STRUCTURAL HEALTH MONITORING OF CONCRETE BRIDGE BASED PREDICTIVE MODEL ON CHLORIDE INGRESS

WONG CHEE LUM

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Faculty of Civil Engineering & Earth Resources
UNIVERSITI MALAYSIA PAHANG

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ABSTRACT

Concrete Bridge is a very useful structure nowadays to link the different community together by provided the path for human to across river, lake and sea. However, bridges possess high risk attack by corrosion by chloride ingress if directly contact with sea water. The sea water contains high level of chloride compare to sulfate. Corrosion due to the chloride ingress becomes a serious issue nowadays. The concrete bridge should repair with an amount of cost to ensure the safety. Some of the concrete bridge even end of service life and cause the replacement of the old concrete bridge should carry out. The predictive model may use to determine the service life and the maintenance period. The engineer may assist by the model to make the decision on which method suitable use to maintenance in order to provide the safe structure and low cost maintenance fee. Thus, the objectives of this project are investigate the corrosion monitoring instruments, review the predictive model and estimate probability of rise of corrosion initiation phase at given time. The model will create by using Fick's second law. Monte Carlo simulation is widely used to obtain parameters by repeating sampling method. Bayes' Theorem may use to interpret the parameters into Fick's second law with the experimental data to update the result. The analysis shown that the parameters will influence the result of the predictive model, good quality of parameter will give a good quality of result. The prior distribution may be updated to posterior distribution by using likelihood function. The likelihood function plays an important role in updating process because the likelihood strongly effect on the posterior distribution. So, it is very important to get the likelihood function right in order produce an accurate posterior distribution. The research shows the significance of providing the useful information to predict the condition of concrete bridge under the chloride ingress. An action may be performs with the help of the model in order to solve the problem by select the low cost and effective way.

Keywords : Chloride ingress, predictive model, corrosion, health monitoring, concrete bridge

ABSTRAK

Jambatan Konkrit ialah struktur yabg sangat berguna pada masa kini. Fungsi jambatan konkrit adalah membolehkan manusia seberang sungai, tasik dan laut. Walau bagaimanapun, jambatan konkrit bole mengalami kakisan disebabkan oleh kemasukan klorida jika bersentuh dengan air laut yang mengandungi klorin yang tinggi. Pada masa kini, kakisan wujud pada struktur konkrit adalah isu yang serius. Jambatan konkrit perlu dibaiki dengan kos yang tinggi jika kakisan berlaku untuk memastikan keselamatan. Sebahagian daripada jambatan konkrit perlu diganti dengan baru disebabkan jambatan tersebut tidak dapat berfungsi. Model ramalan boleh digunakan untuk ramal hayat perkhidmatan jambatan konkrit. Jurutera boleh menggunakan model tersebut untuk memilih cara untuk baiki struktur dengan kos yang rendah. Objektif- obkektif projek ini adalah untuk mengaji alat pengawasan untuk kakisan dalam konkrit, mengaji model ramalan dan meramal kebarangkalian berlakunya kakisan pada fasa permulaan kakisan pada masa tertentu. Model tersebut boleh dihasil dengan menggunakan Fick's second law bersama dengan Monte Carlo simulasi yang digunakan secara meluas. Bayes' Theorem digunakan untuk mengemaskini model tersebut untuk jadikan ia lebih jitu. Selepas membuat analisis, didapati parameter- parameter yang digunakan akan megaruhi keputusan model. Prior tasrif boleh dikemsakini dengan menggunakan fungsi kebolehjadian dan mendapatkan posterior tasrif. Fungsi kebolehjadian tersebut sangat mempengaruhi posterior tasrif. Jadi, fungsi kebolehjadian tersebut perlu ditentukan dengan jitu supaya dapat posterior tasrif yang jitu. Parameter yang berkualiti akan menghasilkan model yang berkualiti dan sebaliknya. Pengajian ini dapat menyediakan maklumat yang berguna untuk meramal keadaan jambatan konkrit di bawah isu kakisan yang disebabkan oleh kemasukan klorida. Model ini dapat membantu jurutera untuk membuat keputusan yang sesuai dalam membaiki struktur konkrit.

Kata kunci: kemasukan kloride, model ramalan, kakisan, pengawasan kesihatan, jambatan konkrit

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

%	Percentage
θ	Point estimate a parameter of a single population
σ^{-2}	Variance

LIST OF ABBREVIATIONS

PDF	Probabilty density function

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Concrete is the common structure in this world. Basically concrete is make from cement, and the reason of concrete became famous is the durability. Concrete very high in compression resistance, but it is very weak in term of tension. The steel bars embed in the concrete to provide the tension resistance function.

Concrete used to construct many type of structure such as factory, house, road, bridge and etc. Although concrete shown durable properties, but it will fail in term of crack. One of the reasons of this happen is due to the deterioration. Concrete bridge is one of the structures which possess high risk in deterioration in term of corrosion due to the presence of acidity (chloride ion, sulfate ion and etc.) and humidity at the surrounding of the structure.

According to 2011 Bridge Inventory, the total of the bridge structures in America is 602,091 in 2011 (Barbaccia, 2011). There are 23% of concrete bridge are structurally deficient and functionally obsolete. These shown that there are 23% of bridge structures need to repair and replace. Corrosion is one of the reasons lead this happen, as the acidic ion such as chloride pass through the concrete and start to accumulate on the surface of steel bar, 'depassivation' will occur.

Although the chloride in the concrete was monitoring to an allowable amount, but the chloride ion steel can attack from the external. In fact, it is no perfect method to avoid chloride ingress into concrete. To ensure the bridge structures are safe, some modeling will carry out to determine the service life of the bridge structure and provide the data to ensure the bridge owner can manage its maintenance plan.

1.2 PROBLEM STATEMENT

Reinforcement concrete is a common material use in construction. According to Angst (2011), reinforcement concrete is a most common material use by the construction all over the world due to the good durable. Bridge is one of the reinforcement concrete structures, it is very important in human daily life. Bridge play a critical role in the development of a regional transportation network (Knight, 2004), it enable human travel from one place to another place by across river, lake or sea.

Chloride ingress is one of the issues to cause the failure of reinforcement concrete. Omar (2002) said that majority of bridge in Malaysia are concrete, cracking and spalling of concrete are the most common in Malaysia. In Malaysia, the corrosion induced majority cause by carbonation and chloride ingress due to the carbon dioxide produced by high number of vehicles and the high content of chloride in sea water. Bastidas (2010) said that the corrosion which induces by chloride ion has become a critical issue for most of the reinforced concrete structure especially concrete bridge. Vladimir (2003) reported that the corrosion if reinforcement concrete will start to occur if chloride are pass through the protective film which exist on the surface of steel bar. This will easy to happen as the steel bar surrounded by high acidic environment.

According to the Fick's first law, the solute will goes from a region with high concentration to the region of low concentration. It is stated that the concentration of solute are constantly at any time. To predict the concentration of chloride ion, Fick's second law is selected. Fick's second law provides the concentration of chloride ion changes with time by diffusion method compare to Fick's first law which only consider that concentration is constantly at given time. According to Comisu (2005), a large amount of iterations must perform to create a sufficient result. Monte Carlo simulation is very useful and widely used. Monte Carlo simulation is set of repeated sampling method which the values are randomly from theoretical distribution. The Bayes' Theorem is very useful to determine the condition of concrete bridge. Bayes' Theorem is results of all the conditional probabilities which created by Monte Carlo simulation.

In this case, a model created by using the law, simulation and the theorem to estimate the condition of the concrete bridge at given time. This model may assist the decision maker to make an appropriate decision according to the condition of the concrete bridge.

1.3 OBJECTIVES

To conduct this study, the objectives of this study are developed to the study are carry out based on certain goals. The objectives were:

1) To investigate the corrosion monitoring instruments.
2) To review predictive model of concrete bridge.
3) To estimate probability of rise of corrosion initiation phase at given time.

1.4 SCOPE OF STUDY

This research will be carried out by create a predictive model. Fick's second law will be using to obtain the concentration of chloride ion changes with time by diffusion method. Monte Carlo simulation will be using to determine the uncertainty by repeating the sampling method. Next, Bayes' theorem will be used to obtain the result from the conditional probabilities. However, the predictive model will not describe the condition of the concrete bridge fully due to the model is generated based on the data related to natural. Human are not able to describe the natural very accurate but they can make the prediction almost always close to natural. Also, the large numbers of data from sensor are required to generate the accurate predictive model as the sensors give the reading according to the natural process.

1.5 RESEARCH SIGNIFICANCE

This research will be significance endeavor in creating the awareness about the significance of chloride ingress predictive concrete bridge among the structural engineering community in Malaysia. This research will show the prediction ways of chloride ingress in order to create the predictive model to shown the service life and the maintenance period. The information created will assist the engineer to make decision to repair the structure. Also, this research will provide more information about the chloride ingress to assist the next researcher.

CHAPTER 2

LITERATURE REVIEW

2.1 CORROSION

Iron is the original element for making steel. Iron is named as ferrum as scientific name with the symbol Fe and the electron number of 26. Steel are making by alloyed iron. The iron alloyed with other element which is nonferrous to improve the properties such as strength. In order to produce steel, the iron is alloyed with carbon. Even the alloyed iron is stronger than pure iron, but it still has weakness. The steel is very weak in resistance of corrosion.

Corrosion is a chemical process that causes deterioration of material when the material expose to different environment. Degradation of the materials will happen during the corrosion due to loss of the original strength.

Corrosion is a process which weaken a material and make it will not function as desire. These agree by Barbara (2006). Barbara said that all material undergo degradation, metal will undergo degradation by corrosion. Corrosion will cause the degradation of materials' properties such as strength. She also mention that the corrosion occur due to the interactions of the material with the environment.

Ricard (2010) said that the corrosion of reinforced steel is categorized as galvanic corrosion. These category states that the different materials with different chemical and electrochemical properties in the same environment will cause the corrosion happen provide that the electrical circuit complete the joint between the two different materials. Current will be generating when two different metals immerse in same electrolyte. Once the current completed, the corrosion process will start. Figure 2.1 illustrated the galvanic corrosion of a single metal.

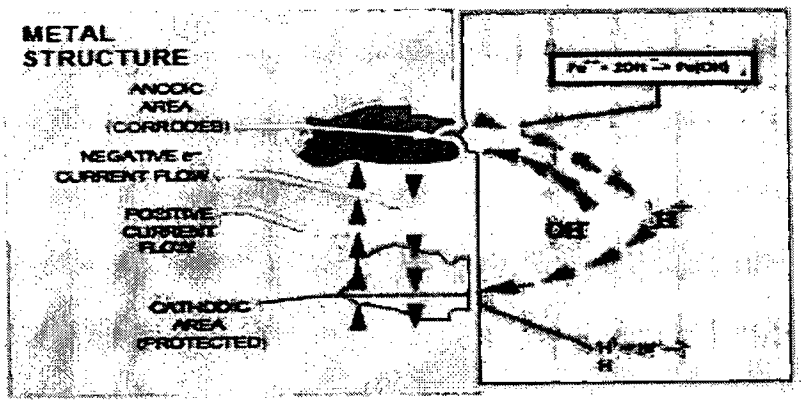

Figure 2.1: Galvanic corrosion of single metal

Source: Wikimedia Common 2007

The basic condition for the corrosion happen due to chloride ingress is sufficient of concentration of chloride ions, moisture, and oxygen. The absence of one of this element, the corrosion will not start. In the matter of fact, the steel is produced from alloy of iron under chemical and mechanical step. The corrosion process is the process that restores the steel to its original element.

2.2 MECHANISM OF CORROSION

Steel often used as reinforcement bar in concrete to contribute the tensile strength. Basically, steel are easy attack by corrosion with the present of water and oxygen. Concrete used to protect the steel due to its alkali properties which provide an alkali environment for steel in order to avoid the happen of corrosion. The alkali environment enable the formation of invisible passive film of Ferric Oxide for protect the steel.

According to Charng (1984), two simultaneous reactions are requiring to start the corrosion reactions:

1. Oxidation of metal (anode):

   At anode surface: $Fe \longrightarrow 2e^{-} + Fe^{2+}$ (2.1)

2. Reduction of substance (cathode)

At cathode surface: $O_2 + 2H_2O + 2e^- \rightarrow 2(OH)^-$ (2.2)

The formation of rust at anode:

At anode: $Fe^{++} + 2(OH)^- \rightarrow FeO.(H_2O)$ (2.3)

Figure 2.1 illustrate the process of steel corrosion embedded in concrete with the sufficient moist and oxygen.

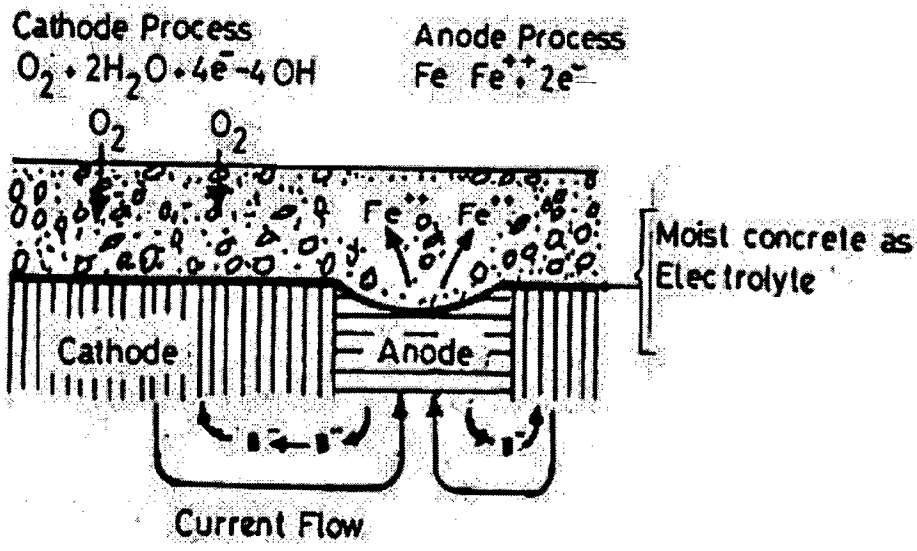

Figure 2.2: Process of steel corrosion embedded in concrete

Source: Charng 1984

The formed will reduce the cross section area of the reinforced bars. Also, the volume of rust formed is higher than the reinforced bars, this result the expansive pressure in the concrete and make the concrete crack and spall.

2.2.1 Causes of Corrosion

Corrosion of steel are not occur immediately, the reason is the protected passive film on the reinforced bar should be destroy first to enable occurrences of corrosion.

There are two common causes of the corrosion of reinforced bar.

i. Breakdown of protected passive film on concrete by acidic ion
ii. Breakdown of protected passive film on concrete by neutralization of the concrete

For the pier which directly contact with the sea water, the high contain of chlorides in sea water will attack the alkaline condition which provided by the concrete. In order to initiate the corrosion, the concentration of the chloride should reach the threshold level, its approximate 1%. Also, the corrosion only occurs with the sufficient oxygen and moisture. Although the calcium in concrete able to react with the chlorides ion to bound chloride ion in non- active form, however the active chloride ion still exist in due to the excessive chloride ion. The active chloride ion can de- passivate the protected passive film on concrete in order to make the rebar activate and ready for corrosion.

Carbonation is another cause of concrete. The carbonation rate depend on the humidity, the ideal humidity is 50% - 70%. The carbonation is not able to happen in dry condition as there are not sufficient of water. The wet condition will dissolve the carbon dioxide in water. On the other hand, carbonation occurs due to the penetration of carbon dioxide into the concrete. Usually, the carbon dioxide penetrates into concrete by diffusion method. Carbonation rate mostly higher in town, the reason is the vehicle and the industrial will produce huge amount of carbon dioxide to environment, this increase the chance of contact between concrete and carbon dioxide. The carbon dioxide will react with calcium to form calcium carbonate cement.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \qquad (2.4)$$

This product will cause the environmental in the concrete drop below pH 7, this results the concrete are not stay in alkanity anymore. The protected passive film on the reinforced bars will destroy due to the acidic environment in concrete. This will enhance the chloride induce corrosion of the reinforced bar.

Alkali- silica reaction in the concrete is depending on the alkali from the cement and the silica from the reactive aggregate with the presence of sufficient moisture. Generally, alkali- silica reaction not happen due to the external condition, that mean the moisture is provided by the pore water in the concrete. This reaction will produce an

expansive ASR gel which will exert pressure from internal of the concrete. The reason of ASR gel will exert the pressure is due to the ASR gel will absorb the pore water in the concrete in order to start swelled. The pressure will cause the concrete crack as concrete is a rigid structure. The crack will facilitates the corrosion process due to it become more permeable to acidic solution.

The major reason of corrosion is due to the permeability of the concrete (Kabir & Mahmud, 2010). High water- cement ration is one of the reasons to cause the high permeability in order to facilitate the corrosion. The higher contain of water may lead the segregation in the concrete and cause the aggregate expose to atmosphere, this facilitates the chloride ingress, carbonation and alkali silica reaction.

Poor workmanship also will cause the crack. The fresh worker or worker with less expertise will not able to handle the fresh concrete during placing. They may drop the concrete from higher level and not compacting well in order to cause the concrete segregate or bleeding. Improper curing will make the concrete crack due to not enough of water to ensure the complete of hydration process during hardening of concrete. Gereiene (2001) said that the concrete may crack due to the change of use of the concrete structure. Some of the structure owner will change the type of building by their own. They may add one more storey on the existing structure to cause the higher load applied on the structure than the original design. Also, they may remove the main component of the structure especially the beam and the column of the structure which give the support to the whole building.

2.2.2 Chloride Attack

Chloride attack on reinforced bar is one of the major environmental attacks to the concrete structure which direct contact with sea water or also called marine structure. The high permeability of the concrete will assist the chloride ingress in order to causes the corrosion of the rebar. These happen will make the structure weak and less durability than desired. According to Xianming (2011), the chloride- induced rebar corrosion will results reduction in strength, aesthetics, and serviceability of the concrete structure. The oxygen and hydroxide that accumulate in the pore of concrete that near to the rebar will build up a hoop stress will causes crack and spall, which turn to assist the ingress of water, oxygen and chloride ions.

As a matter of fact, sea water consist high amount of chloride. Over the time, the repeating apply of chloride solution on the concrete structure, at last, the chloride reach the reinforced bar in the concrete. Although, the corrosion will not start immediate after reaching the reinforced bar, but the corrosion will start to happen at critical concentration of chlorides ion, provided the sufficient of oxygen and water. The volume of corrosion product are larger than the original reinforced bar, these cause the expansion force in concrete in order to make the concrete crack and spall.

After the crack and spall, the reinforced bars were exposing to environment in order to cause the rapid corrosion. The volume of rust keeps increasing while the volume of steel keeps decreasing. Finally, the surface area of steel which contact to concrete decrease, these mean the bond between the concrete and steel are weaken.

2.2.3 Chloride Attack Mechanism

In the case of chloride attack into the concrete, there are several modes or mechanism to enable chloride to attack concrete structure:

i. Capillary absorption
ii. Diffusion
iii. Permeation

Capillary absorption is driven by moisture gradient. At the splash zone of the pier, it will undergo wetting and drying cycle, once the concrete contact with water after dried, the concrete will take up the water by capillary absorption method through the pores inside the concrete. According to Hong (1998), the unsaturated concrete will draw the solution up by the surface tension. This mechanism defines as absorption.

Diffusion is driven by the different of concentration of the chloride ions. If one side of the environmental contains high concentration of chloride ions, it will tend to diffuse into concrete through the pores provided there are continuous liquid phase. According to Kabir (2010), diffusion is the common method of chloride ingress and may define as the movement due to the different of the concentration gradient. Diffusion is the predominant mechanism for the structure that submerge in the liquid especially pier.

Permeation is driven by the different of the pressure head, if high pressures exist on one side, it will permeate into the concrete. But, this method is not significant

compare to the other. This support by Olga, he said that the permeation is movement due to the hydraulic pressure. The solution will penetrate into concrete and determine by convection.

2.2.4 Diffusion Mechanism of Chloride Ions

Even concrete is strong material, but it is a porous material. Even the concrete product by using the pozzolanic to make the concrete more dense, but the concrete still consist of a lot of pore. Thus, diffusion of chloride ions into concrete is favourable by this reason. Capillary absorption, diffusion, and hydrostatic pressure are the means that the chloride ions can penetrate into the concrete. But among the method, diffusion is the most familiar method to enable chloride ions to penetrate into concrete through the pores.

According to Yeih (1994), there are two main methods to enable the chloride penetrate into the concrete. One is due to the pressure difference inside the concrete and the environmental, this always happen in submerged zone. The other one is due to the different of the concentration of chloride ions which enable the diffusion occur. The high concentration of chloride ions in the environmental will tend to diffuse into concrete through the pores to reach the equilibrium. Normally, the penetration due to different pressure is not significant compare to the diffusion method.

Also, the chloride ions that will react with C_3A and C-S-H will not contribute in the corrosion process. On other hand, the C-S-H gel will block the Chloride ions to reach the reinforced bars. It is shown that only the free chloride ions which can move freely into concrete are taking part in the corrosion process.

2.2.5 Consequences

The consequences of corrosion are effect on the safe, reliable and the efficiency of the material. Generally, the failures of material need an expensive cost to repair and replacement. In concrete, even the concrete made by using pozzolonic material to reduce the internal voids, but it is still a porous material. The chlorides will ingress into concrete successfully at certain period in order to accumulate on the reinforced bars to initiate the corrosion.

One the other hand, corrosion is one of the important durability issues of concrete structure. The reinforced bars responsible in the tensile strength while the concrete responsible in the compressive strength. Also, the concrete used to protect the reinforced bars by created a passive protective film on the reinforced bars due to the alkanity of the concrete. However, the pore system of the concrete is the disadvantage of concrete structure. The reason is the pore system allows the diffusion and the absorption of the acidic solution.

According to Apostolopoulos (2012), chloride on the surface of the concrete will enter into concrete through the pore system by diffusion or absorption method or combination of the both method. In the initiate phase of corrosion, the free chloride ingress will accumulate on the surface of reinforced bars in order to depassive the protective film on the surface of the reinforced bars in the concrete, this results the reinforced bar no longer to be protected and propagation phase will start soon once the concentration, moisture condition and oxygen are satisfied.

First, the chloride ingress will cause the deterioration of the concrete in order to reduce the compressive strength. Furthermore, the consequences of the rust formation due to corrosion will cause the reduction of cross section area of the reinforced bars. These make the reinforced bar failed to contribute the desire tensile strength. The corrosion can concluded as an electrochemical process which results the degradation of reinforced concrete structure.

Also, the happen of corrosion in bridge structure involved a costly maintenance fee. A huge amount of money requires repairing the bridge structure as the corrosion occurs. Besides that, if the corrosion not able to detect early, the whole structure may need to destructure. Demolition involved relative higher cost.

2.2.6 Stage of Corrosion

Corrosion due to the chloride ingress can comprises in two stages:

i. Initiate stage
ii. Propagation stage

In the initiate stage, the free chloride ions play important roles. The free or active chloride ions penetrate into concrete by diffusion or capillary suction or combination of both. These ions will start to accumulate in the concrete. When the critical concentration

of the chloride ions reach, the protective film on the reinforce bars will be depassive in order to make the reinforced bars more porous and easy to be attack. In this condition, the reinforced bars are ready to undergo corrosion.

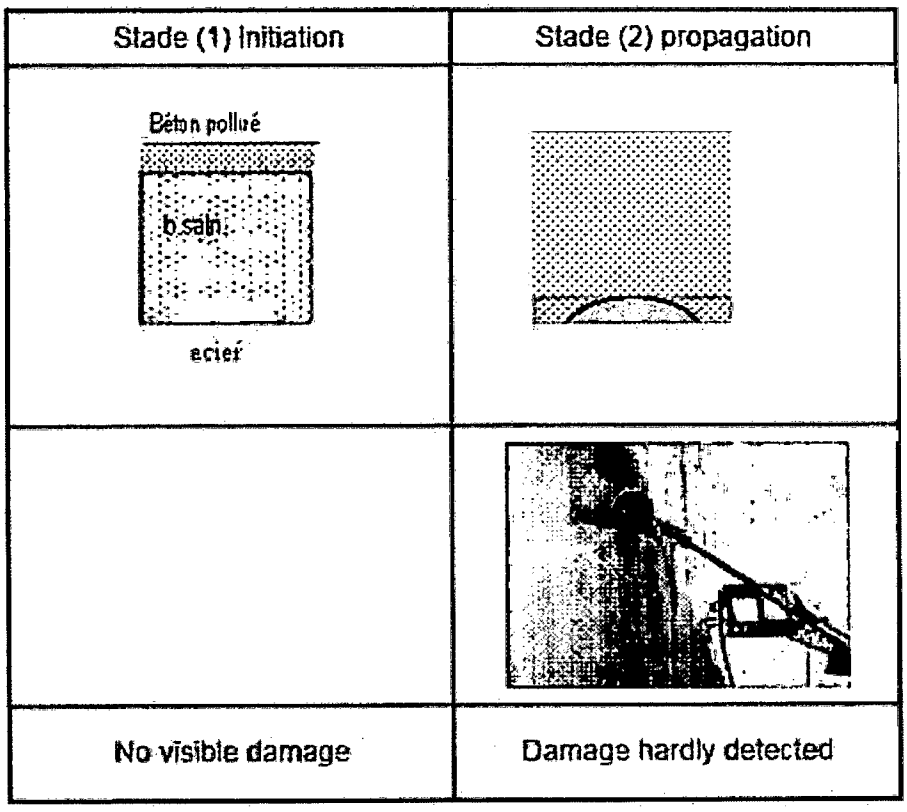

Figure 2.3: Condition of concrete

Source: Apostolopoulos 2012

The next stage is continuing by propagation stages, with the presence of the high concentration of chloride ions, moisture, and oxygen, an electrochemical reaction will start. The anode and cathode will formed in order to produce rust. The process may refer to section 2.2. Figure 2.3 show the condition of concrete during initiation and propagation stage.

The figure 2.4 shown the chloride ingress into the concrete and the happen of corrosion on the reinforced bars.

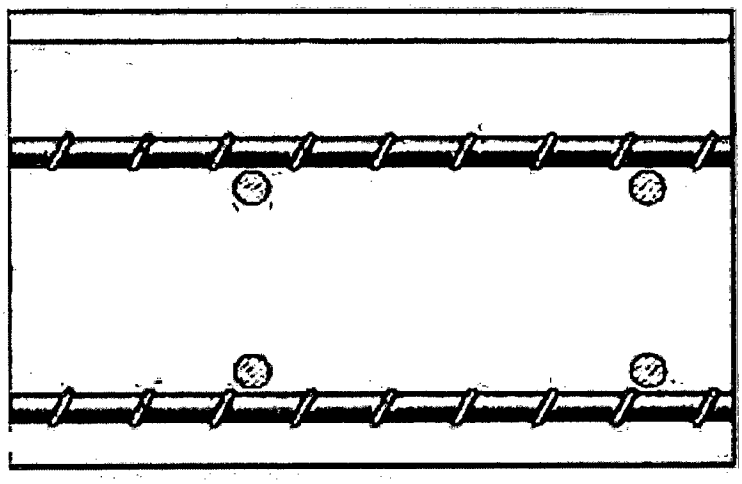

Figure 2.4a: Chloride penetrate into concrete

Source: Corrosion- Club 2003

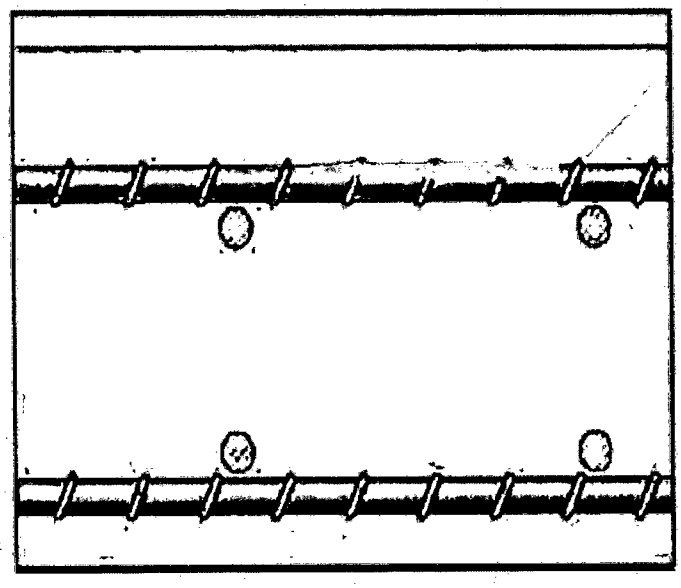

Figure 2.4b: Chloride reachs reinforced bars

Source: Corrosion- Club 2003