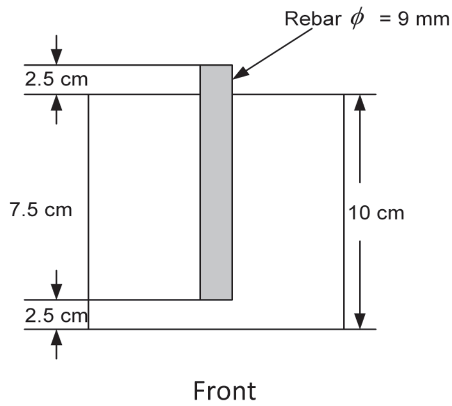

Figure 4 Conceptual sketch of specimens

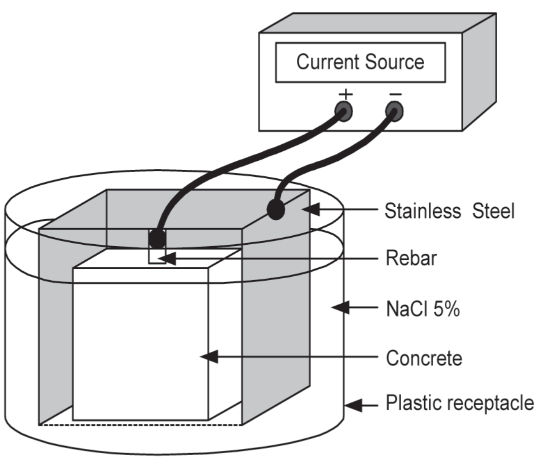

Figure 5 Conceptual sketch of electric current was used to accelerate the corrosion

Table 1 Specifications of electromagnetic field generatoring equipment

Item	Specifications
Method	Sine wave
Frequencies	100 kHz
Transmissmion	10Vp-p(at load 50Ω)

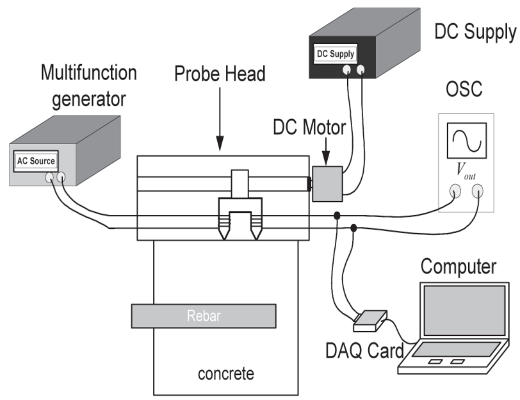

Figure 6 Conceptual sketch of electromagnetic field of installed NDT measuring arrangement

4. Results and discussions

The corrosion level of steel reinforcements in fly ash concrete has been identified by E_{rms} using an electromagnetic method. This is a nondestructive analysis which can monitor the weak spots resulting from corrosion levels in the reinforcement of the structure. Figure 7 shows the results from the identification of fly ash concrete without rebar. The induced E_{rms} in sensing coil appears to decrease from 2.80V, 2.79V and 2.75V, respectively. A high magnetic reluctance is evident since the voltage in the coil induced by the magnetic flux is decreasing as the density of the fly ash in the aggregate is increasing. Figure 8 shows the measured results of corrosion levels of the reinforcements in 0% fly ash concrete. The E_{rms} measurement at the sensing coil shows the results from the normal and low corrosion levels have not changed since little corrosion appears at the cross-section area.

The E_{rms} from the medium and high corrosion levels induced in the sensing coil are 2.920V and 2.890V, respectively. Additionally, the average steel loss is 1.94% and 3.09%, respectively. Because the corrosion decreases the cross-section area of reinforcements, so this causes a high magnetic reluctance. Figure 9 shows the measured results of corrosion levels of the reinforcement in 20% fly ash concrete. The E_{rms} measurement at the sensing coil shows the results from the normal and low corrosion levels have not changed, because little corrosion appears at the cross-section area of reinforcements. Nevertheless, the measurement results of medium and high corrosion levels of reinforcement of fly ash concrete at the E_{rms} sensing coil are appears to decrease as 2.923V and 2.897V, respectively. The average steel losses are 1.81% and 2.75%, respectively. Because the corrosion produces a decrease in the cross-section area of the reinforcement, there is a high magnetic reluctance. Figure 10 shows the measured results of corrosion levels of the reinforcement in 40% fly ash concrete. The E_{rms} measurement at the sensing coil shows the results from the normal, low and medium corrosion levels have not changed because little corrosion appears at the cross-section area of reinforcements. However, for the measurement results of high corrosion level of reinforcement of 40% fly ash concrete the E_{rms} induced in the sensing coil is 2.950V. The average steel loss was 1.46%. Because the corrosion causes a decrease in the cross-section area of reinforcements it has a high magnetic reluctance. Figure 11 shows the comparison of results between corrosion level of reinforcement in fly ash concrete. For that matter, the measurement results of the E_{rms} at sensing coil are decreasing as the corrosion level is increasing. The results of the increasing corrosion appears as a decrease in the cross-section area of reinforcement. Figure 12 shows the comparison of results between corrosion level and the average steel loss percentage in reinforcement of fly ash concrete, showing that the measurement results of average steel loss percentage of reinforcement increase. The E_{rms} induced in the sensing coil decreases because the corrosion causes a decrease in the cross-section area of reinforcement, producing a high magnetic reluctance. The electromagnetic method can measure an average steel loss percentage, which is 1.46%. As a result, the corrosion brings about a decrease in the cross-section area of the reinforcement.

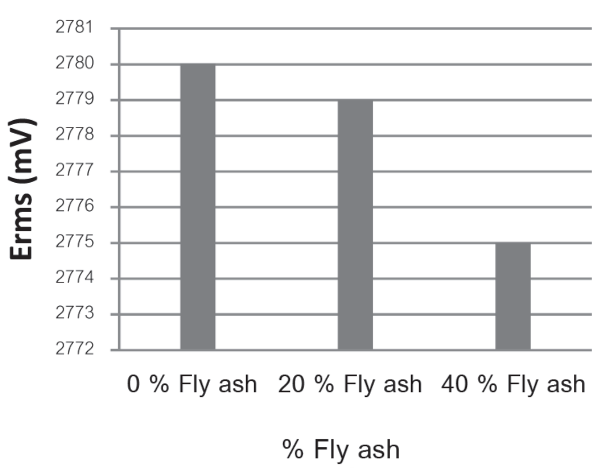

Figure 7 Measured results of fly ash concrete

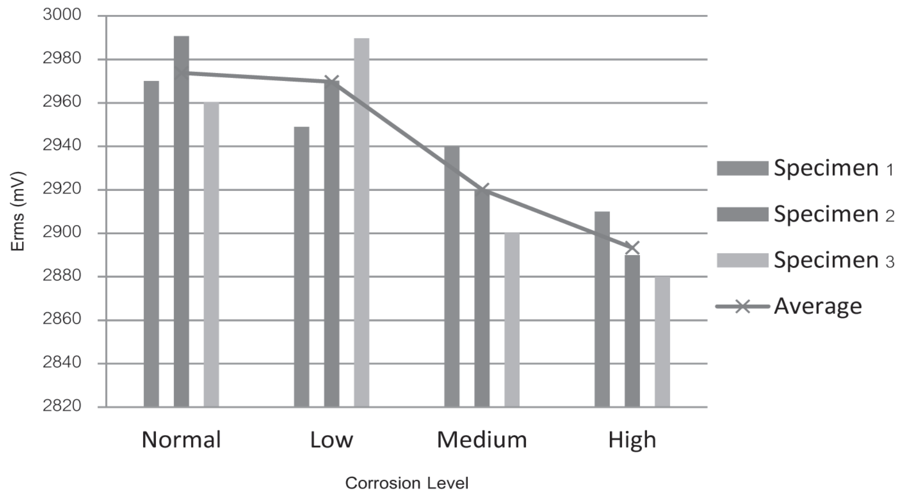

Figure 8 Measured results of corrosion levels in reinforcements of 0% fly ash concrete

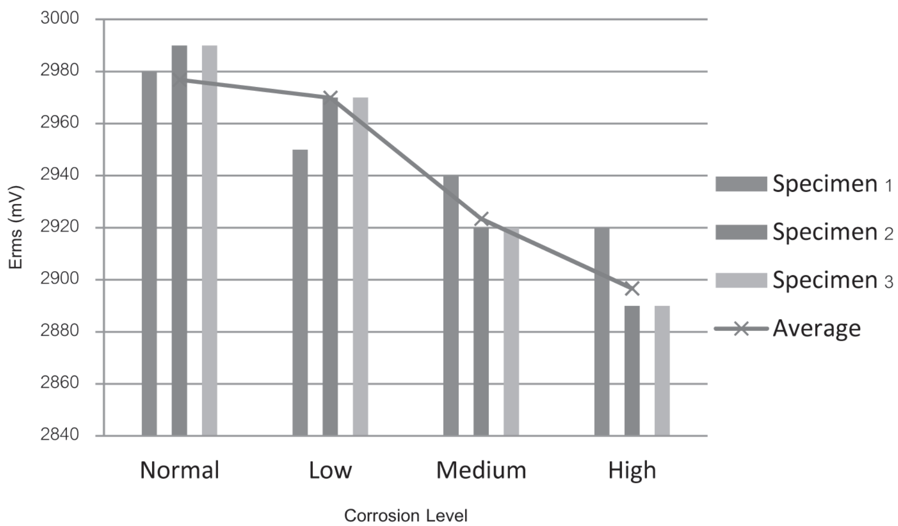

Figure 9 Measured results of corrosion levels in reinforcement of 20% fly ash concrete

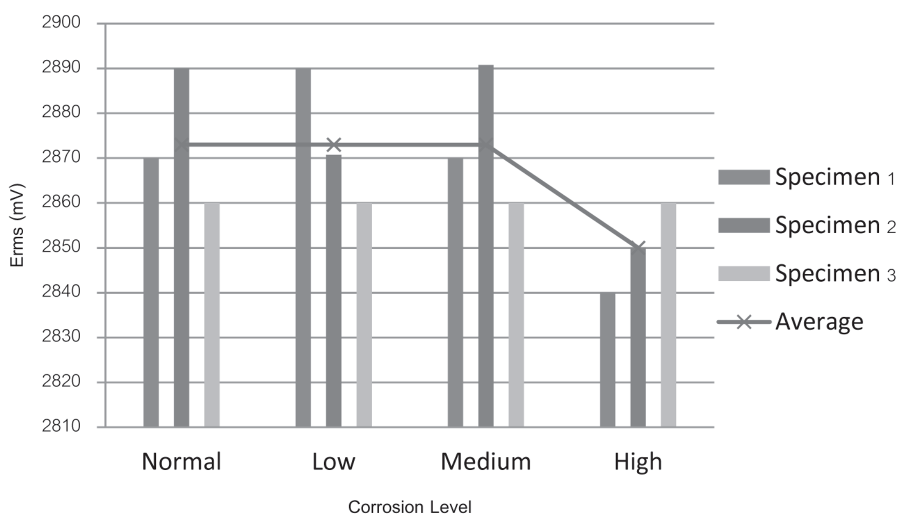

Figure 10 Measured results of corrosion levels in reinforcement of 40% fly ash concrete

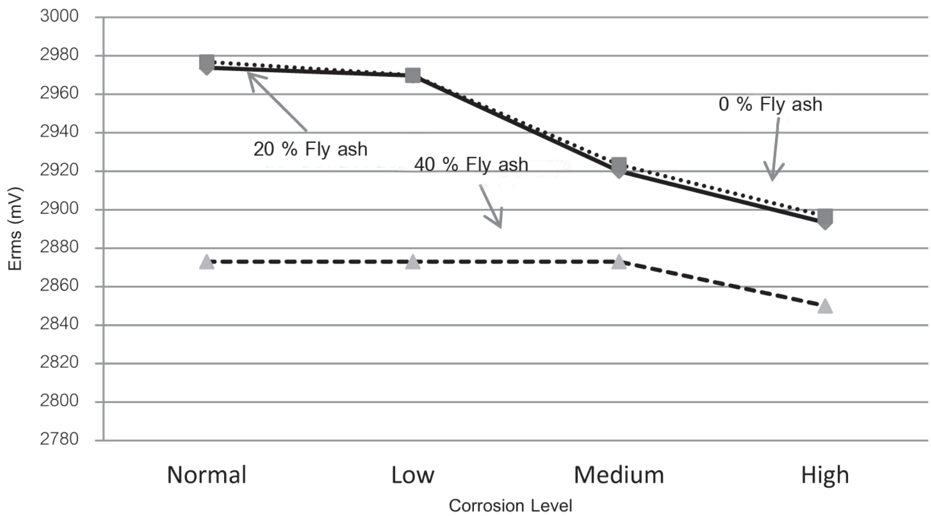

Figure 11 Comparison of results of corrosion levels in reinforcement of fly ash concrete

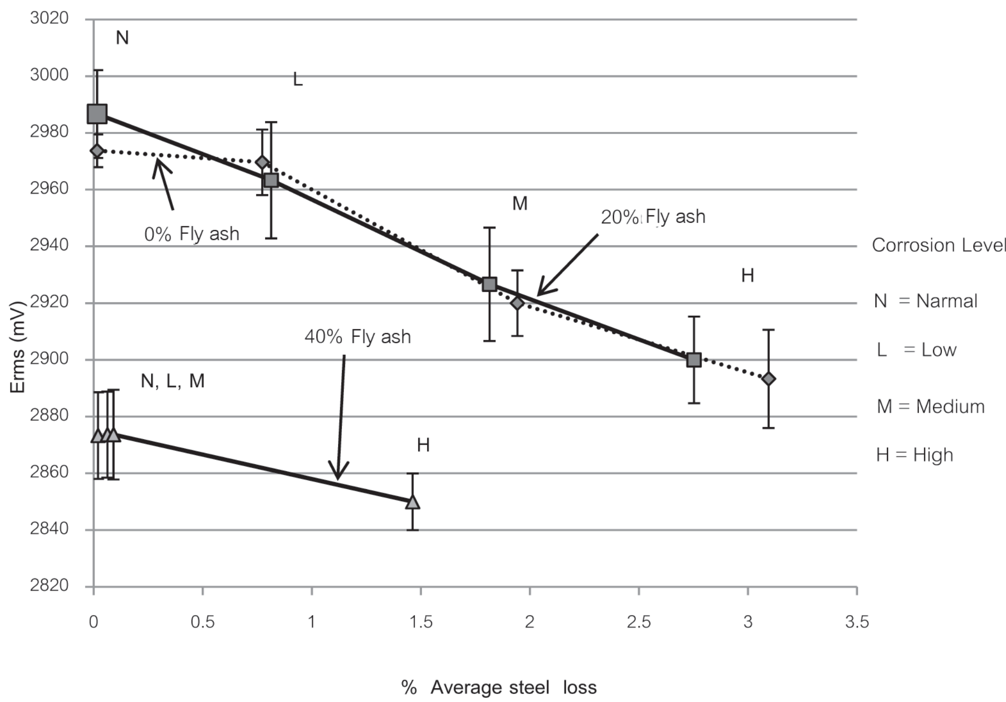

Figure 12 Comparison of results of average steel % loss of reinforcement in fly ash concrete

5. Conclusion

The conclusions of this experiment are:

a) We can use the electromagnetic field method to identify types of concrete with 0%, 20% and 40% fly ash.

b) The electromagnetic field method can be used to identify medium and high corrosion levels in reinforced 0% and 20% fly ash concrete.

c) The electromagnetic field method can be used to identify a high corrosion level in reinforced 40% fly ash concrete.

d) The results show that there is an 80% uncountable noun obtained in an average of the real measure of three specimens. However, the root mean-square voltage has a low signal in mV and error of environment which the authors will further develop in future work.

6. Acknowledgements

The authors would like to thank Department of Electrical Engineering, Faculty of Engineering, Khon Kaen University, the Government's Science and Technology Scholarship 2007 for their financial support, the Sustainable Infrastructure Research and Development Center Khon Kaen University (SIRDC), and Department of Physics, Faculty of Science, Mahasarakham University for instrumental support.

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