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## QUANTITATIVE ASSESSMENT OF DETERIORATED RC STRUCTURES DUE TO REINFORCING STEEL CORROSION

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### Abstract

Corrosion of steel reinforcement is one of the main causes of damage in concrete structures. Thus, the detection and prevention of corrosion of steel in concrete is important for the condition assessment and rehabilitation of reinforced concrete structures. Corrosion is an electrochemical process requiring an anode, a cathode, and an electrolyte. A moist concrete matrix forms an acceptable electrolyte and the steel reinforcement provides the anode and cathode. Electrical current flows between the cathode and anode, and the reaction results in an increase in metal volume as the iron (Fe) is oxidized into  $\text{Fe}(\text{OH})_2$  and  $\text{Fe}(\text{OH})_3$  and precipitates as  $\text{FeO} \cdot \text{OH}$  (rust color). Water and oxygen must be present for the reaction to take place. In good quality concrete the corrosion rate will be very slow. Accelerated corrosion will occur if the alkalinity (pH) is lowered (carbonation) or if aggressive chemicals or dissimilar metals or uneven chemical environment are introduced into the concrete.

The structural capacity of a concrete member is affected by bar corrosion and cracking of surrounding concrete. Researches conducted on flexural beams found that in steel with more than 1.5 percent corrosion, the ultimate load capacity was reduced by 12 percent probably as a result of reduced bar diameter.

The present research introduces an evaluation of the harmful effects of steel reinforcing corrosion on different kinds of structures. It also suggests a Quantitative Assessment program to estimate the rate of corrosion and the residual bearing capacity of RC elements containing corroded reinforcement based on mathematical techniques.

**Key Words:** Corrosion, degree of deterioration, mathematical interpretation, diagnostic/prognostic investigation, promoters, inhibitors, Quantitative assessment.

## **1. INTRODUCTION**

Steel has the advantage of having the tensile strength that concrete lacks, and is highly compatible in its chemical and physical characteristics. The matching of thermal expansion coefficients is critical to the versatility of reinforced concrete. In concrete, the presence of abundant amount of calcium hydroxide and relatively small amounts of alkali elements, such as sodium and potassium, gives concrete a very high alkalinity with pH of 12 to 13. At the early age of the concrete, this high alkalinity results in the transformation of a surface layer of the embedded steel to a tightly adhering film, that is comprised of an inner dense spinal phase in epitaxial orientation to the steel substrate and an outer layer of ferric hydroxide. As long as this film is not disturbed, it will keep the steel passive and protected from corrosion. This passivity layer in addition to the concrete cover protects steel reinforcement from access of aggressive salts and acids that cause corrosion, [1].

When concrete cover reduces to the limit that steel bars are exposed to surrounding conditions, corrosion starts to take place in the presence of oxygen and humidity. But, even there is an enough cover; corrosion can take place if pH reduces to 10.5 or less due to carbonation process. Then the passivity layer becomes unstable and starts breaking. This allows electric current to pass and metal loss increases.

To better estimate of the degree of deterioration of concrete structures, one has to inspect other deterioration mechanisms. Then operating a diagnostic/prognostic investigation of the current condition of structure, in order to deduce the vulnerability aspects and degree of stability. The following sections will summarize deterioration mechanisms to get an overview, then analyzing corrosion mechanism in Quantitive basis.

## **2. DETERIORATION MECHANISMS**

Like masonry and brick, reinforced concrete structures deteriorate under attack from external elements such as freeze-thaw damage (the expansion of frozen moisture within the structure as it thaws), and erosion. In a composite man-made material such as concrete there are additional mechanisms caused by the greater complexity of its composition. Of particular concern today is the alkali silica reaction in the concrete and the corrosion of the reinforcing steel, both of which are affected by the alkalinity of Portland cement concrete. Portland cement is made by burning constituents which include lime in a kiln and grinding the result to a fine powder. This produces a highly

alkaline material which reacts with water and hardens. When it is added to coarse and fine aggregate and mixed with water, the cement combines with the aggregate and hardens to form concrete. The hardening process (hydration reaction) is complex and continues over many months if not years, depending on the amount of water in the mix. There must be excess water for workability and a pore network therefore develops as it dries out. Excess calcium hydroxide and other alkaline hydroxides are present in the pores and a solution of pH 12.0 to 14.0 develops (pH 7.0 is neutral; values below indicate acidity, and alkalinity above). It is this pore network and the solutions it contains that are critical to the durability of the concrete.

### **2.1. ALKALI SILICA REACTIVITY (ASR) MECHANISM**

ASR occurs if the wrong aggregates are used in the mix. Some siliceous minerals, including quartzes and opals, react with water in a high alkaline environment to form silica gel, a material used to absorb moisture. As silica gel swells when it absorbs moisture, the material can cause concrete to crack, and white, weeping deposits of silica appear. In many cases ASR is superficial and harmless, but it is unattractive and difficult to treat. The most effective remedy is to dry out the structure.

Many if not most types of concrete incorporate some material which is susceptible to ASR. However, very few structures show signs of significant ASR damage, as the reactive aggregate components which cause the problem are consumed in the process.

### **2.2 CORROSION OF REINFORCING STEEL MECHANISM**

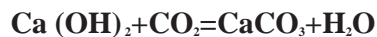
Although the alkalinity within the concrete pore structure can lead to ASR, the high pH value also provides a protective coating of oxides and hydroxides on the surface of the steel reinforcement. Without this layer, which is known as a 'passive' film, the steel would be exposed to the air and moisture in the pores, leading to rapid corrosion. It is the main chemical reason why reinforced concrete is a durable construction material. The layer is durable and self repairing, and it can last for hundreds of years if the alkalinity is maintained. However, the passive layer itself can be attacked by chlorides in salt and the alkalinity of the concrete can be reduced by reaction with atmospheric carbon dioxide, a process known as 'carbonation'.

Corrosion of steel reinforcement occurs by an electrochemical process which involves exchanges of electrons similar to that which occurs in a battery. The important part of

the mechanism is the separation of negatively charged areas of metal or 'anodes' where corrosion occurs and positively charged areas or 'cathodes' where a harmless charge balancing reaction occurs (Chart A). At the anode the iron dissolves and then reacts to form the solid corrosion product, rust. The rust is formed at the metal/oxide interface, forcing previously formed oxide away from the steel and compressing the concrete, causing it to spall.

### 2.3 DETERIORATION THROUGH CARBONATION

Carbon dioxide, which is present in the air in proportions of around 0.3 per cent by volume, dissolves in water to form a mildly acidic solution. Unlike other acids that may chemically attack and etch the surface of the concrete, this acid forms within the pores of the concrete itself where the carbon dioxide dissolves in any moisture present. Here it reacts with the alkaline calcium hydroxide forming insoluble calcium carbonate. The pH value then drops from more than 12.5 to about 8.5. The carbonation process moves as a front through the concrete, with a pH drop across the front. When it reaches the reinforcing steel, the passive layer decays when the pH value drops below 10.5. The steel is then exposed to moisture and oxygen and is susceptible to corrosion. The following equations describe carbonation process.



Concrete inside the building frequently carbonates totally without any sign of deterioration as the concrete dries out, leaving the steel exposed to air but not moisture. Problems are seen externally where concrete is exposed to the elements and in certain situations internally, such as kitchens and bathrooms, where the concrete is susceptible to condensation or water-leakage. External facades are particularly vulnerable, especially where cladding panels have poorly placed handling steel that is near the surface. Carbonation does not have to penetrate far and the concrete quality may be of poor quality.

## 2.4 DETERIORATION DUE TO CHLORIDE

Salt causes corrosion by a different mechanism. When dissolved in water sodium chloride forms a versatile, highly corrosive solution of sodium ions (Na<sup>+</sup>) and chloride ions (Cl<sup>-</sup>). Salt is used for de-icing roads and its presence in sea water is a major problem for reinforced concrete structures. The very mobile chloride ions disperse through concrete pores in solution and where they come into contact with the reinforcing steel they attack the passive layer.



Steel oxidizes in the presence of air and water to form rust which has a volume of up to 3-10 times that of the steel consumed. As concrete has a low tensile strength it will crack when as little as a tenth of a millimeter of steel has been consumed. Horizontal cracks form, causing corners to 'spall' and surfaces to 'delaminate' as the reinforcement's concrete cover becomes detached and falls away in sheets. The consequence can be seen on the underside of road bridges and many buildings and structures beside the sea,[2].

## 3. CORROSION ANALYSIS

If corrosion of steel in concrete is suspected, a deterioration survey must be carried out to identify the cause, mechanism and extent of corrosion. An inadequate investigation can lead to higher costs and inadequate repairs. There are certain tests which are specific to the corrosion assessment of steel in concrete, relying on the electrochemical nature of the corrosion process. These are half-cell potential measurement, resistivity measurement and corrosion rate measurement. But, before all, the current condition of steel reinforcement must be verified. There are four states of embedded reinforcement:

1. **Passive / protected reinforcement:** where which the reinforcing steel is totally protected by the passive film of iron oxide adherent to steel surface and inhibits corrosion, the high alkalinity of surrounding concrete permits this protection (pH > 10).

2. **Corrosive/ unprotected:** where which the surface of bars corrodes regularly as a result of the low alkalinity due to carbonation and chemicals attack or chloride penetration. The degree of corrosion depends upon the quality of concrete, its permeability, humidity, abundance of O<sub>2</sub>, salts concentrations, etc.....
3. **A part of Reinforcement is corrosive:** certain positions are exposed to rapid corrosion due to presence of cracks (may be normal to steel direction) in addition to other promoting conditions (humidity, abundance of O<sub>2</sub>, salts concentrations).
4. **Unprotected/ anticorrosive:** this is when corrosion is inhibited electrically like those of submerged concretes where environment lacks oxygen which is necessary to complete reaction.



The present research aims at suggesting a diagnostic/prognostic program to evaluate the degree of deterioration of RC structures due to reinforcing steel corrosion.

### 3.1 AMBIENT PROMOTING CONDITIONS

It was found that the presence of certain conditions eases the corrosion of embedded reinforcement. These conditions include; humidity, CO<sub>2</sub>, O<sub>2</sub>, Cl<sup>-</sup>, cracking, carbonation (reducing alkalinity), and existence of dissimilar metals inside concrete, see chart A. The following tables provide the limits required for corrosion occurrence.

Table.1: Factors affecting corrosion of reinforcement

FACTOR	LIMITS	EFFECT
Alkalinity pH	≤ 10	Strong effect
Humidity	50 -75%	Enable corrosion to take place
Cl <sup>-</sup> * by cement Wt	0.3% -1%	Strong effect, but these limits stands for Cl <sup>-</sup> that already in concrete mix
Cl <sup>-</sup> by concrete Wt	0.05 - 0.15%	
Cracking** (crack width)	≥ 0.3 mm	Strong effect when parallel to steel direction

\*Table.2: Scale of Cl<sup>-</sup> concentrations according to ACI-224R-90

<b>CL<sup>-</sup> EXISTENCE</b>	<b>LOW</b>	<b>MEDIUM</b>	<b>HIGH</b>
<b>In side concrete mix by cement Wt</b>	< 0.4 %	0.4% -1%	> 1%
<b>In side concrete mix by concrete Wt</b>	< 0.05 %	0.05% - 0.15 %	> 0.15 %
<b>Exposure from outside concrete</b>	-----	< 0.05 %	-----

It is important to distinguish between externally- impregnated chlorides and already in-mix chlorides, as the first has more harmful effect. Impregnated chlorides increase with depth for certain limit then reduce, meanwhile chlorides that already existed in concrete mix increase too but still constant afterwards. So, taking samples at different depths and analyzing chlorides content can determine their source, [1].

\*\*Table.3: Scale of allowable crack width according to ACI-224R-90

<b>EXPOSURE CONDITION</b>	<b>TOLERABLE CRACK WIDTH (IN)</b>	<b>TOLERABLE CRACK WIDTH (MM)</b>
<b>Dry air, protective membrane</b>	0.016	0.41
<b>Humidity, moist air, soil</b>	0.012	0.3
<b>De-icing chemicals</b>	0.007	0.18
<b>Sea water, spray, wet- dry</b>	0.006	0.15
<b>Water retaining/structures</b>	0.004	0.1

It is of interest to mention that some factors if exceeds certain limits loses its effect like chlorides ions; if their concentration exceeds the double of sea water concentration (which equals 70.5 p.p.m of NaCl), then no harm effect will be resulted as oxygen can't be solved in such high concentrations, [2]. Otherwise, the effect of impregnated chloride ions from external source is more harmful to activate corrosion process than those existing already in concrete mix. As existing chlorides in concrete gather in pores and still restricted in major, meanwhile a small part is solved in pores water and becomes free to attack steel bars and delays reactions of passivity film around these bars. On contradict, impregnated

chlorides have their major portion free to attack steel and thus has more harmful effect, [3]. Another point is carbonation, as the rate of carbonation decreases with increase of carbonation depth due to inhibiting the impregnation of CO<sub>2</sub> inside totally carbonated concrete. There are acceptable empirical equations to estimate the carbonation depth depending on many factors like time, type of cement, water cement ratio, and moisture content, [4]. These equations will be developed later in Quantitative assessment.

$$D = C \times [T_1]^{0.5} \dots\dots\dots (1)$$

Where: **D**: represents the depth of carbonation in mm.

**T<sub>1</sub>**: the time required to achieve this depth in years.

**C**: constant depends on factors affecting carbonation process.

$$C = \frac{[46 w/c - 17.6]}{2.7} \times C_1 \times C_2 \dots\dots\dots (2)$$

**2.7**

Where: w/c represents the water cement ratio in concrete mix.

**C<sub>1</sub>**: constant depends on cement type, equals 1 for Ordinary Portland Cement type I, equals 0.6 for Ordinary Portland Cement type II, equals 1.4 for ferrous cement contains 30%- 40% ferrous slag, and equals 1.4 for ferrous cement contains 60% ferrous slag.

**C<sub>2</sub>**: constant depends on the atmospheric conditions of concrete, equals 0.3 for wet concrete, equals 0.5 for externally exposed concrete members, and equals 1 for internally exposed members.

The above equation gives an average value for depth of carbonation, as it differs from location to another, thus the values obtained from equation.1 is less than maximum carbonation depth with 5-10 mm, [5]. On the other hand, the time **T<sub>1</sub>** represents the time required till carbonation approaches the steel bars. It must be added to the time required for corrosion to take place and spalling of concrete cover starts, **T<sub>2</sub>**. **T<sub>2</sub>** is given by the following equation:

$$T_2 = \frac{0.08 \times t}{[\emptyset \times dM/dT]} \dots\dots\dots (3)$$

Where: **T<sub>2</sub>**: represents the time required for corrosion to take place and spalling of concrete starts.

**t**: the thickness of concrete cover in mm.

**∅**: the diameter of steel bar in mm.



**dM/dT:** the rate of corrosion in mm/year, it ranges between 0.015- 0.09 mm/year and is taken 0.04 mm/year as average value.

Thus, the total time of corrosion **T** must equal the sum of **T<sub>1</sub>**, **T<sub>2</sub>**.

$$T = T_1 + T_2 \dots \dots \dots (4)$$

The source of error in this equation comes from the first part which neglects other factors affecting corrosion; like CO<sub>2</sub> concentration. In addition to this, estimating the rate of corrosion **dM/dT** approximately leads to inaccurate results. The following section introduces a mathematical approach to determine **dM/dT** with high accuracy depending upon a governing property in corrosion process, alkalinity (pH). It manipulates the pH-dM/dT relationship deduce the rate of corrosion at any pH value.

#### 4. PREDICTING THE RATE AND DURATION OF CORROSION FROM pH VALUE

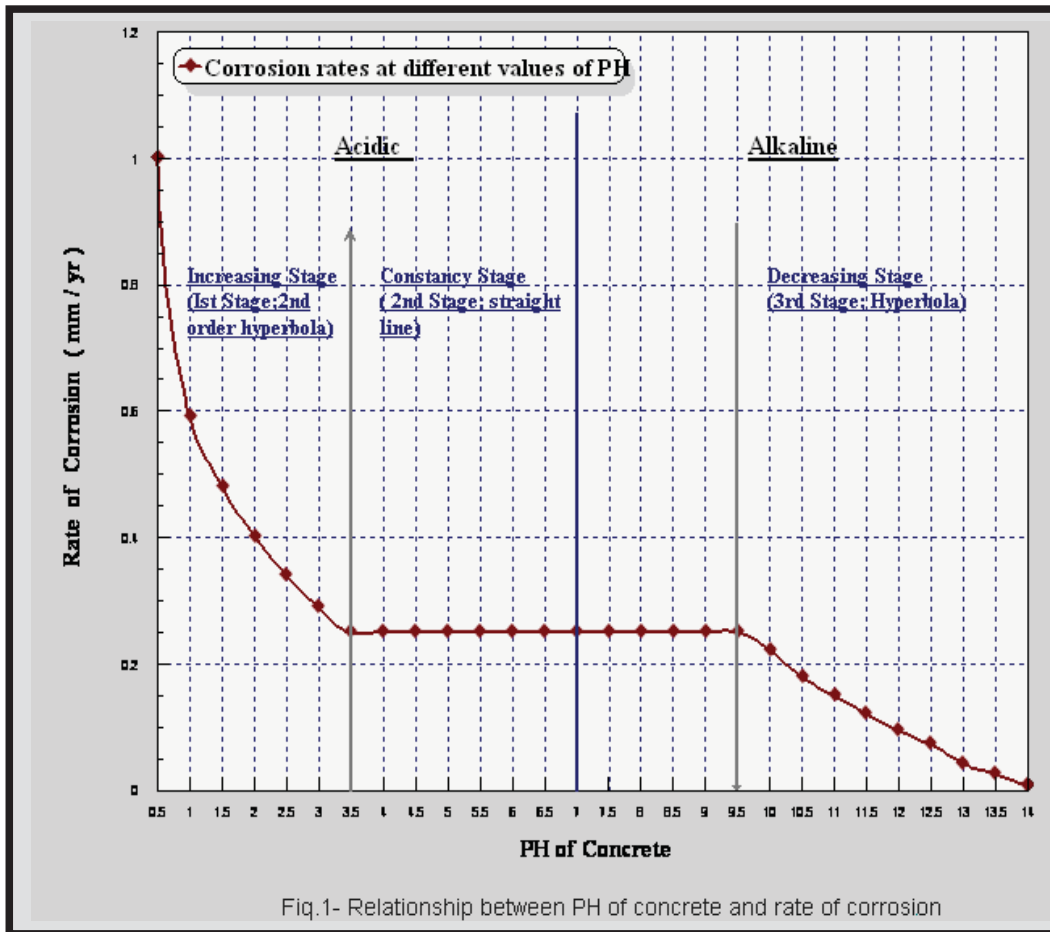


Figure.1 illustrates the relationship between rate of corrosion and pH value. From fig.1, it appeared that pH- dM/dT graph consists of three sequent curves denoted as three successive stages; increasing, constancy, and decreasing. The corresponding data was interpolated to deduce the fitting curves of these stages. Then, the fitting curves were tested and iterated in order to determine precisely the fitting equations of each stage. Depending on these equations, the rate of corrosion can be accurately calculated by determining (experimentally) pH of concrete.

**If X = pH value**

**, and Y = f (X) = rate of corrosion in mm/year.**

- The fitting curve for first increasing stage: (2<sup>n</sup>order hyperbola), [14≥X≥9.6]

$$Y_1 = 1.484 - (5.016/ X) + (4.541/X^2) \dots\dots\dots (5)$$

The fitted equation 5 with 99.11% accuracy, calculates the rate of corrosion from pH value in acidic conditions.

- The fitting curve for second constancy stage: ( straight line), [9.6≥ X ≥3.6]

$$Y_2 = 0.25 \dots\dots\dots (6)$$

The fitted equation 6 with 100% accuracy, calculates the rate of corrosion from pH value in intermediate conditions.

- The fitting curve for third decreasing stage: (hyperbola), [3.6 ≥X≥ -∞]

$$Y_3 = - 0.5155 + (7.318/ X) \dots\dots\dots (7)$$

The fitted equation 7 with 99.63% accuracy, calculates the rate of corrosion from pH value in alkaline conditions.

Now, the rate of corrosion (dM/dT) can be easily calculated from pH value. But how to predict the time passed for corrosion to occur. **T<sub>1</sub>**, **T<sub>2</sub>** have been introduced before as the time required for carbonation to approach steel bars, and time required for corrosion to take place and cause spalling of concrete.

From equation.3

$$T_2 = \frac{0.08 \times t}{[\emptyset \times dM/dT]}$$

Let's compensate with **Y<sub>1</sub>**, **Y<sub>2</sub>**, and **Y<sub>3</sub>** from the fitted equations 5, 6, 7 instead of dM/dT.

$$\Rightarrow T_2 = \frac{0.08 \times t}{Y} \dots\dots\dots(8)$$

$$[\emptyset \times Y]$$

Let's denote constants  $K_1, K_2$  as:

$$K_1 = \underline{0.08} \times t \dots\dots\dots(9)$$

$$[\emptyset]$$

$$K_2 = 1/ C^2 \dots\dots\dots (10)$$

Where C is the constant depending on carbonation factors, see equations 1, 2.

Rewriting equation (1),  $T_1 = D^2/ C^2 \dots\dots\dots (11)$

$$\Rightarrow T_1 = K_2 D^2, T_2 = K_1/ Y$$

$$\Rightarrow T = T_1 + T_2 = K_2 D + K_1/ Y \dots\dots\dots(12)$$

The modified equation 12 can be used to estimate the total time required for corrosion to take place and cause spalling of concrete.

### 5. PREDICTING CONCRETE RESISTIVITY FROM pH VALUE

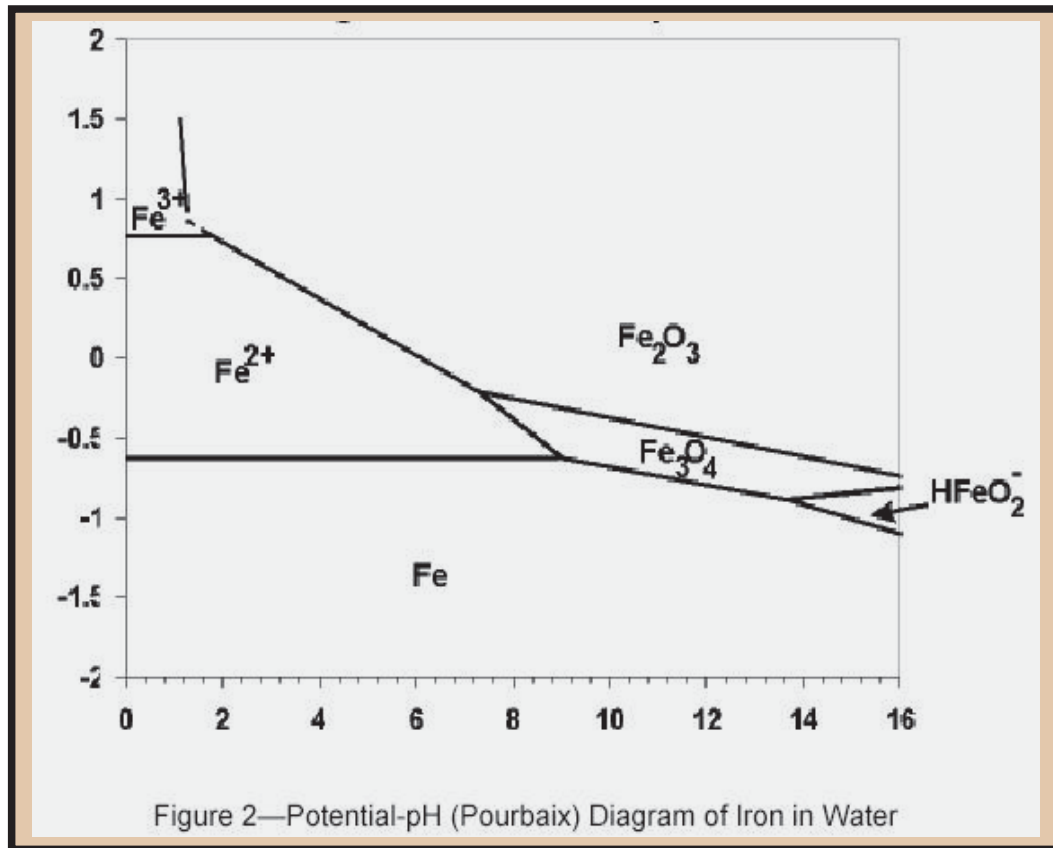


Figure 2 (Pourbaix diagram) illustrates the relationship between pH and concrete resistivity. While pH varies from 0 to 14 along X-axis, V (resistivity) varies from -

2 to 2 along Y-axis. Determining V experimentally contains many measurement errors and effected by many factors. If V is determined from pH value, this will give more accurate results. To do so, it must be referred to Faraday's law of electrolysis, [5].

$$M = E \times (I \times T) \dots \dots \dots (13)$$

Where: M is the mass of liberated iron.

I: current density (attributed here to the intensity of corrosion current in ampere)

T: time run (attributed here to duration of corrosion)

E: constant equals the electrochemical equivalent of iron material, equals for mild steel  $2.78333 \times 10^{-4}$  gm/ampere. second.

(I×T): is represented by the area under current-time curve.

V: the voltage of induced corrosion current.

Referring to equation 13, by differentiating both sides with respect to time:

$$dM/dT = E \times I \dots \dots \dots (14)$$

Where **dM/dT**: the rate of corrosion.

But, the voltage can be verified as:  $V = I \times R \dots \dots \dots (15)$

Compensating with I value from equation 15 in equation 14:

$$dM/dT = E \times (V/R) \dots \dots \dots (16)$$

Thus, if pH and V are determined, the rate of corrosion can be estimated.

Furthermore, V can be detected using pH value by fitting Pourbaix diagram.

**If X = pH value**

**, and V = f (X) = concrete resistivity.**

- The fitting curve for first stage:, [1.8 ≥ (X= pH) ≥ 1.6]

$$V_1 = 1 / (3.436 \text{ Ln } X - 0.9902) \dots \dots \dots (17)$$

- The fitting curve for second stage:, [7 ≥ pH ≥ 1.8]

$$V_2 = 1.324 - 0.2133 X - (0.2428/X) \dots \dots \dots (18)$$

- The fitting curve for third stage:, [8 ≥ pH ≥ 7]

$$V_3 = 16.52 - 1.36 X - (50.4/X) \dots \dots \dots (19)$$

- The fitting curve for fourth stage:, [14 ≥ pH ≥ 9]

$$V_4 = 0.6146 - 0.6093 \text{ Ln } X \dots \dots \dots (20)$$

- The fitting curve for fifth stage:, [ pH ≥ 14]

$$V_5 = - 4.1 + (67.4/ X) - (336/X^2) \dots \dots \dots (21)$$

The accuracy of these fitting curves ranges from 99.25% to 100%. So, concrete resistivity can be calculated using pH value. Then, it is the choice of the reader to evaluate the corresponding rate of corrosion using either pH or V value and compensating in equations 5, 6, 7 or 16. Furthermore, the duration of corrosion can be estimated.

## 5. HOW TO QUANTITATIVELY INVESTIGATE CORROSION OF EMBEDDED REINFORCEMENT

The proposed technique is quite simple and avoids complicated tests. It depends on simple laboratory analysis (pH, concrete resistivity, carbonation indicators, and atmospheric conditions). It can be summarized as following:

- **Run simple petrographic analysis:** to verify if carbonation occurred a spray of phenolphthalein in ethanol gives an indication of carbonation, if concrete color turns to intense red it means that pH >10, if it becomes colorless it means that concrete has been carbonated (pH<10). Further examinations may clarify the concrete make-up, electrochemical activity, chloride content, concrete resistivity, pH value, carbonation depth, sulfate attack, etc...
- **Check the ambient promoting conditions:** to inspect the possibility of corrosion occurrence; conditions like humidity( 50-75%), CO<sub>2</sub> or SO<sub>2</sub> exposure, presence of cracks, honey-combed structure, and Cl<sup>-</sup> attack, all represent corrosion promoters. See charts from A to E.
- **Operate Quantitative assessment and prediction of corrosion:** chart F describes the sequence of steps adopted in proposed methodology.
- **Operate safety procedures depending upon the current condition of member, and evaluate required rehabilitation techniques.**

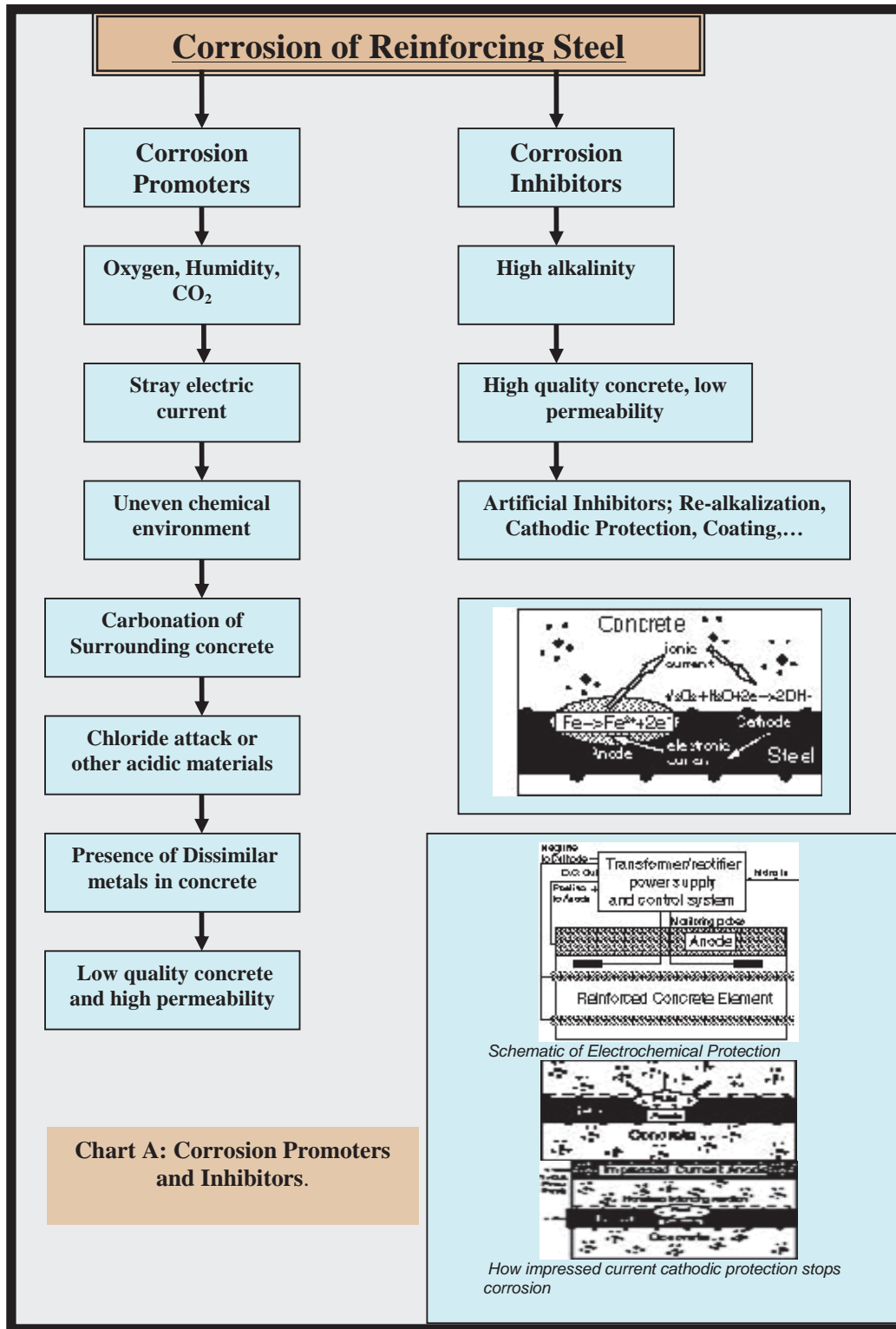
## CONCLUSION

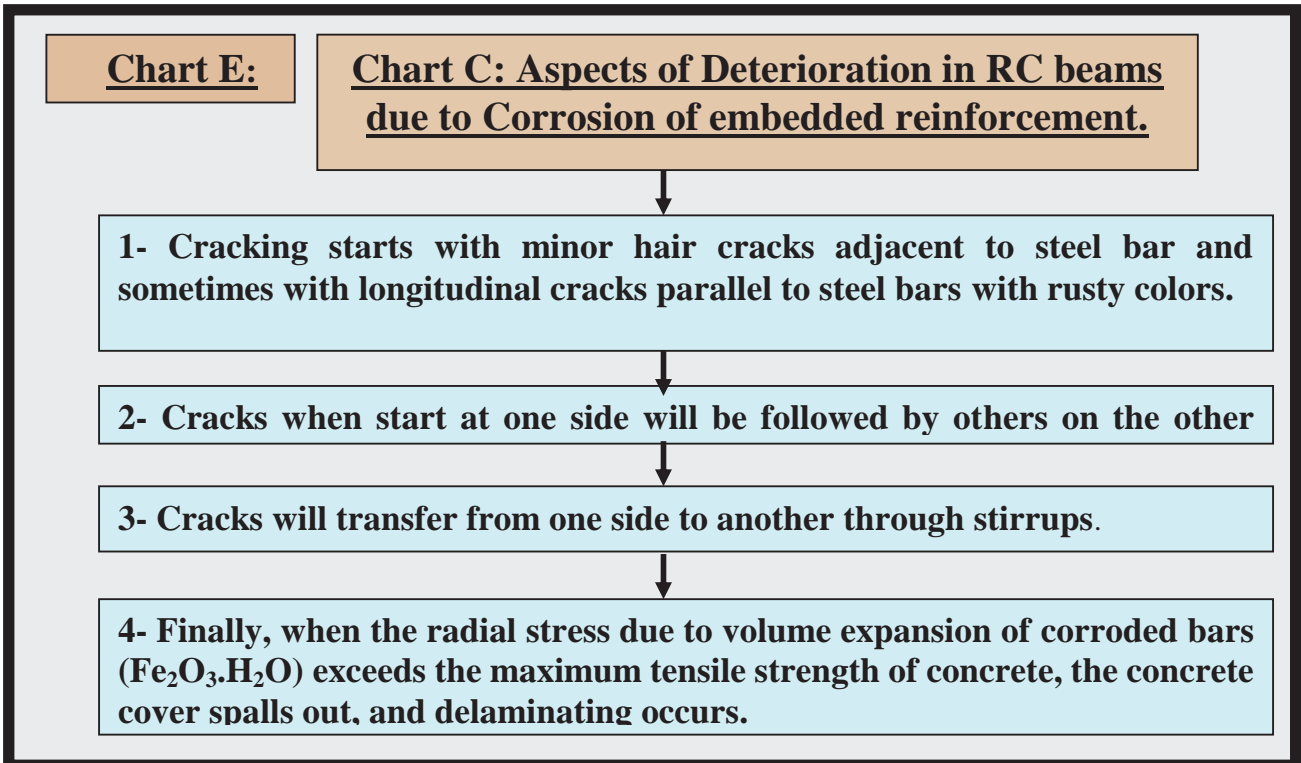
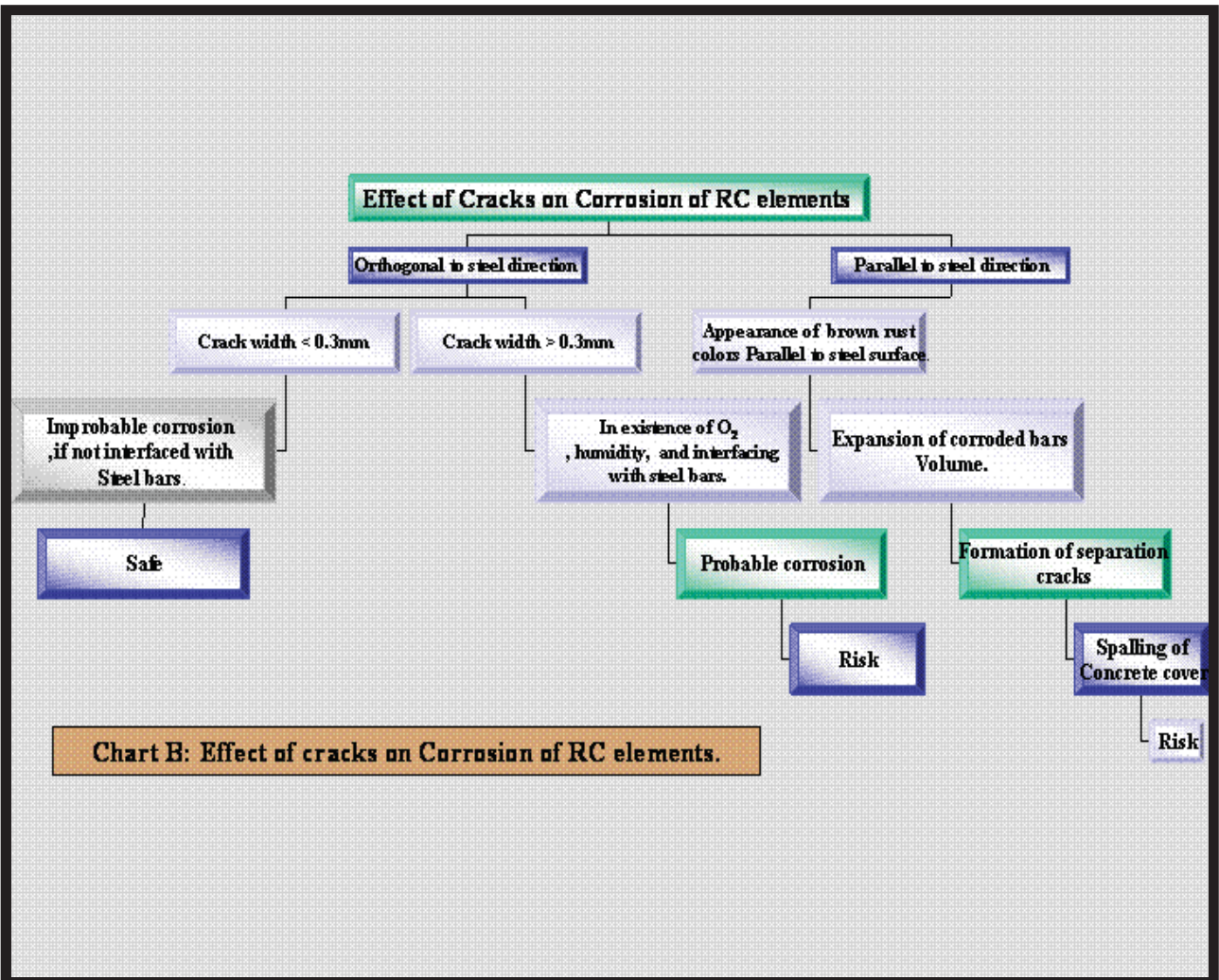
If corrosion of steel in concrete is suspected, a deterioration survey must be carried out to identify the cause, mechanism and extent of corrosion. The present research aims at suggesting a diagnostic/prognostic program to evaluate the degree of deterioration of RC structures due to reinforcing steel corrosion. The proposed technique is quite simple and avoids complicated tests. It depends on simple laboratory analysis and visual inspection. It introduces a Quantitative

assessment of deteriorated RC members due to reinforcement corrosion based on mathematical relationships.

## REFERENCES

1. Stanley, Christopher C. Highlights in the History of Concrete. British Cement Association, Crowthorne, Berks. 1986.
2. Cathodic Protection of Reinforced Concrete Status Report. Report No. SCPRC/001.95 Society for the Cathodic Protection of Reinforced Concrete, London, 6 February 1995.
3. Concrete Society Technical Reports:  
No 26 Repair of Concrete Damaged by Reinforcement Corrosion, October 1994.No 36 Cathodic Protection of Reinforced Concrete, 1989.
4. Broomfield, J.P. Assessing Corrosion Damage on Reinforced Concrete Structures Corrosion and Protection of Steel in Concrete, Edited by Narayan Swamy, Sheffield Academic Press 1994.
5. D. Bjegovic and B. Miksic (CORTEC), "Migrating Corrosion Inhibitor Protection of Concrete", Materials Performance Vol. 38, No. 11, pp. 52-56 (1999) November.







**Chart F: A Proposed Program to estimate the Degree of Deterioration of RC element due to Reinforcement Corrosion**

1- Check pH value of concrete using petrographic indicators.

2- Find rate of corrosion from pH – rate relationship.

3- Find experimentally the resistivity of concrete R, and then deduce the Corresponding induced voltage V due to corrosion current.

4- Compensate in Faraday's law, instead of  $dM/dT=E.I$  use  $dM/dT=E.V/R$ , where  $dM/dT$  represents the rate of corrosion and E is known constant.

5- Convert the obtained  $dM/dT$  to represent the rate of corrosion per year.

6- Calculate the corroded perimeter of rebar cross section.

7- Calculate  $\Delta D/D_0$ , where  $\Delta D$  represents the loss of bar diameter, and  $D_0$  represents the original bar diameter (without corrosion).

8- Relate the calculated  $\Delta D/D_0$  to the allowable codal specifications.

9- Calculate the time required to approach the allowable reduction in bar diameter due to these codal specifications and calculated rate of corrosion.

10- Calculate the current and predicted bearing capacity of element cross section due to future reductions.

11- Evaluate the current condition of member and required safety procedures.