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MEASUREMENT OF REINFORCEMENT CORROSION IN MARINE STRUCTURES

By

Mohammad Ismail, PhD
Nordin Yahaya, PhD
Faculty of Civil Engineering
Universiti Teknologi Malaysia
81310 Skudai, Johor Bahru
Johor

ABSTRACT

The marine environment is known to be aggressive. Structures constructed on this belt need to undergo periodic assessment in order to ensure no defects or signs of deterioration had occurred. One of the most common deterioration that occurs on marine structures is corrosion of the reinforcement. Corrosion is an electrochemical process. The product of corrosion can increase the reinforcement volume, hence causing cracking on concrete cover. If no action is taken, delamination and spalling of concrete will follow and this will affect the structures' integrity. It is therefore important to know the state of the structures' condition by monitoring them periodically. NDT techniques that can detect the occurrence of corrosion of reinforcement in concrete uses half cell and resistivity meter. The method of application and interpretation of results are discussed.

Keywords: reinforced concrete, breakwaters, shore protection, durability

INTRODUCTION

Reinforced concrete is widely used throughout the world as a major material of construction. The application is not limited to on-shore structure but also in the aggressive off-shore marine environment (e.g. bridges, tunnels, jetties, breakwater, and ports). When suitably designed, constructed and maintained, reinforced concrete can provide service life of many years to such structures. However, there are several degradative processes which can cause these structures to loose of their serviceability or even collapse. Corrosion of reinforcement is one of the major factors and is widely discussed all over the world.

In North America alone the estimated cost of restoration of structures suffering from corrosion of reinforcement is in the order of ten billion dollars [1]. In the UK, the work has been estimated to be worth 500 million pounds. Similar figures have been found in Europe but the situation is worse in the Middle East due to the more severe conditions. Corrosion may occur well within the design life of the structure.

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Concrete normally provides embedded steel with a high degree of protection. The aqueous environment in concrete is normally alkaline in nature. In this alkaline environment a thin protective film of gamma-ferric oxide (γ-Fe_2O_3) is formed on the steel surface. Under certain circumstances this protective film can be disrupted either by the lowering of the pH of the aqueous environment in the concrete (e.g. carbonation) or by the presence of aggressive ions (e.g. chloride). Corrosion of the steel reinforcement is an electrochemical process. It occurs at an interface between the reinforcing bars and the cementitious matrix. It consists of two type of processes:

(a) anodic reaction $Fe \rightarrow Fe^{2+} + 2e^-$ (characterised by pitting)

(b) cathodic reaction $1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$ (characterised by rust formation)

The overall reaction is

$$Fe^{2+} + 2(OH)^- \rightarrow Fe(OH)_2 \text{ (ferrous hydroxide)}$$

The unstable hydroxide is further converted as follow:

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \text{ (ferric hydroxide, red rust)}$$

The ferric hydroxide undergoes further reaction to

$$2Fe(OH)_3 \rightarrow Fe_2O_3.H_2O + 2H_2O \text{ (hydrated ferric oxide)}$$

The formation of corrosion product around the corroded steel will increase the volume of the steel up to four fold [2]. This process will induce stresses around the reinforcement, which can result in cracking and spalling of the concrete cover.

Carbonation

Carbon dioxide in the atmosphere can diffuse into the capillaries of the concrete or through cracks formed by shrinkage, creep or plastic settlement to form neutral calcium carbonate. This neutralization process is known as carbonation with the reaction as follows:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \text{ (neutral calcium carbonate)}$$

The carbonation process progressively lowers the initial alkalinity of concrete from pH 12-13 to below 9.5 which is no longer sufficient to support the passivating oxide film. The access of moisture and oxygen will cause the steel reinforcement to corrode.

Chloride

In the highly alkaline environment corrosion of steel reinforcement can still proceed due to localized attack from corrosive substances such as chloride ions. Chloride present in concrete either during the mixing process (admixture) or diffused from the aggressive environment. Calcium chloride breaks down in water to form a strong electrolyte:

$$CaCl_2 \rightarrow Ca_2^+ + 2Cl^-$$

The consequence of this reaction is the reduction of the concrete alkalinity, increase inflow of corrosion current and the final breakdown of the protective passivating oxide film on the steel surface. Chlorides may be present in the concrete in several states viz. Chlorides strongly bounded by C_3A hydrates and C_4AF hydrates are mainly in the form of calcium aluminate. Chlorides loosely bound by calcium silicate hydrates and chlorides as free ions in solution within the pore space. It is mainly the free chloride ions, which are responsible for the increase in corrosion.

Repair and maintenance to concrete members affected by corrosion of reinforcement is very costly. The corroded area, if not properly repaired, can spread again to the repaired area. It is therefore important to ensure that the areas of concretes requiring repair are adequately defined and mapped before it is too late. Apart from the standard visual inspection which is normally carried out to look for signs of deterioration, two non-destructive testing equipments namely the half cell and reistivity meter are employed to indicate where the corrosion is probably be occuring.

NON DESTRUCTIVE TESTING

The choice of non-destructive tests to assess for corrosion of reinforcement can be classified under three groups [3] namely:

(i) Visual, chemical and physical appraisal, (ii) Electrochemical (Half cell & Potential wheel) and (iii) Resistance measurement (resistivity)

This paper however, will only discuss method (ii) and (iii).

Half cell

The electrical potential of reinforcing steel can be measured by coupling a reference half cell to the concrete surface and measuring the potential between this and a connection to the bar. An electrical continuity of reinforcement is checked before carrying out the measurement. The method of survey is shown in Figure 1. A clean and solid contact to the reinforcement is made at W and the positive lead taken back to a high impedance multimeter or data logger V; the negative lead is connected to the reference probe which is moved over the marked out grid, noting the reading and location. Using the grid and reference probe values a plot can then be made using lines of equal potential and a contour map can be presented as also shown in Figure 1.

The values of reinforcement potential, generally accepted as indicating corrosion in ASTM C876-80 [4] is shown in Table 1:

Potential Wheel

For large structures, the potential wheel is normally used. The potential wheel is actually a half cell with a wheel for a tip as shown in Figure 2. Potential wheel comprises of a reference half cell coupled to the concrete via a conductive wheel. When the wheel is rolled along the surface of the concrete, the reinforcement potential and the position of the wheel is automatically fed into a portable data logger (data bucket). The output of the potential survey can be in the form of either a voltage plot or a contour plot as shown in Figure 3. Interpretation of potential wheel results is similar to the half cell but with reverse convection.

Resistivity Meter

Anodic and cathodic regions can be established in reinforced concrete due to differences in oxygenation, chloride contamination and alkalinity. These regions can be detected by conducting potential surveys as described above. However, one of the important factors influencing the rate at which corrosion occurrs is the ease at which hydroxyl ion can pass through the concrete adjacent to the reinforcement from the cathodic to the anodic regions [5]. Hence a measurement of electrical resistivity of the concrete can be used to assess the significance of active corrosion sites.

The resistivity of the concrete can be measured by using the four electrode method devised by Wenner for determination of soil resistivity [6]. An alternating current is induced through the two outer electrodes and the potential between the inner electrodes is measured (figure 4). For a semi-infinite homogenous material the resistivity is given by:

$$\rho = 2 \pi a \frac{V}{I}$$

Where a is an electrode spacing.

The interpretation of resistivity measurement as given by [7] is as in Table 2.

FIELD WORK (Marine structures)

A shore defence construction, consisting of offshore breakwater and shore line structures were constructed on the coastline of the Wirral, in the Northwest of England as shown in Figure 5. The aim of this construction was to reduce and redirect wave energy to prevent the scour and erosion of sand from the beaches. For the breakwater construction, a reinforced concrete reef block unit was designed. The units were interlocking and were placed on the sea shore. On the shoreline, anti reflection units were constructed. These units consisting of primary and secondary diode units were again constructed using steel reinforced concrete. The installation of these units was completed in 1985.

Both reef block and diode units were reinforced by welded mild steel. The nominal cover to the reinforcement is 60 mm, concrete cube strength is 55 N/mm^2 and water cement ratio is 0.45. The dimension and isometric view of these units are as shown in Figure 6. 48 units were chosen as a study sample, of these 20 were cast with concrete containing a 30% flyash cement replacement. 5 are reef block units in the tidal zone and 15 are diode units occasionally wetted. The tides covered the reef block units twice daily. The survey was carried out to study durability of the steel reinforcement in this highly aggressive environment. Visual inspection, electrical potential and resisstivity measurement have been employed. Results of some of the samples are discussed below.

RESULTS AND DISCUSSIONS

Diode Units

The potential measurements on the diode unit were carried out upon identifying the exact unit. The survey points were cleaned from any growth (seaweeds and green moss). It was then wetted with tap water so that the wheel makes a better contact with the surface of the structure. Figure 7 shows the arrangement of diode units along the shoreline. Figure 8 shows the potential and resistivity results of unit D-P-8. Anodic peak of -320 mV was observed around point 19. The highest resistivity reading recorded around point 19 was 31000 Ωcm. These results implied that there was some corrosion activity in this unit but there was still no visible sign of corrosion such as cracking or rust staining observed yet.

After an impact by rock, slight damage occurred to unit D-P-18. The potential reading around the affected area was therefore very high as shown in Figure 9. Repair work was then carried out and survey results three years later no longer show any peak at that particular point. The resistivity value at that spot was 9400 Ωcm. This observation indicate that the repair was successful. The potential peak for unit D-O-17 that was cracked due to impact damage of about 0.5-1 mm around point 13 was observed one year after the incident (Figure 10). After being repaired, no peak was picked up from the potential measurement. The peak was, however picked up by potential wheel after two years of being repaired. This is obviously due to repair failure which has resulted in corrosion of the reinforcement as shown in Figure 10. The resistivity measurement on the point was 10300 Ωcm, indicating medium corrosion rate.

Reef Block Units

Thirteen reef blocks units were included in the monitoring. Ten were located on the sea shore as shown in Figure 11 and three on the field adjacent to the coastline as control sample. None of the thirteen units surveyed showed any peak curve on any of the survey points. The typical results are as shown in Figure 12.

CONCLUSION

The present work has shown that half cell (potential wheel) has been found to be suitable for field work. The ability to collect data in a relatively short time is very much appreciated Slight corrosion activity after impact damage or due to repair failure was picked up by the half cell. However, it is essential for the operator of any corrosion monitoring equipment in reinforced concrete to have knowledge of reinforced concrete, parameters related to corrosion of reinforcement and knowledge on the equipment used. Half cell should be used in conjuction with visual inspection as well as resistivity measurement as a means of conclusion about the state of the reinforcement.

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TABLE 1: Interpretation of Half cell Measurement

Measured Potential	**Statistical Risk of Corrosion**
More negative than -350 mV	90% probability of corrosion
-200 mV to -350 mV	50% probablity of corrosion
Less negative than -200 mV	10% probability of corrosion

TABLE 2: Resistivity as an indicator of corrosion

Resistivity (Ωcm)	**Likelihood**	**Rate of corrosion**
Greater than 12000	Unlikely	Low
5000 to 12000	Probable	Intermediate
Less than 5000	Almost certain	High

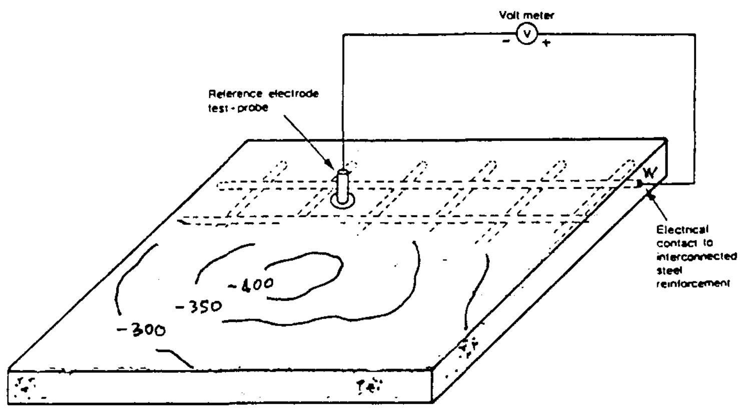


FIGURE 1: Half cell and Potential Plot

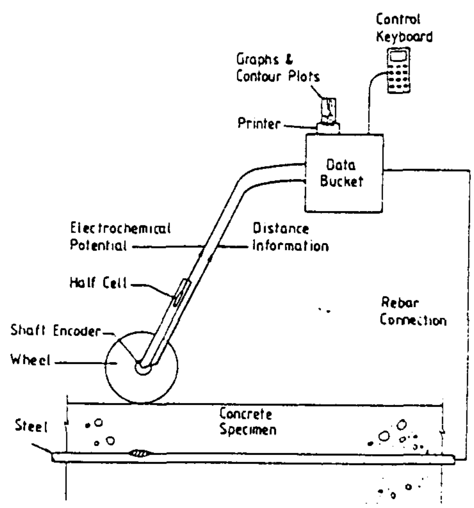


FIGURE 2: Potential Wheel

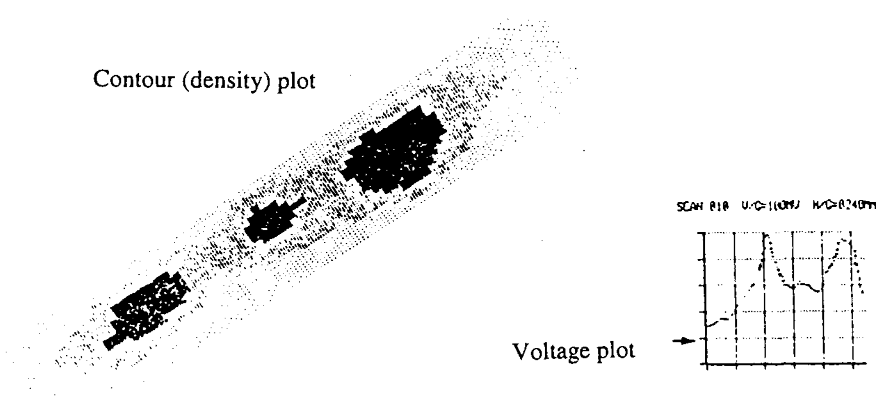


FIGURE 3: Output from Potential Wheel

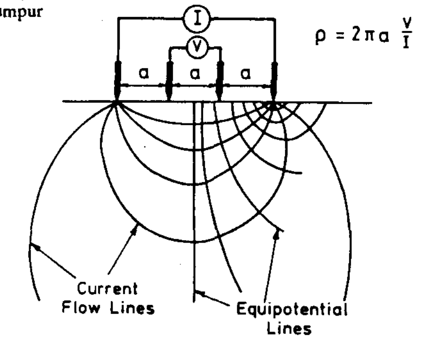


FIGURE 4: Resistivity Meter

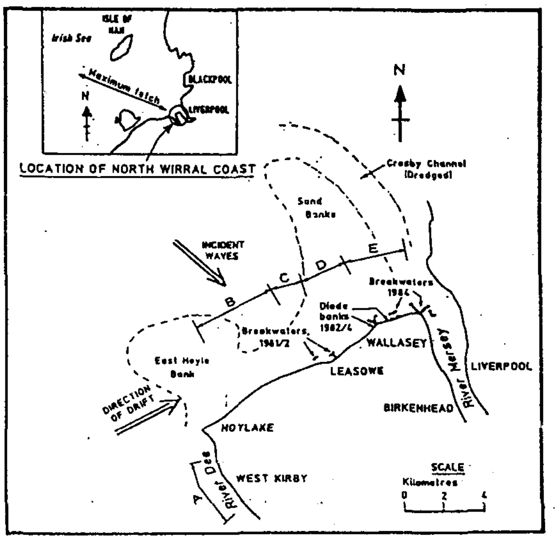


FIGURE 5: Location of Coastal Defences on the North Wirral

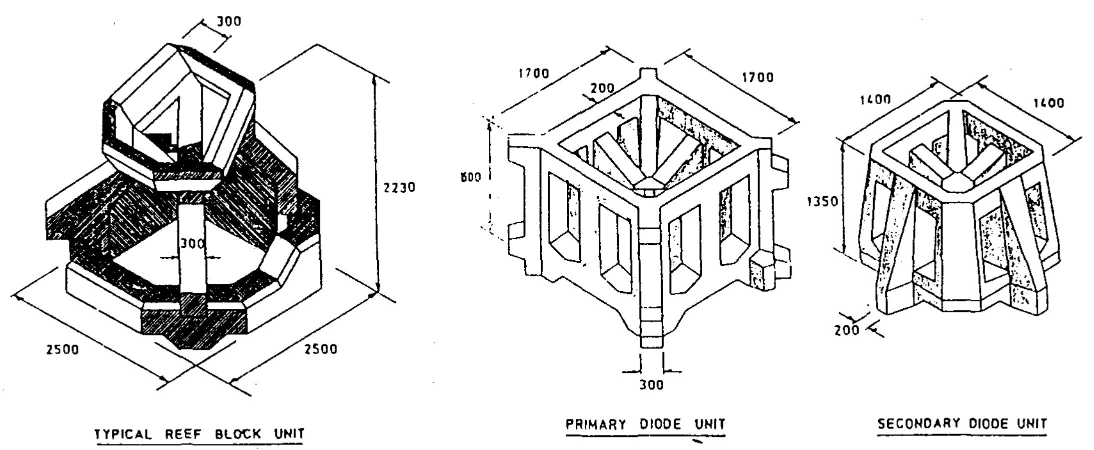
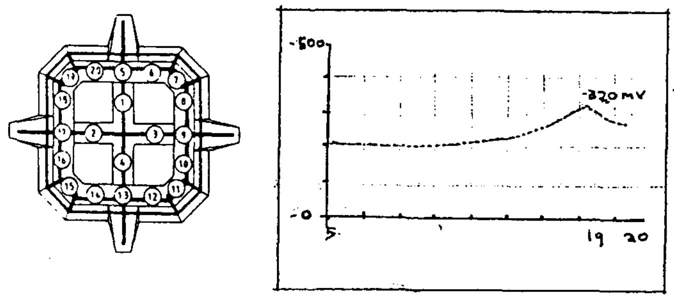


FIGURE 6: Isometric Detail of Armour Units

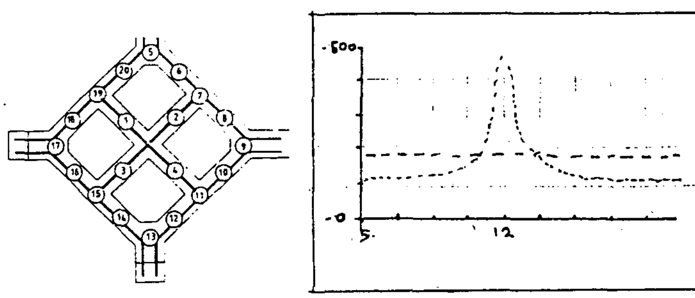
FIGURE 7: Diode Units



CONCRETE RESISTIVITY (K-Ω cm)

6	12	14	18	19	20
37.71	17.5	14.9	15.7	31	40.1

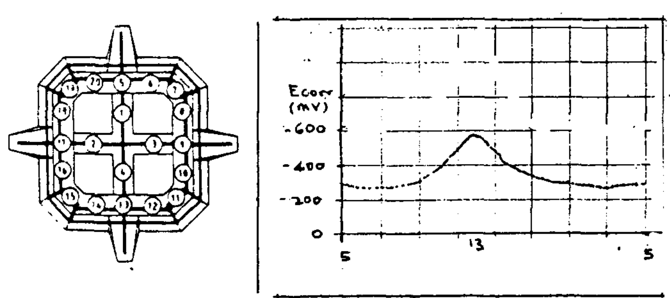
FIGURE 8: Survey Results of D-P-8



CONCRETE RESISTIVITY (K-Ω cm)

6	8	10	12	14	16	18	20
109	102	95	9.4	96.8	107.2	106	95.5

FIGURE 9: Survey Results of D-P-18



CONCRETE RESISTIVITY (K-Ω cm)

6	11	12	14	16	18	20
14.3	4.3	7.8	10.3			16

FIGURE 10: Survey Results of D-O-17

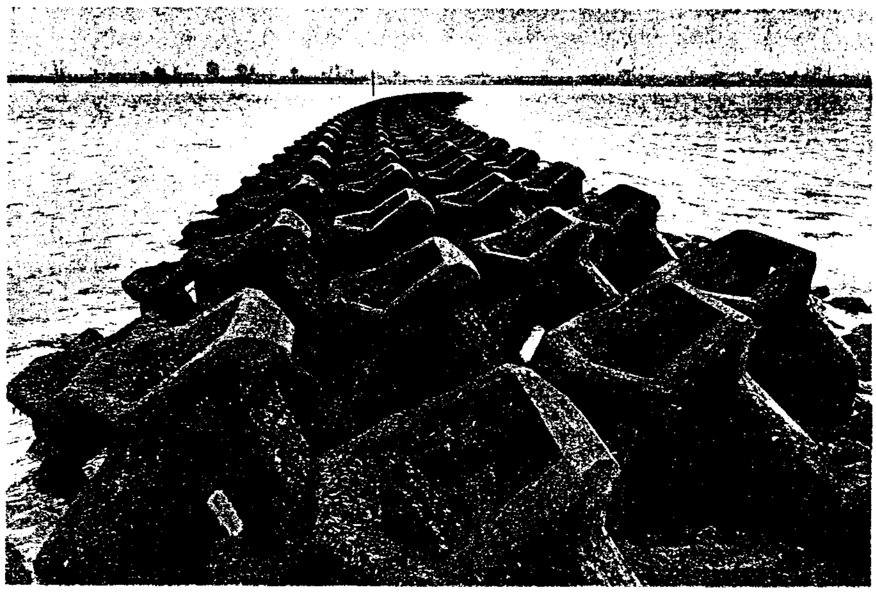


FIGURE 11: Reef Block Units

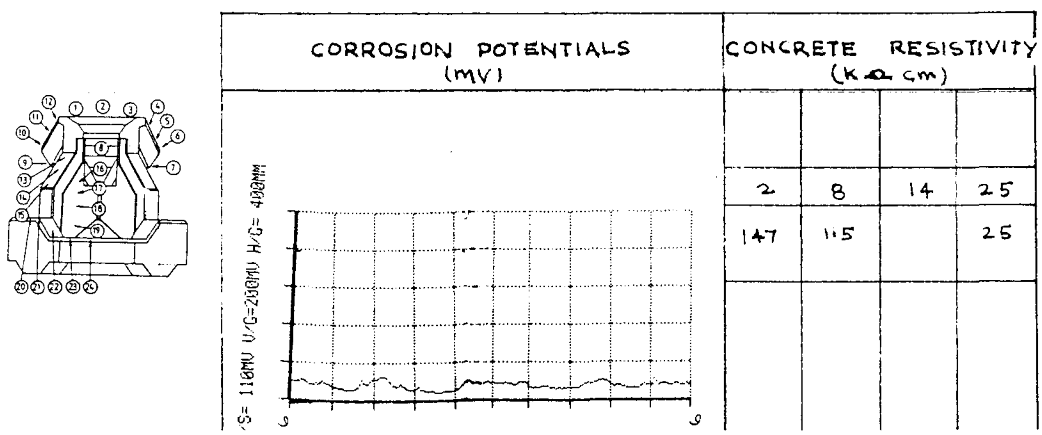


FIGURE 12: Typical Survey Results of Reef Block Units