

**CORROSION ASSESSMENT ON
REINFORCED CONCRETE AND ITS SERVICE LIFE PREDICTION**

SYED BURHANUDDIN HILMI BIN SYED MOHAMAD



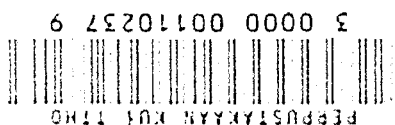
**MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA
SERDANG, SELANGOR**

2005



PTTA UTHM

PERPUSTAKAAN TUNKU TUN AMINAH



**CORROSION ASSESSMENT ON
REINFORCED CONCRETE AND ITS SERVICE LIFE PREDICTION**

By

SYED BURHANUDDIN HILMI BIN SYED MOHAMAD



A Project Report Submitted in Partial Fulfillment of
The Requirement For The Degree Of Master of Science
In Structural Engineering and Construction
In The Department Of Civil Engineering,
Universiti Putra Malaysia
Serdang, Selangor, Malaysia.

2005

Best dedicated to my beloved family and friends...

PTTAUTHM

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No. Aksesyen 02090	No. Panggilan 7F 200 '893 2005 2h
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ABSTRACT

Deterioration of structural concrete may be caused either by chemical or physical effects. Corrosion of embedded steel is a major cause of deterioration of concrete structures at the present time. This lead to structural weakening due to loss of steel cross-section, surface staining, cracking or spalling and delamination of concrete and then gradually reduces the service life of the reinforced concrete structures. The most biggest problem is concerned with the structural integrity and safety of reinforced concrete structures by reducing the load carrying capacity.

This project was to assess the degree of corrosion on reinforced concrete structure and estimating the residual service life. It was conducted based on electrochemical methods. These methods include galvanostatic pulse method and linear polarization method. A Non-Destructive Test techniques called GalvaPulse was used in this study. These equipments allow us to determine the degree of corrosion, rate of corrosion and interpret the result in corrosion mapping.

From the results, assessment on the validation of corrosion in short and long terms by using predictive models are discussed.

ABSTRAK

Kemerosotan struktur konkrit bertetulang adalah berkemungkinan berpunca daripada tindakbalas kimia dan keadaan semulajadi konkrit. Pengaratan tetulang besi di dalam konkrit merupakan punca utama kemerosotan struktur konkrit bertetulang pada masa ini. Ini akan membawa kepada kelemahan struktur akibat kehilangan luas keratan tetulang besi, kekotoran pada permukaan konkrit, keretakan, pecah dan jatuh dalam bentuk serpihan. Ini akan mengurangkan tempoh khidmat struktur konkrit bertetulang dan memberi kesan terhadap integriti dan keselamatan struktur konkrit bertetulang dengan mengurangkan kapasiti menanggung beban.

Projek ini adalah untuk menilai tahap pengaratan struktur konkrit bertetulang dan menganggarkan tempoh khidmat struktur. Ini dilaksanakan berdasarkan teknik "electrochemical". Ini termasuklah teknik "galvanostatic pulse" dan "linear polarization". Kedua-dua teknik ini menggunakan ujian tanpa musnah yang dikenali GalvaPulse. Peralatan ini akan membolehkan kita untuk mengenalpasti darjah pengaratan, kadar pengaratan dan juga menafsirkan keputusan melalui pemetaan pengaratan.

Daripada keputusan yang dicapai, penilaian terhadap pengaratan dalam masa yang singkat dan masa yang panjang akan dapat dikenalpasti dengan menggunakan model-model ramalan tempoh perkhidmatan struktur.

ACKNOWLEDGEMENT

The author want to thank especially to project supervisor, Associate Professor Ir. Dr. Mohd. Saleh Bin Jaafar for his guidance and advice in completing this project. All his efforts in guiding towards to achieve the project objectives are very highly appreciated. Thank you.

Not forgotten to give a sincere gratitude also to Associate Professor Dr. Waleed A. M. Thanoon and Associate Professor Dr. Jamaloddin Noorzaei, as the examiners of this project. Thank you.

The author would like to express his greatest love and gratitude to his beloved parent and family for being supported throughout the project.


Last but not least, thank you very much to those who does not mentioned here for their help in completion of this project report.



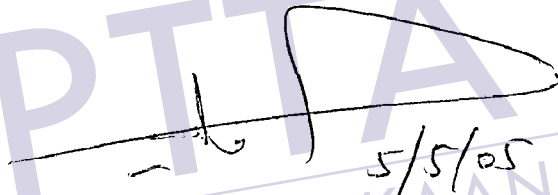
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APPROVAL

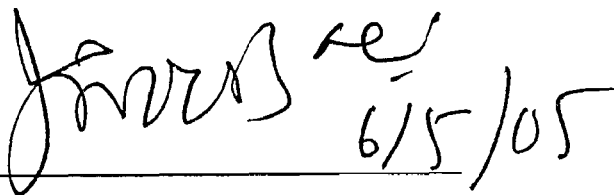
This project report attached herewith, entitled "Corrosion Assessment On Reinforced Concrete and Its Service Life Prediction" submitted by Syed Burhanuddin Hilmi Bin Syed Mohamad in partial fulfillment of the requirement for the degree of Master of Science (Structural Engineering and Construction) is hereby accepted.


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DECLARATION

I hereby declare that the project report is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for other any other degree at UPM or other institutions.



Syed Burhanuddin Hilmi Bin Syed Mohamad

Date: *6 MEI 2005*



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NOTATION

A	=	area of the reinforcement
B	=	empirical constant for corroding steel
$Cd1$	=	capacity of double layer
F	=	Faraday constant (96500 C)
K	=	correction factor for corrosion uniformity
$R(t)$	=	corrosion rate at time t
R_A	=	anode reaction electrical resistance
R_c	=	cathode reaction electrical resistance
R_E	=	concrete electrical resistance
R_p	=	polarisation resistance
R_{Ω}	=	ohmic resistance
T	=	time
V	=	valence
W_m	=	molecular mass
$d(0)$	=	initial diameter of the reinforcement
$d(t)$	=	reinforcement diameter at time (t) after the beginning of propagation period.
i	=	electrical current
i_{corr}	=	corrosion intensity
ΔU	=	voltage in the macrocell element
ΔD	=	loss of diameter with time
ΔE	=	potential response
Δi	=	applied current
β_a	=	anodic Taffel constant
β_c	=	cathodic Taffel constant

CHAPTER I

INTRODUCTION



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CHAPTER 1

INTRODUCTION

1.1 Introduction


Concrete, when used in reinforced concrete structures, should perform two basic functions. It must show adequate mechanical and bond strength with the reinforcement and must be sufficiently fire resistant. As far as concrete durability is concerned, concrete should be resistant to weather conditions and aggressive environmental effects and should provide sufficient protection against reinforcement corrosion.

Portland cement concrete is an ideal environment for steel because it provides both a physical barrier to the access of aggressive species and chemical protection because in the highly alkaline pore solution of the cement paste, steel is readily passivated (I. L. H. Hansaon & C. M. Hansson, 1993).

Steel reinforcement embedded in concrete will not normally corrode due to the deformation of a protective iron oxide film which passivates the steel in the strongly alkaline conditions of the concrete pore fluid. This passivity can be destroyed by chlorides penetrating through the concrete and due to carbonation. Corrosion is then initiated. Steel corrosion is an electrochemical process involving establishment of corroding and passive sites on the metal surface.

In addition to evaluation of different types of sensors new developed portable equipment using galvanostatic pulse technique was tested under laboratory conditions. The objective of laboratory tests is testing suitability of portable monitoring equipment for non-destructive and unambiguous determination of reinforcement corrosion. Comparing achieved results regarding their accordance to real conditions shall provide background information for on site situations.

The main investigation of corrosion is detection, degree of corrosion, measuring rate of corrosion, resistivity and determination of the remaining service life of the reinforced concrete structures using available prediction model. This project presents the study of corrosion, test technique and laboratory test by GalvaPulse equipment, analysis data from tests results and determination of remaining or residual service life.



1.2 Problems of Statement

The deterioration of concrete structures is a major problem in many countries throughout the world. There is no sufficient data on the corrosion rate of reinforcement exposed by methods of detection to different environments, such as acidic environment, chloride environment and marine environment. Thus, the real behaviour of reinforcements is not fully understood.

Corrosion always related to the deterioration of the service life. This has proceeded the search for methods of predicting the service life of both existing and new

structures. The remaining service life of corroded reinforcement cannot be accurately estimated without reliable technical data on degree and corrosion rate

Prediction of the remaining service life of a corroding reinforced concrete structure is done with the help of empirical models and experimental methods. The problems is that, which one of the predictive models that available is reliable for predicting the service life towards the time taken to build up critical concentration at the reinforcement bar level to cause corrosion in certain conditions. The estimation of this initiation period is important in the estimation of the service life of the structure.

However, this project is trying to collect more data on degree and corrosion rate of reinforcement, which is needed in estimating the remaining service life using the validated predictive models. This will be carry out by using the new method known as Galvanostatic pulse method.

1.3 Project Objectives

The aim of this project is to study the corrosion detection and service life predictive model which are available and validated for reinforced concrete structures.

Thus, the objectives of this project are as follows:

- a) To carry out laboratory test to determine the corrosion potential, corrosion rate and resistance.

- b) Compare the corrosion rate by GalvaPulse and weight loss measurement to determine the reliability of GalvaPulse.
- c) To assess the validation of short term accelerated test data and observation on long term corrosion.

1.4 Scope of Project

The scope of this project is focused on measurement of corrosion potential, corrosion rate and corrosion resistance of reinforcement using available NDT techniques (GalvaPulse).

Laboratory testing on exposed reinforcement of five different environments were prepared to determine corrosion detection. Corrosion mapping was carried out on laboratory specimens. Result is analyzed to determine the reliability of GalvaPulse with respect to degree and corrosion rate.

The result collected from the probes will be use to determine the variables of corrosion and rate of corrosion.

Lastly, a study on service life of reinforced concrete structures will be carry out by using available predictive models and assess the validation of short term accelerated test data and observation on long term corrosion.

CHAPTER II

LITERATURE REVIEW



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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete has been created to be one of the most resistant materials against high chemical, physical and mechanical loading and its maintenance costs are low. For many years, concrete have shown that this material has a very long services life. Concrete always exposed to natural elements such as air moisture, sunlight heat and rainwater (Hendriks, 1998).

The durability of a structure is the property which shows whether or not the structure will remain useful for its full design life even though it may not be subjected to loads sufficient to destroy it. The long term durability of reinforced depends on the ability of the near surface concrete to protect the reinforcing steel from detrimental substances found in its environment. Given a temperate climate and moderate exposure conditions durable concrete can be achieved by giving due consideration to the constituents, compaction, cover and curing “the four C’s” (Nolan,1995).

Once initiated, reinforcement corrosion can quickly propagate, impairing a structure’s utility and ultimately leading to collapse. Corrosion of embedded steel is probably the major cause of deterioration of concrete structures at the present time. This may lead to structural weakening due to loss of steel cross-section, surface

staining and cracking or spalling. In some instances, internal delamination may occur.

The main cause of reinforcement corrosion is low cover to the reinforcement and also to a lesser extent of poor quality concrete. The presence of chlorides, whether added as calcium chloride or ingresses as de-icing salt, whilst of significance is less common than corrosion caused by low cover, however when chloride corrosion does occur, its effects may be wide ranging.

Mechanisms Affecting Durability.

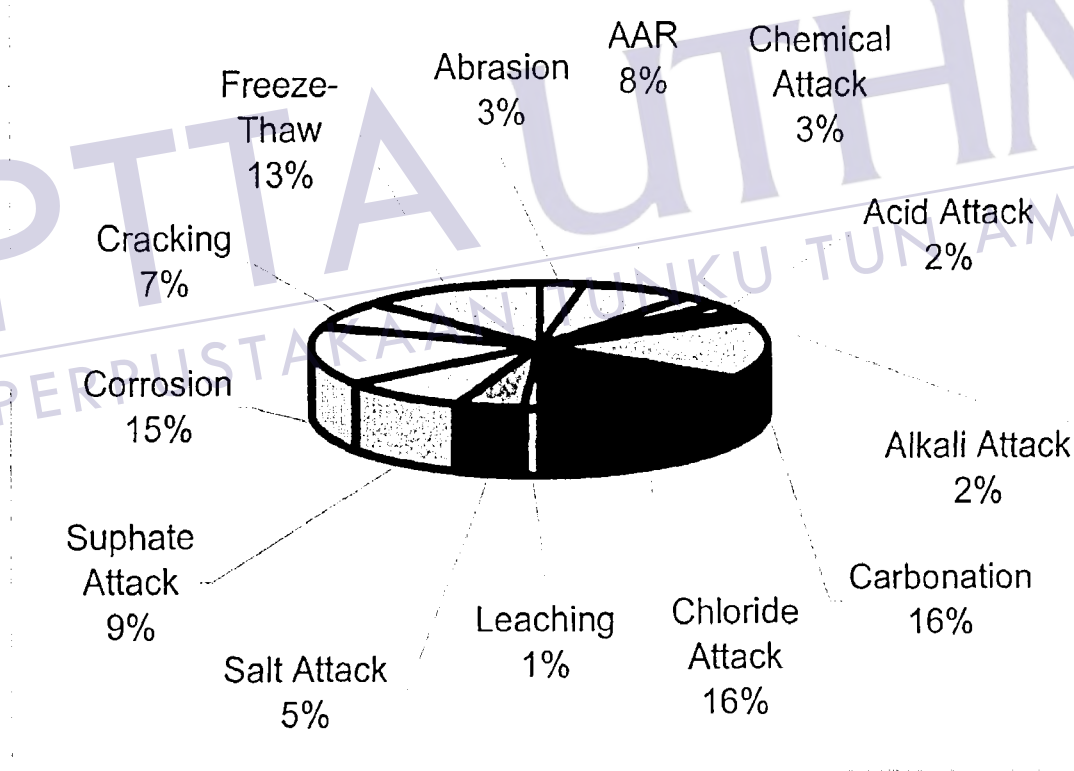


Figure 2.1: Contribution of Various Mechanisms Affecting Durability

(Basheer, 1995)

2.2 Definition of Corrosion

Deterioration of structural concrete may be caused either by chemical and physical environmental effects upon the concrete itself or by damage resulting from the corrosion of embedded steel. Corrosion is an electrochemical phenomenon, in which the potential of the steel and the exchange of electrical current between steel and concrete pore solution plays an important roles (Rob B. Polder, 2002).

Concrete Society, 1984 defined reinforcement corrosion as an electrochemical process requiring the presence of moisture and oxygen and can only occur when the passivating influence of the alkaline pore fluids in the matrix surrounding the steel has been destroyed, most commonly by carbonation or chlorides.

2.3 Corrosion of Reinforcement In Concrete

The electrochemical reactions which lead to the corrosion of steel in concrete need the presence of water and oxygen near the steel. The rate at which corrosion occurs and the time to initiation is significantly influenced by the permeation properties. Chemical processes govern the rate of decomposition of concrete and its durability. Research has indicated that a concrete which is low in permeation properties lasts longer without exhibiting signs of distress and deterioration (Basheer 1991).

Permeation characteristics and fracture strength are the fundamental properties of concrete that influence the initiation and extent of damage and can form the basis by which deterioration can be predicted.

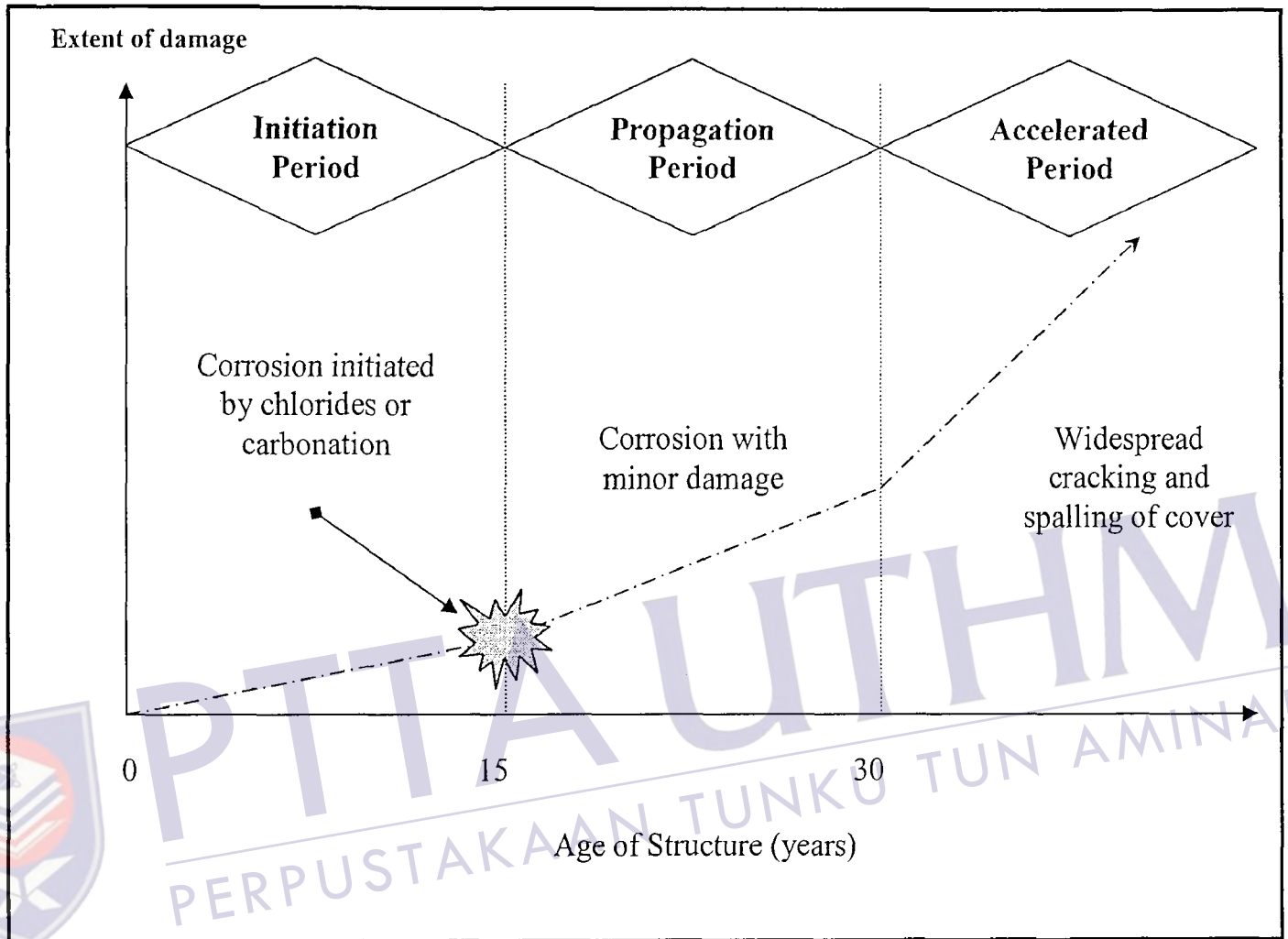


Figure 2.2: The Three Stages Model of Corrosion Damage

Corrosion of reinforcement bar on concrete can be divided into two stages as follows:-

- (i) **Initial Stages:** Time required to disrupt the concrete cover and make reinforcement bar corrosion but no damage to surrounding concrete.
- (ii) **Propagation Stage:** Time required for the corroding reinforcement bar to create sufficient expansion force to cause damage to the surrounding concrete after disruption

Cracking and spalling on the concrete surfaces are the visual signs of corrosion damages. The degree of corrosion of the reinforcement bar to cause the damage (propagation stage) is governed by parameters such as the concrete cover thickness, bar diameter and water to cement ratio (w/c).

2.4 Mechanism of Corrosion

Corrosion is an electrochemical process. A chemical process and a flow of electricity are necessary conditions for this phenomenon. The reinforcement in concrete may achieve this condition by having two areas in different concentrations of moisture, oxygen or dissolved substances.

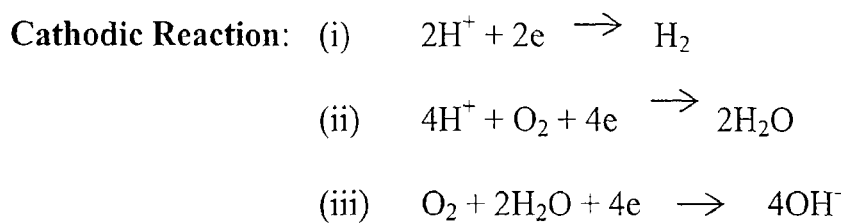
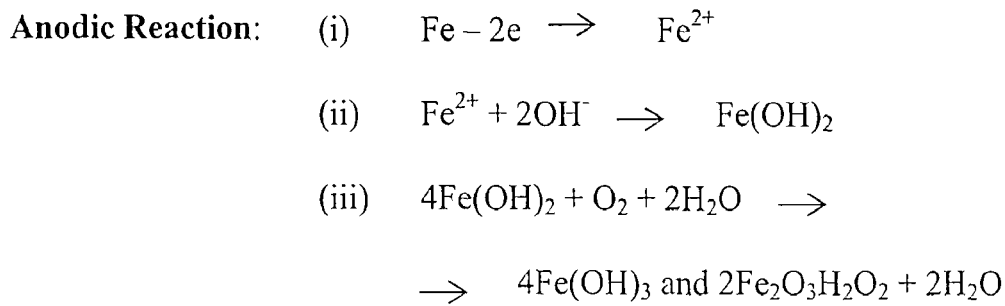
The essential requirements for the electrochemical reactions which lead to corrosion of steel in concrete are the presence of water and oxygen near the steel.

Concrete permeability therefore plays a significant role in the initiation and intensity of the corrosion reaction (Verbeck and Tutti, 1982).

The corrosion process that takes place in concrete is electrochemical in nature, very similar to a battery. Corrosion will result in the flow of electrons between anodic and cathodic sites on the reinforcement bar. For corrosion to occur four basic elements are required:

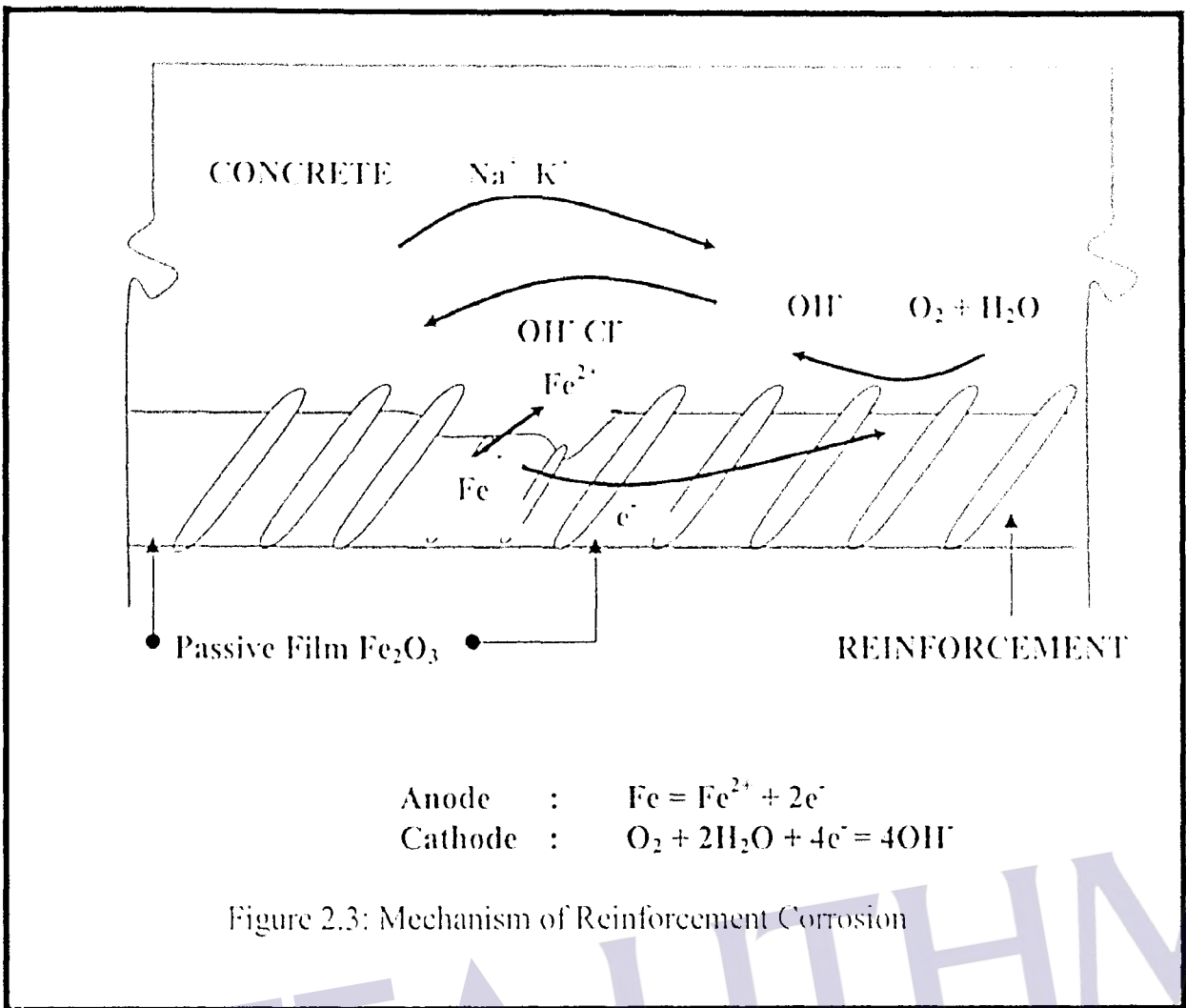
- Anode – site where corrosion occurs and current flows from.
- Cathode – site where no corrosion occurs and current flows to.
- Electrolyte – a medium capable of conducting electric current by ionic current flow (i.e. soil, water or concrete).

· Metallic Path – connection between the anode and cathode, which allows current return and completes the circuit.

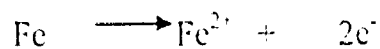


The development of anodic and cathodic regions on the surface of a steel reinforcing bar results in a transfer of ions within the concrete cover and of electrons along the bar and hence a flow of corrosion current (Bungey, 1996).

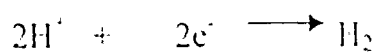
The formation of rust results in a decrease in the strength of the reinforcing steel. In addition, the rust, occupying more than twice the volume of iron from which it is formed, may exert sufficient pressure to crack the concrete (V. S. Ramachandran, 1976). The rate of reaction at the cathode depends on the sizes of the anode and the cathode, the concentration of oxygen, temperature and electrical resistivity of the solution.



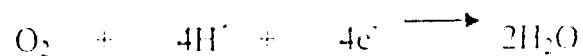
Chemical reactions involved in the corrosion of steel can generally be described as following. The anodic reaction is:



The cathodic or reduction reactions are:

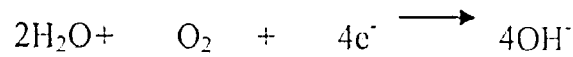


(Hydrogen ion reduction)



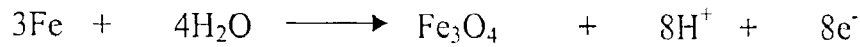
(Reduction of dissolved oxygen in acid media)

OR



(Reduction of dissolved oxygen in basic media)

The corrosion products usually are iron oxides such as Fe_3O_4 or Fe_2O_3 ,



An impermeable concrete, normally associated with a high electrical resistivity will restrict ionic flow and hence result in low rates of corrosion. A thick and impermeable cover region will also restrict the availability of oxygen to the cathode region and further reduce the rate of corrosion.

The corrosion of reinforcing steel has the following two major detrimental effects on the durability of reinforced concrete structures:

- (i) Since the rust produced as a result of corrosion has a volume 2.4 times than that of steel, it causes volume expansion developing tensile stresses in concrete, which ultimately results in cracking and spalling of the cover concrete. Due to the loss of cover concrete there may be significant reduction in the load bearing capacity of the structure.
- (ii) Corrosion reduces the cross-sections of the steel and thereby the load carrying capacity of the structure. Pitting (i.e., localized) corrosion of the rebar is more dangerous than uniform corrosion because it progressively reduces the cross-

sectional area of rebar to a point where the rebar can no longer withstand the applied load leading to a catastrophic failure of the structure.

2.5 Causes of Corrosion

Most of the factors that initiate and propagate the corrosion process of reinforcing steel are directly related to the permeability and fracture strength of concrete (Raharinaivo, A. et al., 1986). The process of hydration of cement in freshly placed concrete develops a high alkalinity, which in the presence of oxygen stabilizes the film on the surface of embedded steel and ensuring continued protection while the alkalinity is retained.

The term pH is a measure of the alkalinity or acidity, ranging from highly alkaline at 14 to highly acidic at zero, with neutrality at 7. Normally, concrete exhibits a pH range 12.5 to 13.5 because of the presence of calcium hydroxide, potassium hydroxide and sodium hydroxide and steel in concrete is safe against corrosion as long as the pH is high. If conditions are such as to cause pH values to decrease to lower values the protective layer is disrupted and iron corrodes (V. S. Ramachandran, 1976).

Dissolved oxygen will accelerate corrosion in slightly basic or acid solutions. In a partly dried concrete or in a cracked concrete the possibility of corrosion is enhanced because of better accessibility of air. As already stated, the presence of moisture in concrete is essential for the occurrence of corrosion (Lewis, 1959)

Moisture is a medium through which dissolved oxygen, chloride salts and carbon dioxide are transported to the reinforcement. The penetration of CO₂ of the air through the concrete can decrease the pH value. This results in the formation of carbonate and bicarbonates of calcium and hence the protective film is impaired.

Corrosion due to CO₂ may increase when concrete is placed at higher water: cement ratio and a low cement factor or has a thin concrete cover over steel or is badly cracked or poorly consolidated (Hamada, 1968).

There are two major factors influencing corrosion of reinforcing steel can occur.

1. Chloride Contamination
2. Carbonation

2.5.1 Chloride Contamination

The presence of free chloride ions within the pore structure of the concrete interferes with the passive protective film formed naturally on reinforcing steel.

Chloride ions exist in two forms in concrete namely *free chloride ions*, mainly found in the capillary pore water and *combined chloride ions* which result from the reaction between chloride and the cement hydration process. These occur in proportions that depend on when the chloride entered the concrete. There are two methods by which chlorides can be the cause of corrosion in reinforced concrete.

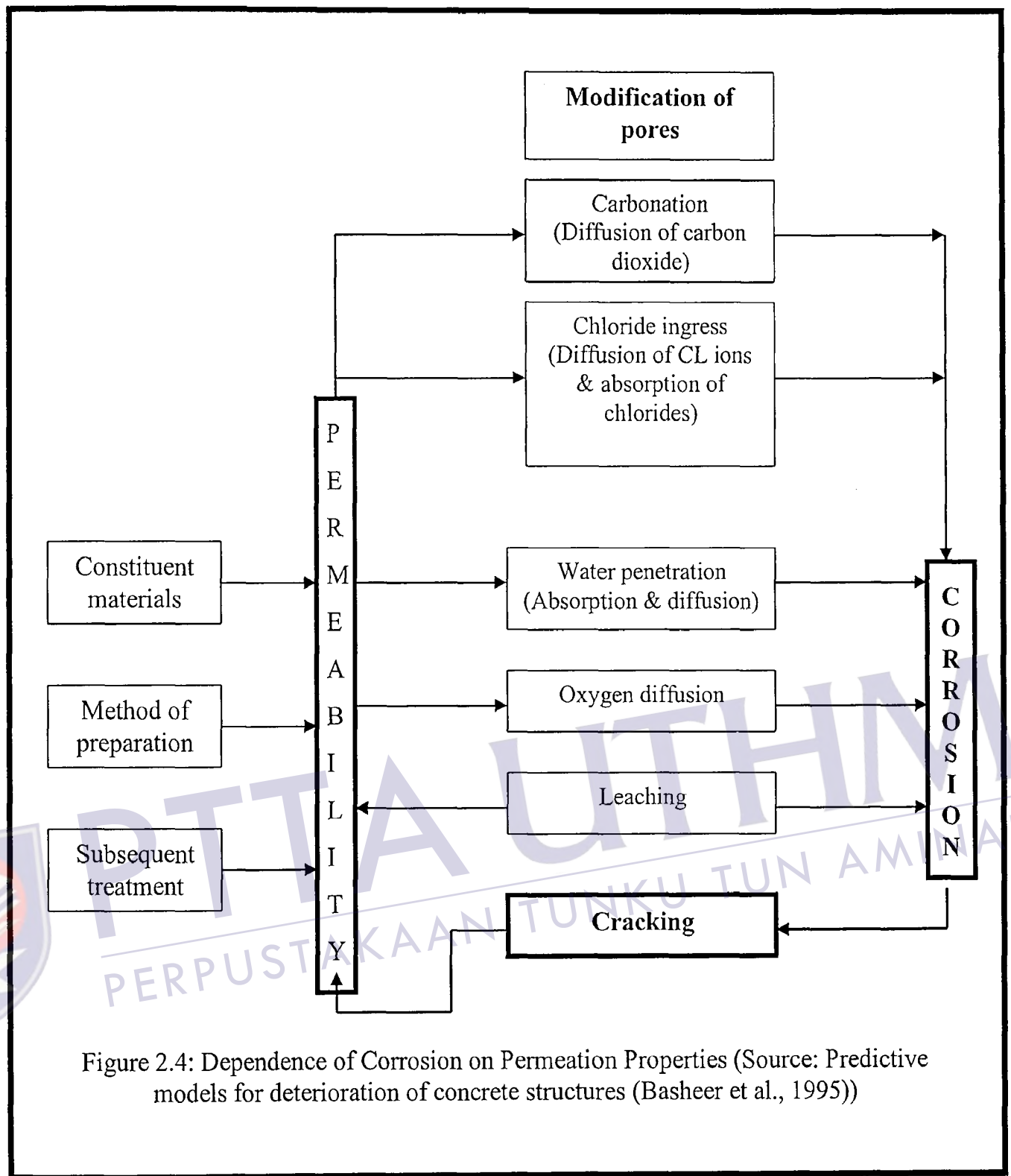


Figure 2.4: Dependence of Corrosion on Permeation Properties (Source: Predictive models for deterioration of concrete structures (Basheer et al., 1995))

1. Cast in chlorides usually calcium chloride added at the time of mixing.

The presence of calcium chloride cast within the mix usually attracts a chloride level significantly greater than 0.4% by weight of cement. Ingresses of chlorides through the outer surface of the concrete are variable in nature.

The presence of calcium chloride within the mix is further exaggerated by the presence of deep carbonation. The presence of carbonation releases combined chlorides into solution to form free chloride ions and increasing the corrosion. For this reason many properties built approximately 20-30 years ago may only now start causing problems on the basis that carbonation has mobilised chloride ions within the concrete pore structure.

2. An ingress chlorides by the penetration of the outer surface of the concrete from de-icing salts

Chloride ions can enter into the concrete from de-icing salts that are applied to the concrete surface or from seawater in marine environments. Other sources include chloride containing admixtures which are used to accelerate curing, contaminated aggregates and/or mixing water, air born salts, salts in ground water and salts in chemicals that are applied to the concrete surface.

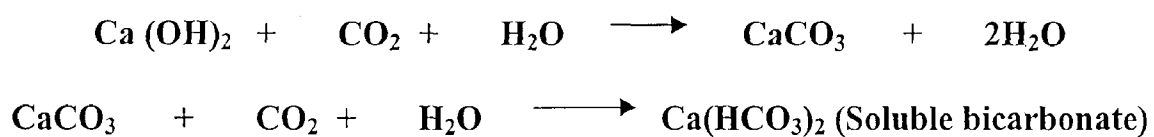
The overall effect of reinforcement corrosion caused by chlorides must be considered in association with the depth of reinforcement and the depth of carbonation.

2.5.2 Carbonation Induced Corrosion

Carbonation is a process in which carbon dioxide from the atmosphere diffuses through its capillary pores of concrete and neutralizes the alkalinity of concrete. The carbonation process will reduce the pH to approximately 8 or 9 in which the oxide

film is no longer stable. Corrosion of reinforcement caused by low cover is commonly referred to as carbonation induced corrosion (Gosta, 1985).

The presence of a high pH is responsible for the presence of a passive film on the surface of embedded reinforcing steel. The presence of calcium hydroxide however may be reduced by the presence of free water passing through the concrete or by the effects of carbonation. The reaction corresponds to the carbonation is:



An adequate supply of oxygen, moisture and electrolyte, corrosion will start. Carbon dioxide reacts with and removes the calcium hydroxide. This is called *carbonation*. An electrolyte can be formed by very small quantities of carbon dioxide, sulphates or chlorides in the water. Electrolyte are defined as chemical substances containing ions that migrate in electric fields. Electrolyte are includes raw and treated water, salt water and fresh water, soil of many varieties, atmosphere rain and air borne contaminants.

The rate of penetration of concrete structures by carbonation is a slow process, which is determined by the rate at which carbon dioxide can penetrate into the concrete. The rate of penetration depends on the porosity and permeability of the concrete. It is rarely a problem on structures that are built with good quality concrete with adequate depth of cover over the reinforcing steel.

Carbonation of concrete takes place rapidly when the relative humidity is around 50%-60%. The rate of corrosion is maximum, when relative humidity is 90%-95%. The rate of corrosion is independent of humidity in the presence of chloride.

2.5.3 Environmental Effects

Corrosion itself is the consequence of environmental effects. Members in the splash zone usually have the most severe corrosion because of the combined effects of oxygen, salt and water. Atmospheric corrosion is less serious and underwater corrosion is the lightest. It is also proved that freezing can accelerate the corrosion process of the reinforcement.

2.5.4 Construction Quality

It is very important to ensure construction quality for preventing the R.C. structures from corroding. The main reason is that the concrete is not well compacted. Some general problems of construction quality include: the thickness of concrete cover is not enough; the joints between beams and slabs are not constructed carefully or the concrete is not compacted properly and the reinforcement is not placed correctly.

2.5.5 Thickness of the Concrete Cover

The thickness of the concrete cover plays an important role in preventing the corrosive substance from reaching the surface of the reinforcement. The results of the test show that when cover thickness is increased from 3 to 4 cm, both the rate of weight loss and the rate of rusting could be reduced about 91% after six cycles of wetting and drying.

2.5.6 Property of the Concrete Material

The best protection against corrosion of reinforcement is to use well-compacted concrete, while the density of concrete is mainly affected by several factors: the water cement ratio, the content of the cement, the size of the aggregate and the quality of the water reducing agent.

Regarding the effect of aggregate size, the larger the size of the coarse aggregate, the more serious the corrosion of the reinforcement. This is because the non-uniform shrinkage cracks are formed easily in concrete with larger size of the coarse. Adding a water reducing agent to the concrete mixture is another effective approach to improve the density of the concrete.

2.5.7 Structure Type

As for the structure type, convex and concave parts should be avoided if possible, because these parts are easily frozen and rusted, and it is difficult to get

well compacted concrete in these parts. For example, the flanges of T beams were easily corroded.

2.6 Corrosion Measurement Parameters

The electrical resistivity of concrete is an important component of reinforcing steel corrosion cells, as high resistivity of the concrete will reduce corrosion currents and slow the rate of corrosion. Lower resistivity, would produce larger corrosion currents.

This can be seen in a modified equation of Ohms Law where, $I = E / R$. Electrical resistivity is fundamentally related to the permeability of fluids and diffusivity of ions through porous materials such as concrete.

The information about the state of reinforcement corrosion is obtained usually in terms of three measurement parameters, namely:

- (i) Half-cell Potential, E_{corr} ;
- (ii) Concrete Resistivity, ρ ;
- (iii) Corrosion Current Density, I_{corr} . These parameters are summarized as below:

(i) Half-cell Potential (E_{corr})

The Half-cell Potential, also called the open-circuit potential or rest potential or corrosion potential (E_{corr}) is measured at several distinct points over a given area to

be surveyed. Interpretation of Half-cell Potential test results is carried out as per the ASTM C876 guidelines, as presented in Table 2.1.

Half-cell Potential (mV) relative to Cu/CuSO ₄ reference electrode	Percentage chance of active corrosion
<-350	90
-200 to -350	50
>-200	10

Table 2.1: Interpretation of Half-cell Potential values as per ASTM C876

(ii) **Concrete Resistivity (ρ)**

The electrical resistance of the concrete plays an important role in determining the magnitude of corrosion at any one specific location. This factor is measured in terms of electrolytic resistivity of concrete and is usually expressed in ohm-centimeters. Classification of the likelihood of corrosion, actually occurring, can be obtained on the basis of the values given in Table 2.2, and this is best suited when Half-cell Potential measurements indicates that corrosion is possible.

Resistivity (ohm cm)	Likelihood of significant corrosion (non-saturated concrete when steel is actived)
<5000	Very High
5000 – 10,000	High
10,000 – 20,000	Low / Moderate
>20,000	Low

Table 2.2: Interpretation of Concrete Resistivity with regard to Reinforcement

Corrosion (Bungey, 1989)

The resistivity of concrete is related to moisture and the content of charged ions and their mobility. Resistivity measurements can thus give valuable information for the interpretation of electrode potential results made under the same conditions.

The distribution and size of the aggregates can affect measurements of concrete resistivity. When the thickness of the concrete cover is significantly larger (as in this study), the condition of the top layer of concrete has a larger influence on the resistivity measurement than the condition of the concrete layer near the reinforcement level.

In general, corrosion rates increase as the temperature increases. Because of changes of temperature in concrete will also result in changes of other parameters such as resistance of concrete and oxygen diffusion, the overall effect of temperature on corrosion rate in concrete is very complex and controlled by interactions among other factors.

As is known, corrosion of steel in concrete requires a sufficient supply of oxygen for the cathodic reaction to take place, as well as moisture to act as an electrolyte of low resistance. Usually, the oxygen availability at the steel surface exceeds the amount needed for corrosion for normal outdoor concrete exposures. Therefore, corrosion rate of steel in concrete increases as concrete resistance decreases in normal outdoor exposure conditions.

(iii) Corrosion Current Density (I_{corr})

The corrosion rate is measured in terms of the corrosion current density, I_{corr} and is a quantitative index which represents an overall estimate of the corrosion attack of reinforcement. The I_{corr} is measured electrochemically. The electrochemically measured value of I_{corr} can be converted (Ijsseling FP, 1986) to the instantaneous corrosion rate, J_r and penetration rate, P_r through Faraday's law, as follows:

$$J_r = \left(\frac{W}{F} \right) I_{corr}$$

$$P_r = \left(\frac{W}{F \rho_{st}} \right) I_{corr}$$

where:

W = equivalent weight of steel = $55.85 / 2 = 27.925\text{g}$.

F = Faraday's constant = 96487 C (or Ampere-second).

ρ_{st} = density of steel (7.85 gm/cm^3).

I_{corr} = corrosion current density (Amp/cm^2).

J_r = instantaneous corrosion rate ($\text{gm/cm}^2/\text{s}$).

P_r = penetration rate (cm/s).

The corrosion rate measured may be either passive or active depending on the corrosion rate. Passive state rate of corrosion of rebar is found to be relatively low in the order of 10^{-9} to 10^{-7} Amp/cm^2 whereas the active state corrosion rate is found to be relatively high, compared to that of passive state, in the order of 10^{-6} to

10^{-5} Amp/cm².

2.7 Non-Destructive Testing of Corrosion in Reinforced Concrete

The main research of corrosion is detection and measuring of defects in the initial stage of corrosion process. Monitoring the corrosion rate, assuming the uniform corrosion and the loss in diameter decreases linear with the corrosion rate will allow the engineers to calculate the remaining load carrying and the safety of the structure. The following are types of electrochemical methods for corrosion rate measurement in reinforced concrete structures:

2.7.1 Electrochemical Methods

There are many electrochemical methods in the field but here, the relevant types which are related with this project will be described.

2.7.1.1 Static Measurements

(i) Half-Cell Potential Measurements

The method was first developed in the late 1950's (1) and has been extensively used in USA for assessment of concrete bridges. It was adopted in 1977 as an ASTM method C-876 (2). This method has wide use in Europe among other countries since beginning of 1980 (3).

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