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University of Babylon  
College of Engineering  
Department of Civil Engineering



# **EFFECT OF USING CORROSION INHIBITORS ON CONCRETE PROPERTIES AND THEIR ACTIVITY**

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَأَنْزَلْنَا الْحَدِيدَ فِيهِ بَأْسٌ شَدِيدٌ  
وَمَنَافِعُ لِلنَّاسِ

يُخْرِجُ الْحَدِيدَ وَالنَّعْلَمَ وَالْأَعْلَمَ وَالْأَعْلَمَ

سورة الحديد (الآية ٢٥)



*To all  
My lovely  
Family and  
Especially my  
father*

# CERTIFICATION

We certify that the preparation of this thesis, in titled **"Effect of Using Corrosion Inhibitors on Concrete Properties and Their Activity"**, was prepared by **"Abeer Mohammed Abdul Amir"**, under our supervision at the University of Babylon in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, construction materials.

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***Abeer Mohammed***

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# ***ABSTRACT***

The corrosion of the reinforcing steel in concrete is one of the major issues concerning the durability of reinforced concrete. Different methods have been used to protect the reinforcing steel, but still corrosion of reinforced concrete structures continues to be a serious problem causing enormous costs in their restoration and rehabilitation.

The use of corrosion inhibitors (Sodium benzoate and Potassium Dichromate) and SBR (Styrene- Butadiene- Rubber) admixture in the production of Ordinary Portland Cement (OPC) concrete improve its resistance to corrosive species as a result of the inhibitor reaction, which forms a passive layer on the surface of the steel bar and as a result of reducing the absorption and permeability of the concrete.

In this investigation, the effect of using sodium benzoate, potassium dichromate as corrosion inhibitors in three concentrations (1%, 2% and 3% by weight of cement) and SBR (Styrene- Butadiene- Rubber) emulsion in three concentrations (10%, 15% and 25% by volume of water) is studied on concrete properties; compressive strength, splitting tensile strength, flexural strength and absorption. The activity of these three admixtures in their three concentrations to reduce the corrosion rate where the three electrode polarization resistance is used to measure the corrosion rate.

A total of (220) specimens include: 99 cubes (150\*150 mm), 33 cubes (100\*100 mm), 33 cylinders (100mm diameter \*200mm height), 33 prisms (100\*100\*400 mm) and 22 reinforced concrete samples (140\*150\*200mm)

are prepared using different types of admixtures with the concrete mix, with mixing ratio 1:1.8:2.5 and water/cement ratio 0.48. All specimens are cured in tap water.

Then the 22 reinforced concrete samples were immersed partially in 3.5% NaCl solution for three months. Half of these samples were loaded with 10% of the design load after 6 weeks of immersing to make micro cracks in the concrete body.

The test results indicate that the use of sodium benzoate, potassium dichromate in 2% conc. by weight of cement cause a considerable reduction in compressive strength about 15% and 4% at 28 days respectively, but in the later ages the specimens got an increase in compressive strength about 7% and 11% at 90 days respectively (they works as a retardar admixture). The adding of these admixtures lead to considerable improvement in the other mechanical properties of concrete mixes with increasing in; splitting tensile strength about 17% for sodium benzoate and 21% for potassium dichromate, flexural strength about 18% and 20% respectively, also they cased reduction in absorption test with 38% and 42% respectively, with a reduction in the economical cost of 12% and inhibitor efficiency about 98% for each one.

The test results of SBR emulsion in conc. 25% by volume of water leads to a considerable improvement in all mechanical properties of concrete mixes with an increase in; compressive strength about 8%,11% and 7% at ages 28,60 and 90 days respectively, splitting tensile strength and flexural strength about 37%, and cased a maximum reduction in absorption about 77% with inhibitor efficiency of 97%. Where the reduction in economical cost is 13%

# LIST OF CONTENT

| SUBJECT                                            | PAGE |
|----------------------------------------------------|------|
| <b>Chapter One : Introduction</b>                  |      |
| 1.1 General                                        | 1    |
| 1.2 Aim of the Study                               | 5    |
| 1.3 Research Layout                                | 6    |
| <b>Chapter Two : Literature Review</b>             |      |
| 2.1 Introduction                                   | 7    |
| 2.2 The corrosion Process                          | 8    |
| 2.3 Passivation                                    | 10   |
| 2.4 Causes and Mechanisms of Corrosion             | 11   |
| 2.4.1 Carbonation                                  | 11   |
| 2.4.2 Chloride Attack                              | 14   |
| 2.4.3 Stray Current Induced Corrosion              | 17   |
| 2.4.4 Vertical and Horizontal Cracks and Corrosion | 17   |
| 2.4.5 Thickness of The Concrete Cover              | 18   |
| 2.5 Initiation and Propagation of Corrosion        | 19   |
| 2.6 Corrosion Rate                                 | 20   |
| 2.7 Polarization                                   | 22   |
| 2.7.1 Linear Polarization Resistance               | 23   |
| 2.7.2 Stern - Geary Equation                       | 24   |
| 2.8 Effects of Concrete Environment on Corrosion   | 25   |
| 2.9 Electrical Resistance of Concrete              | 30   |
| 2.10 Polymer Portland Cement Concrete (PPCC)       | 33   |
| 2.11 Corrosion Inhibitors                          | 36   |
| 2.11.1 Inhibitor Efficiency                        | 41   |
| <b>Chapter Three : Experimental Work</b>           |      |
| 3.1 Introduction                                   | 46   |
| 3.2 Materials                                      | 46   |
| 3.2.1 Cement                                       | 46   |

| <b>SUBJECT</b>                                                     | <b>PAGE</b> |
|--------------------------------------------------------------------|-------------|
| 3.2.2 Fine aggregate                                               | 46          |
| 3.2.3 Coarse Aggregate                                             | 46          |
| 3.2.4 Water                                                        | 47          |
| 3.2.5 Admixture                                                    | 49          |
| 3.2.5.1 Corrosion Inhibitors                                       | 49          |
| 3.2.5.2 Permeability Reducer                                       | 51          |
| 3.2.6 Steel Reinforcement                                          | 52          |
| 3.3 Concrete Mixes                                                 | 53          |
| 3.4 Mixing of Concrete                                             | 56          |
| 3.5 Preparation, Casting and Curing of The Test Specimens          | 56          |
| 3.6 Concrete Testing                                               | 56          |
| 3.6.1 Compressive Strength Test                                    | 56          |
| 3.6.2 Chloride Concentration (Cl <sup>-</sup> ions)                | 56          |
| 3.6.3 Splitting Tensile Strength Test                              | 57          |
| 3.6.4 Flexural Strength Test                                       | 57          |
| 3.6.5 Absorption Test                                              | 58          |
| 3.7 The Mold of Reinforced Concrete Specimens                      | 58          |
| 3.8 Electrochemical Tests                                          | 60          |
| 3.8.1 Electrical Resistance Test For Reinforced Concrete Specimens | 60          |
| 3.8.2 Polarization Resistance of Steel Reinforcement Wires         | 61          |
| 3.8.2.1 Instrument                                                 | 61          |
| 3.8.2.2 Test Procedure                                             | 61          |
| <b>Chapter Four : Results and Discussion</b>                       |             |
| 4.1 Introduction                                                   | 64          |
| 4.2 Compressive Strength test                                      | 64          |
| 4.3 Splitting Tensile Strength test                                | 68          |
| 4.4 Flexural Strength test                                         | 69          |
| 4.5 Absorption test                                                | 72          |
| 4.6 Concrete Electrical Resistance Test                            | 73          |
| 4.7 Corrosion Rate of non pre cracked reinforced concrete Samples  | 76          |

| <b>SUBJECT</b>                                                   | <b>PAGE</b> |
|------------------------------------------------------------------|-------------|
| 4.8 Corrosion Rates of pre cracking reinforced concrete samples. | 79          |
| 4.8.1 Sodium benzoate (SB) inhibitor                             | 79          |
| 4.8.2 potassium dichromate inhibitor                             | 80          |
| 4.8.3 SBR (Styrene- Butadiene -Rubber) admixture                 | 82          |
| 4.9 The Time Effect                                              | 83          |
| 4.10 Inhibitor Efficiency                                        | 83          |
| 4.11 (Cl <sup>-</sup> ) Concentration                            | 86          |
| 4.12 Classification Degree of corrosion current                  | 87          |
| 4.13 Polarization Resistance                                     | 87          |
| 4.14 Economical Cost                                             | 91          |
| <b>Chapter Five : Conclusions and Recommendations</b>            |             |
| 5.1 Conclusions                                                  | 96          |
| 5.2 Recommendations                                              | 97          |
| References                                                       | 99 - 105    |
| Appendix A                                                       | 106         |
| Appendix B                                                       | 109         |

## LIST OF FIGURES

| FIGURES | SUBJECT                                                                                                                                 | PAGE NO. |
|---------|-----------------------------------------------------------------------------------------------------------------------------------------|----------|
| (1.1)   | Cracking due to corrosion.                                                                                                              | 3        |
| (1.2)   | Spalling and delamination of the concrete cover.                                                                                        | 4-5      |
| (2.1)   | Structural consequences of corrosion in reinforced concrete structure.                                                                  | 7        |
| (2.2)   | Increasing in volume of steel due to corrosion.                                                                                         | 8        |
| (2.3)   | The anodic and cathodic reactions.                                                                                                      | 9        |
| (2.4)   | The corrosion reactions on steel.                                                                                                       | 10       |
| (2.5)   | Pourbaix diagram for iron.                                                                                                              | 11       |
| (2.6)   | Steps of carbonation process.                                                                                                           | 12       |
| (2.7)   | Schematic representation of corrosion rate of steel in different concretes and exposure condition.                                      | 13       |
| (2.8)   | Relation ship between the relative humidity and corrosion rate in carbonation mortar with and without the presence of chlorides         | 14       |
| (2.9)   | Relationship between chloride content found in bridge decks and percentage of reinforcement showing corrosion                           | 16       |
| (2.10)  | Corrosion induced cracking and spalling                                                                                                 | 18       |
| (2.11)  | Initiation and Propagation of corrosion                                                                                                 | 20       |
| (2.12)  | Corrosion rate as a function of external relative humidity in case of initiation due to chloride for concrete with low and high density | 20       |
| (2.13)  | Effect of pH on corrosion of iron in aerated Soft water at room temperature                                                             | 21       |
| (2.14)  | Effect of concentration of sodium chloride on corrosion rate                                                                            | 21       |

| FIGURES | SUBJECT                                                                                                      | PAGE NO. |
|---------|--------------------------------------------------------------------------------------------------------------|----------|
| (2.15)  | Reduction of the initiation time of corrosion due to local reductions in the thickness of the concrete cover | 22       |
| ( 2.16) | Schematic anodic polarization curve of steel in non carbonated concrete without chlorides                    | 23       |
| (2.17)  | The relationship between corrosion rate and concrete resistivity                                             | 31       |
| (2.18)  | Protection mechanism of corrosion inhibitors                                                                 | 41       |
| (2.19)  | The relationship between corrosion rate and concrete resistivity                                             | 29       |
| (3.1)   | Sodium Benzoate admixture                                                                                    | 50       |
| (3.2)   | . The white layer on the surface of the concrete specimens due to the using of sodium benzoate admixture .   | 50       |
| (3.3)   | Potassium Dichromate admixture .                                                                             | 51       |
| (3.4)   | SBR [Styrene – Butadiene –Rubber ] emulsion                                                                  | 52       |
| (3.5)   | Steel reinforced wires before and after cleaning                                                             | 53       |
| (3.6)   | Curing of specimens in tap water                                                                             | 55       |
| (3.7)   | Details of reinforced concrete specimen                                                                      | 59       |
| (3.8)   | Partial Immersing the reinforced concrete specimens in 3.5% NaCl solution                                    | 60       |
| (3.9)   | Electrical Resistance Test for specimen with Ohm mete                                                        | 60       |
| (3.10)  | Diagram of Electrical Resistance Test Circuit.                                                               | 61       |
| (3.11)  | Diagram of Polarization Resistance Test Circuit.                                                             | 63       |
| (3.12)  | Polarization Resistance Test Circuit                                                                         | 63       |
| (4.1)   | Development of compressive strength with age for mixes with Sodium Benzoate admixture                        | 67       |
| (4.2)   | Development of compressive strength with age for mixes with Potassium Dichromate admixture                   | 67       |
| (4.3)   | Development of compressive strength with age for mixes with SBR admixture                                    | 68       |
| (4.4)   | Splitting Tensile Strength for concrete specimens with different admixtures                                  | 71       |
| (4.5)   | Flexural Strength for different concrete mixes                                                               | 71       |

| <b>FIGURES</b> | <b>SUBJECT</b>                                                                                                                                       | <b>PAGE NO.</b> |
|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| (4.6)          | Absorption for different concrete mixes                                                                                                              | 72              |
| (4.7)          | Electrical resistance for reinforced concrete samples with sodium benzoate admixture without pre cracking                                            | 73              |
| (4.8)          | Electrical resistance for reinforced concrete specimens with sodium benzoate with pre cracking after 6 weeks of immersing in 3.5%NaCl solution       | 74              |
| (4.9)          | Electrical resistance for reinforced concrete specimens with potassium dichromate admixture without micro cracks                                     | 74              |
| (4.10)         | Electrical resistance for reinforced concrete samples with potassium dichromate with pre cracking after 6 weeks of immersing in 3.5%NaCl solution    | 75              |
| (4.11)         | Electrical resistance for reinforced concrete samples with SBR admixture without pre cracking                                                        | 75              |
| (4.12)         | Electrical resistance for reinforced concrete samples with SBR admixture with pre cracking                                                           | 76              |
| (4.13)         | Corrosion rate for reinforced concrete samples with sodium benzoate admixture without pre cracking                                                   | 78              |
| (4.14)         | Corrosion rate for reinforced concrete samples with potassium dichromate admixture without pre cracking                                              | 78              |
| (4.15)         | Corrosion rate for reinforced concrete samples with SBR admixture without pre cracking                                                               | 79              |
| (4.16)         | Corrosion rate for reinforced concrete samples with sodium benzoate admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution      | 80              |
| (4.17)         | Corrosion rate for reinforced concrete samples with potassium dichromate admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution | 81              |
| (4.18)         | Corrosion rate for reinforced concrete samples with SBR admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution                  | 82              |

# LIST OF TABLES

| <b>TABLES</b> | <b>SUBJECT</b>                                                                                                                    | <b>PAGE NO.</b> |
|---------------|-----------------------------------------------------------------------------------------------------------------------------------|-----------------|
| 2.1           | Chloride limits for new concentration                                                                                             | 16              |
| 2.2           | Chloride concentration in reinforced concrete                                                                                     | 16              |
| 3.1           | Chemical composition and main compounds of cement                                                                                 | 47              |
| 3.2           | Physical characteristics of cement                                                                                                | 48              |
| 3.3           | Sieve analysis and some properties of fine aggregate                                                                              | 48              |
| 3.4           | Sieve analysis for coarse aggregate                                                                                               | 49              |
| 3.5           | Typical properties of SBR admixture                                                                                               | 51              |
| 3.6           | Steel reinforcement wires dimensions                                                                                              | 53              |
| 3.7           | Illustrates the proportion of concrete mixtures and some properties of fresh and hardened concretes                               | 54              |
| 4.1           | Results of Compressive Strength Test                                                                                              | 67              |
| 4.2           | Results of Splitting, Flexural and Absorption Tests                                                                               | 70              |
| 4.3           | Inhibitors Efficiency for concrete samples with and without micro cracks after 6 weeks of immersing in 3.5%NaCl solution          | 85              |
| 4.4           | Chlorides concentrations in reinforced concrete samples                                                                           | 86              |
| 4.5           | Classification degree of corrosion current                                                                                        | 88              |
| 4.6           | The Polarization Resistance Values for steel reinforcement wires in concrete at Different ages of Immersing in 3.5% NaCl Solution | 92              |
| 4.7           | The Final Calculation of the Economical Cost study                                                                                | 95              |
| A.1           | The Concrete Electrical Resistance Values at Different ages of Immersing in 3.5% NaCl Solution                                    | Appen. A<br>106 |
| A.2           | The Average Values of the Corrosion Current at different ages of immersing in 3.5% NaCl                                           | Appen. A<br>107 |
| A.3           | The Corrosion Rate Values at different ages of immersing in 3.5% NaCl solution                                                    | Appen. A<br>108 |

# NOTATIONS

| <i><b>SYMBOL</b></i> | <i><b>DEFINITION</b></i>                                                                             |
|----------------------|------------------------------------------------------------------------------------------------------|
| *                    | Making pre cracking in reinforced concrete samples after 6 weeks of immersing in 3.5 % NaCl solution |
| Amp.                 | Ampere (current unit)                                                                                |
| C.R                  | Corrosion rate                                                                                       |
| CI                   | Corrosion Inhibitor                                                                                  |
| Conc.                | Concentration                                                                                        |
| E, ΔE                | Potential (voltage)                                                                                  |
| HPC                  | High performance concrete                                                                            |
| HRWA                 | High Range Water - Reducing Admixture                                                                |
| I corr.              | Corrosion current                                                                                    |
| Icorr. av.           | The average of corrosion current                                                                     |
| k. Ohm               | Kilo ohm (resistance unit)                                                                           |
| M                    | Mole                                                                                                 |
| MCI                  | Migrating Corrosion Inhibitor                                                                        |
| N                    | Normal or Reference concrete mix                                                                     |
| PD                   | Potassium dichromate (corrosion inhibitor)                                                           |
| PD1                  | Concrete mix containing Potassium Dichromate in dosage 1% by weight of cement                        |
| PD2                  | Concrete mix containing Potassium Dichromate in dosage 2% by weight of cement                        |
| PD3                  | Concrete mix containing Potassium Dichromate in dosage 3% by weight of cement                        |
| Ref.                 | Reference                                                                                            |
| SB                   | Sodium Benzoate (corrosion inhibitors)                                                               |
| SB1                  | Concrete mix containing Sodium Benzoate in dosage 1% by weight of cement                             |
| SB2                  | Concrete mix containing Sodium Benzoate in dosage 2% by weight of cement                             |
| SB3                  | Concrete mix containing Sodium Benzoate in dosage 3% by weight of cement                             |

|       |                                                                                    |
|-------|------------------------------------------------------------------------------------|
| SBR   | Styrene -Butadiene-Rubber                                                          |
| SBR10 | Concrete mix containing Styrene -Butadiene-Rubber in dosage 10% by volume of water |
| SBR15 | Concrete mix containing Styrene -Butadiene-Rubber in dosage 15% by volume of water |
| SBR25 | Concrete mix containing Styrene -Butadiene-Rubber in dosage 25% by volume of water |
| w/c   | Water / cement Ratio                                                               |

# ***Chapter One***

## **Introduction**

### **1-1 General**

Corrosion can be defined as: the destruction or deterioration of materials due to reaction with its environment.

Or corrosion : the process by which a refined metals reverts back to its natural state by an oxidation reaction with non- metallic environment (e .g. Oxygen and water) [1].

Corrosion of reinforced concrete structures occurs when the environmental loading on the structure is greater than the ability of the structure to resist it and cause the deterioration

Reinforced concrete is a versatile, economical and successful construction material. It can be molded to a variety of shapes and finishes. Usually it is durable and strong, performing well throughout its service life typically exceeds 50 years. Some times, it does not perform adequately as a result of poor design, poor construction, inadequate materials selection, a more severe environment than anticipated or a combination of these factors [1].

Corrosion of steel reinforcement in concrete is one of the largest infrastructure problems facing all countries around the world, salted bridge decks, coastal and offshore structure sewers, structures in aggressive soils, structures that are subjected to chloride contaminated water and Marine structures are some examples where severe corrosion attack occurs [2].

Reinforced concrete superstructures along the coast can corrode due to marine atmospheric exposure if not properly designed. Marine atmospheric can be defined as that atmosphere within 300m (1000 ft) of ocean or tidal water, tidal water: is any body of surface water having a chloride content of 500ppm or greater [2].

The cost of repairing or replacing deteriorated structures has become a major liability for high way agencies, estimated to be more than \$20 billion and to be increasing at \$500 million per year that's in united state [3].

Reinforcing steel embedded in concrete shows a high amount of resistance to corrosion because the cement paste in good quality concrete provides an alkaline environment with pH (12.5-13.5) that protects the steel from corrosion by passivating or protective ferric oxide film that forms on the surface steel bar when it is embedded in concrete. This passive film is only a few nanometers thick and is stable in the highly alkaline concrete ( pH approx. 11-13.5 ) [1].

The protective action of the passive film is immune to mechanical damage of the steel surface, it can, however, be destroyed by carbonation of concrete or by the presence of chloride ions. The reinforcing steel is depassivated when the pH falls below 10 for any reason then the corrosion may occur [3].

Then carbonation or chloride ions can penetrate through the concrete pores to the oxide layer on the rebar breaking down the passive layer and leaving the steel bar vulnerable against aggressive agents; in the presence of moisture and oxygen the corrosion will occur [2].

The factors influencing the ability of the steel bar that is imbedded in concrete to remain passivated are: Water to cement ratio, Permeability of concrete, Presence of chloride ions, Carbonation, Concrete cover and Concrete admixture.

The following are some ways to preventing or reducing corrosion damage in concrete:

1. Eliminating chloride from the environment;
2. Avoiding or reducing exposure to water;
3. Reducing the permeability of the concrete by reducing water-cement ratio for concrete mix or using a pozzolana or blended cement;
4. Avoiding stray or impressed electrical currents. circuits grounded through steel and carrying large currents will subject the steel to unavoidable electrochemical attack;

5. Protecting the steel with defensive coatings, cathodic protection, and;
6. Using corrosion inhibitors [4].

The flexibility of corrosion inhibitors with regard to dosage and their compatibility with all aspects of construction and operation of structures makes them useful for protection against corrosion. The inhibitor works a safeguard within the concrete to provide a more protective environment for the steel [5].

In Iraq many concrete construction projects show a considerable degree of deterioration within a short period of 5-7 years after construction especially in southern parts of Iraq. In this region the damage of concrete is due to several factors, such as the presence of calcium, magnesium and sodium salts of sulphates and chlorides which extensively contaminate the ground, ground water and the moisture laden environment [5].

The pictures below show some shapes of corrosion problems in Iraq and other places of the world.

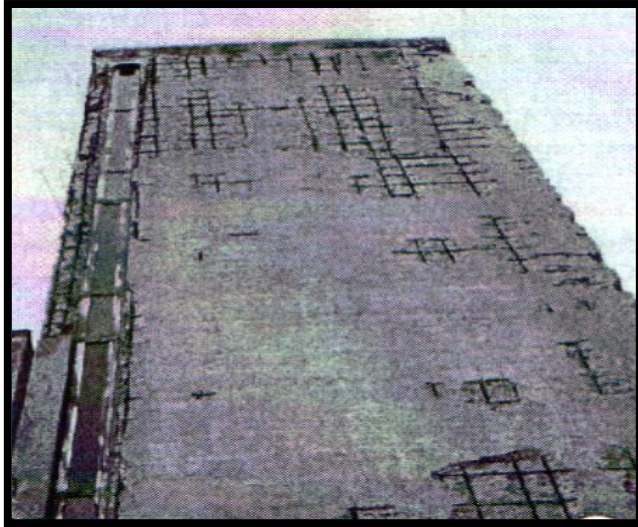


a)



b)

**Fig. (1.1) Cracking due to corrosion of    a) column and cross beam.  
b) sea wall.**



**Melt story building**



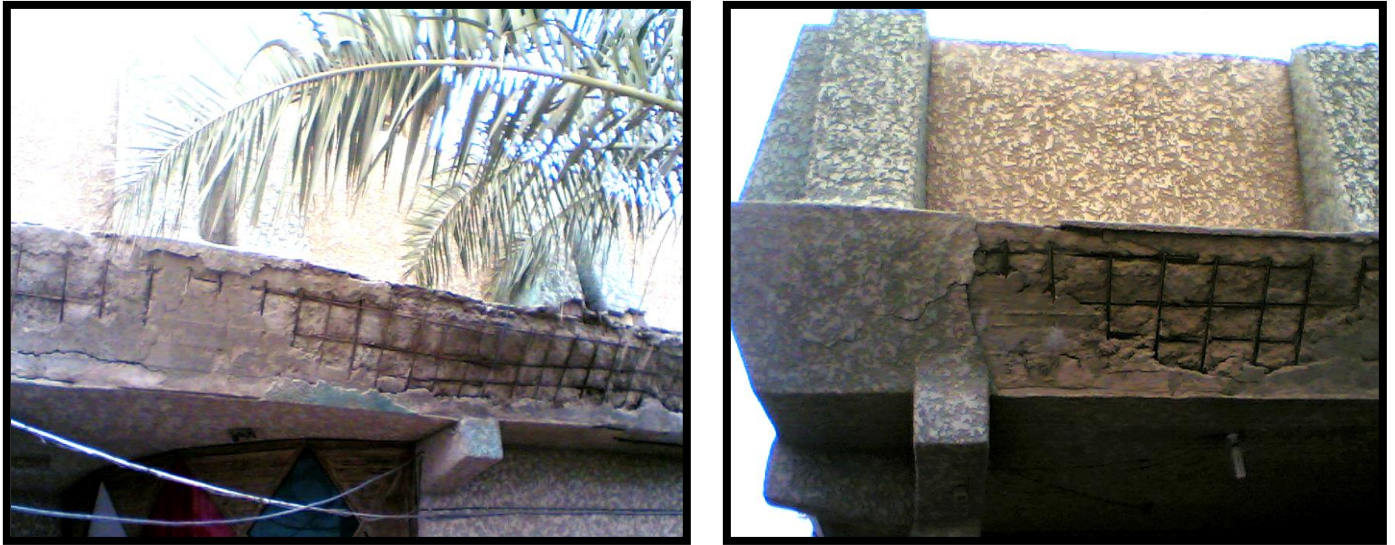
**Bridge piers**



**Concrete sea wall**



**Building of computer science department / Babylon university**



**A house in Al - Hussain Street / Hilla city**

**Fig(1.2) Spalling and delamination of the concrete cover**

## **1-2 Aim of The Study**

The aim of this research is to study the effects of using three type of admixtures (sodium benzoate SB, potassium dichromate PD, and SBR (Styrene-Butadiene- Rubber co-polymer)) in reinforced concrete, in three concentration for each one on concrete properties; compressive strength, splitting, modulus of rupture and absorption. The research also aims to study the activity of these admixtures as corrosion inhibitors to prevent or delay the corrosion of steel reinforced bars that are embedded in concrete exposed to aggressive environment (3.5 % NaCl solution (sea water concentration)) for three months by measuring:

- The electrical resistance for concrete samples.
- The polarization resistance for steel reinforced bars.
- Corrosion current and corrosion rate for steel.

### **1-3 Research Layout**

The work presented in this thesis is given through five chapters;

Chapter Two deals with corrosion process and the factors that influence corrosion, inhibitors efficiency and literature review of previous work on durability , corrosion of embedded steel in concrete and the action of corrosion inhibitors.

Chapter Three includes the mix proportion ,methods of testing the specimens and other experimental details.

In Chapter Four the results of the experimental tests are presented with their discussion and interpretation.

Chapter Five consists of conclusions, which are drawn from the results of this research and suggestions for future work.

## Chapter Two

### Literature Review

#### 2.1 Introduction

Corrosion of steel reinforcement in concrete is one of the biggest infrastructure problems facing all countries around the world because it destroys the aesthetics of the structure (rust stains), reduces the cross section area of the steel bar by its load carrying capacity, and causes cracking and spalling due to formation of expansive corrosion product (the volume of the rust is greater than the original volume about 2-6 time) that is shown in Figure (2.1) and (2.2 ) [6].

Regardless of the exposure condition, steel in concrete will only corrode when it becomes depassivated. Erlin [6] points out that reduction of pH to  $<11.0$  destroys the passivity of the protective film. Depassivation can occur in either of two major ways; carbonation or the attack of aggressive ions.

accelerated corrosion of reinforcing steel.[2]

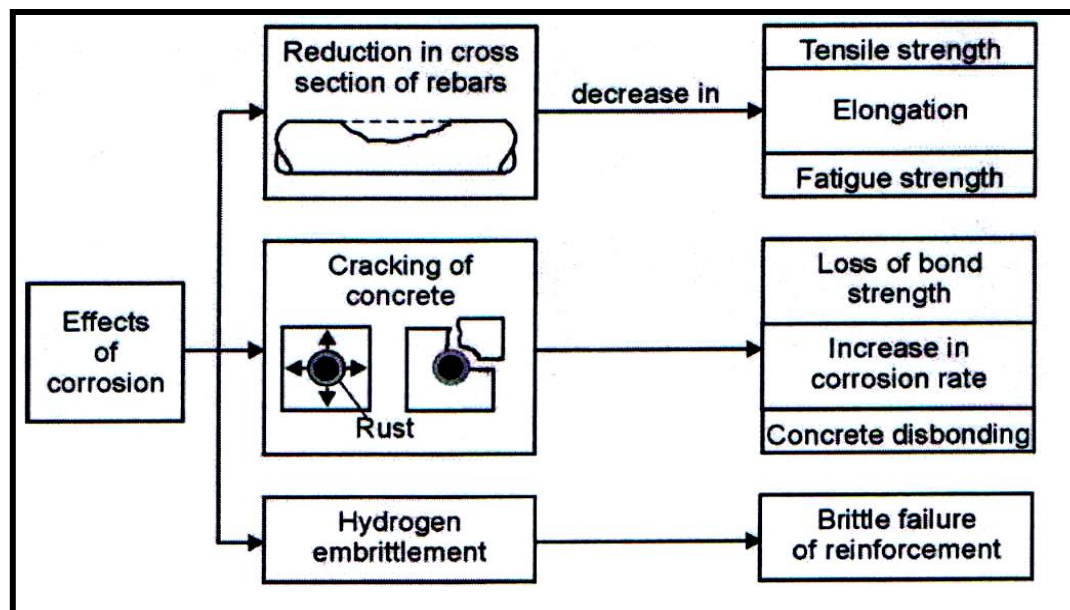


Fig. (2.1) Structural consequences of corrosion in reinforced concrete structure. [6]

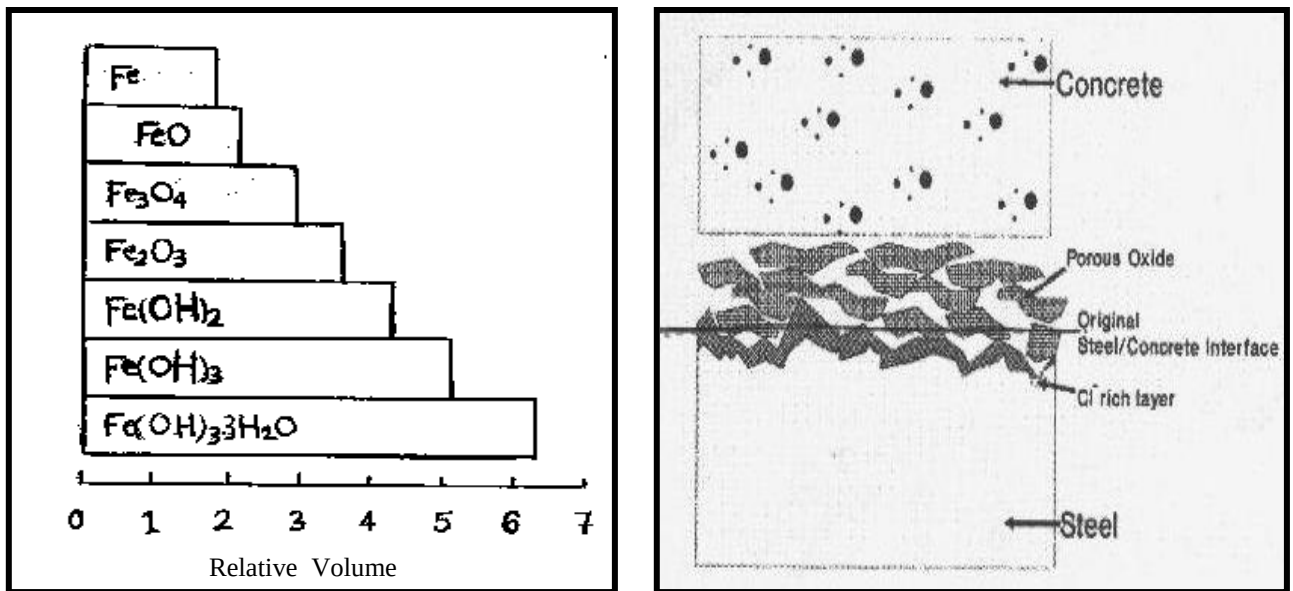
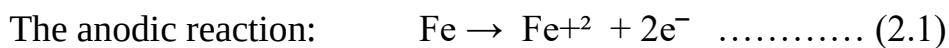


**Fig. (2.2) Increasing in volume of steel due to corrosion. [1,7]**

Contact of the concrete with soil or water containing sulphates can, over time, cause deterioration, increase porosity and decrease the pH of the concrete. In addition to the obvious loss of integrity of the concrete, this degradation may also lead to accelerated corrosion of reinforcing steel.[2]

## 2.2 The Corrosion Process

Once the passive layer breaks down then areas of rust will start appearing on the steel surface. The chemical reactions are the same whether corrosion occurs by chloride attack or carbonation. When steel in concrete corrodes, it dissolves in the pore water and gives up electrons:



The two electrons (2e-) created in the anodic reaction must be consumed elsewhere on the steel surface to preserve electrical neutrality. In other words, it is not possible for large amounts of electrical charge to build up at one place on the steel; another chemical reaction must consume the electrons. This is a reaction that consumes water and oxygen [8]:

The cathode reaction :  $2e^- + H_2O + \frac{1}{2} O_2 \rightarrow 2OH^-$  ..... (2.2)

Hydroxyl ions ( $2OH^-$ ) are generated in the cathodic reaction; These ions increase the local alkalinity and will therefore strengthen the passive layer, warding off the effects of carbonation and chloride ions at the cathode as shown in Figure (2.3) [1].

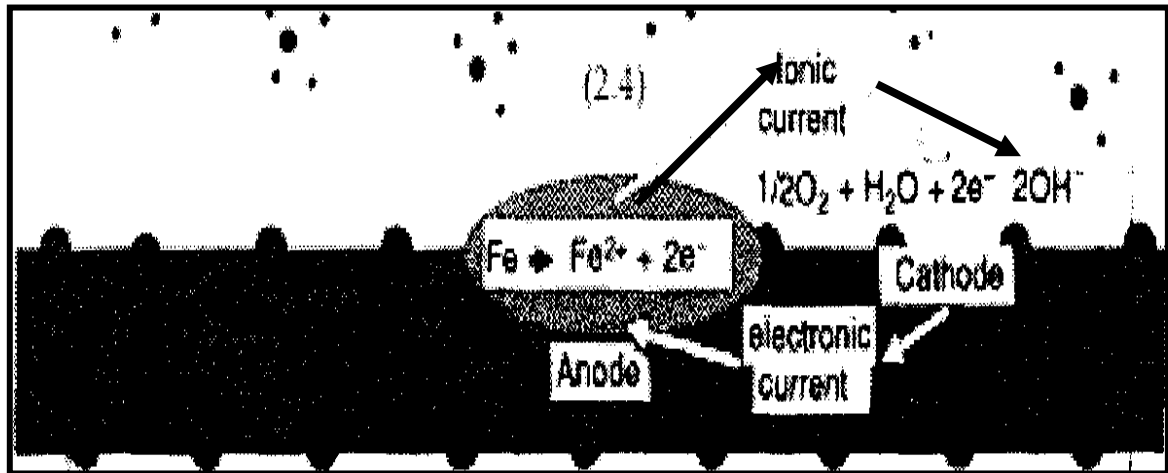
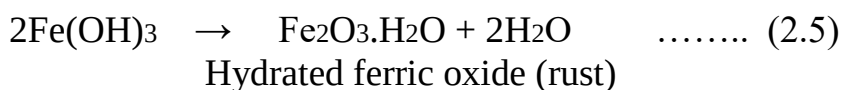
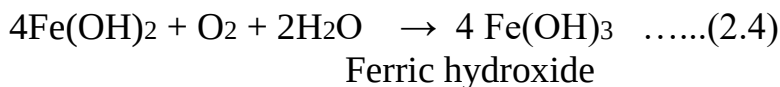
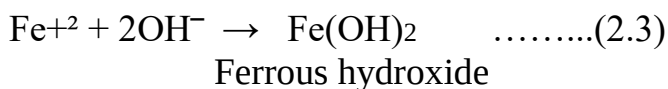


Fig. (2.3) The anodic and cathodic reactions [1].

If the iron is just to dissolve in the pore water (the ferrous ion  $Fe^{+2}$  in equation 2.3 is soluble) cracking and spalling of the concrete can not be seen. Several more stages must occur for rust to form. This can be expressed in several ways; one of which is shown below where ferrous hydroxide becomes ferric hydroxide and then hydrated ferric oxide or rust: [8,10]



Most problems with corrosion of steel in concrete are not due to loss of steel but growth of the oxide that has a volume of about twice to six times that of the steel it replaces when fully dense [6,10]. When it becomes hydrated it swells even more and becomes porous. This means that the volume increases at the steel/concrete interface in two to several times. This leads to the cracking and spalling of the concrete cover that we observe as the usual consequence of corrosion of steel in concrete and the red/brown brittle, flaky rust on the bar and the rust stains seen at cracks in the concrete as shown in Figure (2.4) [1].

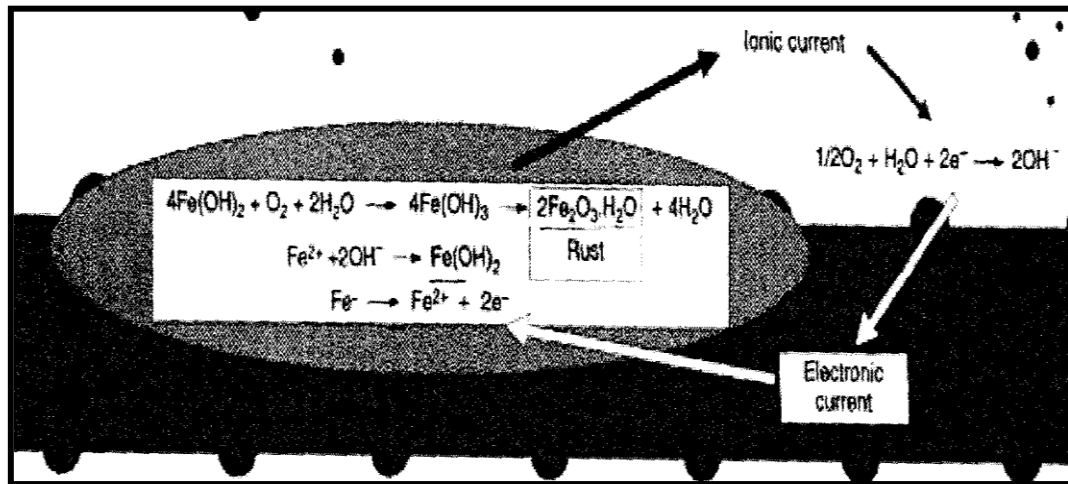


Fig. (2.4) The corrosion reactions on steel [1].

## 2.3 Passivation

Steel in concrete is protected from corrosion by the formation of a passive layer due to the highly alkaline environment (pH 12 -13.8) created by the pore water [5]. The passive layer is a thin and dense layer of iron oxides and hydroxides with some mineral content, that is initially formed as the steel bar is exposed to oxygen and water [11], the oxide layer (corrosion produce) will protect the steel if it is dense which can prevent oxygen and water to reach the steel and continue the oxidation process. Pourbaix diagram for iron in Figure (2.5) shows clearly the passivity and immunity of steel bar [6,12].

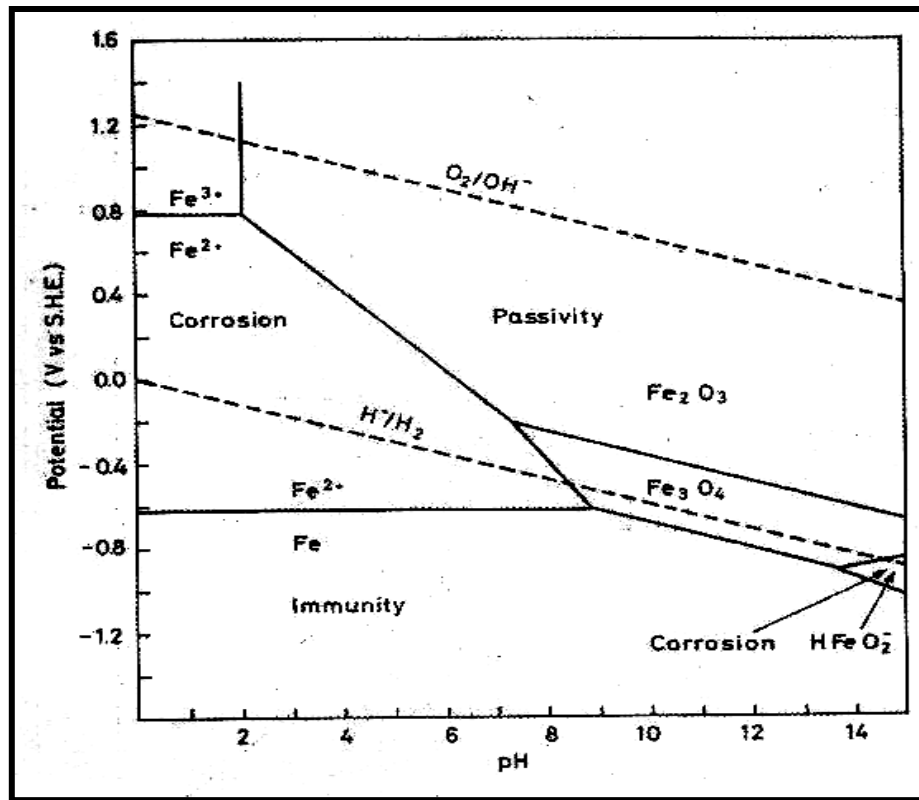


Fig. (2.5) Pourbaix diagram for iron [12]

## 2.4 Causes and Mechanisms of Corrosion

There are two main causes for corrosion of steel in concrete; carbonation and chloride attack. These two causes do not attack the integrity of the concrete but the aggressive chemical species pass through the pores in the concrete and attack the steel [1].

### 2.4.1 Carbonation :

Carbonation is the result of the interaction of carbon dioxide(or sulphur dioxide) gas in the atmosphere with the alkaline hydroxides in the concrete to form the carbonic acid.



Gas    water    Carbonic acid



Carbonic acid Pore solution

Carbonation does not cause any damage to the concrete itself, although it may cause the concrete to shrink but in the case of concrete obtained with Portland cement it may even reduce the porosity and lead to an increased strength, but, it causes reducing in pH value to 8.5 or less and that leads to break the passive film and then corrosion may occur as shown in Figure (2.6) [5,10].

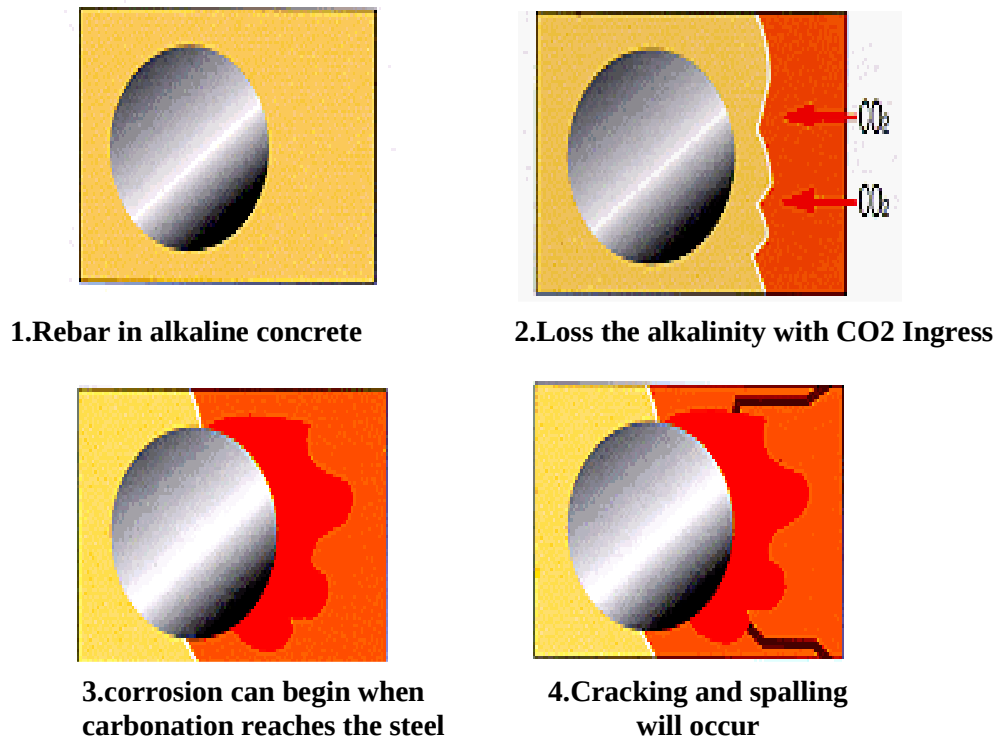


**Fig. (2.6) Steps of carbonation process [13].**

Generally, carbonation is a slow process but it occurs most rapidly when there is little concrete cover over the reinforcement steel, low cement content, high water / cement ratio and poor curing of the concrete, also it is highly dependent on the relative humidity of the environment, highest rate of carbonation occur when the relative humidity is maintained between 50% and 75%, see Figure (2.7)&(2.8) [14].

The average of the depth of carbonation layer rates (20 mm) in 12 years with a max. depth of 32 mm. Generally, the relationship between carbonation layer depth (d) and the exposure time (t) is approximately parabolic in the form:

$$d = A \sqrt{t} \quad \dots (2-8)$$

Where ;

A: constant depends on several variables such as permeability of the concrete, the relative humidity (humidity regions such as those prevailing in the Arabian Gulf seaboard) and the concentration of gas in the service environment. [5,10]

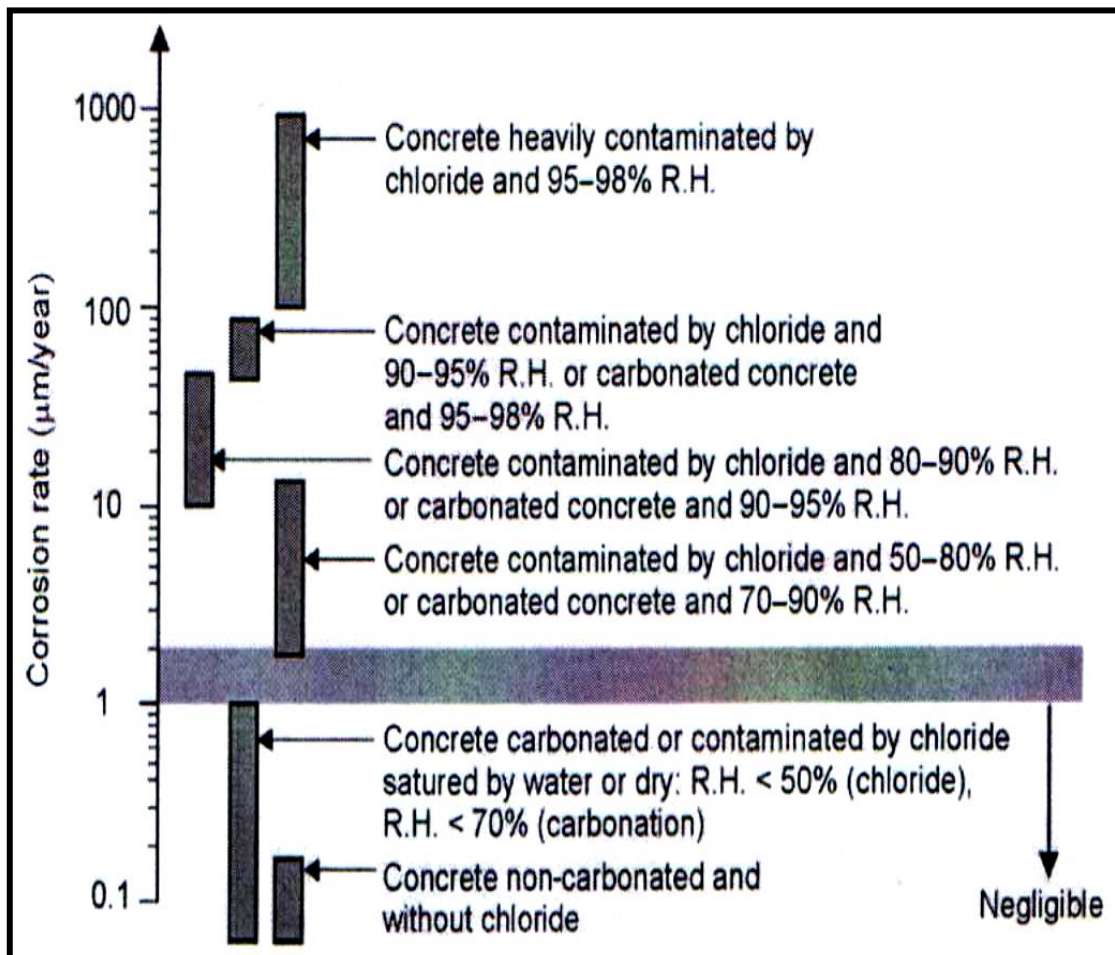


Fig. (2.7) Schematic representation of corrosion rate of steel in different concretes and exposure condition [6].

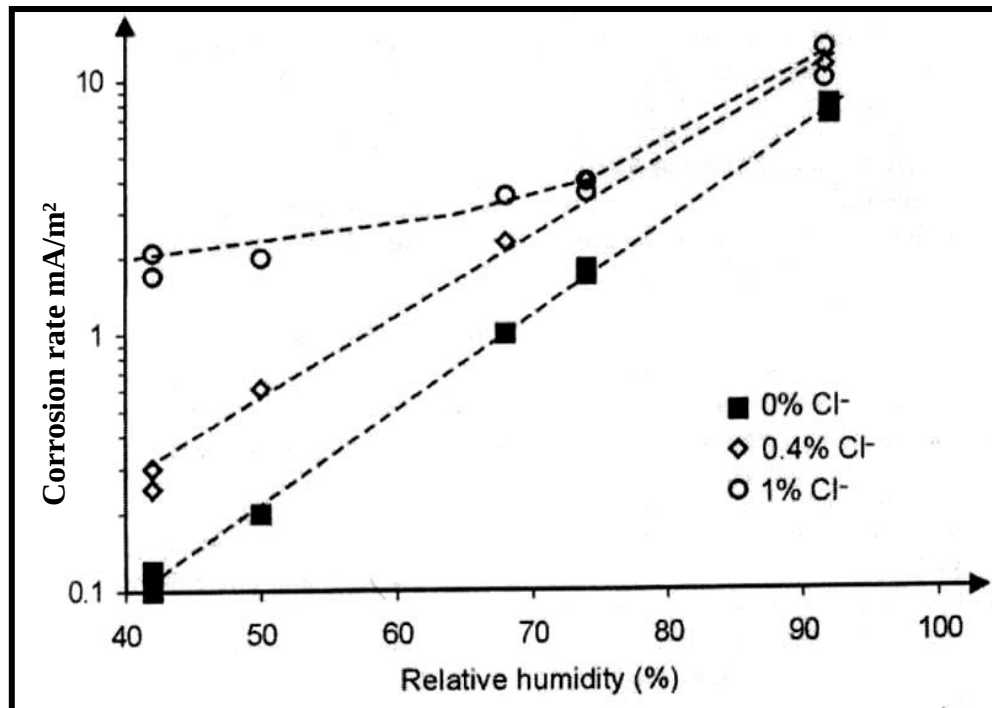


**Fig. (2.8) Relation ship between the relative humidity and corrosion rate in carbonation mortar with and without the presence of chlorides [6]**

### 2.4.2 Chloride Attack

The passivity provided by the alkaline conditions can also be destroyed by the presence of chloride ions, even through a high level of alkalinity remains in the concrete. The chloride ion can locally depassivate the metal and promote active metal dissolution. [6]

Chloride reacts with the calcium aluminates (C3A) and calcium aluminoferrite (C4AF) in the concrete to form insoluble calcium chloroaluminates and calcium chloroferrites in which the chloride is bond in non-active form; however, the reaction is never complete and some active soluble chloride always remains in equilibrium in the aqueous phase in the concrete. At the low concentration levels of chloride in the aqueous phase, the rate of corrosion is very small, but higher concentration increases the risks of corrosion [5]. Thus the amount of chloride in the concrete and, in turn, the amount of free chloride in the aqueous phase (which

is partly a function of cement content and also of the cement type) will influence the risk of corrosion.

While the concrete remains in uncarbonated state the level of free chloride in the aqueous phase remains low (perhaps 10% of the total Cl). However, the influence of severe carbonation is to break down the hydrated cement phase and, in the case of chloroaluminates, the effect is to release chloride. Thus more free chloride is available in carbonated concrete than in uncarbonated materials [14].

Intrusion of chloride ions ( $\text{Cl}^-$ ) in reinforced concrete can cause corrosion if oxygen and moisture are present and that giving low electrical resistance in the concrete and easy transport of ions so the anodes and cathodes can separate easily [1] (there is no corrosion in dry concrete even in high concentration of  $\text{Cl}^-$ ) [4,15].

There are several sources of chloride in concrete:

1. Deliberate addition of chloride set accelerators (calcium chloride ( $\text{CaCl}_2$ ) was widely used until the mid of 1970).
2. Use of sea water in the concrete mix.
3. Contaminated sea aggregates.[5]

According to the European standard EN 206, the maximum allowed chloride contents are 0.2 - 0.4% chloride ions by mass of binder for reinforced concrete and 0.1 - 0.2% for prestressed concrete [1].

The level of chloride ions required to initiate corrosion in concrete corresponds to 0.1% soluble chloride ion by weight of cement. This is equivalent to between 0.6 - 0.8 Kg of chloride per  $\text{m}^3$  of concrete [16].

According to the ACI table 2.1 shows the chloride limits for new construction [15]. And table 2.2 shows chloride concentration in reinforced concrete and classification degree of corrosion [2].

Figure (2.9) shows the percent of probability of corrosion rate with construction of chlorides.

Table 2.1 Chloride limits for new construction [15].

| Category                             | Chloride limit for new construction as a percentage of concrete mass |                              |
|--------------------------------------|----------------------------------------------------------------------|------------------------------|
|                                      | Acid –soluble<br>ASTM C1152                                          | Water –soluble<br>ASTM C1218 |
| Prestressed concrete                 | 0.08                                                                 | 0.06                         |
| Reinforced concrete in wet condition | 0.10                                                                 | 0.08                         |
| Reinforced concrete in dry condition | 0.20                                                                 | 0.15                         |

Table 2.2 Chloride concentration in reinforced concrete [2].

| Cl <sup>-</sup> concentration<br>Kg/m <sup>3</sup> | Cl <sup>-</sup> concentration<br>lb/yd <sup>3</sup> | Assumed condition         |
|----------------------------------------------------|-----------------------------------------------------|---------------------------|
| 0 to 0.7                                           | 0 to 1.2                                            | Passive (non- corroding ) |
| 0.9 to 1.8                                         | 1.2 to 3.0                                          | Corrosion initiation      |
| > 1.8                                              | >3.0                                                | Active corrosion          |

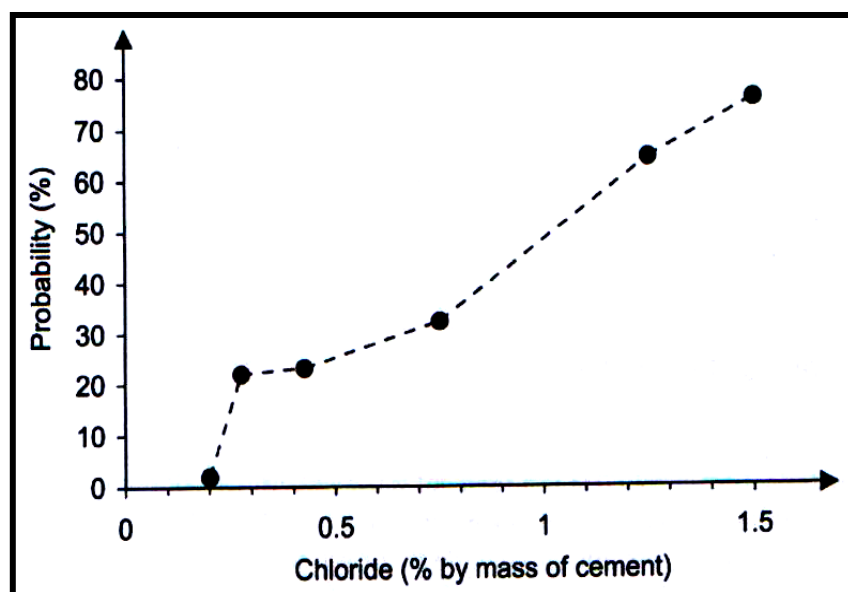


Fig. (2.9) Relationship between chloride content found in bridge decks and percentage of reinforcement showing corrosion [6].

There is a ‘chloride threshold ‘ for corrosion given in terms of the chloride /hydroxyl ratio. When the chloride concentration exceeds 0.6 of the hydroxyl concentration, corrosion is observed. This approximates to a concentration of 0.4% chloride by weight of cement cast into concrete [1, 5].

### **2.4.3 Stray Current induced Corrosion**

The main cause of stray current induced corrosion is the direct current flowing through reinforcing steel due to DC traction systems on trams and electric trains. When current has to jump from one metal conductor to another through an ionic medium (from one reinforcement cage to another via the concrete pore solution ), then one end becomes negative (a cathode, while the other end becomes an anode and corrodes). Stray current induced corrosion does not occur on AC system. To protect the steel against corrosion by stray current, cathodic protection must be used and electrical insulation to avoid current [1,17].

### **2.4.4 Vertical and Horizontal Cracks and Corrosion**

The seriousness of vertical cracks are in accelerating corrosion by allowing access of corrosion agents into the steel surface. If reinforcing steel is doing its job in areas of tension in structure, small cracks will occur when the tensile load exceeds the tensile strength of steel. Most of these are small cracks (less than 0.5 mm) intersecting the reinforcing steel at right angles. They do not lead to corrosion of the steel as any local ingress of chlorides, moisture and carbonation is limited and contained by the local alkalinity [18].

If large cracks (greater than 0.5 mm) stay open the corrosion can be accelerated. Such cracks may be due to plastic shrinkage, thermal expansion or other reasons. Corrosion causes horizontal cracking along the plane of the rebar and the corner cracking around the end rebar. This leads to the loss of concrete cover as shown in Figure (2.10) [1,6].

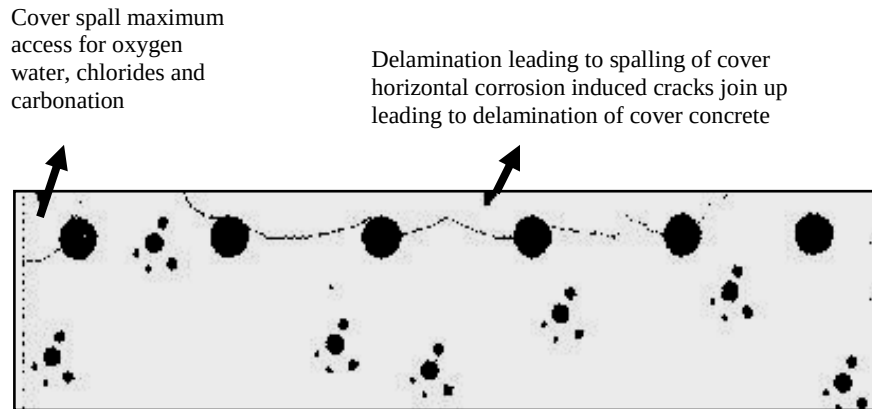


**Fig.( 2.10) Corrosion induced cracking and spalling .[1]**

#### 2.4.5 Thickness of The Concrete Cover

The thickness of concrete cover over the steel should be as large as possible, consistent with good structural design, the severity of the service environment, and cost. The effect of the cover thickness is more than a simple linear relationship. Considering the normal diffusion of an electrolyte into a porous solid without chemical reaction. In the case of cement paste, the diffusion of chloride ions into the paste is accompanied by both physical absorption and chemical binding. These effects reduce the concentration of chloride ion at any particular site and hence the tendency for inward diffusion is further reduced; this is illustrated in Figure (2.11) [1,14] .

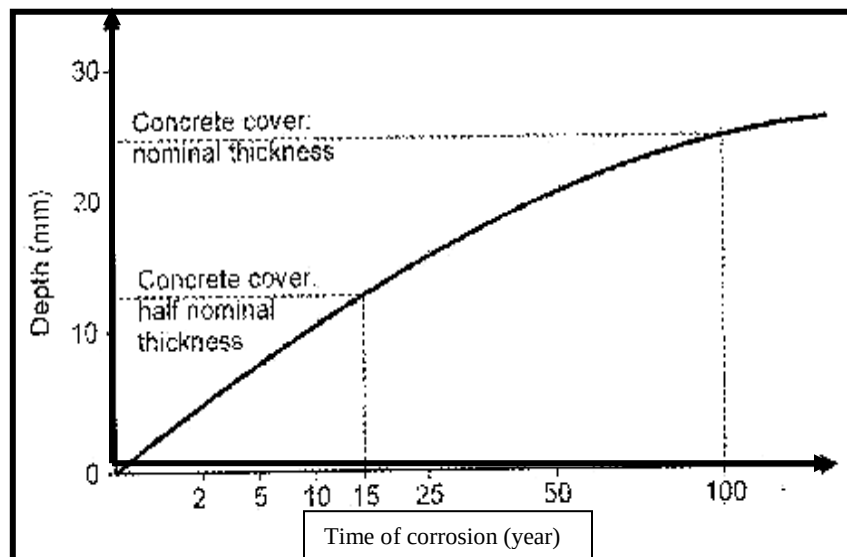


**Fig. (2.11) Reduction of the initiation time of corrosion due to local reductions in the thickness of the concrete cover.**

## 2.5 Initiation and Propagation of Corrosion

The service life of reinforced concrete can be divided into two distinct phases that are shown in Figure (2.12). The first phase is the initiation of corrosion, in which the reinforcement is passive but some phenomena, that can lead to loss of passivity, e.g. carbonation or chloride penetration in the concrete cover, take place. The second phase is propagation of corrosion that begins when the steel is depassivated and finishes when a limiting state is reached beyond which consequences of corrosion cannot be further tolerated. [19,20]

Propagation phase: break down of the protective layer is the necessary prerequisite for the initiation of corrosion. Once this layer is destroyed, corrosion will occur only if water and oxygen are present on the surface of the reinforcement. The corrosion rate determines the time it takes to reach the minimally acceptable state of the structure but this rate can vary considerably depending on temperature and humidity [6]. Carbonation of concrete leads to complete dissolution of the protective layer. Chloride, instead causes localized break down, unless it is present in very large amounts. Therefore:

- \* Corrosion induced by carbonation can take place on the whole surface of steel in contact with carbonated concrete (general corrosion );
- \* Corrosion by chloride is localized (pitting corrosion ), with penetrating attacks of limited area (pits) surrounded by non –corroded areas. Only when high levels of chlorides are present (or the pH decreases ) may the passive film be of a general nature [10].

If depassivation due to carbonation or chlorides occurs only on a part of the reinforcement, a macro cell can develop between corroding bars and those which are still passive. This may increase the rate of attack of the reinforcement that is already corroding [18].

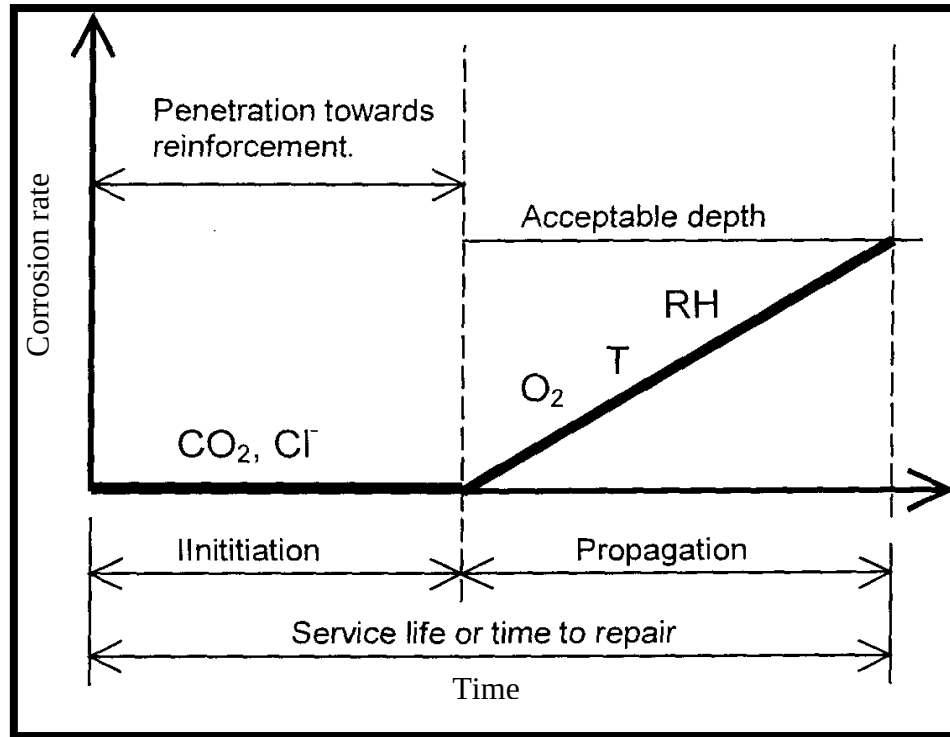


Fig. (2.12) Initiation and Propagation of corrosion [18].

## 2-6 Corrosion Rate

The corrosion rate is usually expressed as the penetration rate and is measured in  $\mu\text{m}/\text{year}$ , or in electrochemical units  $\text{mA}/\text{m}^2$  or  $\mu\text{A}/\text{cm}^2$  or in  $\text{kg}/\text{sec}.\text{m}^2$ . In the case of steel,  $1 \text{ mA}/\text{m}^2$  or  $10\mu\text{A}/\text{cm}^2$  corresponds to a loss of mass equal to approximately  $90 \text{ g}/\text{m}^2.\text{year}$  [12]. The corrosion rate can be considered negligible if it is below  $2 \mu\text{m}/\text{y}$ , low between 2 and  $5 \mu\text{m}/\text{y}$ , high between 50 and  $100 \mu\text{m}/\text{year}$  and very high for values above  $100 \mu\text{m}/\text{y}$ . And that depending on relative humidity, quality of concrete ,pH value and NaCl concentration as shown in Figure 2.13,2.14 & 2.15 [6].

On structures exposed to the atmosphere, the corrosion rate can vary from several tens of  $\mu\text{m}/\text{y}$  to localized values of  $1 \text{ mm}/\text{year}$  as the relative humidity rises from 70% to 95% and the chloride content increases from 1% by mass of cement to higher values. These high corrosion rates have been observed in particular on heavily chloride containing structures such as bridge decks, retaining walls and pillars [15].

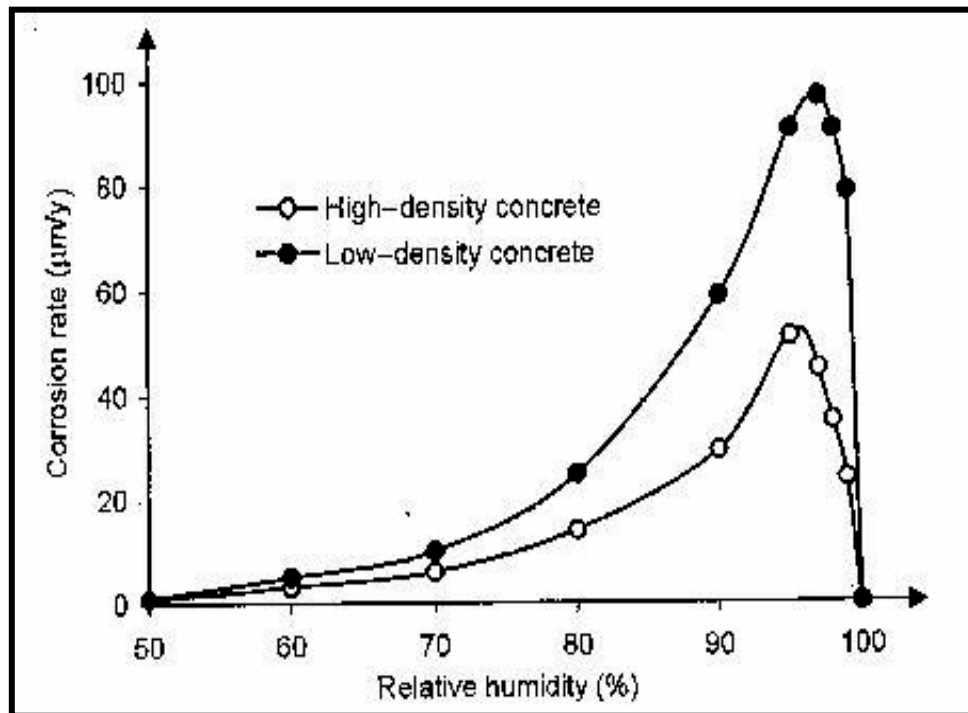


Fig. (2.13) Corrosion rate as a function of external relative humidity in case of initiation due to chloride for concrete with low and high density .[6]

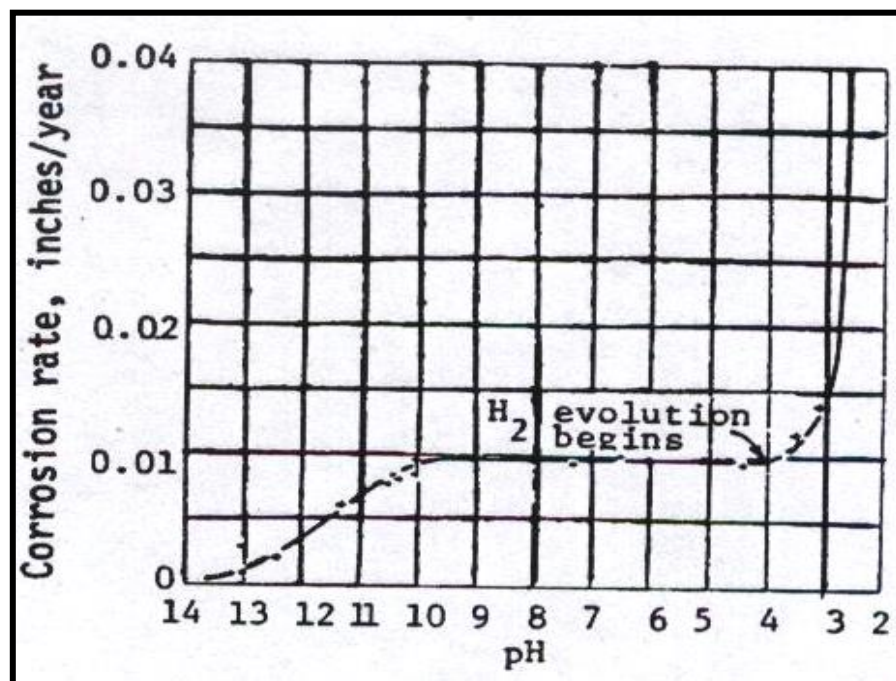


Fig. (2.14) Effect of pH on corrosion of iron in aerated Soft water at room temperature [15].

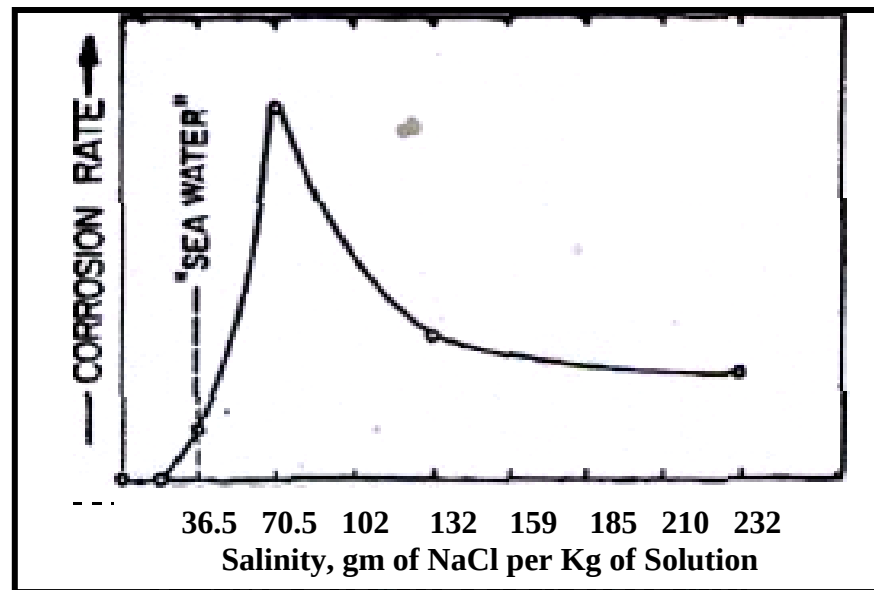


Fig. (2.15) Effect of concentration of sodium chloride on corrosion rate [15].

## 2.7 Polarization

Polarization curve is the rate at which the anodic or the cathodic process take place depending on the potential  $[E]$ . The corrosion behavior of the reinforcement can be described by means of polarization curves that relate the potential and the anodic or cathodic current density [6]. From the cathodic and anodic polarization curves the conditions of corrosion of reinforcement in various situations can be determined.

The corrosion potential of passive reinforcement  $[E_{corr}]$  is determined by the availability of oxygen at the surface of the rebars [12]. The maximum and the minimum values of potential taken on by passive reinforcement under different environmental conditions are; respectively, +100 mv in aerated concrete, and -1 v in the absence of oxygen. This means that in concrete the reinforcement does not reach the conditions of immunity nor of Trans passivity, unless it is polarized by imposing an external current [6,10]. Figure (2.16) shows the anodic polarization curve of steel in non carbonated concrete without chlorides.

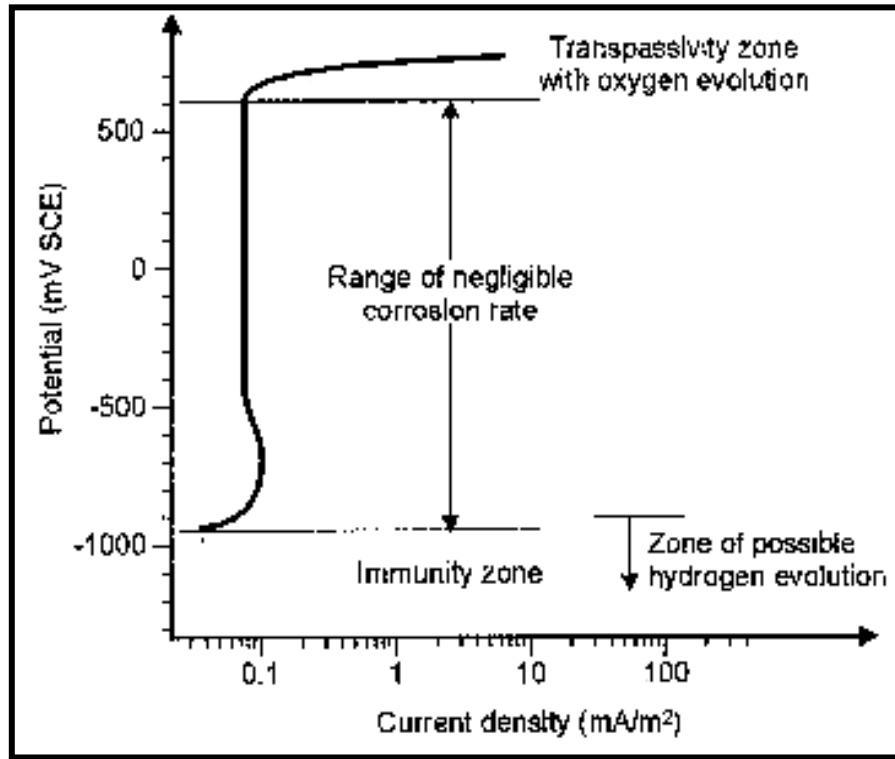


**Fig.(2.16) Schematic anodic polarization curve of steel in non carbonated concrete without chlorides [6].**

### 2.7.1 Linear Polarization Resistance

Corrosion is an electrochemical process so that it can be studied by using electrochemical techniques. The linear Polarization Resistance (LPR) technique, introduced by Stern and Geary (1957). In generally, a three electrode configuration is used to determine the polarization resistance,  $R_p$ , and hence the corrosion rate. This configuration consists of a working electrode, a counter electrode (Auxiliary electrode) to apply the current, and a reference electrode to control the voltage [21].

A polarization resistance measurement is performed by scanning through a potential range of  $\pm 20$  mV about  $E_{\text{corr}}$ . In this potential range an approximate linear relationship exists between the current and the potential. The slope of this line corresponds to the polarization resistance:

$$R_p = \Delta E / \Delta I \quad \dots(2-9)$$

$R_p$  : polarization resistance ( $\Omega$ )

$\Delta E$ : potential gradient (Volt)

$\Delta I$  : current gradient (Amp.)

The corrosion current ( $I_{corr}$ ) which is a measure of the anodic and cathodic reaction, i.e. the flow of electrons from the anodic to the cathodic site, is related to  $R_p$  through the following stage (Stern and Geary 1957) [10].

### 2.7.2 Stern-Geary Equation

With this widely used technique in corrosion monitoring, the polarization resistance of a material is defined as the slope of the potential-current density ( $\Delta E/\Delta i$ ) curve at the free corrosion potential, yielding the polarization resistance  $R_p$  that can be related (for reactions under activation control) to the corrosion current by the Stern-Geary equation [8]:

$$R_p = \frac{B}{I_{corr}} = \frac{(\Delta E)}{(\Delta i)} \quad \text{..(2-10)}$$

$$B = \beta_a \cdot \beta_c / 2.3 (\beta_a + \beta_c) \quad \text{....(2-11)}$$

Where:  $R_p$  : the polarization resistance

$i_{corr}$ : the corrosion current

The proportionality constant,  $B$ , for a particular system can be determined empirically (calibrated from separate weight loss measurements) or, as shown by Stern and Geary, can be calculated from  $\beta_a$  and  $\beta_c$ , the slopes of the anodic and cathodic Tafel slopes [8].

## 2.8 Effects of the Concrete Environment on Corrosion

When Portland cement hydrates, the silicates (C2S and C3S) react with water to produce calcium silicate hydrate and calcium hydroxide as in the following equations:



Differences in the types of cement are a result of variation in composition or fineness or both, not all types of cement have the same ability to provide protection for embedded steel [1].

The main form of binding of the chloride ions is by reaction with C3A to form calcium chloroaluminate,  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$ . A similar reaction with C4AF results in calcium chloroferrite,  $3\text{CaO} \cdot \text{Fe}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$ . It follows that more chloride ions are bound when the C3A content of the cement is higher, and also when the cement content of the mix is higher. For this reason, it used to be thought that cements with a high C3A content are conducive to good resistance to corrosion. This may be true when chloride ions are presented at the time of mixing because they can rapidly react with C3A. However, when chloride ions ingress into concrete, a smaller amount of chloroaluminate is formed and they may become dissociated, releasing chloride ions so as to replenish those removed from the pore water by transport to the surface of the steel.

In the case of cement containing ground granulated blast furnace slag, it has been suggested that binding of chlorides takes place also by the aluminates in the slag, but this has not been fully confirmed. In connection with a possible use of cement with a high C3A content, a high C3A content results in a higher early rate of heat evolution, and therefore temperature rise. This behavior can be harmful in moderately large concrete mass often associated with structures exposed to the sea.

Chloride ions in concrete made with high-alumina cement lead to a more aggressive situation than with Portland cement, the comparison being made at the same chloride ion content. It can be recalled that the pH value in high-alumina cement concrete is lower than with Portland cement so that the passive state of the steel may be less stable [22].

According to Weise in 1961[23], a well hydrated Portland cement may contain from (15 to 30)% calcium hydroxide by weight of original cement that keep the solution at a pH about 13 in the concrete independent of moisture content. No reactions have been detected between chloride ions and silicates ( $C_2S$  &  $C_3S$ ) [23].

Portland cement also contains  $C_3A$  &  $C_4AF$ .  $C_3A$  reacts rapidly in the cement system to cause flash set unless it is retarded. Calcium sulphate (Gypsum) is used as a retarder, since it forms a coating of ettringite ( $C_3A.3CaSO_4.32H_2O$ ) around the aluminate grains there by reduces their reactivity. Calcium chloride also forms insoluble reaction products the aluminates in cement ( $C_3A.CaCl_2.xH_2O$ ). The rate of formation of this material is slower than that of ettringite. The chloride aluminate complex forms after ettringite and prevents further reactions of sulphate with the remaining aluminates [15].

Rosenqvist in 1961 [15] has described the rapid steel corrosion in a tropical concrete where a pozzolana was added to the Portland cement. Corrosion of the reinforcement occurred shortly after construction was completed. Measurements of pH gave values between 5.7 to 8.5. When the pozzolana was omitted, an increase in pH was obtained and no damage was observed.

Spellman and Stratfull in 1973 [24] showed that a pozzolana did not adversely affect the performance of steel in concrete that was partially immersed in a saturated salt solution in this study the pozzolana was a calcined volcanic tuff that was added to the concrete at dosages of 16% and 32% by weight of the cement.

This means that the protective qualities and mechanism of pozzolanic materials are related to its source or generic type.

Lukas in 1981 [25] studied the effect of different types of cement and w/c ratio with and without the addition of high –range water reducing admixture on chloride diffusion. Reference concrete containing cement content of 350 kg/m<sup>3</sup> and w/c ratio =0.49 was prepared super plasticized concrete was also prepared using 1.75% Melament L10 super plasticizer with the same composition as the reference concrete .In other category, the w/c ratio was reduced to 0.42 and the same quantity of HRWR admixture was used to obtain a high quality low w/c ratio concrete .

Lukas [25] pointed out that the penetrated chloride content decreases with a reduction in w/c ratio. High quality concrete with a w/c ratio has a considerably smaller chloride content than other concrete of the same consistency. Results also demonstrated that super plasticized concrete has a smaller tendency to absorb chloride than untreated concrete of the same w/c ratio.

Rasheeduzzafar et al in 1990 [26], studied the influence of cement type (reflecting particularly the C3A content) on the corrosion of reinforcement and sulfate resistance of concrete. Results indicated that the type I cement (C3A=9.5%) performed 1.7 times better than type V cement (C3A=2.8%) in terms of time of initiation of corrosion. Accelerated sulfate resistance test showed that a 20% micro silica blended with type I cement (C3A=14%) performed 1.4 times better against sulfate attack than a type V Portland cement with 1.88% C3A.

Al- Amoudi et al in 1993 [27] evaluated the relationship between the early age properties, such as compressive strength ,porosity and permeability, and the long term corrosion resistance of control, fly ash, and blast furnace slag cement concretes .Results were evaluated up to 180 days of water curing for compressive strength, porosity, and permeability. The long-term corrosion resistance was

evaluated after 7 years of immersion in 5% NaCl using electrochemical techniques. Results indicated that the rate of corrosion of steel in pozzolana /slag cement concrete specimens were about (1/2 to 1/12) that in control ordinary cement concrete specimens. This indicates that the use of properly characterized pozzolanic materials can lead to significant technological and economic benefits.

Al-Ani in 1995 [28] investigated the effect of stability and compatibility of concrete exposed to the high concentrations of sulphates and chlorides salts on the corrosion of embedded reinforcement bars in concrete cylinder specimens with cement : sand : gravel ratio of 1:1.667 :3.09 were cast at times of vibration of 2, 5, 10, 15, 25 and 60 seconds per layer and with water/cement ratio of 0.34, 0.38, 0.4 and 0.5. The specimens were cured under exposure condition of partial submersion and alternate cycles of wetting and drying.

Results showed that, reinforced concrete specimens with cement content of 375 kg /m<sup>3</sup> and with a concrete cover of 38 mm were inefficient in protecting reinforcement for corrosion if they were poorly compacted or made from water /cement ratio far from the optimum ratio.

Yousif H.A in 1997 [29] ,studied the effect of high range water –reducing admixture (HRWA) and the joint action of Rice husk ash (RHA) and (HRWA) on the strength development, electrical resistance and corrosion behavior of steel in concrete containing various amounts of cementanous materials.

Concrete column samples were prepared and partially submerged in Cl<sup>-</sup>+SO<sub>4</sub><sup>-2</sup> solutions at concentration tended to simulate severely aggressive environment.

Results indicated that the addition of HRWA produced considerable increases in strength and electrical resistance compared to reference concrete and the use of RHA and HRWA can produce additional improvement in these vital characteristics relative to the corresponding HRWA concrete. The study also revealed that the use

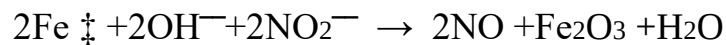
of HRWA resulted in considerable reduction in corrosion activity ,and significantly further improvement was achieved when RHA – HRWA was used .

Baweja et al in 1998 [30] presented results from a five year study on chloride induced corrosion in concrete .

Reinforced concrete slabs (300\*300 mm) having a thickness of 56mm were prepared using four binder materials ,a high C3A Portland cement (PC), a low C3A Portland cement, a slag blended cement containing 35% Ground granulated blast furnace slag (Ggbfs), and a fly ash blended cement containing 25% flay ash. Concrete were cast at nominal w/b ratios of 0.36, 0.45, 0.55 and 0.65. The slump was between 75 and 90 mm. All concrete slabs were immersed partially in a 3% NaCl solution modeling sea water condition.

The results show that ,the low w/b ratio blended cement concrete is most likely to insure optimized performance of concrete in terms of corrosion of steel under high chloride conditions.

Ramasubramanian et al in 2001 [31] studied the corrosion rate on carbon steel rebar samples under different pH condition (9, 12.5) and in presence and absence of chloride ions in solution. They used calcium nitrite in different concentration (0.15, 0.3, 0.75, and 1.2 mole  $\text{Ca}(\text{NO}_2)_2 \cdot \text{H}_2\text{O}$  ) in sever condition of 3.5% NaCl solution for a period of 850 days. The potential that measured with half cell potential for bars that immersed in calcium nitrite were stable because the inhibitor (nitrite) forms the barrier oxide film around the rebars that nitrite undergoes a chemical reaction with the ferrous iron :



And the researchers found that the increasing of concentration of nitrite ions beyond an optimum value dose not provide additional protection.

Kelestemur and Yildiz in 2006 [32] studied the corrosion of reinforced steel in the concrete samples with various concentrations of NaCl and with the addition of

Styrofoam which replaced 15% of the aggregate volume in the concrete structure was investigated. Additionally, the change in the corrosion of steel in the concrete samples with Styrofoam and /or with silica fume 10% in the cement volume was explored. Three groups of concrete samples containing various NaCl concentrations were prepared. In the first group ,the samples were without any additional material, the second group was produced by addition of Styrofoam (15%) and the third group of samples prepared with the addition of Styrofoam plus silica fume (10%). The corrosion rate was measured according to the galvanic current method on the samples. The corrosion potential has been measured by applying the ASTM-C-876-91 method for 90 days and using Cu/CuSO<sub>4</sub> reference electrode. The results indicate that the corrosion rate of steel in concrete samples with Styrofoam increased with the increasing of the portion of NaCl. However, the corrosion rate of steel in the samples decreased with the addition of silica fume.

All that mean the addition of pozzolana: silica fume, fly ash, melamine 10 ,.. that give good quality concrete, low w/c ratio, high cover thickness, low permeability, high compressive strength, in spite of low pH they decrease the corrosion rate.

## **2-9 Electrical Resistance of Concrete**

Electrical resistance: it is the opposition that appeared from any material against electrical current flow.  $E.R (\Omega) = \text{potential (volt)} / \text{current (amp.)}$

The resistivity of concrete is an important factor used to describe the degree of water saturation, the resistance to chloride penetration or the corrosion rate .

The resistivity of concrete may have value from a few tens to many thousand of  $\Omega.m$  , as a function of the water content in the concrete (relative humidity), the type of cement used (Portland or blended cement ), the w/c ratio, the presence of chloride ions or whether the concrete is carbonated or not [14].

At early ages, the resistivity of concrete is low and considerable increases occur due to hydration of the cement. All of these factors can be rationalized on the basis of ions migration in the porous and tortuous concrete microstructure: a high relative humidity increases the amount of water –filled pores (decrease of resistivity ), the w/c ratio and type of cement determine the pore volume and pore size distribution (less but more coarse pores with pure Portland cement; more but finer pores and less interconnectivity of pores with blast furnace slag or fly ash), chloride ions increase the conductivity of the pore solution and carbonation decreases it. An increased resistivity is accompanied by a reduced corrosion rate see Figure (2.17) [6].

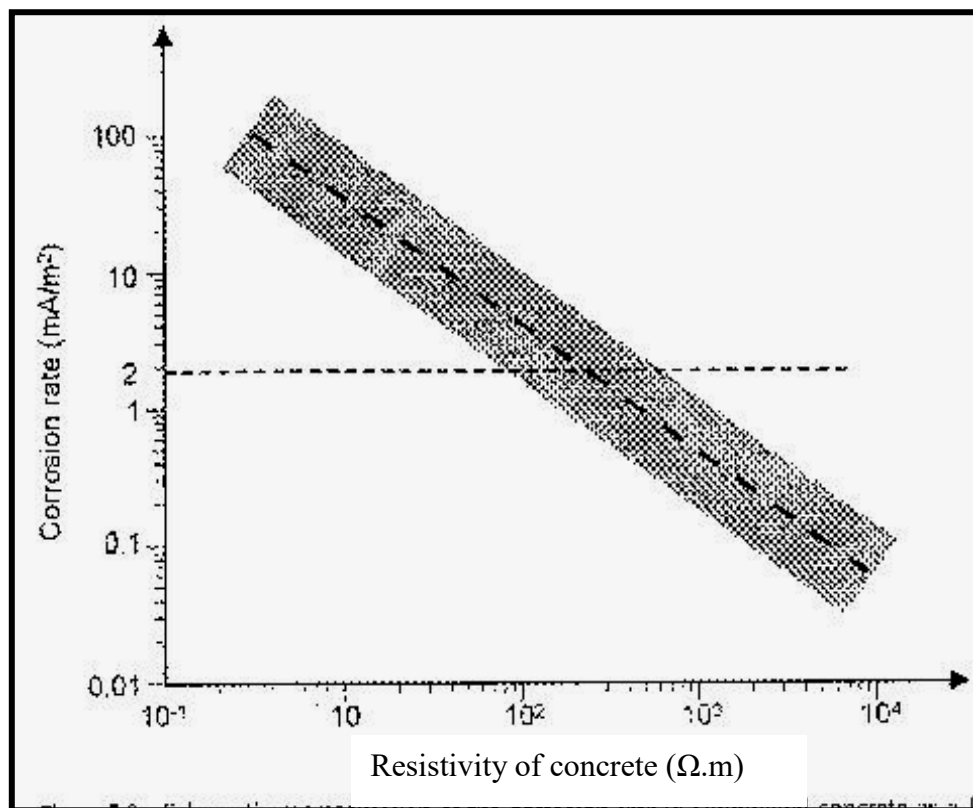


**Fig. (2.17)The relationship between corrosion rate and concrete resistivity.[6]**

Virmani et al in 1983 [33] started an outdoor exposure study to investigate the effectiveness of calcium nitrite as a corrosion inhibiting admixture in reinforced concrete. Thirteen slabs were made containing two mats of black steel bars and

varying amount of admixed chloride and 2.75% calcium nitrite (by weight of cement). Also five control slabs were made containing calcium nitrite .

The reinforcement was evaluated by measuring the macro cell corrosion current , half – cell potential, driving voltage, concrete electrical resistivity, and by visual inspection. Calcium nitrite was found to be effective in reducing the corrosion rate in black steel bars at chloride to nitrite ratio of 1.79 and less. The study determined that at a chloride-to-nitrite ratio of 1.25, it would take at least 10 years for the same amount of iron to be consumed as would be consumed in 1 year in concrete with the same chloride concentration and no inhibitor [33].

After 7 years of observation , the maximum ratio of chloride to nitrite ions necessary to reduce the rate of corrosion in the steel was reduced to 0.90. [34].

These ratios could have been affected by the fact that the chloride ions were added to the concrete at the same time as the calcium nitrite, but the researchers still concluded that protection could be provided by maintaining the ratio of chloride – to-nitrite ions at less than 1.0 at the level of the steel throughout the life of the structure [35].

Bull Mater in 2002 [36] studied the influence of heavy metal oxides on chloride induced corrosion of steel reinforcement in concrete. The researcher found that the using of oxides of zinc, copper, and lead (Metallic Oxide)(Me Ox) may act as inhibitors of chloride induced corrosion. The samples of mortar with reinforced steel were prisms of (20\*20\*80mm),cement: sand ratio was1:3, w/c =0.5, with addition of 4% CaCl<sub>2</sub> and 1% MeOx by weight of cement. These samples were compared with normal concrete samples with only CaCl<sub>2</sub> after curing for a period of 90 days at temp. 20°C and R.H of 95%.

Bull found that this metallic oxide causes :

- Formation of a protective film on the surface of the steel ,formed by the reaction products of (Me Ox) and components of pore solution in the embedded mortar.
- Decrease of the pH value , increase of electrical conductivity.
- He also found that PbO , CuO are the best metallic oxides that can be considered under the corrosion inhibitors admixtures.

Yilmas et al in 2002 [37] investigated the corrosion of reinforcing steel in concrete and the effects of chloride ions, oxygen diffusion and detergent additives of linear alkyl benzene (LAB) and linear alkyl benzene sulfonate (LAS), potentiokinetic experiments were carried out .

Thus, by embedding steel electrodes into concrete specimens with a water/cement ratio of 0.45, current potential curve were obtained and the compressive strength of the specimens was measured.

It was found that the diffusion of chloride and oxygen through concrete and the reduction of oxygen on the metal surface are important parameters controlling reinforcing steel corrosion.

The results were that these additives caused lower in porosity of concrete or block the pores and that help to lower the corrosion rate by reducing diffusion , they also caused an increasing in compressive strength.

## **2.10 Polymer Portland Cement Concrete (PPCC)**

ACI committee 548 [38] reports that the PPCC mixtures are normal Portland cement concrete mixtures to which a water soluble or emulsified polymer has been added. As the concrete cures, hardening of the polymer also occurs, forming a continuous matrix of polymer throughout the concrete.

PPCC is generally prepared by latex materials such as polyvinyl esters or styrene butadiene rubber. The latex modified concrete (LMC) possesses excellent bonding to the steel reinforcement and to old concrete, good ductility, resistance to

penetration by water and salt, and excellent durability under freeze – thaw cycle. PPCC application have included over - layer of bridge decks, parking garages and floors, plus precast operations and patching any concrete surface [39].

- In this research latex modified concrete (LMC) is used as a polymer concrete by adding (SBR).

Emulsion SBR has many advantages:

1. Plasticizing action.
2. Waterproofing action.
3. Improves adhesion.
4. Reduces permeability.
5. Increases mechanical strength.
6. Up-grades chemical resistance.
7. Versatile and easy to use.
8. Cost effective.
9. Improves freeze-thaw resistance.
10. Compatible with many type of cement.[40]

. Al-Tayyip and Al-Zahrani [41] studied in 1990 the effect of adding polypropylene fibers to reinforced concrete structures on corrosion of steel reinforcement. They prepared samples of reinforced concrete with Portland cement type I ,limestone coarse aggregate, with max. size 19mm, deformed steel bars with 12mm in diameter, and portable water with different w/c ratios 0.45, 0.55 and 0.65 with and without polypropylene fibers of 0.2% by volume of concrete. The samples were subjected to severe condition (5% NaCl solution )for a period of more than 7 months.

The results of the electrical resistivity, water absorption and permeability tests did not show any significant improvement due to inclusion of polypropylene fibers ,also they had no noticeable effect in retarding corrosion of steel in concrete.

Folic and Radonjanin in 1998 [42] studied the mechanical properties and determined the optimal curing conditions of (latex dispersion on the basis “ styrene butadiene rubber (SBR)” was used as a cement modified. The researcher used concrete modified with 2.5%, 5% and 7.5% polymer by weigh of cement. Ordinary Portland cement and river aggregate were used with maximum aggregate size of 32mm ,the cement content of all different mixtures was (360 Kg/m<sup>3</sup>).

The results showed that the optimum curing condition were combination of curing in high humidity condition (up to 6 days) and curing in air for 21 days. The compressive strength was slightly increased with increase of the SBR cement – ratio (1%-7.5% by weight of cement) .Tensile strength increased with the increase of polymer - cement ratio. The increase of flexural strength for concrete modified with 7.5% of polymer admixture was 40% above the reference concrete. Shrinkage of the modified concrete with 7.5% of polymer (SBR) admixture on the cement mass was almost 50% less than the shrinkage of reference concrete. And water absorption decrease with the increase of polymer (SBR)-cement ratio.

Al-Bderriy in 2001 [43] investigated the ability of produce high performance polymer concrete by using SBR emulsion, high range water-reducing agent (HRWRA) +SBR emulsion and high range water-reducing agent (HRWRA) only.

The compressive, splitting tensile and flexural strengths, dynamic modulus of elasticity, initial surface absorption, total absorption, porosity, permeability and penetration of sulfate ion tests were investigated for reference, HRWRA, SBR and HRWRA-SBR concretes.

The tests results of Al-Bderriy [44] indicate that the use of 6% super plasticizer by weight of cement leads to produce high efficiency concrete especially with regard to mechanical properties relative to corresponding reference concrete when the specimens were cured in water. But HRWRA concrete exhibited reduction in those properties when the specimens were exposed to salt solution at older ages.

Further HRWRA concrete showed slight improvement drying shrinkage and high reduction in values of durability tests (initial surface absorption, total absorption and porosity) for both specimens cured in water or exposed to salts solution. The using 7% (SBR) emulsion by weight of cement leads to considerable improvement in all mechanical and physical properties of concrete mixes. The compressive strength in 28 days reached 64.4 MPa. While the percentage of reduction in drying shrinkage after drying age of 90 days was 47.2% compared with reference concrete. Also this concrete has high resistance to penetration of sulfate ions and excellent improvement in durability properties.

HRWRA-SBR concretes exhibited superior performance in all tested properties for specimens cured in water exposed to  $\text{Cl}^- + \text{SO}_4^{2-}$  solution. The 28-day compressive strength was 69.3 MPa and the percentage of reduction in drying shrinkage after drying age of 90 days was 52% compared with reference concrete. On the other hand, this concrete showed superior improvement in values of initial surface absorption, total absorption, porosity and penetration of sulfate ions compared with the other concrete mixes.

## **2.11 Corrosion Inhibitors**

Corrosion inhibitors technology has been used around since 1960, but has only been available to the construction industry for the past ten years. Corrosion inhibitors are chemical admixtures when added to concrete mix in very small concentration can be able to prevent or delay the corrosion that happens in reinforcement bars [12]. Corrosion inhibitors are generally used as admixtures in concrete for construction, but they can also be used for repairs by being admixed into concrete for paths, sprayed or painted onto the surface of the concrete or applied by saturation treatment [45].

There is accomplished behavior for inhibitor molecules to penetrate the concrete through cracks and pores and then react with the cement and

reinforcement steel to restore with successfully the passivating film to the steel and extend the useful life of the concrete structure [1].

Corrosion inhibitors are organic or inorganic. Inorganic inhibitors like, potassium dichromate, zinc and lead chromate, sodium benzoate, calcium hypophosphite, and calcium nitrite and organic inhibitors like, sodium cinematic, ethanolamine [46]. In general, they are classified based on their protection mechanism that are added to a water source or other fluids or gases in small amounts to stop or delay corrosion of metals exposed to corrosive environment, they can protect by affecting the anodic reaction or the cathodic reaction or both reaction (mixed) [1, 11].

Inhibitors have been classified in many ways ,including by composition ,mechanism of action or form [5]. According to the mechanism of action inhibitors fall into several classes, Passivation, Precipitators, Vapor phase, Cathodic, Anodic, Neutralizing and absorbents [47].

Organic inhibitors are adsorbed layer formers, which strongly adsorb to the metal surface and interfere with the anodic and cathodic reaction in the area of adsorption. The chemical structure of the inhibitor molecule plays a significant role and often determines whether or not compounds will effectively inhibit a specific system in this study [46].

They also may :

- Increase the anodic or cathodic polarization behavior;
- Reduce the movement or diffusion of ions to the metallic surface, and;
- Increase the electrical resistance of the metallic surface [48].

There are three major concerns regarding the use of corrosion inhibitors. The first one is the long-term stability and performance of the inhibitor. The second is the inhibitor's effect on corrosion propagation after corrosion initiation. The third

is the inhibitor's effect on concrete's physical properties over the service life of the structure. [5].

Currently , there are only a few commercially available corrosion inhibiting admixtures . The most common example of an anodic inhibitor is calcium nitrite which has been commercially available as Darex Corrosion Inhibitor (DCI and DCI-S) since 1978 [49].

Berke in 1989 [50] studied the corrosion inhibiting properties of calcium nitrite ,and he states that calcium nitrite is successfully being used because it provides corrosion inhibition in the presence of chloride ; it is not detrimental to concrete properties ; and it is available in sufficient quantities for commercial use in concrete .

Trepanier in 1994 [51] evaluated the effectiveness of four inhibitors namely, darex/SP/Circler corrosion inhibitor (DCI), Euco corrosion inhibitor, Rheocrete /SP/Circler 222, and NR 1900, in preventing the corrosion of reinforced concrete exposed to external source of chloride ions. Mortar cylinders containing a steel bar were immersed in sodium chloride solution to study the effect of each inhibitor at three dosages and two water/ cement ratios (0.5 and 0.7). Half cell potential test and AC impedance test were used to determine the presence and the severity of corrosion . Parameters such as the time to corrosion, corrosion rate, and electrical resistance were observed for a comparative evaluation of the inhibitors.

Trepanier [51] pointed out that the inhibitors were found to delay the onset of corrosion but they could not prevent it. DCI a calcium nitrite based corrosion inhibitor, was most effective in delaying corrosion . Its performance increases when raising the dosage. Once corrosion began, the corrosion rates were very similar for all cylinders containing the inhibitors. None of the admixtures had a negative impact on the compressive strength of the concrete but the Rheocrete 222 significantly decreased the effectiveness of the air entraining agent .

Trepanier is suggested that the use of higher quality concrete (i.e. lower water/cement ratio and higher concrete cover above the steel reinforcement ), instead of inhibitors, may delay corrosion to the same extent as when corrosion inhibitors are incorporated in a concrete mix of lesser quality.

Hope and Thompason in 1995 [52] found during an investigation on the effectiveness of corrosion inhibitors that, all samples of concrete containing NaCl which were soaked in saturated  $\text{Ca}(\text{NO}_2)_2$  solution undergo severe mortar deterioration. The mortar cracked and bulged without corrosion of reinforcing steel due to the use of corrosion inhibitors.

Qian and Cusson in 2004 [53] studied eight different types of corrosion inhibitors ;sodium benzoate, sodium; potassium and barium nitrite, and chromates/dichromate as concrete admixture. To inhibit corrosion in reinforced concrete bridge decks with epoxy coated rebar and a control span for comparison. This study included rebuilding ten 34 m spans of a concrete barrier wall with w/c ratio of 0.36 and a 28 –day compressive strength of 45 MPa and different concrete cover 13, 25, 38 and 50mm. The bridge structure has experienced harsh climatic conditions over 5 years, temperature (-25 to 30 c°), R.H. (30-100%) and up to 23 freeze – thaw cycles.

The study included measurement of half- cell potential, the corrosion rate and concrete resistivity. All tests were performed in the electrochemical cells composed of three electrodes: a working electrode (steel sample) a counter electrode made of platinum foil of mesh, and saturated calomel reference electrode (SCE,  $\text{Cu}/\text{CuSO}_4$ ). The samples were tested in laboratory was a reinforced steel to a size of 10 mm in length and 8 mm in diameter. Each one was soldered to a copper wire which was isolated from the solution by a glass tube that containing two types of electrolyte a saturated calcium hydroxide  $[\text{Ca}(\text{OH})_2]$  solution (pH=12.6) and a simulated solution containing  $[0.002 \text{ M } \text{Ca}(\text{OH})_2 + 0.45 \text{ M } \text{NaOH}]$

+0.26 M KOH ( pH =13.5) before testing; samples were polished with silicon carbide paper and immersed in the electrolyte solution. Afterward NaCl was added to the cells .Its concentration was increased 0.2% to 0.5% every week to 6% NaCl until corrosion developed [53].

The readings of half –cell potential in the first 2 years were more than -350 mv that means all span should be rated as having a high probability of corrosion. but they were increased after 5 years. The corrosion rates were low in all spans after 5 years although some spans showed relatively high rate in the first and second year that is due to the formation of passive film.

Stephen in 2004 [54] investigated the use of penetrating corrosion inhibitors to extend the life of existing reinforced concrete bridge decks .

The idea of simply applying inhibitors to the concrete surface is appealing. It is critical that the inhibitor not only penetrates the concrete but also reaches the reinforcing steel in sufficient concentrations to inhibit corrosion. They used the vacuum to remove residual moisture from the concrete followed by the application of pressure to inject an inhibitor into the concrete. This technique reduces the corrosion rate by hindering the anodic reaction, the cathodic reaction, or both. The two corrosion inhibitors evaluated were TPS-II and Ferrogard 903.

On September 2002 TPS-II was applied to the bridge decks surface with using the compression sprayer (2 spans were treated and one span remained without treatment as control span).

Measurements included half-cell potential (versus copper- copper sulfate reference electrode [CSE]), corrosion rate (by measuring the polarization resistance), and degree of delamination. Testes were made before and following treatment, after 28 days and 190 days. After one year the study found that the treated spans had a more positive values of half – cell potential than the control

span that means the corrosion rates were reduced and the corrosion inhibitor has a good effect to coat the rebar surface with protective layer.

### 2.11.1 Inhibitor Efficiency

The efficiency of the inhibitor is measured by :

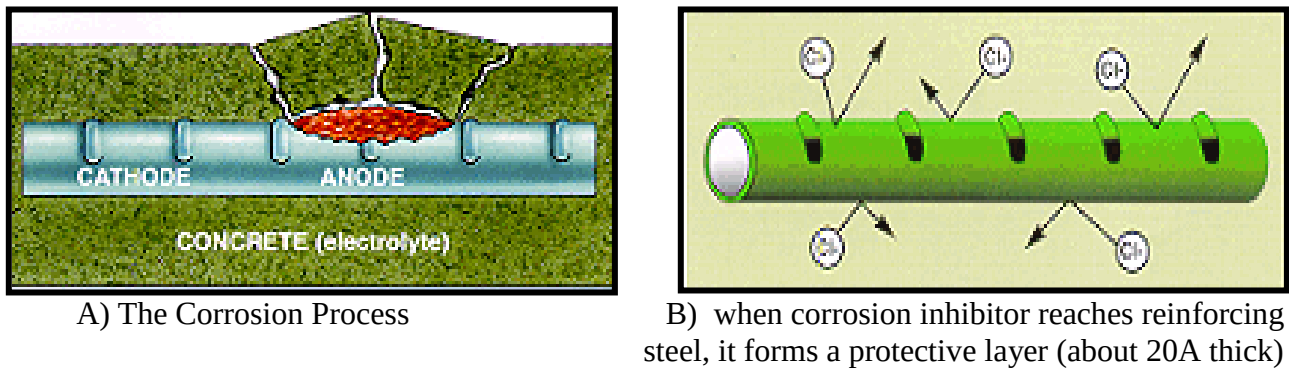
$$\text{Inhibitor Efficiency (\%)} = 100 * (\text{CR}_{\text{uninhibited}} - \text{CR}_{\text{inhibited}}) / \text{CR}_{\text{uninhibited}}$$

where:

$\text{CR}_{\text{uninhibited}}$  = corrosion rate of the uninhibited system

$\text{CR}_{\text{inhibited}}$  = corrosion rate of the inhibited system.

In general, the efficiency of an inhibitor increases with an increase in inhibitor concentration. The available literature allows us to conclude that admixed inhibitors with the correct dosage can strongly delay the onset of chloride –induced corrosion [45].



that protects the steel in anodic or cathodic areas .

**Fig.(2.18) Protection mechanism of corrosion inhibitors [11].**

Limaye et al in 2000 [55] studied the ability of new generation of corrosion inhibitors (CPCI a Concrete–surface applied Penetrating Corrosion–Inhibitor), which is based on bipolar mechanism and which can penetrate even dense concrete by virtue of its vapor pressure and affinity for the embedded steel in concrete. The

inhibitor was used in both as an admixture in fresh concrete and as a coating on hardened concrete.

Cylinder concrete specimens were cast in a split mould of 40mm diameter and 80mm long, with a high yield strength deformed bar of 8mm in diameter embedded into it, with 16 mm cover on all sides including top and bottom. After 28 days of curing the specimens were immersed in (3.5 NaCl solution).

Limaye et al [55] used two types of concrete mix ; weak and strong. The result was that the using of penetrating corrosion inhibitor as admixture to concrete did not impair any mechanical properties or physical properties like workability, water absorption, initial and final setting time and other properties did not show any change, also compressive strength and bond strength showed improvement at ambient temperature and even at higher temperature of 60°C .

The corrosion rate that was measured with half cell potential has an reduction in both weak and strong concrete. However, this effect is more pronounced in weak concrete as compared to stronger concrete grades.

James and Arnine in 2001 [4] tested the activity of calcium nitrite by putting pieces of steel in a container that containing 2% NaCl solution and showing that at the anode, ferrous ions diffuse from the rebar and react with a complex indicator to produce a blue color. At the cathode, oxygen molecules are reduced to hydroxide ions. In the other container they put the same concentration of NaCl with 2% calcium nitrite, and they found no loss of metal or oxygen reaction is observed . That take the same reaction with steel in reinforced concrete.

Bavarian in 2002 [16] investigated the effect of using migrating corrosion inhibitors MCI 2021 and 2022 to protect the steel rebar in concrete against corrosion. Ten concrete specimens with dimension (200\*100\*100 mm) with varying densities (2100, 2250 and 2400 kg/m<sup>3</sup>). Each sample consisted of one steel rebar with 100mm in length and 12.5mm in diameter. With w/c ratio of 0.5, and

cover concrete of 2.5 cm for all samples. Their compressive strength after 28 days of curing was 27 to 30 MPa. The samples were immersed in 3.5 % NaCl solution for a period of 380 days.

The results of test with half –cell potential for samples with MCI 2021 & 2022 inhibitors showed that the corrosion potential was between (-120 to -145 mv ) according to ASTM C 876 that means a 90% probability that no reinforcing steel has corroded (-200 mv or higher ).In the opposite side the samples with out MCI 2021 & 2022 the corrosion potential was between (-400 to -600 mv) and this indicates a 90 % probability of corrosion happened in steel reinforcement (-350 mv or lower ). He also found that MCI 2022 had better corrosion protection than MCI 2021.

The lower density samples coated with MCI inhibitor showed the greatest amount of corrosion resistance, because the MCI migrates into the concrete first by diffusion through moisture that is normally available in concrete, then by its high vapor pressure and finally by following hairline and micro cracks therefore lower density concrete samples provide an easier path for the MCI in ward diffusion , and faster corrosion retardation. That explain the results that Al- Habboubi which will started below.

Al- Habboubi in 2001 [9] studies the effects of using (HRWA), (HRWA) + slag and (HRWA)+ slag + [Ci] corrosion inhibitor (MCI 2005) on the corrosion behavior of steel embedded in high performance concrete. The slag was used as a partial replacement by weight of cement or/and a partial replacement of fine aggregate. The researcher studies the properties of concrete; compressive strength ,electrical resistance, initial surface observation and the corrosion rate of steel in concrete. The reinforced concrete column samples were immersed partially in  $\text{Cl}^-$  +  $\text{SO}_4^{2-}$  solution for a period of 240 days.

Al- Habboubi [9] found that the use of (HRWA)+ slag + [Ci] in concrete could provide adequate corrosion protection to reinforced steel in concrete exposed to aggressive ions but in small different values compared with HPC with(HRWA) + slag and HPC with(HRWA) only. But, it leads to considerable reduction in compressive strength at early ages and that becomes negligible at 180 days of exposure. However, (HRWA)+ slag + [Ci] concrete shows lower initial surface observation and lower CSE potential than those of the corresponding mixes without inhibitor. This admixture (HRWA)+ slag + [Ci] also caused significant reduction in electrical resistance and corrosion rate compared to the reference concrete.

Mogoda and Al-Haleem in 2003 [56] studied the effectiveness of the dichromate salt as a corrosion inhibitor for antimony was more pronounced in  $\text{Na}_2\text{SO}_4$  solution. The rate that anodic oxide film thickened of antimony was found to increase with increasing dichromate concentration in the formation medium and current density and decreased with the increase of temperature.

Jamil et al in 2004 [57] investigated the behavior of amino-alcohol –based inhibitors currently used to prevent (preventive inhibitors) and to control (curative inhibitors) corrosion of steel in concrete, respectively, in the presence of chloride ions. An extract solution was obtained from a cement mix having a water /cement ratio of 0.5 and the pH of the solution was between 12.5 to 13. Sodium chloride was adding in concentration of 1%, 2% and 3% of mix water. The corrosion inhibitors (Ferrogard 901 (preventive inhibitors) and Ferrogard 903 (curative inhibitors)) were added to the solution in the concentration of 4% (v/v), the working electrodes were commercial steel with 1.4cm in diameter.

The scanning vibration electrode technique (SVET) measurements were performed an applicable electronics apparatus , the scanned area was 2mm\*2mm..

The result was that the samples of steel that immersion in solution without any type of inhibitors during first 48h were had strong corrosion activity. After this period the solution was replaced with a new one containing both chloride and corrosion inhibitors. After 2h of replacing the corrosion activity was strongly reduced.

## ***Chapter Three***

### **Experimental Work**

#### **3.1 Introduction**

In this chapter, the details of the experimental program of the study are presented . these include the materials used ,specimens preparation and the tests carried out .

#### **3.2 Materials**

##### **3.2.1 Cement**

Ordinary Portland cement type I locally available was used in this study conforming to the Iraqi specification IQS No.5/1984 [58]. It was kept in laboratory and stored in a dry place. The chemical composition and physical properties of this cement are given in tables 3.1& 3.2 respectively as tested in cement test laboratory/ Babylon University.

##### **3.2.2 Fine aggregate**

Graded sand was used in this study. It was washed and left in laboratory to dry and brought from Al-Akhader - Karbalaa. Table 3.3 shows the sieve analysis ,Mud % , SO3 % and Fineness modulus according to IQS 45 :1984specification [59].

##### **3.2.3 Coarse aggregate**

Graded gravel used in this study. It was brought from Al-Nibae -Baghdad with maximum aggregate size 20 mm. It was washed and left in laboratory to dry and table 3.4 shows the sieve analysis, Mud %, SO3 % and limits according to specification for IQS 45:1984 [59].

## 3.2.4 Water

tap water was used throughout this work for both making and curing the specimens .

**Table 3.1 Chemical composition and main compounds of ordinary portland cement**

| Oxide                                        | Content %                 | Limits according to IQS No.5/1984                                    |
|----------------------------------------------|---------------------------|----------------------------------------------------------------------|
| SiO <sub>2</sub>                             | 20.82                     | -----                                                                |
| CaO                                          | 62.45                     | -----                                                                |
| MgO                                          | 1.53                      | <= 5%                                                                |
| Fe <sub>2</sub> O <sub>3</sub>               | 3.60                      | -----                                                                |
| Al <sub>2</sub> O <sub>3</sub>               | 5.46                      | -----                                                                |
| SO <sub>3</sub>                              | 2.41                      | <= 2.5% if C <sub>3</sub> A < 5%<br><= 2.8% if C <sub>3</sub> A > 5% |
| Free lime                                    | 1.23                      | -----                                                                |
| Loss of Ignition                             | 3.05                      | <= 4%                                                                |
| Insoluble Residue                            | 1.10                      | <= 1.5%                                                              |
| L . S . F                                    | 0.88                      | 0.66 – 1.02                                                          |
| <i>Main compounds<br/>(Bogue's equation)</i> | <i>% by wt. of cement</i> |                                                                      |
| C <sub>3</sub> S                             | 42.29                     |                                                                      |
| C <sub>2</sub> S                             | 27.78                     |                                                                      |
| C <sub>3</sub> A                             | 8.38                      |                                                                      |
| C <sub>4</sub> AF                            | 10.95                     |                                                                      |

Table 3.2 Physical characteristics of cement

| Physical properties                                                                                                                                                   | Test results | Limit of Iraqi specification<br>IQS No.5/1984 |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|-----------------------------------------------|
| <ul style="list-style-type: none"> <li>Setting Time, min      Initial</li> <li>                                         Final</li> </ul>                              | 105<br>220   | $\geq 45$ min<br>$\leq 600$ min               |
| <ul style="list-style-type: none"> <li>Fineness (Blain Method) in<br/>cm<sup>2</sup>/gm</li> </ul>                                                                    | 2880         | $\geq 2300$                                   |
| <ul style="list-style-type: none"> <li>Compressive strength :</li> <li>in MPa      at      3 days</li> <li>                                         7 days</li> </ul> | 18.0<br>27.0 | $\geq 15$<br>$\geq 23$                        |

Table 3.3 Sieve analysis and some properties of fine aggregate

| Sieve size<br>(mm)                                                                            | % Passing | Limit of Iraqi Specification<br>No.45/1984 (zone 1) |
|-----------------------------------------------------------------------------------------------|-----------|-----------------------------------------------------|
| 10                                                                                            | 100       | 100                                                 |
| 5                                                                                             | 95        | 90– 100                                             |
| 2.36                                                                                          | 80        | 60 – 95                                             |
| 1.18                                                                                          | 67        | 30 – 70                                             |
| 0.6                                                                                           | 51        | 34 – 75                                             |
| 0.3                                                                                           | 21        | 5 – 20                                              |
| 0.15                                                                                          | 4         | 0 – 10                                              |
| 0.075                                                                                         | 0         | $\leq 5\%$                                          |
| SO <sub>3</sub> % = 0.14 ,      Limit of Iraqi Specification for SO <sub>3</sub> % $\leq 0.5$ |           |                                                     |
| Mud % = 0 ,      F.M= 2.8                                                                     |           |                                                     |

Table (3.4) Sieve analysis for coarse aggregate

| Sieve size<br>(mm)                                                                                                | % Passing | Limit of Iraqi Specification<br>No.45/1984 ,5-20 mm |
|-------------------------------------------------------------------------------------------------------------------|-----------|-----------------------------------------------------|
| 37.5                                                                                                              | 100 %     | 100 %                                               |
| 20                                                                                                                | 100 %     | 95 – 100 %                                          |
| 10                                                                                                                | 35 %      | 30 – 60 %                                           |
| 5                                                                                                                 | 5 %       | 0 – 10 %                                            |
| 2.36                                                                                                              | 0 %       | ----                                                |
| <b>SO<sub>3</sub> % = 0.08 ,      Limit of Iraqi Specification for SO<sub>3</sub> % ≤ 0.1</b><br><b>Mud % = 0</b> |           |                                                     |

### 3.2.5 Admixtures

The freshly –mixed and hardened properties of concrete can be modified by adding liquid or mineral admixtures to the concrete during batching .In this work two types of admixtures according to ASTM C494 [28] were used ;

**1. Corrosion inhibitors.**

**2. Permeability reducer.**

#### 3.2.5.1 Corrosion Inhibitors:

Two type of anodic, inorganic corrosion inhibitors were used :

##### 1. Sodium Benzoate (SB) ( $C_6H_5COONa$ )

The trade name is 71300 Natriumbenzoat, with purity >97%, soft powder material with white color (see Figure 3.1) and it is an anodic, inorganic inhibitors.

(SB) has approximate density of (572.2) kg /m<sup>3</sup>, it was used in three concentrations (1%, 2% and 3% by weight of cement), it was added to mixing water with stirring until diffusing completely then added to the concrete mix. After hardening, the concrete specimens will show on their surfaces a white thin layer which was easy to peel with hand or water as shown in Figure (3.2) .



**Fig. (3.1) Sodium Benzoate admixture**



**Fig. (3.2) ) The white layer on the surface of the concrete specimens due to the using of sodium benzoate admixture .**

## **2. Potassium Dichromate (PD) ( $K_2Cr_2O_7$ )**

The trade mark of Potassium dichromate is REACHIM, with purity 99.8%.

(PD) grains look like sugar grains in size and shape with orange color (see Fig.3.3).

(PD) has approximate density of  $(1281)kg/m^3$ , it was also used in three concentrations (1% ,2% and 3% by weight of cement ), it was added to water mix and stirred until diffusing completely, then added to the concrete mix. After hardening the concrete specimens have a green color due to adding this admixture.



**Fig (3.3) Potassium Dichromate admixture**

### 3.2.5.2 Permeability Reducer

#### Styrene- Butadiene- Rubber (SBR) admixture

SBR is used for concrete repair as bonding additive (bonding old concrete with new concrete) with typical properties as shown in table (3.5).

**Table (3.5) Typical properties of SBR admixture<sup>[40]</sup>**

|                         |                                  |
|-------------------------|----------------------------------|
| <b>Appearance</b>       | Milky white emulsion             |
| <b>Specific gravity</b> | 1.018 gm/cm <sup>3</sup> in 25°C |
| <b>pH</b>               | 9.5                              |
| <b>Packaging</b>        | 5 liter, 25 liter , 200 liter    |
| <b>Shelf life</b>       | 12 months minimum                |
| <b>Fire</b>             | non-flammable                    |
| <b>Solid content</b>    | 30%                              |

The researcher studied the ability of this admixture to delay or stop corrosion of steel in reinforced concrete.

SBR that shown in Fig.(3.4) was used in three concentrations (10%, 15% and 25%) by volume of mixing water [by replaced volume of water with SBR ,  
 $\text{water/cement ratio} = (\text{water} + \text{SBR})/\text{cement ratio}$ ].



**Fig. (3.4) SBR [Styrene – Butadiene –Rubber ] emulsion**

### **3.2.6 Steel Reinforcement**

The steel reinforcement that was used in this work were wires of 0.5 cm in diameter. These wires were cleaned with wetted grinding paper (rough then smooth) then immersed in cleaner liquid (flash liquid ) to remove any rust or deposits on their surface. See table 3.6.

**Table (3.6) Steel reinforcement wires dimensions**

| <b>Diameter of wire ( mm)</b> | <b>Cross section area (mm<sup>2</sup>)</b> | <b>Length of embedded wire In concrete (mm)</b> | <b>Surface area of imbedded wire in concrete (mm<sup>2</sup>)</b> |
|-------------------------------|--------------------------------------------|-------------------------------------------------|-------------------------------------------------------------------|
| <b>5</b>                      | <b>19.64</b>                               | <b>180</b>                                      | <b>2830.53</b>                                                    |



Fig. (3.5) Steel reinforced wires before and after cleaning

### 3.3 Concrete Mixes

Concrete mixes were designed in accordance with the American mix design method (ACI 211) to have a compressive strength 25 MPa at age of 28 days .Ordinary Portland cement concrete mix with cement : sand : gravel ratio of 1 : 1.8 : 2.5 and water / cement ratio of 0.48 was prepared for casting specimens. The materials were mixed by using an electrically driven batch mixer.

Ten types of concrete mixes were prepared throughout this study :

1. Reference concrete mix without any admixture (two mixes).
2. Three concrete mixes containing sodium benzoate (SB) in three concentrations (1%, 2% and 3% by weight of cement ).
3. Three concrete mixes containing potassium dichromate (PD) in three concentrations (1%, 2% and 3% by weight of cement ).
4. Three concrete mixes containing SBR emulsion in three concentrations (10%, 15% and 25% by volume of mixing water), obtaining (water + SBR) /cement ratio =0.48.

Table (3.7) illustrates the proportion of concrete mixtures and some properties of fresh and hardened concrete.

Table (3.7) Illustrates the proportion of concrete mixtures and some properties of fresh and hardened concretes .

| Type of mix           |                          |                         | Slump in<br>mm<br>In 30-40C° | wet density<br>kg/m <sup>3</sup> |
|-----------------------|--------------------------|-------------------------|------------------------------|----------------------------------|
| Symbol of<br>mix      | Type of admixture        | % of adding             |                              |                                  |
| <b>N</b><br>Reference | No adding                | Nil                     | <b>80</b>                    | <b>2410</b>                      |
| <b>SB 1</b>           | Sodium benzoate          | 1% by weight of cement  | <b>80</b>                    | <b>2400</b>                      |
| <b>SB 2</b>           | Sodium benzoate          | 2% by weight of cement  | <b>78</b>                    | <b>2385</b>                      |
| <b>SB 3</b>           | Sodium benzoate          | 3% by weight of cement  | <b>75</b>                    | <b>2380</b>                      |
| <b>PD 1</b>           | Potassium dichromate     | 1% by weight of cement  | <b>78</b>                    | <b>2400</b>                      |
| <b>PD 2</b>           | Potassium dichromate     | 2% by weight of cement  | <b>77</b>                    | <b>2375</b>                      |
| <b>PD 3</b>           | Potassium dichromate     | 3% by weight of cement  | <b>74</b>                    | <b>2475</b>                      |
| <b>SBR 10</b>         | Styrene-Butadiene-Rubber | 10 % by volume of water | <b>50</b>                    | <b>2390</b>                      |
| <b>SBR 15</b>         | Styrene-Butadiene-Rubber | 15 % by volume of water | <b>35</b>                    | <b>2400</b>                      |
| <b>SBR 25</b>         | Styrene-Butadiene-Rubber | 25 % by volume of water | <b>25</b>                    | <b>2405</b>                      |

### **3.4 Mixing of Concrete**

Mixing process was carried out by using 0.1 m<sup>3</sup> pan type mixer for all concrete mixes, the interior surface of the mixer was cleaned and moistened before it was used. The dry constituents of all concrete mixes were initially mixed for 1.5 minutes. Then the required amount of water mixed with required amount of admixture were added to the mixer, and the whole mix constituents were mixed for another 1.5 minutes.

### **3.5 Preparation, Casting and Curing of the Test Specimens**

A(220) specimens were prepared (99 cubes 150\*150mm for compressive strength test, 33 prisms 100\*100\*400mm for flexural strength test, 33 cylinders 100\*200mm for splitting tensile strength test, 33 cubes 100\*100mm for absorption test and 22 reinforced concrete specimens for electrochemical tests).

The molds were thoroughly cleaned and oiled before casting to avoid adhesion with the concrete surface. Casting was conducted for three layers for each concrete specimen and compaction was performed by vibrating table, each layer was vibrated for a sufficient period then the specimens were leveled and covered with polyethylene sheets to prevent moisture evaporation from the concrete surface as well as to prevent plastic shrinkage cracking.

The test specimens were taken out from the molds after 24 hours of casting and then they were completely immersed in tap water for a period of 27 days. That's for specimens of splitting tensile strength test, flexural strength test, absorption test and compressive strength test for 28 days age. The reinforced concrete samples cured in tap water for a period 80-85 days (see Figure 3.6) and then immersed partially in 3.5% NaCl solution for three months.

For safety: when the chemical admixture be used, it must used carefully (get it away from the skin).



**Fig. (3.6) Curing of specimens in tap water**

## **3.6 Concrete Testing**

### **3.6.1 Compressive Strength Test**

The concrete compressive strength was measured with 150 mm cube by using the machine of compressive strength test (CONTROLS –MILANO-ITALY with 200 Ton capacity). The Cubes were removed from the curing water at age of 28, 60 and 90 days. The reported values were the average of three specimens for each age (nine for each mix) [60].

### **3.6.2 Chloride concentration (Cl ions)**

After breaking the cubes of compressive strength that were cured in tap water, samples of broken concrete were tested in environmental laboratory to calculate the Cl concentration in the hardened concrete.

### 3.6.3 Splitting Tensile strength Test

The concrete splitting tensile strength was measured with 100 \*200 mm cylinders by using the machine of compressive strength test according to ASTM C 496-86 [61].

The cylinders were removed from the curing water at age of 28 days.

Splitting tensile strength can be calculated by using the following equation :

$$St = 2P / \pi DL \quad \text{.....(3.1)}$$

Where : **St** : splitting tensile strength (N/mm<sup>2</sup>).

**P**: applied load (N).

**D**: diameter of cylinder (mm).

**L**: length of cylinder (mm) [62].

The reported values were the average measured on three specimens for each mix.

### 3.6.4 Flexural Strength Test

Test of flexural strength was carried out on (100\*100\*400 mm) simply supported prisms with a clear span of 300 mm. The prisms were tested according to arrangement two - point load. The test was performed according to B.S.1881- part 118 – 1989 [62].

The average of three prism specimens was adopted and the specimens were tested at age of 28 days.

Flexural strength can be calculated from the following equation [61]:

$$fs = PL / bd^2 \quad \text{.....(3.2)}$$

Where :

**fs**: flexural strength (N/mm<sup>2</sup>).

**P**: applied load (N).

**L**: effective length (mm).

**b** : width of prism (mm).

**d** : depth of prism (mm).

### 3.6.5 Absorption Test

The concrete absorption was measured on 100 mm cube specimens after 28 days of curing in tap water, these specimens were dried in  $105 \pm 5^\circ\text{C}$  for 72 hours until the weight be constant then the specimens immersed in water for 24 hours [62]. The average result of three specimens was adopted.

The percentage of total absorption was calculated with the following equation :

$$\text{Absorption (\%)} = ( (W2 - W1) / W1 ) * 100 \quad \text{.....(3.3)}$$

Where :

**W1** : the average weight of dry specimens (gm).

**W2** : the average weight of wet specimens (gm).

All these tests were conducted in the materials construction laboratory/ Civil Engineering Department / College of Engineering / Babylon University.

## 3.7 The Mold of Reinforced Concrete Specimen

The details of reinforced concrete specimens with dimensions are shown in Fig. (3.7).

The reinforced concrete specimens were taken out of the curing tap water after 80-85 days instead of 28 days because the delay in preparing the machine that was used to measure the polarization resistance and getting a concrete with low porosity and good hydration. After recording the first electrical resistance and polarization data for each specimens, the specimens were immersed partially in aggressive solution (3.5% NaCl solution see Figure (3.8) for three months, through this period the recording of data were continued.

The three bars of reinforced concrete samples arranged as equal leg triangular with 9 cm leg length as shown in Figure (3.7).

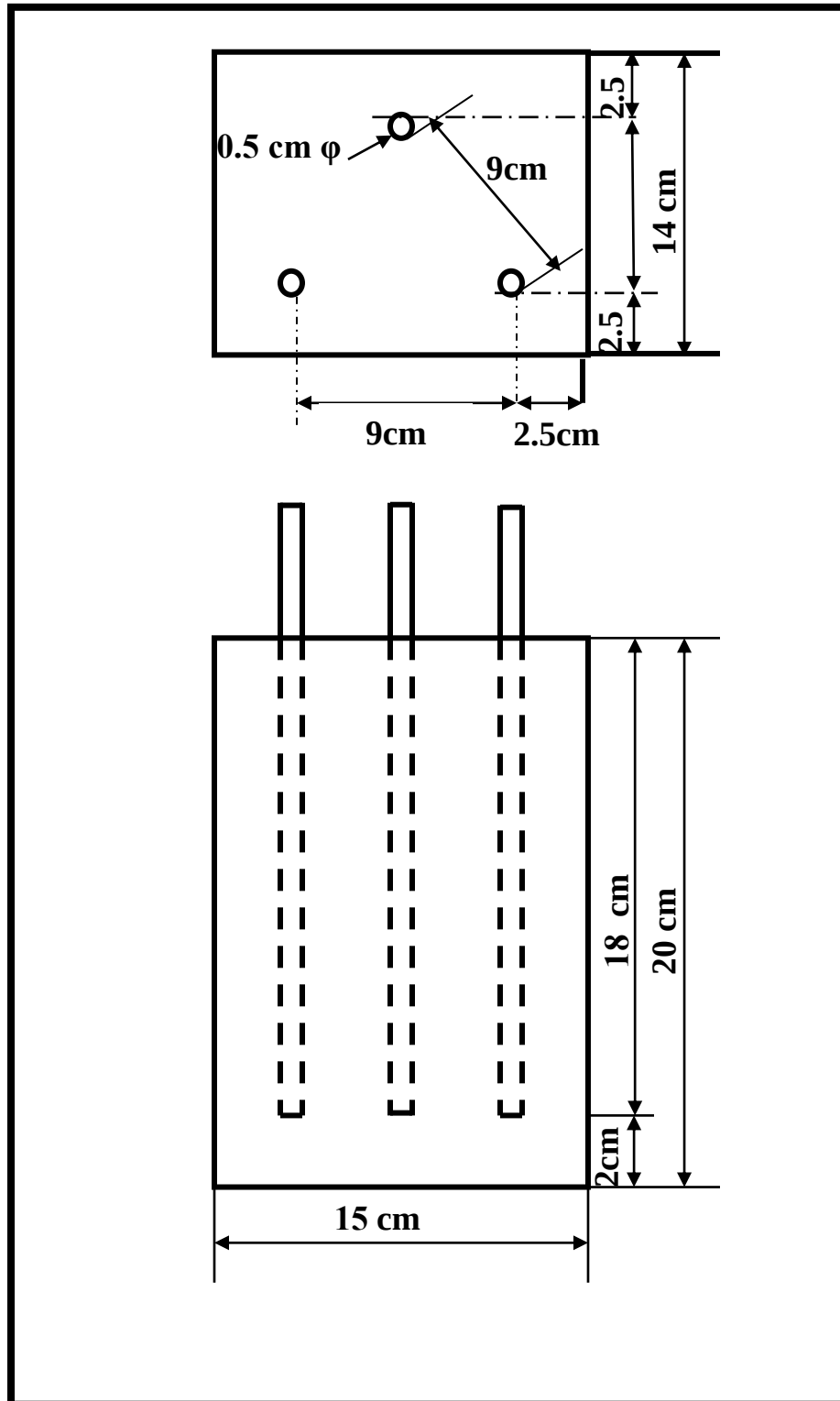


Fig. (3.7) Details of reinforced concrete specimen



**Fig.(3.8) Partial immersing of the reinforced concrete specimens in 3.5%NaCl solution**

### 3.8 Electrochemical Tests

#### 3.8.1 Electrical Resistance Test for Reinforced Concrete Specimens

(140\*150\*200 mm) concrete prisms reinforced with three 5 mm diameter longitudinal wires were cast for this test. see Fig. (3.7 ).

The reinforcement cage is illustrated in Figure (3.9) and (3.10).



**Fig. (3.9) Electrical Resistance Test for specimen with Ohmmeter**

The electrical resistance for the reinforced concrete specimens was measured with using

Ohmmeter machine (MX 553 – Metcix ) digital multimeter by measuring the electrical resistance between each two wires [57] .

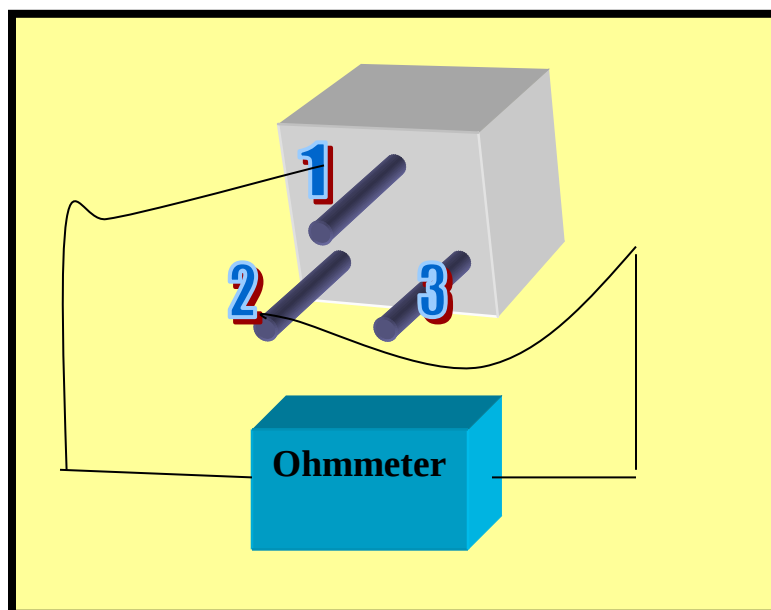


**Fig. (3.10) Diagram of Electrical Resistance Test Circuit.**

The average of three readings was recorded and the reading was in  $K\Omega$  (Kilo Ohm) units. The results of the electrical resistance before and after partial immersing of specimens in [3.5% NaCl solution] for three months were measured and given in Chapter Four .

## 3.8.2 Polarization Resistance of Steel Reinforcement Wires

### 3.8.2.1 Instrumentation

The setup used for polarization measurement (Three electrode method) according to ASTM STP 908 [64] shown in Fig. (3.11) and Fig. (3.12) includes the following parts:

1. Power supply (EIS CO. Low voltage power supply ) D.C Voltage max. 250 v, D.C Amps. max. 4A.
2. Current measuring instrument (MX 553 – Metcix ) digital multimeter.
3. Voltage measuring instrument (MX 553 – Metcix ) digital multimeter.

### 3.8.2.2 Test Procedure

The details of the electrochemical techniques (Three electrode method) according to ASTM STP 908 [64]. **The Working Electrode (W.E)** potential is measured against the reference electrode, provided that an ohmic resistance

gradient is significantly reduced and current flows only between the auxiliary electrode and the working electrode. **The Auxiliary Electrode (A.E)** : It passes current to the working electrode (specimen) to be studied. **The Reference Electrode (R.E)** do not carry the polarizing current[64]. And to calculate linear polarization resistance and corrosion rate the researcher dependent the following:

1. Wire1 is a Reference electrode (R.E).  
Wire2 is a Working electrode (W.E).  
Wire3 is an Auxiliary electrode (A.E).
2. The electrical circuit for polarization and corrosion rate measurement is connected as shown in Fig. (3.11) and (3.12).
3. The following voltages are applied [ -120mv, -90mv, -60mv, 60mv, 90mv and 120mv ] ,In each value of these voltages the current value is recorded .  
The readings are recorded before and after immersing in (3.5% NaCl solution) along three months of immersing.

After six weeks of immersing the reinforced concrete specimens in 3.5% NaCl solution, no corrosion happened in the reference mix (without any admixture) because it was a good quality concrete (high cement content, low water/cement ratio).

To overcome this problem (no corrosion in concrete samples without any adding), 10% of the design load was applied over the half number of the reinforced concrete specimens after 6 weeks of immersing in 3.5 % NaCl solution by compressive strength test machine. This procedure was adopted to make initial micro cracks in the concrete specimens to make a path for chlorides to ingress and reach the steel wires faster that normal time.

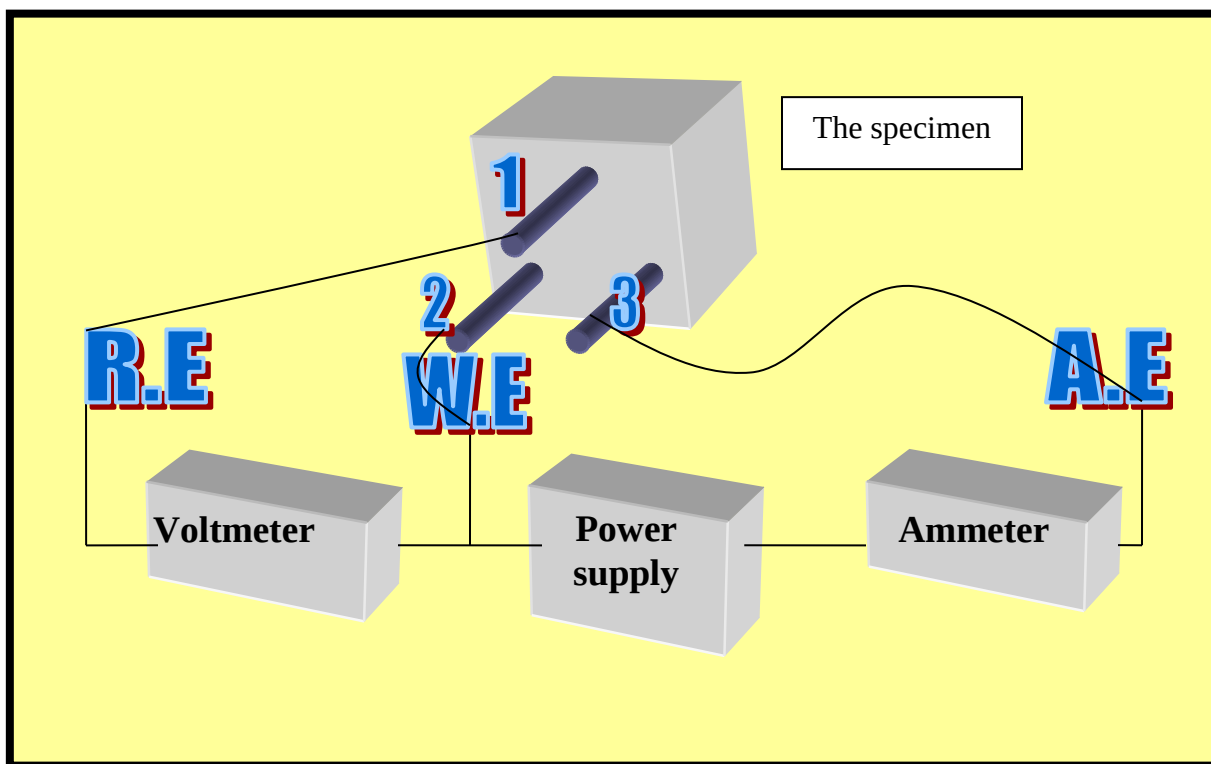


Fig. (3.11) Diagram of Polarization Resistance Test Circuit.



Fig. (3.12) Polarization Resistance Test Circuit.

## **Chapter Four**

### **Results and Discussion**

#### **4.1 Introduction**

In this chapter , the results of the tests described in Chapter Three are presented and discussed. Tests were carried out in laboratory conditions. To summarize the data, only the average values are provided in the tables and figures below.

#### **4.2 Compressive Strength Test**

Table 4.1 shows the results of compressive strength test on 28, 60 and 90 days for each mix. The results were showed that :

**1)** For Sodium Benzoate admixture in conc. (1% by weight of cement) there is no reduction in compressive strength in ages 28 ,60 and 90 days , and the specimens have given results higher than the reference mix (C25) by approximate 12%, 15% and 14% for ages 28 ,60 and 90 days respectively.

The using of Sodium Benzoate as corrosion inhibitor in conc. 2% and 3% by weight of cement affect compressive strength at early ages (28 days) with a considerable reduction 15% for 2% addition. And 11.5% for 3% addition, but in the later ages the specimens have got an increase in compressive strength by about 7% and 17% at age 90 days respectively and that is consistent with Trepanier [49] who used four types of inhibitors in concrete. He states that ‘no one of the admixtures had a negative impact on the compressive strength of the concrete’.

This admixture may be works as a retardar.

**2)** For Potassium Dichromate admixture with conc. of (1% and 2% by weight of cement) compressive strength has got a considerable reduction of 8% and 4% respectively at ages 28 days and obtained a development in compressive strength at ages 60 and 90 days, with an increase 49% and 11% at age of 90 days respectively.

That's may be due to this admixture works as a retardar, it retards the action of C3S or C3A who get the compressive strength at the early ages of the concrete.

For 3% addition of potassium dichromate by weight of cement has improved the compressive strength of 15.4%, 15% and 14% for ages 28 ,60 and 90 days respectively as shown in figure (4.2) These results agree with Trepanier's [49] results mentioned above and Limaye & Angal [53] who used two types of corrosion inhibitors in two types of concrete: strong and weak; they state that "the using of penetrating corrosion inhibitor as admixture to concrete did not impair any mechanical or physical properties also compressive strength and bond strength showed improvement at ambient temperature and even at higher temperature of 60°C".

Concrete specimens with SBR (Styrene - Butadiene -Rubber) admixture (10% by vol. of water) have exhibited a reduction in compressive strength for all ages and that was agree with Folic and Radonjanin [42] who studied the mechanical properties and determined the optimal curing conditions of " styrene butadiene rubber (SBR)" The researcher used concrete modified with 2.5%, 5% and 7.5% polymer by weigh of cement.The results showed that the compressive strength was slightly increased with increase of the SBR cement –ratio (1% - 7.5% by weight of cement). Also these results contradicts with the produces publication [40] .

The concrete specimens with SBR 15% by vol. of water have shown insignificant increase of 4%, 4% and 2% for ages 28, 60 and 90 days respectively, this is agree with Folic and Radonjanin [42] that explain above and disagree with Al-Bderriy [43] who states that 'the using of 7% SBR emulsion by weight of cement (15% SBR by volume of water = 7.2% SBR by weight of cement) leads to a considerable improvement in all mechanical and physical properties of concrete mixes. He records that: the compressive strength in 28 days has given an increase of 34%.

The present work specimens with SBR in 25% conc. by vol. of water have obtained an increase in compressive strength about 8%, 11% and 7% for ages 28, 60, and 90 days respectively.

**Table 4.1 Results of Compressive Strength Test**

| Type of mix                  |                                 |                                | Compressive Strength in MPa |         |         |
|------------------------------|---------------------------------|--------------------------------|-----------------------------|---------|---------|
| Symbol of mix                | Type of admixture               | % of adding                    | 28 days                     | 60 days | 90 days |
| <b>N</b><br><i>Reference</i> | <i>No admixture</i>             | <i>Nil</i>                     | 26                          | 27      | 29      |
| <b>SB 1</b>                  | <i>Sodium benzoate</i>          | <i>1% by weight of cement</i>  | 29                          | 31      | 33      |
| <b>SB 2</b>                  | <i>Sodium benzoate</i>          | <i>2% by weight of cement</i>  | 22                          | 29      | 31      |
| <b>SB 3</b>                  | <i>Sodium benzoate</i>          | <i>3% by weight of cement</i>  | 23                          | 27      | 34      |
| <b>PD 1</b>                  | <i>Potassium dichromate</i>     | <i>1% by weight of cement</i>  | 24                          | 31      | 39      |
| <b>PD 2</b>                  | <i>Potassium dichromate</i>     | <i>2% by weight of cement</i>  | 25                          | 27      | 31      |
| <b>PD 3</b>                  | <i>Potassium dichromate</i>     | <i>3% by weight of cement</i>  | 30                          | 31      | 33      |
| <b>SBR 10</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>10 % by volume of water</i> | 24                          | 25      | 26      |
| <b>SBR 15</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>15 % by volume of water</i> | 27                          | 28      | 29.5    |
| <b>SBR 25</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>25 % by volume of water</i> | 28                          | 30      | 31      |

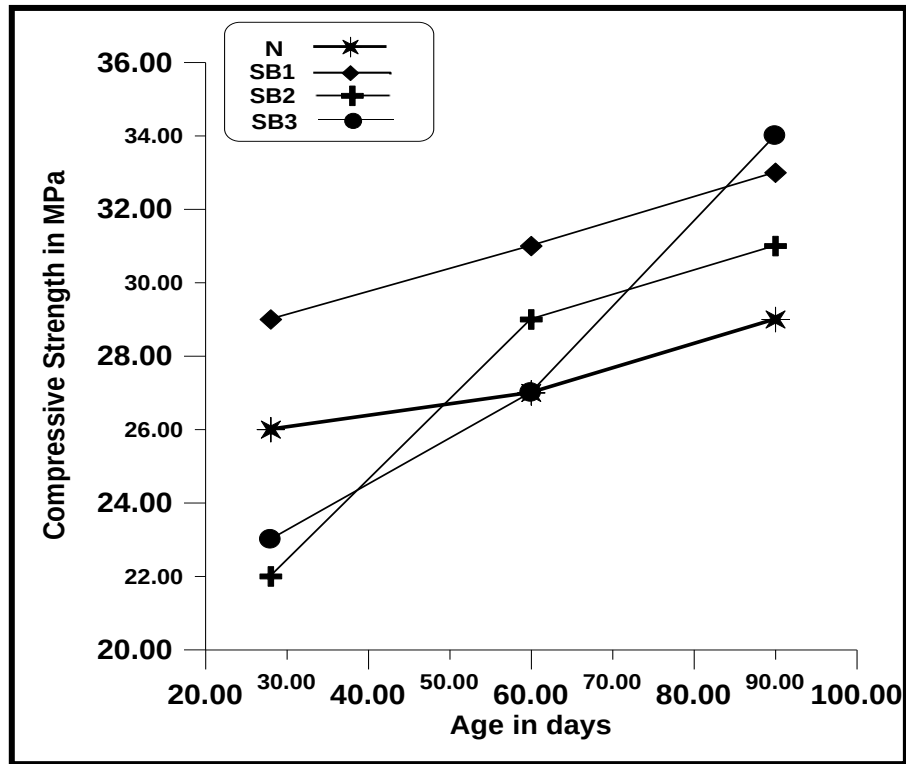


Fig. (4.1) Development of compressive strength with age for mixes with Sodium Benzoate admixture

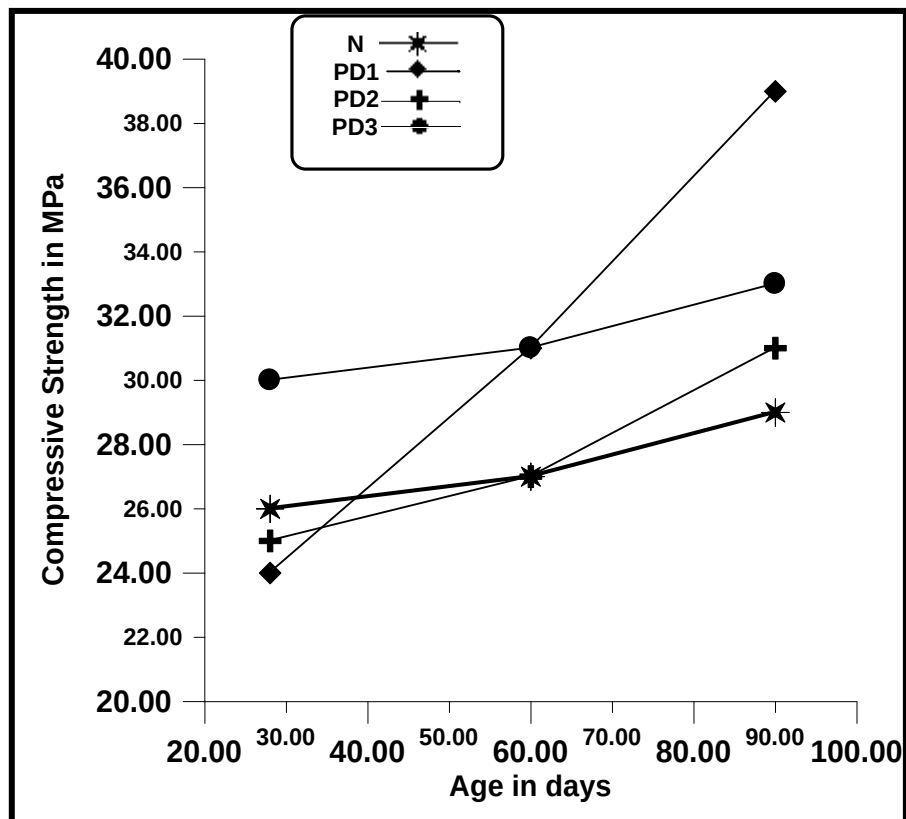


Fig. (4.2) Development of compressive strength with age for mixes with Potassium Dichromate admixture

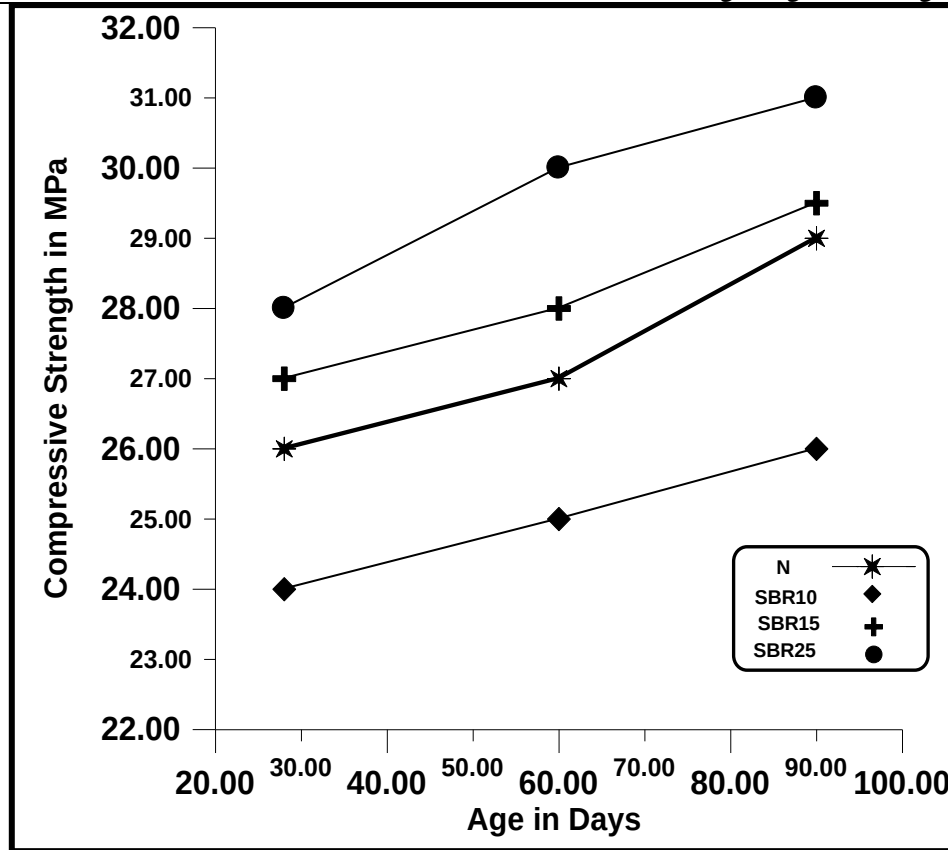


**Fig (4.3) Development of compressive strength with age for mixes with SBR admixture**

### 4.3 Splitting Tensile Strength Test

concrete with different admixtures in different concentrations yield increasing in splitting tensile strength which tested at age of 28 days as compared with the reference mix as shown in table (4.2) and Fig. (4.4).

The concrete with Sodium Benzoate admixture revealed an increase in splitting tensile strength by about 10%, 16.6% and 17% for concrete specimens with 1%, 2% and 3% of admixture by weight of cement respectively.

The concrete with Potassium Dichromate admixture gave an increase in splitting tensile strength by about 15%, 21% and 30% for concrete specimens with 1%, 2% and 3% of admixture by weight of cement respectively.

Results showed an increase in splitting tensile strength with the increase of the percentage adding for the two corrosion inhibitors which used in this study ; and this

agrees with Berke [50] who states that: corrosion inhibitor provides corrosion inhibition in the presence of chloride and improves the concrete properties with increasing the percentage of adding.

And the concrete with SBR admixture recorded an increase with 4%, 22% and 37% for conc. 10%, 15% and 25% by vol. of water respectively, that's because the fact that this admixture used to reduce permeability, porosity, absorption and improved the density of concrete and mechanical properties as recorded in the produces publication [40].

#### **4.4 Flexural Strength Test**

The concrete mixes with different admixtures in different concentrations recorded an increase in values of modulus of rupture as compared with the reference concrete mix as shown in table 4.2 and figure (4.5).

The concrete mixes with Sodium Benzoate admixture exhibited an increase in modulus of rupture by about 13%, 18% and 24% for mixes with conc. of 1%, 2% and 3% by weight of cement respectively.

The concrete mixes with Potassium Dichromate admixture recorded increase with 15%, 20% and 29% concentrations 1%, 2% and 3% by weight of cement respectively.

And the concrete mixes with SBR admixture recorded a little increase with 2%, 20% and with maximum increase of 37% for concentrations 10%, 15% and 25% by vol. of water respectively. Results showed an improvement in flexural strength with the increase of dosage for the three admixture which are used in this study; this agrees with that is found by Berke [50] who states that: corrosion inhibitor provides corrosion inhibition in the presence of chloride and improves the concrete properties with increase the percentage of adding.

**Table 4.2 Results of Splitting, Flexural Strength and Absorption Tests**

| <b>Type of mix</b>           |                                 |                                | <b>Splitting<br/>Tension<br/>MPa</b> | <b>Flexural<br/>Strength<br/>MPa</b> | <b>Absorption<br/>%</b> |
|------------------------------|---------------------------------|--------------------------------|--------------------------------------|--------------------------------------|-------------------------|
| <b>Symbol of<br/>mix</b>     | <b>Type of<br/>admixture</b>    | <b>% of adding</b>             |                                      |                                      |                         |
| <b>N</b><br><i>Reference</i> | <b>No</b><br><i>admixture</i>   | <i>Nil</i>                     | <b>3.00</b>                          | <b>3.1</b>                           | <b>6%</b>               |
| <b>SB 1</b>                  | <i>Sodium benzoate</i>          | <i>1% by weight of cement</i>  | <b>3.3</b>                           | <b>3.5</b>                           | <b>4.2%</b>             |
| <b>SB 2</b>                  | <i>Sodium benzoate</i>          | <i>2% by weight of cement</i>  | <b>3.5</b>                           | <b>3.65</b>                          | <b>3.75%</b>            |
| <b>SB 3</b>                  | <i>Sodium benzoate</i>          | <i>3% by weight of cement</i>  | <b>3.8</b>                           | <b>3.85</b>                          | <b>3.25%</b>            |
| <b>PD 1</b>                  | <i>Potassium dichromate</i>     | <i>1% by weight of cement</i>  | <b>3.45</b>                          | <b>3.55</b>                          | <b>4.0%</b>             |
| <b>PD 2</b>                  | <i>Potassium dichromate</i>     | <i>2% by weight of cement</i>  | <b>3.63</b>                          | <b>3.7</b>                           | <b>3.5%</b>             |
| <b>PD 3</b>                  | <i>Potassium dichromate</i>     | <i>3% by weight of cement</i>  | <b>3.9</b>                           | <b>4.0</b>                           | <b>3.1%</b>             |
| <b>SBR 10</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>10 % by volume of water</i> | <b>3.13</b>                          | <b>3.15</b>                          | <b>3.5%</b>             |
| <b>SBR 15</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>15 % by volume of water</i> | <b>3.65</b>                          | <b>3.7</b>                           | <b>2.3%</b>             |
| <b>SBR 25</b>                | <i>Styrene-Butadiene-Rubber</i> | <i>25 % by volume of water</i> | <b>4.1</b>                           | <b>4.24</b>                          | <b>1.4%</b>             |

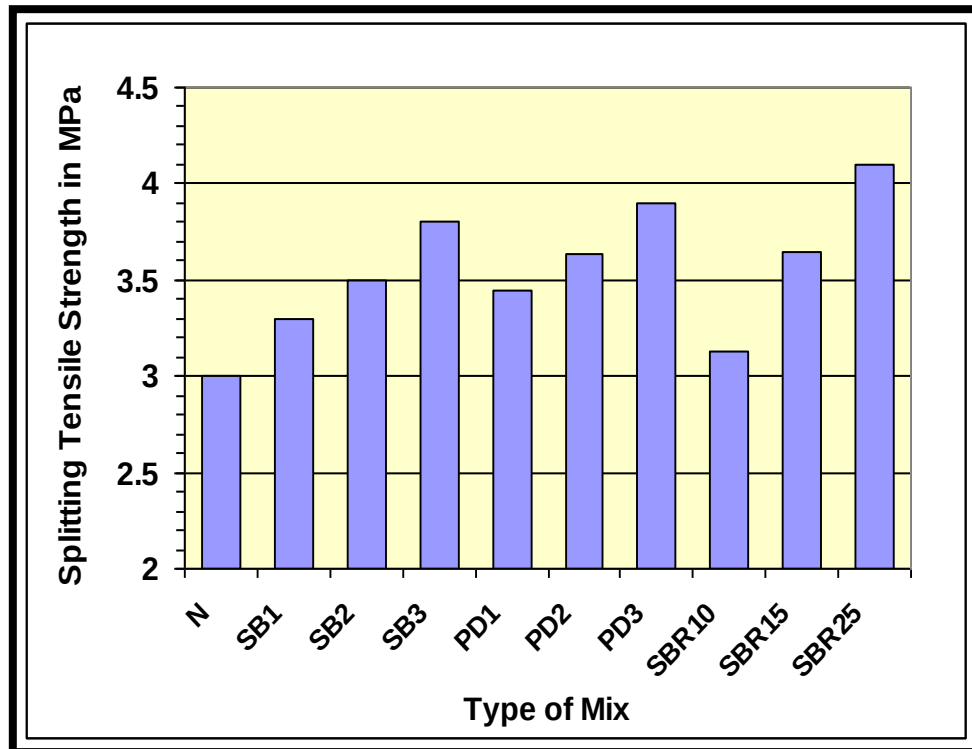


Fig (4.4) Splitting tensile strength for concrete specimens with different admixtures

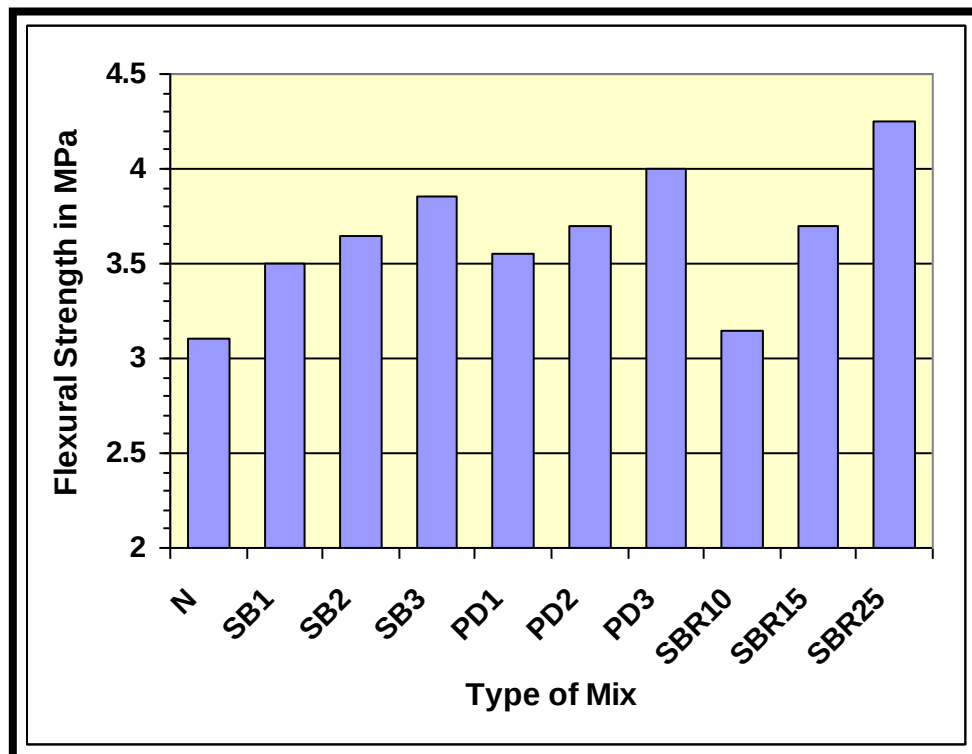


Fig (4.5) Flexural Strength for different concrete mixes

## 4.5 Absorption Test

Concrete mixes with different admixtures in different concentrations showed a noticeable reduction in water absorption. This reduction increases with increasing of the concentrations for all admixtures. SBR admixture in conc. of 25% by vol. of water was the best one which recorded a reduction of 77% in percentage absorption. This agrees with production publication [40] which states that; SBR emulsion has many advantage; water proofing action, improves adhesion, reduces permeability.

This finding conforms with properties of corrosion inhibitors which prevent or delay the corrosion of steel reinforcement without any effect or with a little effect on concrete properties with decreasing the absorption and porosity of concrete mix [53]. See table 4.2 and Figure (4.6).

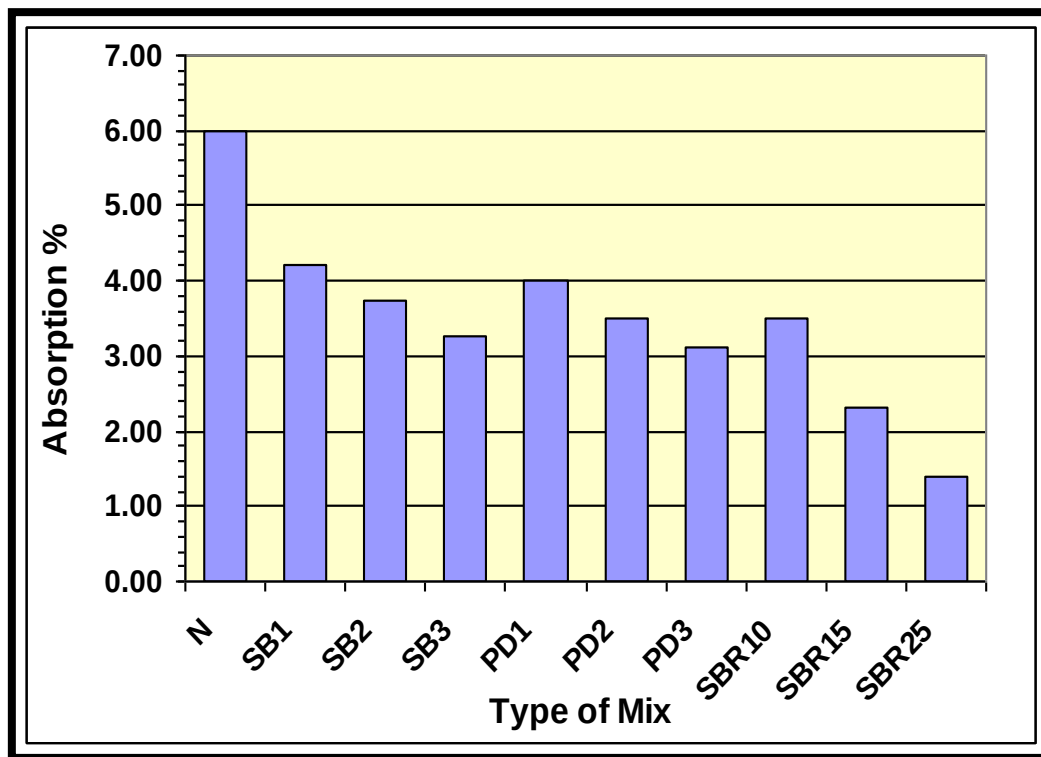


Fig. (4.6) Absorption for different concrete mixes

## 4.6 Concrete Electrical Resistance Test

The results of electrical resistance test for reinforced concrete samples in (k.ohm) are shown in table (A.1 ) (see Appendix A) and in Figure (4.7), (4.8), (4.9), (4.10), (4.11) and (4.12). When the concrete produced with a good quality, its electrical resistance will be high. The micro cracks in concrete mass that open a way for water and salts to go through increase the conductivity and decrease the electrical resistance for concrete.

Chloride ions, if found, increase the conductivity of the pores solution and carbonation decreases it. Therefore, an increase in electrical resistance of concrete is accompanied by a reduced corrosion rate. In this investigation the electrical resistance of concrete is an indication to the corrosion rate.

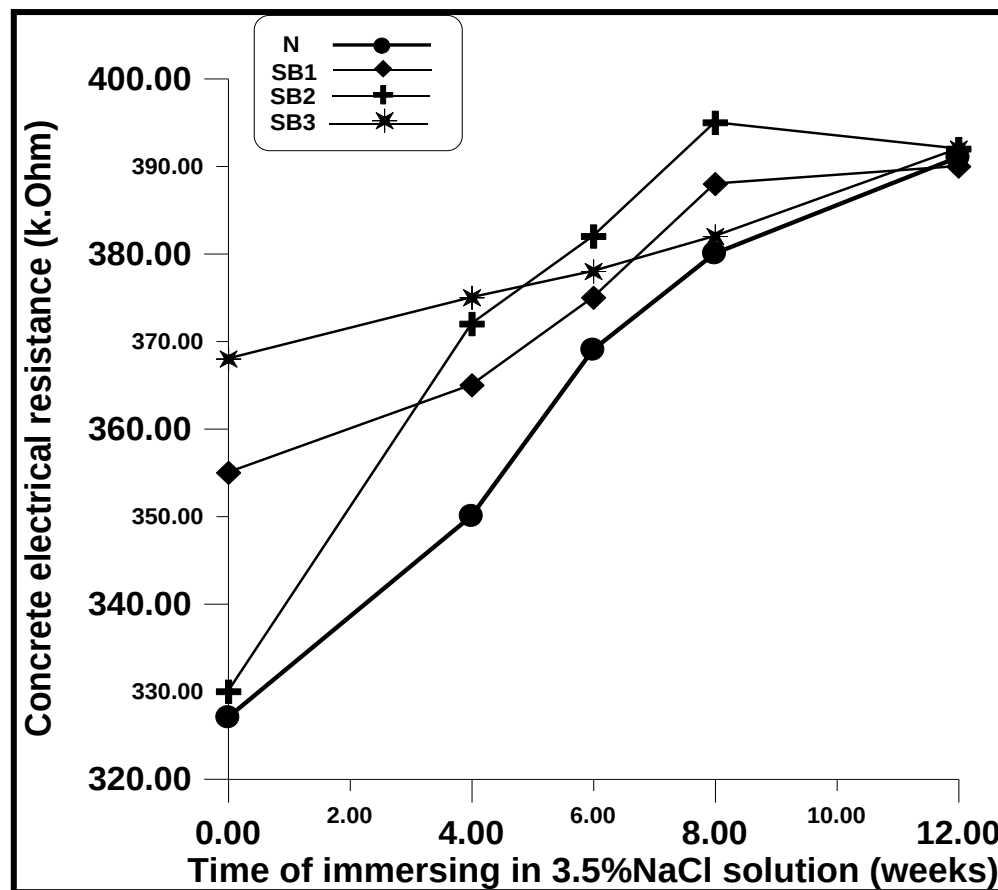


Fig.(4.7) Electrical resistance for reinforced concrete samples with sodium benzoate admixture without pre cracking

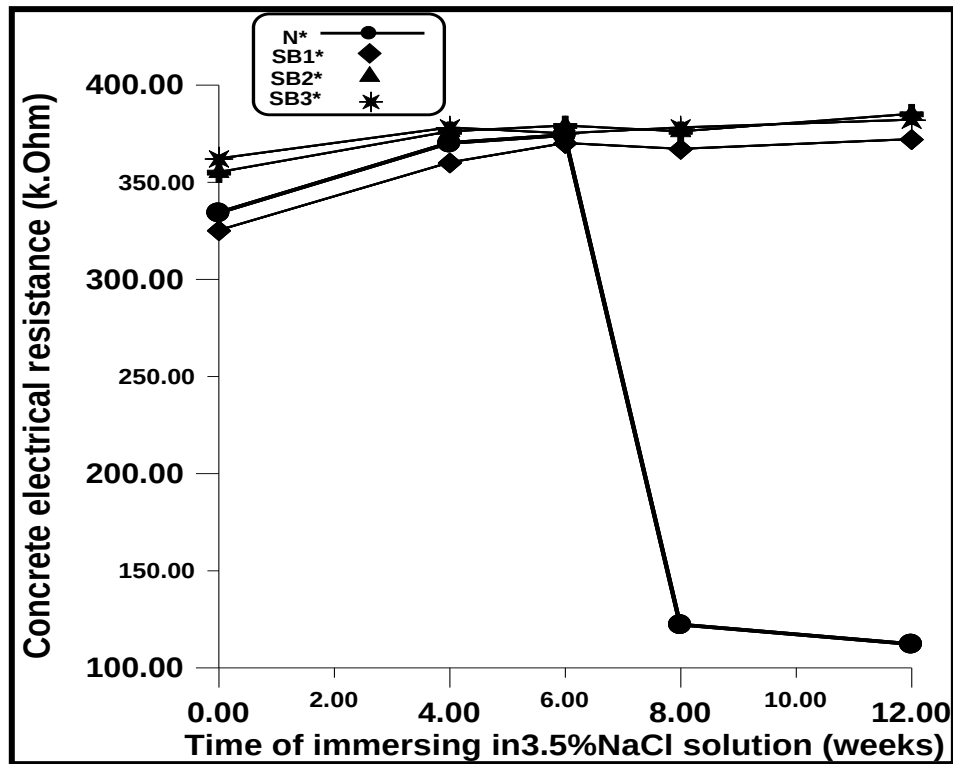


Fig.(4.8) Electrical resistance for reinforced concrete specimens with sodium benzoate with pre cracking after 6 weeks of immersing in 3.5%NaCl solution

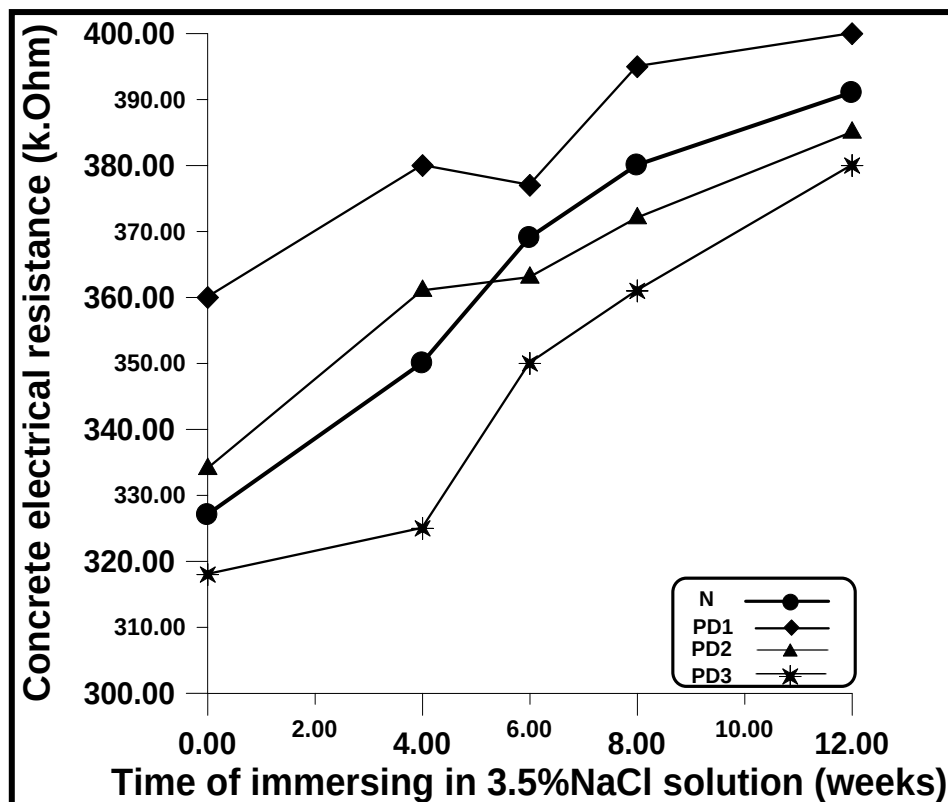


Fig.(4.9) Electrical resistance for reinforced concrete specimens with potassium dichromate admixture without pre cracking

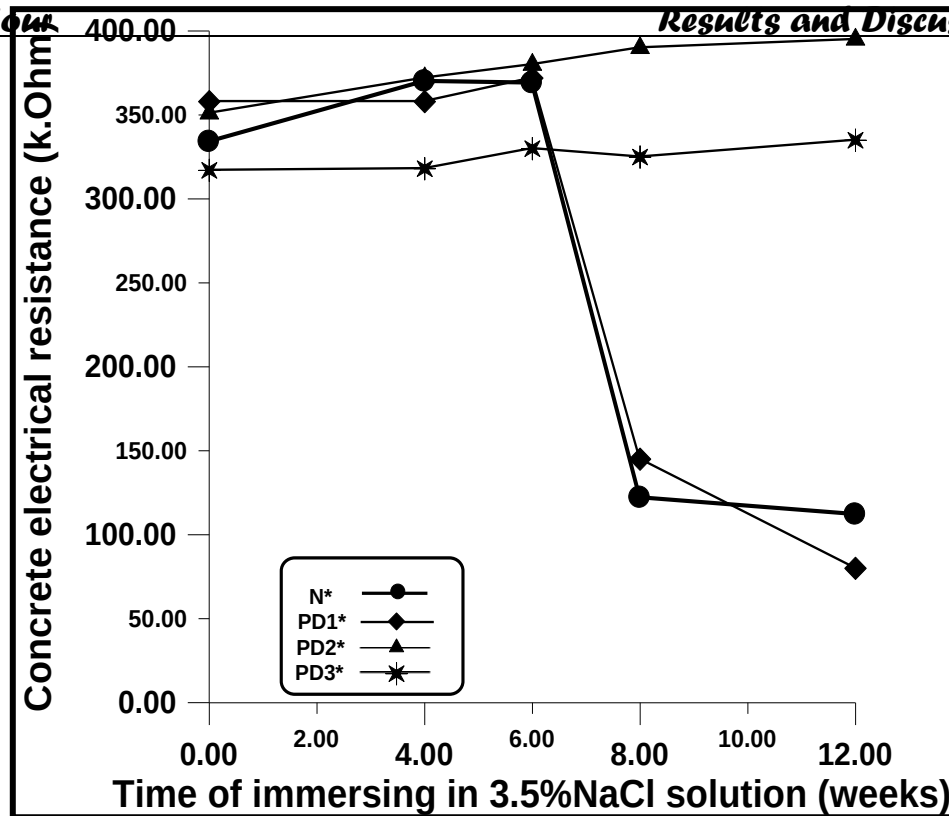


Fig.(4.10) Electrical resistance for reinforced concrete specimens with potassium dichromate with pre cracking after 6 weeks of immersing

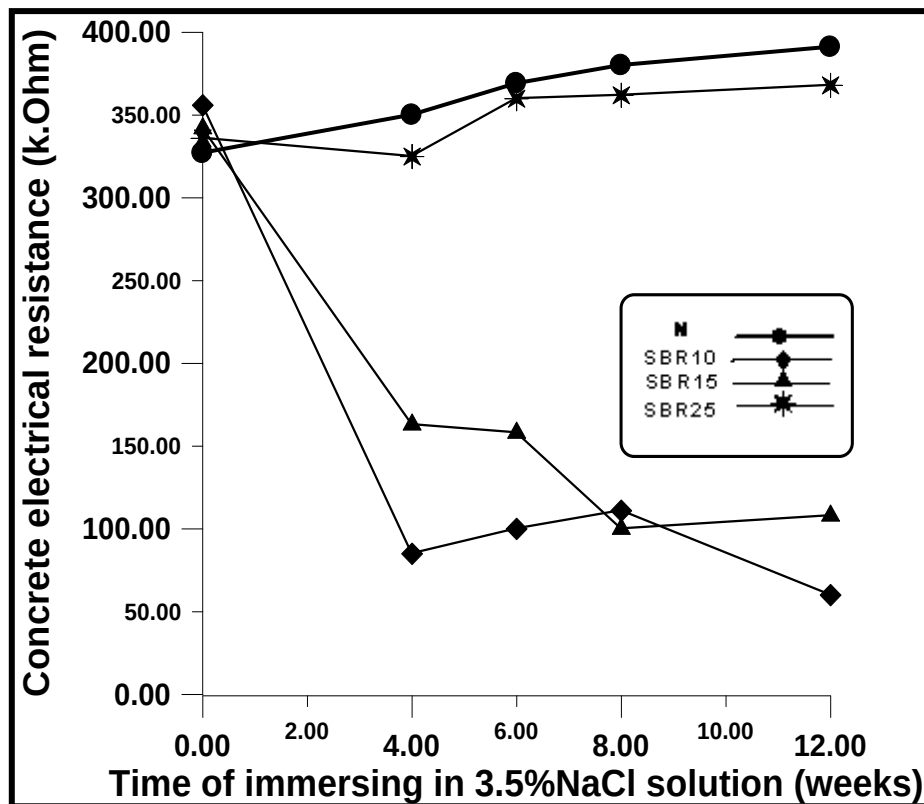


Fig.(4.11) Electrical resistance for reinforced concrete specimens with SBR admixture without pre cracking

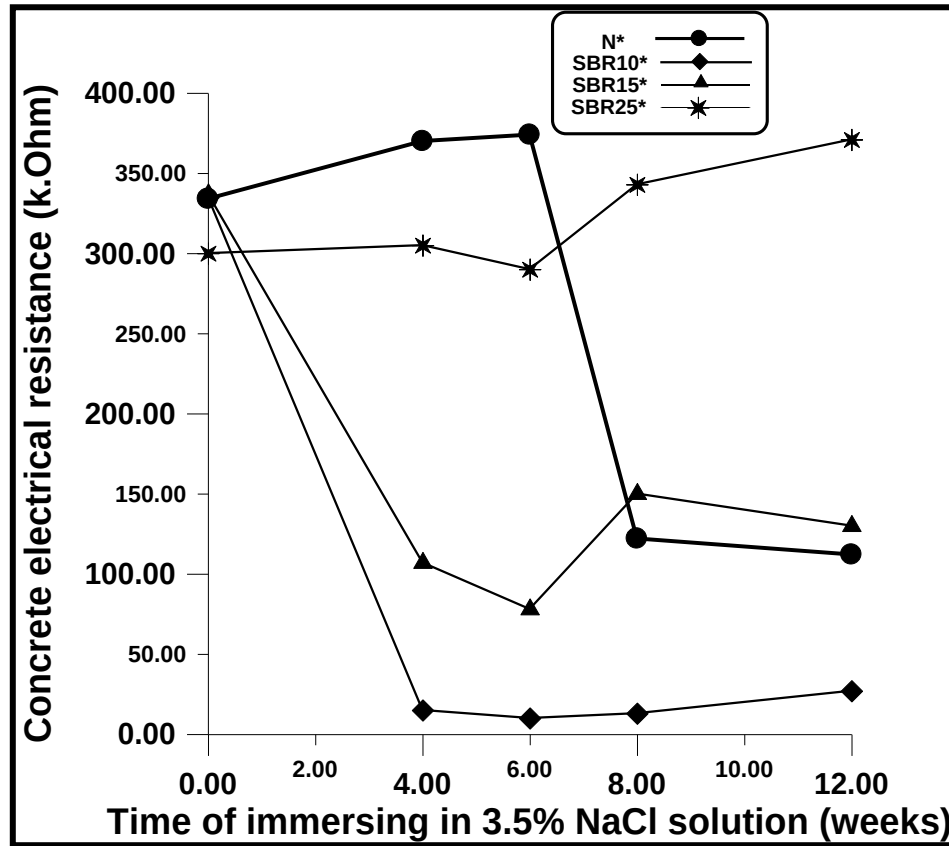


Fig.(4.12) Electrical resistance for reinforced concrete specimens with SBR admixture with pre cracking

#### 4.7 Corrosion Rate of non pre Cracked Reinforced Concrete Samples.

The corrosion currents ( $I_{corr.}$ ) were calculate by using two equations from **Barnart Method** [65] (see Appendix B):

$$1. \quad I_{corr. 1} = I_1 / (R_1 + 4R_2)^{0.5} \quad \dots\dots (4.1)$$

Where :  $R_1 = I_3 / I_1$

$$R_2 = I_1 / I_4$$

$$2. \quad I_{corr. 2} = I_1 / ((R_3 * R_4)^2 + 4R_3)^{0.5} \quad \dots\dots (4.2)$$

Where :  $R_3 = I_1 / I_4$

$$R_4 = I_6 / I_4$$

And

$$I_{corr. av.} = ( I_{corr. 1} + I_{corr. 2} ) / 2$$

$$C.R = I_{corr. av.} * 0.10189$$

...(4.3) (see appendix B)

Where :

*I<sub>corr.</sub> : corrosion current (Ampere)*

*ΔE : the potential (voltage)*

*I<sub>1</sub>: the current in Amp. at ΔE<sub>1</sub>= 0.060 volt*

*I<sub>3</sub>: the current in Amp. at ΔE<sub>3</sub>= 0.120 volt*

*I<sub>4</sub>: the current in Amp. at ΔE<sub>4</sub>= -0.060 volt*

*I<sub>6</sub>: the current in Amp. at ΔE<sub>6</sub>= -0.120 volt*

*C.R : Corrosion Rate (kg / sec. m<sup>2</sup>)*

Good quality concrete can make a perfect protection to keep the steel reinforcement wire away from corrosive solution and corrosive elements with a very low corrosion rate due to the high pH value and low porosity and permeability.

The results of corrosion rates that were tested at (0,2,4,6,8,10 and 12 weeks of immersing in 3.5% NaCl solution) for the samples without pre cracking are low except the mixes with (SBR10 and SBR15) and that's may be due to the fact that emulsion SBR is made by termination – free, anionic polymerization initiated by alkyl lithium compounds, this means that there is a lithium element in component of the SBR admixture and because of that fact, corrosion process happened faster in presence of lithium chloride than in presence of sodium chloride [40].

The corrosion current and corrosion rate increase with time from (1 to 12 weeks) in all samples and that is clear in Figures (4.13), (4.14), (4.15) and table (A.2),(A.3).

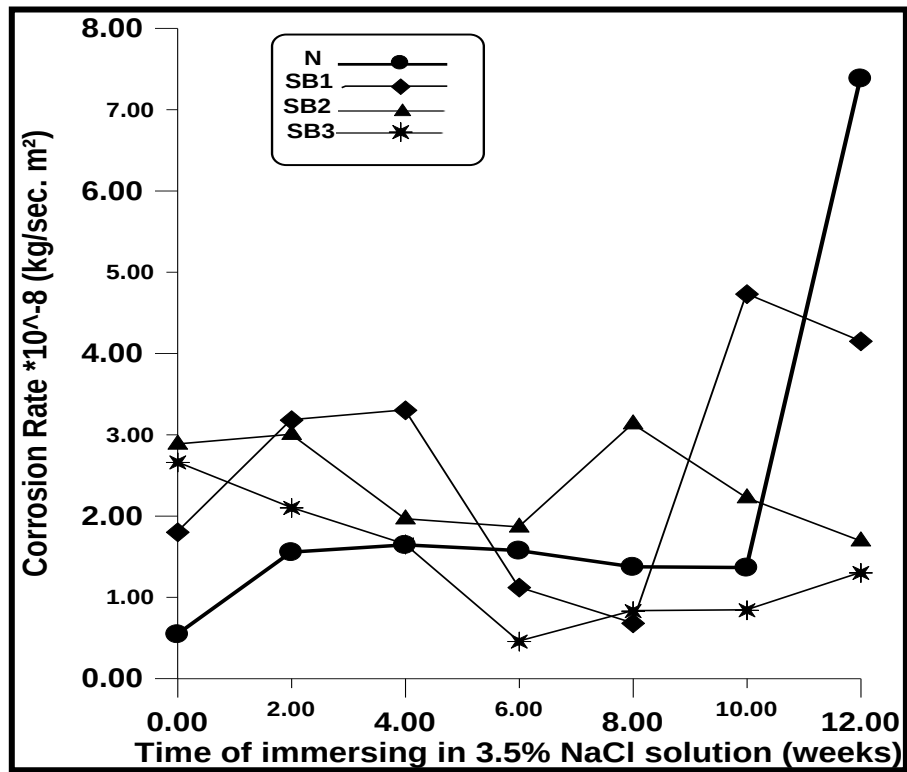


Fig. (4.13) Corrosion rate for reinforced concrete samples with sodium benzoate admixture without pre cracking

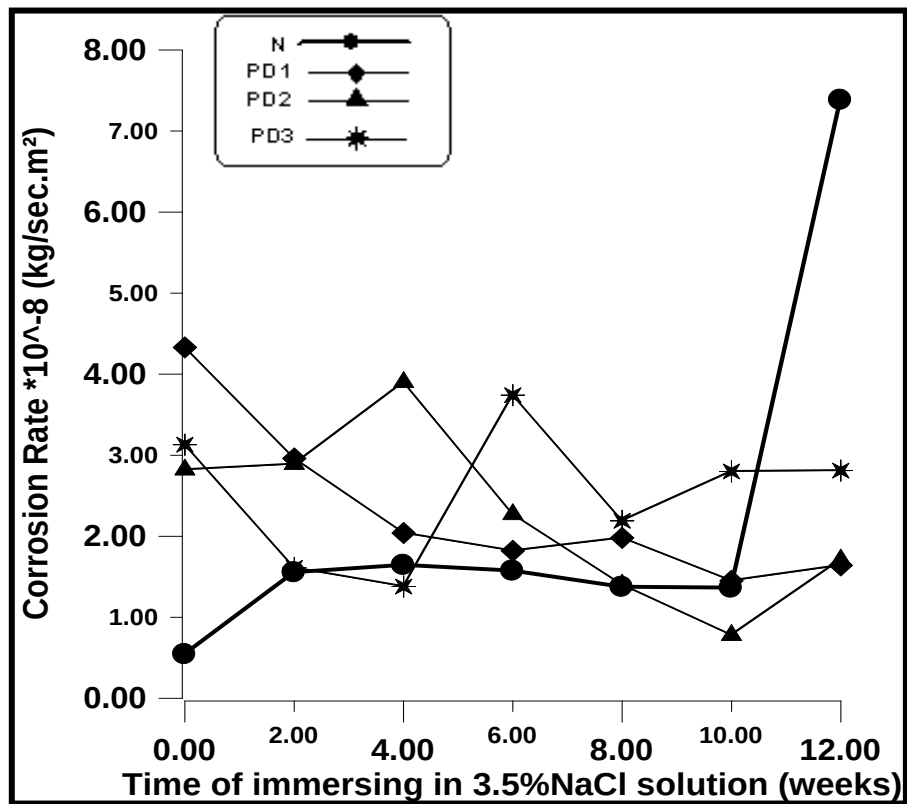


Fig. (4.14) Corrosion rate for reinforced concrete samples with potassium dichromate admixture without pre cracking

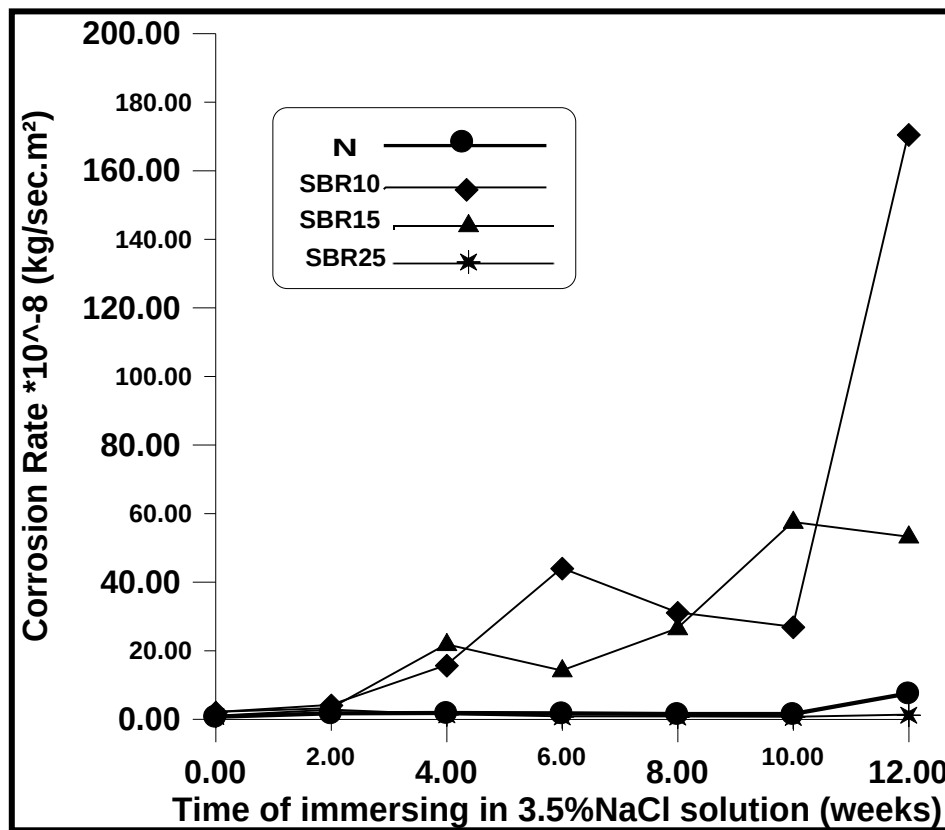


Fig. (4.15) Corrosion rate for reinforced concrete samples with SBR admixture without pre cracking

## 4.8 Corrosion Rates of pre cracking Reinforced Concrete Samples.

### 4.8.1 Sodium Benzoate Inhibitor (SB)

The sodium benzoate inhibitor decrease the corrosion rate in all concentration as shown in Figure (4.16).

The inhibitor efficiency for (SB2\*) is better than (SB1\*) and (SB3\*) after 12 weeks of immersion in salt solution.

The corrosion rates are low in the three concentrations (1%, 2% and 3% by weight of cement) and they do not indicate any noticeable increase or decrease with time in (8 to 12 weeks).

The sodium benzoate inhibitor has good efficiency because it enhances the alkaline environments. The adhered layer that is produced on the steel bar due to the effect of sodium benzoate will protect in form further attack. The presence of

oxygen can form a strong chemical bond ( $\text{C}_6\text{H}_5\text{COO Na}$ ) with iron and this will reduce the active regions on the surface of the iron and facilitates the passivation of remaining regions [67].

The corrosion rate of ( $\text{SB1}^*$ ) and ( $\text{SB3}^*$ ) samples were more than corrosion rate of ( $\text{SB2}^*$ ) samples, and corrosion rate of sample ( $\text{SB1}^*$ ) was more than corrosion rate of sample ( $\text{SB3}^*$ ), this can be attributed to the fact that ; sodium benzoate does not possess oxidizing properties and does not lead to partial passivation of the iron due to the high concentration of NaCl, the corrosion rate decreased as concentration of SB is increased.

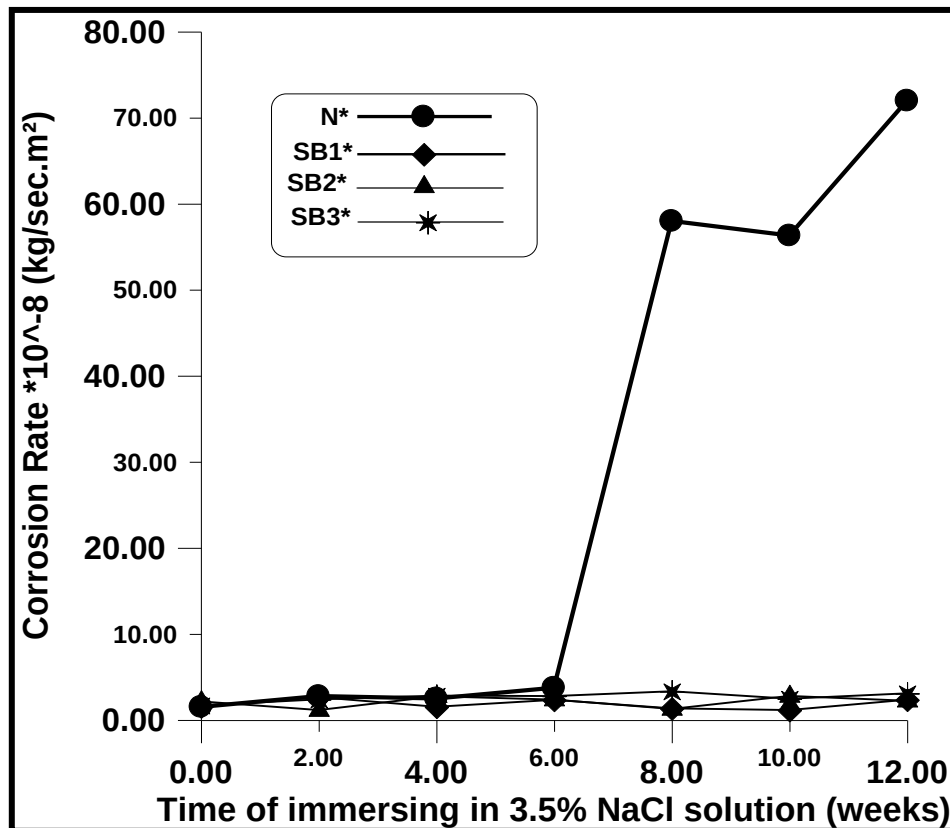


**Fig. (4.16) Corrosion rate for reinforced concrete samples with sodium benzoate admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution**

#### 4.8.2 Potassium Dichromate Inhibitor (PD)

The corrosion rate of sample ( $\text{PD1}^*$ ) increased after 12 weeks of immersion in salt solution. The chromate is an anodic inhibitor. It can, in case of incomplete

protection, increase the corrosion rate intensity. There is a critical concentration below which the corrosion intensity steadily increases. When the inhibitor concentration is increased beyond the critical value, the corrosion intensity begins to drop, as in samples (PD2\*) and (PD3\*) see figure (4.17).

Hence, the inhibition efficiency of (PD2\*) and (PD3\*) samples are better than (PD1\*) due to the higher dosage of the inhibitor. The presence of  $\text{Cl}^-$  increases the corrosion rate and needs more dosage of the inhibitor. The following explanation was stated by Rozenfeld [66] and Anton [67]: “Anodic inhibitor which cause a large shift in the corrosion potential are called passivating inhibitors, they are also called dangerous inhibitors because, if used in sufficient concentrations they cause pitting corrosion and some times an increase in corrosion rate”. The corrosion rate is almost equal in sample (PD2\*) through 6 weeks to 12 weeks .

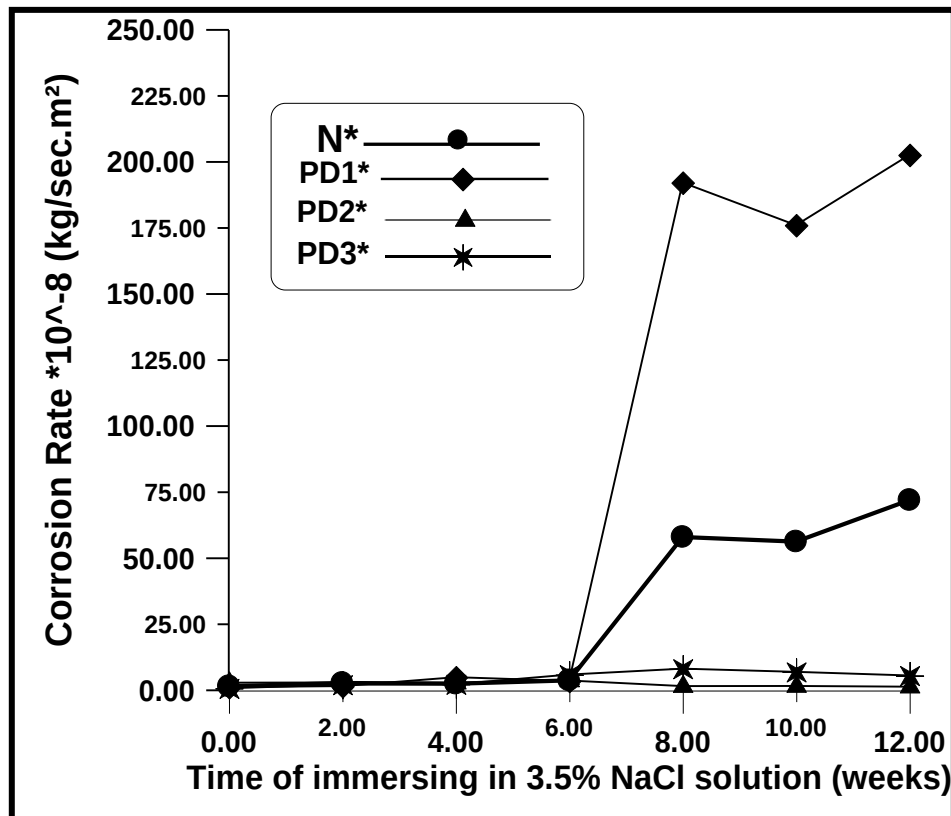


**Fig. (4.17) Corrosion rate for reinforced concrete samples with potassium dichromate admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution**

### 4.8.3 SBR (Styrene- Butadiene -Rubber) admixture

The corrosion rates of samples (SBR10\*) and (SBR15\*) increased at 2- 12 weeks of partial immersing in 3.5% NaCl solution. On the contrary, the corrosion rate of sample (SBR25\*) was decreased. The SBR admixture reduces the porosity and permeability. In (SBR10\*) and (SBR15\*) samples SBR admixture is not enough to decrease porosity and prevent the corrosive ions from reaching the iron surface. The opposite reaction of (SBR10\*) and (SBR15\*) samples of increased corrosion rate may be due to the fact that emulsion SBR is containing alkyl lithium compounds that's come from manufactured. And because of that fact, corrosion process happened faster in presence of lithium chloride than in presence of sodium chloride, that may be the cause of the high rate of corrosion in samples (SBR10\*) and (SBR15\*) [40].

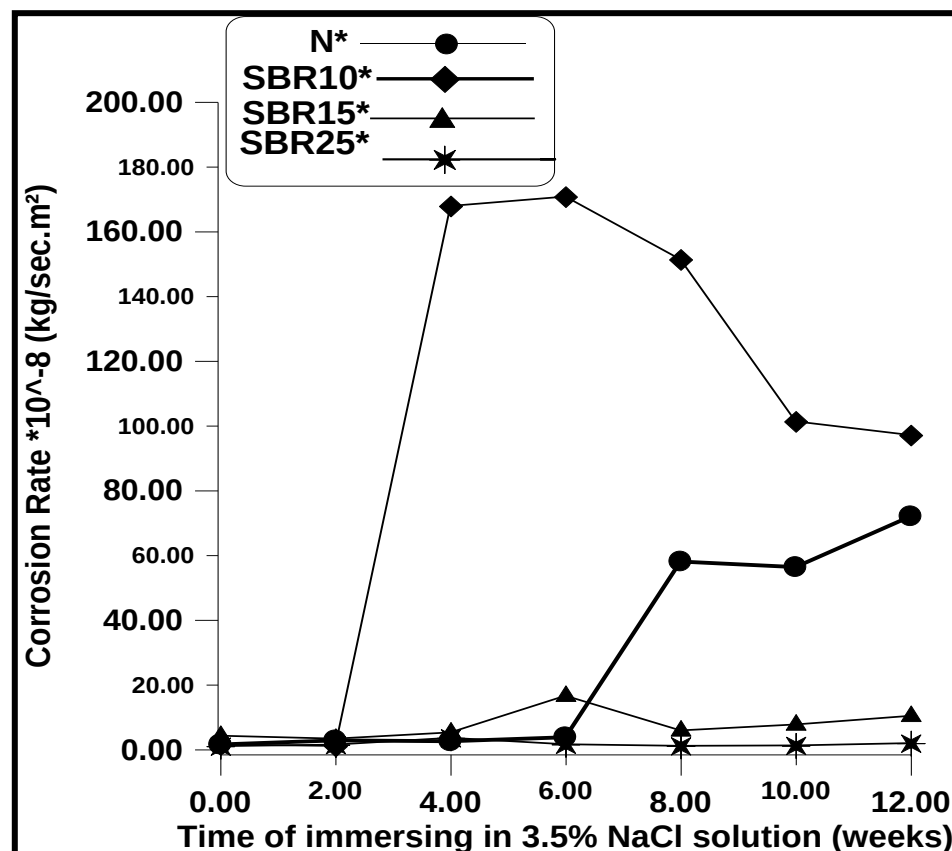


Fig. (4.18) Corrosion rate for reinforced concrete samples with SBR admixture with pre cracking after 6 weeks of immersing in 3.5%NaCl solution

## 4.9 The Time Effect

In all samples with inhibitors and for all dosages, the corrosion rates increase with time especially in samples with high corrosion rates. The corrosion rate in the first week is the lowest while the corrosion rate in the 12<sup>th</sup> week is the highest. This occurs because the ions need time to diffuse through pores, cracks and capillary tubes to reach the bar surface and then produce the corrosion product which has a volume several times more than iron and this will apply a high pressure which can make cracks and concrete spalling ( the pressure may be about 10<sup>5</sup> psi or more) [67]. The formed cracks make easy for ions to diffuse and then the corrosion rate will increase in exponential and dangerous rate.

## 4.10 Inhibitor Efficiency

The efficiency of the inhibitor is measured by :

$$\text{Inhibitor Efficiency (\%)} = 100 * (\text{CR}_{\text{uninhibited}} - \text{CR}_{\text{inhibited}}) / \text{CR}_{\text{uninhibited}}$$

where:  $\text{CR}_{\text{uninhibited}}$  = corrosion rate of the uninhibited system

$\text{CR}_{\text{inhibited}}$  = corrosion rate of the inhibited system.

In general, the efficiency of an inhibitor increases with the increase in inhibitor concentration [24], that was clear for mixes without pre cracking; the inhibitor efficiency for sodium benzoate increased from 44% for concrete mix with 1% dosage to 82% for concrete mix with 3% dosage of (SB) as shown in table 4.3.

Where the mixes with potassium dichromate (PD) show some convergent in values of inhibitor efficiency that shown in table 4.3 but, all of these values are less than sodium benzoate inhibitor's efficiency.

The mixes with SBR admixture in dosage 10% and 15% by vol. of water showed very insignificant efficiency which functioned as corrosion accelerator not as corrosion inhibitor because of the low concentrations.

The mixes with SBR for 25% dosage by vol. of water showed the best value of inhibitor efficiency with 84% for concrete samples without pre cracking and 97% for sample with pre cracking .

On the other hand, the corrosion inhibitors (SB and PD) and SBR admixture had a better efficiency in concrete samples with micro cracks because corrosion inhibitors migrate into the concrete first by diffusion through moisture that is normally available in concrete, then by its high vapor pressure and finally by following hairline and micro cracks therefore, low density concrete provides an easier path for corrosion inhibitors in ward diffusion, and faster corrosion retardation [16], as shown in table 4.3.

Therefore, from table (4.3) sodium benzoate with 2% conc. (SB2\*), potassium dichromate with 2% conc. (PD2\*) and SBR25\* with conc. 25% by vol. of water are the best dosage for highest efficiency.

The opposite action of (PD1\*) sample (potassium dichromate in 1% addition with pre cracking) is due to the low concentration of the anodic corrosion inhibitor (PD) which acts as corrosion accelerator if it is not added enough to make complete passivity, so the un passive area will behave as anode for passive area and then will be attacked intensively and the metal destroyed [67].

The opposite action of (SBR10), (SBR10\*) and (SBR15\*) samples is due to the fact that SBR emulsion which is made by termination – free, anionic polymerization initiated by alkyl lithium compounds. The alkyl lithium which used as terminator in SBR reaction make polar bond in the end at the copolymer [40] which may let the copolymer behaves as a accelerator or catalyst to increase the probability of reaction

of iron or its oxide with environment and then will increase corrosion at low concentration while SBR in dosage 25% by vol. of water behave as a good inhibitor of corrosion due to the decrease in porosity.

**Table(4.3) Inhibitors Efficiency for concrete samples with and without pre cracking after 12 weeks of immersion in salt solution**

| <i>Type of mix</i>       |                                                           | <i>Type of admixture and % of adding</i>            | <i>Inhibitors Efficiency %</i> |
|--------------------------|-----------------------------------------------------------|-----------------------------------------------------|--------------------------------|
| <i>Symbol of the mix</i> | <i>Making pre cracking after 6 weeks of immersion (*)</i> |                                                     |                                |
| SB1                      |                                                           | Sodium benzoate<br>1% by weight of cement           | 44%                            |
| SB1                      | *                                                         |                                                     | 97%                            |
| SB2                      |                                                           | Sodium benzoate<br>2% by weight of cement           | 77%                            |
| SB2                      | *                                                         |                                                     | 97%                            |
| SB3                      |                                                           | Sodium benzoate<br>3% by weight of cement           | 82%                            |
| SB3                      | *                                                         |                                                     | 96%                            |
| PD1                      |                                                           | Potassium dichromate<br>1% by weight of cement      | 78%                            |
| PD1                      | *                                                         |                                                     | (-) adverse effect             |
| PD2                      |                                                           | Potassium dichromate<br>2% by weight of cement      | 77%                            |
| PD2                      | *                                                         |                                                     | 98%                            |
| PD3                      |                                                           | Potassium dichromate<br>3% by weight of cement      | 62%                            |
| PD3                      | *                                                         |                                                     | 92%                            |
| SBR10                    |                                                           | Styrene-Butadiene-Rubber<br>10 % by volume of water | (-) adverse effect             |
| SBR10                    | *                                                         |                                                     | (-) adverse effect             |
| SBR15                    |                                                           | Styrene-Butadiene-Rubber                            | 86%                            |

|       |   |                          |                    |
|-------|---|--------------------------|--------------------|
| SBR15 | * | 15 % by volume of water  | (-) adverse effect |
| SBR25 |   | Styrene-Butadiene-Rubber | 84 %               |
| SBR25 | * | 25 % by volume of water  | 97%                |

#### 4.11 (Cl<sup>-</sup>) Concentration :

Table (4.4) shows results of chlorides concentration in reinforced concrete samples before and after partial immersing in 3.5% NaCl solution for 12 weeks, as tested in environment laboratory / Civil engineering department / Babylon university.

**Table (4.4) Chlorides concentrations in reinforced concrete samples**

| Symbol of sample | Cl <sup>-</sup> concentration in reinforced concrete samples with pre cracking after 12 weeks of immersing in 3.5% NaCl solution (% by weight of concrete) | Symbol of sample | Cl <sup>-</sup> concentration in reinforced concrete samples without pre cracking after 12 weeks of immersing in 3.5% NaCl solution (% by weight of concrete) |
|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| N*               | 0.02                                                                                                                                                       | N                | 0.00372                                                                                                                                                       |
| SB1*             | 0.0128                                                                                                                                                     | SB1              | 0.0042                                                                                                                                                        |
| SB2*             | 0.011                                                                                                                                                      | SB2              | 0.0037                                                                                                                                                        |
| SB3*             | 0.0096                                                                                                                                                     | SB3              | 0.0034                                                                                                                                                        |
| PD1*             | 0.0142                                                                                                                                                     | PD1              | 0.0048                                                                                                                                                        |
| PD2*             | 0.0140                                                                                                                                                     | PD2              | 0.00421                                                                                                                                                       |
| PD3*             | 0.0112                                                                                                                                                     | PD3              | 0.0034                                                                                                                                                        |
| SBR10*           | 0.009                                                                                                                                                      | SBR10            | 0.0035                                                                                                                                                        |
| SBR15*           | 0.0048                                                                                                                                                     | SBR15            | 0.00341                                                                                                                                                       |
| SBR25*           | 0.0050                                                                                                                                                     | SBR25            | 0.00401                                                                                                                                                       |

**NOTE:** Cl<sup>-</sup> concentration in all reinforced concrete samples before immersing in 3.5% NaCl solution was between (0.0034-0.0035) % by weight of concrete.

From table (4.4), it was found that the  $\text{Cl}^-$  concentrations in reinforced concrete samples without pre cracking were less than the  $\text{Cl}^-$  concentrations in reinforced concrete samples with pre cracking that's due to the pre cracking which made an easy way for chlorides to penetrate into the concrete body.

And  $\text{Cl}^-$  concentrations decrease with increase of inhibitor dosage that's means the inhibitor works as reducer for permeability and porosity of concrete beside of its working as corrosion inhibitor.

#### 4.12 Classification Degree of corrosion current

Corrosion can be classify as the following degree [1].

**Passive condition :**  $I_{\text{corr}} < 0.1 \mu\text{A} / \text{cm}^2$

**Low corrosion :**  $I_{\text{corr}} (0.1 - 0.25) \mu\text{A} / \text{cm}^2$

**Moderate corrosion :**  $I_{\text{corr}} (0.25 - 0.75) \mu\text{A} / \text{cm}^2$

**High corrosion :**  $I_{\text{corr}} (0.75 - 1) \mu\text{A} / \text{cm}^2$

**Sever corrosion :**  $I_{\text{corr}} > 1 \mu\text{A} / \text{cm}^2$

Classification degree of corrosion current at the end of the 12 weeks of partial immersing in 3.5% NaCl solution shows in table (4.5).

#### 4.13 Polarization Resistance

The polarization resistance values in table 4.6 indicate that P.R decrease in high rate with time for samples that suffering from corrosion with and without inhibitors addition, and polarization resistance decrease in lower rate for samples which didn't have corrosion. The polarization resistance is inversely proportional with corrosion rate, so it's results lead to the same conclusion for the calculation by Barnarte method.

Table (4.5) Classification degree of corrosion current

| Symbol<br>Of<br>sample | Making pre cracking<br>after 6 weeks of<br>immersing in 3.5%<br>NaCl solution * | I <sub>corr.</sub> (μA/cm <sup>2</sup> ) | Classification<br>Degree |
|------------------------|---------------------------------------------------------------------------------|------------------------------------------|--------------------------|
| N                      | *                                                                               | 0.248                                    | low                      |
| N                      |                                                                                 | 0.025                                    | Passive                  |
| SB1                    | *                                                                               | 0.009                                    | passive                  |
| SB1                    |                                                                                 | 0.0143                                   | Passive                  |
| SB2                    | *                                                                               | 0.0076                                   | Passive                  |
| SB2                    |                                                                                 | 0.0058                                   | Passive                  |
| SB3                    | *                                                                               | 0.0106                                   | Passive                  |
| SB3                    |                                                                                 | 0.0045                                   | Passive                  |
| PD1                    | *                                                                               | 0.699                                    | Moderate                 |
| PD1                    |                                                                                 | 0.0056                                   | Passive                  |
| PD2                    | *                                                                               | 0.0047                                   | Passive                  |
| PD2                    |                                                                                 | 0.0059                                   | Passive                  |
| PD3                    | *                                                                               | 0.0193                                   | Passive                  |
| PD3                    |                                                                                 | 0.0097                                   | Passive                  |
| SBR10                  | *                                                                               | 0.335                                    | Moderate                 |
| SBR10                  |                                                                                 | 0.058                                    | Passive                  |
| SBR15                  | *                                                                               | 0.183                                    | Low                      |
| SBR15                  |                                                                                 | 0.0357                                   | Passive                  |
| SBR25                  | *                                                                               | 0.0066                                   | Passive                  |
| SBR25                  |                                                                                 | 0.0041                                   | Passive                  |

**Table (4.6) The Polarization Resistance Values for steel reinforcement wires in concrete at Different ages of Immersing in 3.5% NaCl Solution**

| SYMBOL<br>OF<br>SPECIMENS | RP1 at m=2<br>RP2 at m=1.5 | Polarization Resistance of Steel Reinforced Wires *10 <sup>3</sup> (Volt. / Amp.)<br>at Different ages of Immersing in 3.5% NaCl Solution |         |         |         |         |         |         |
|---------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|---------|---------|---------|---------|---------|---------|
|                           |                            | 0 week                                                                                                                                    | 2 week  | 4 week  | 6 week  | 8 week  | 10 week | 12 week |
| N1*                       | RP1                        | 150.000                                                                                                                                   | 82.758  | 81.818  | 62.608  | 3.819   | 4.029   | 3.031   |
|                           | RP2                        | 91.836                                                                                                                                    | 43.269  | 44.117  | 37.500  | 2.320   | 2.493   | 1.851   |
| N1                        | RP1                        | 360.000                                                                                                                                   | 114.285 | 97.297  | 104.347 | 135.849 | 138.461 | 31.441  |
|                           | RP2                        | 236.842                                                                                                                                   | 65.217  | 50.000  | 57.692  | 78.947  | 76.271  | 19.650  |
| SB1*                      | RP1                        | 144.000                                                                                                                                   | 93.506  | 146.938 | 98.630  | 175.609 | 211.764 | 97.297  |
|                           | RP2                        | 86.538                                                                                                                                    | 56.962  | 90.000  | 55.555  | 115.384 | 132.352 | 63.380  |
| SB1                       | RP1                        | 146.938                                                                                                                                   | 69.902  | 68.571  | 150.000 | 399.999 | 46.451  | 53.731  |
|                           | RP2                        | 65.217                                                                                                                                    | 43.689  | 38.135  | 88.235  | 264.705 | 29.801  | 34.351  |
| SB2*                      | RP1                        | 53.731                                                                                                                                    | 288.000 | 94.736  | 79.120  | 200.000 | 80.898  | 105.882 |
|                           | RP2                        | 31.468                                                                                                                                    | 160.714 | 49.450  | 54.216  | 102.272 | 48.387  | 60.000  |
| SB2                       | RP1                        | 94.736                                                                                                                                    | 83.720  | 118.032 | 124.137 | 72.727  | 104.347 | 150.000 |
|                           | RP2                        | 55.555                                                                                                                                    | 49.450  | 75.000  | 80.357  | 47.368  | 60.000  | 93.750  |
| SB3*                      | RP1                        | 144.000                                                                                                                                   | 101.408 | 82.758  | 86.746  | 70.588  | 91.139  | 72.727  |
|                           | RP2                        | 83.333                                                                                                                                    | 63.380  | 50.561  | 54.878  | 44.554  | 56.250  | 45.454  |
| SB3                       | RP1                        | 88.888                                                                                                                                    | 107.462 | 120.000 | 239.999 | 288.000 | 266.666 | 189.473 |
|                           | RP2                        | 49.450                                                                                                                                    | 66.176  | 69.320  | 562.499 | 136.363 | 155.172 | 95.744  |
| PD1*                      | RP1                        | 180.000                                                                                                                                   | 135.849 | 45.000  | 64.864  | 1.073   | 1.333   | 1.145   |
|                           | RP2                        | 102.272                                                                                                                                   | 80.358  | 26.946  | 43.689  | 0.6656  | 0.8220  | 0.6985  |
| PD1                       | RP1                        | 51.063                                                                                                                                    | 77.419  | 94.736  | 133.333 | 114.285 | 122.033 | 128.571 |
|                           | RP2                        | 30.612                                                                                                                                    | 45.454  | 59.210  | 61.643  | 70.312  | 70.312  | 80.357  |
| PD2*                      | RP1                        | 80.898                                                                                                                                    | 78.260  | 78.260  | 54.545  | 160.000 | 124.137 | 109.090 |
|                           | RP2                        | 54.878                                                                                                                                    | 47.872  | 45.918  | 32.142  | 81.818  | 75.000  | 63.380  |
| PD2                       | RP1                        | 80.898                                                                                                                                    | 80.000  | 60.000  | 97.297  | 194.594 | 449.999 | 138.461 |
|                           | RP2                        | 48.387                                                                                                                                    | 48.387  | 37.190  | 58.441  | 150.000 | 150.000 | 104.651 |

| SYMBOL OF SPECIMENS | RP1 at m=2<br>RP2 at m=1.5 | Polarization Resistance of Steel Reinforced Wires *10 <sup>3</sup> (Volt. / Amp.)<br>at Different ages of Immersing in 3.5% NaCl Solution |         |         |         |         |         |          |
|---------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|---------|---------|---------|---------|---------|----------|
|                     |                            | 0 week                                                                                                                                    | 2 weeks | 4 weeks | 6 weeks | 8 weeks | 10weeks | 12 weeks |
| PD3*                | RP1                        | 171.428                                                                                                                                   | 107.462 | 93.506  | 35.820  | 28.346  | 33.644  | 41.142   |
|                     | RP2                        | 115.384                                                                                                                                   | 93.750  | 69.230  | 22.500  | 18.442  | 20.000  | 24.725   |
| PD3                 | RP1                        | 75.789                                                                                                                                    | 150.000 | 130.909 | 48.979  | 99.999  | 80.000  | 80.898   |
|                     | RP2                        | 50.561                                                                                                                                    | 73.770  | 69.230  | 28.846  | 56.250  | 54.878  | 60.810   |
| SBR10*              | RP1                        | 150.000                                                                                                                                   | 300.00  | 1.395   | 1.376   | 1.554   | 2.273   | 2.403    |
|                     | RP2                        | 97.826                                                                                                                                    | 118.42  | 0.877   | 0.849   | 0.953   | 1.415   | 1.512    |
| SBR10               | RP1                        | 122.033                                                                                                                                   | 55.384  | 5.611   | 4.029   | 7.766   | 8.450   | 16.551   |
|                     | RP2                        | 70.312                                                                                                                                    | 33.333  | 3.557   | 3.125   | 4.864   | 5.363   | 7.908    |
| SBR15*              | RP1                        | 31.034                                                                                                                                    | 60.504  | 45.000  | 14.117  | 40.223  | 34.782  | 23.225   |
|                     | RP2                        | 20.089                                                                                                                                    | 31.914  | 18.672  | 8.555   | 19.067  | 19.396  | 21.327   |
| SBR15               | RP1                        | 109.090                                                                                                                                   | 45.569  | 7.938   | 11.556  | 7.766   | 4.044   | 4.311    |
|                     | RP2                        | 58.441                                                                                                                                    | 25.280  | 4.563   | 6.456   | 4.433   | 2.501   | 2.535    |
| SBR25*              | RP1                        | 313.043                                                                                                                                   | 118.032 | 57.142  | 109.090 | 146.938 | 175.609 | 116.129  |
|                     | RP2                        | 132.352                                                                                                                                   | 62.500  | 36.290  | 70.312  | 86.538  | 97.825  | 69.230   |
| SBR25               | RP1                        | 133.333                                                                                                                                   | 79.120  | 150.000 | 400.000 | 449.999 | 719.998 | 225.000  |
|                     | RP2                        | 83.333                                                                                                                                    | 48.387  | 93.750  | 214.285 | 236.842 | 346.153 | 112.500  |

The calculated P.R (polarization resistance) at (60 mv and 90 mv) and (60 mv and 120 mv) is inversely proportional with corrosion current and results is similar to the results of Barnart method( see appendix B).

### 4.14 Economical Cost

To study the economical cost of using the corrosion inhibitors; Sodium Benzoate in dosage 2% by weight of cement, Potassium Dichromate in dosage 2% by weight of cement and SBR (Styrene– Butadiene– Rubber) in dosage 25% by vol. of water, and estimating which one of the three is the best economically, The following equations are used:

$$1) \text{ A.R.C.V for each mix} = \frac{\text{C.M for } 1\text{m}^3 \text{ con.} - \text{P. } 1\text{m}^3 \text{ con. after S. L}}{\text{No. Y. S.L}}$$

$$2) \text{ Benefit over the av. of E.C} = \frac{(\text{C.M for } 1\text{m}^3 \text{ con.} + \text{P. } 1\text{m}^3 \text{ con. after S. L}) * \text{B}}{2}$$

**Where:**

**A.R.C.V. for each mix** : Annual Reduction for Capitalism Value for each mix.

**C.M for 1m<sup>3</sup> concrete** : The cost of materials to cast 1m<sup>3</sup> of concrete (ID).

**P. 1m<sup>3</sup> concrete after S.L** : The price of 1m<sup>3</sup> concrete after the service life (ID).

**No. Y. S.L** : Number of years of the building's Service Life ( from Icorr. av. table)

**Benefit over the average of E.C** : Benefit over the average of the exploitation cost (ID)

**B** : The benefit (%)

Some information are needed about the cost of the points below :

- The cost of the work to cast 1m<sup>3</sup> concrete (ID).
- The cost of Durability (ID).

**Example:**

#### 1. For Reference concrete mix

- The cost of materials to cast 1m<sup>3</sup> concrete = 200,000 ID
- The price of 1m<sup>3</sup> concrete after the service life (ID) = 0

- No. of years of the building's Service Life = 10 years (according to some investigations they state that: many concrete construction projects showed a considerable degree of deterioration within a short period of 5-7 years after construction especially in southern parts of Iraq) [9].
- The cost of the work to cast 1m<sup>3</sup> concrete (ID) = 150,000 ID
- The cost of Durability (ID) = 100,000 ID
- The benefit (%) = 10%

$$1) \text{ Annual Reduction C.V for Ref. mix} = \frac{200,000 - 0}{10} \approx 20,000 \text{ ID}$$

$$2) \text{ Benefit over the average of E.C} = \frac{(200,000 + 0) * 10\%}{2} = 10,000 \text{ ID}$$

-----

## **2. For concrete mix with Sodium Benzoate in dosage 2% by weight of cement**

- The cost of the corrosion inhibitor (SB) in dosage 2% = 7.88 kg/ m<sup>3</sup> \* 40,000 ID  
 $\approx 315,200 \text{ ID}$
- The cost of materials to cast 1m<sup>3</sup> concrete (ID) = 200,000 ID
- The total cost (materials and inhibitor) for 1m<sup>3</sup> concrete (ID) = 200,000 + 315,200  
 $= 515,200 \text{ ID}$
- The price of 1m<sup>3</sup> concrete after the service life (ID) = 0
- No. of years of the building's Service Life = 43 years
- The cost of the work to cast 1m<sup>3</sup> concrete (ID) = 150,000 ID
- The cost of Durability (ID) = 60,000 ID
- The benefit (%) = 10%

$$1) \text{ Annual Reduction C.V for Ref. mix} = \frac{515,200 - 0}{43} \approx 12,000 \text{ ID}$$

$$2) \text{ Benefit over the av. of E.C} = \frac{(515,200 + 0) * 10\%}{2} \approx 25,800 \text{ ID}$$

-----

### **3. For concrete mix with Potassium Dichromate in 2% conc. by weight of cement**

- The cost of the corrosion inhibitor (PD) in 2% conc. =  $7.88 \text{ kg/ m}^3 * 45,000 \text{ ID}$   
 $\approx 355,000 \text{ ID}$
- The cost of the materials for  $1\text{m}^3$  concrete (ID) = 200,000 ID
- The total cost (materials and inhibitor) for  $1\text{m}^3$  concrete (ID) =  $200,000 + 355,000$   
 $= 555,000 \text{ ID}$
- The value of  $1\text{m}^3$  concrete after the service life (ID) = 0
- No. of years of the building's Service Life = 60 years
- The cost of the work to cast  $1\text{m}^3$  concrete (ID) = 150,000 ID
- The cost of Durability (ID) = 60,000 ID
- The benefit (%) = 10%

$$1) \text{ Annual Reduction C.V for Ref. mix} = \frac{555,000 - 0}{60} \approx 9,250 \text{ ID}$$

$$2) \text{ Benefit over the av. of E.C} = \frac{(555,000 + 0) * 10\%}{2} = 27,750 \text{ ID}$$

-----

#### 4. For concrete mix with (SBR) in dosage 25% by volume of water

- The cost of the admixture (SBR) in 25% conc. =  $\frac{47.28 \text{ L} * 30,000 \text{ ID}}{(5 \text{ L})}$   
 $\approx 285,000 \text{ ID}$
- The cost of the materials for 1m<sup>3</sup> concrete (ID) = 200,000
- The total cost (materials and SBR) for 1m<sup>3</sup> concrete (ID) = 200,000 + 285,000  
 $= 485,000 \text{ ID}$
- The value of 1m<sup>3</sup> concrete after the service life (ID) = 0
- No. of years of the building's Service Life = 48 years
- The cost of the work to cast 1m<sup>3</sup> concrete (ID) = 150,000 ID
- The cost of Durability (ID) = 60,000 ID
- The benefit (%) = 10%

$$1) \text{ Annual Reduction C.V for Ref. mix} = \frac{485,000 - 0}{48} \approx 10,100 \text{ ID}$$

$$2) \text{ Benefit over the average of E.C} = \frac{(485,000 + 0) * 10\%}{2} = 24,250 \text{ ID}$$

| Details | Ref.<br>mix | Mix with<br>2%SB | Mix with<br>2% PD | Mix with<br>25% SBR |
|---------|-------------|------------------|-------------------|---------------------|
|---------|-------------|------------------|-------------------|---------------------|

|                                                              |         |         |         |         |
|--------------------------------------------------------------|---------|---------|---------|---------|
| • The cost of the work to cast 1m <sup>3</sup> concrete (ID) | 150,000 | 150,000 | 150,000 | 150,000 |
| • The cost of Durability (ID)                                | 100,000 | 60,000  | 60,000  | 60,000  |
| • Annual Reduction for Capitalism Value for each mix (ID)    | 20,000  | 12,000  | 9,250   | 10,100  |
| • Benefit over the average of the Exploitation Cost (ID)     | 10,000  | 25,800  | 27,750  | 24,250  |
| The summation (ID)                                           | 280,000 | 247,800 | 247,000 | 244,350 |

**Table 4.7 The Final Calculation of the Economical Cost study**

From table 5.1 the three admixtures in the conc. above have improved the economical cost **but the SBR with 25% conc. seems the best one with a reduction of 13% in economical cost.**

## ***Chapter Five***

### **Conclusions and Recommendations**

#### **5-1 Conclusions**

If the concrete is produced in compressive strength 25 MPa with high cement content (390 kg), low water / cement ratio, good compacting, good curing and high thickness of concrete cover, the steel reinforcement will have a good protection (pH 12- 13.5 and low permeability) against corrosion even in aggressive environment.

Through the use of two anodic, inorganic corrosion inhibitors and SBR admixtures it can be observed that:

- 1. If some kinds of anodic corrosion inhibitors (like potassium dichromate are used in low dosages,** they will act as corrosion accelerators not as corrosion inhibitors therefore they are known as dangerous inhibitors.
- 2.** Corrosion inhibitors work better in concrete with micro cracks than in concrete without micro cracks.
- 3.** The Sodium Benzoate admixture in dosages 2% and 3% by weight of cement has no significant effects on concrete properties it only has an effect on compressive strength at (28 days), but that effect diminishes at later ages (60 and 90 days). Also this admixture is active to protect the steel reinforcement wires against corrosion after initiating cracking for 90 days of immersing in 3.5% NaCl solution. The inhibitor efficiency is 97% and 96% respectively.
- 4.** The potassium dichromate admixture in dosage of 1% by weight of cement acts as corrosion accelerator and not as corrosion inhibitor.
- 5.** The Potassium Dichromate admixture in dosage of 2% and 3% by weight of cement has no detrimental effects on concrete properties. It just has an effect on compressive strength in the age (28 days), but that effect diminishes at

the later ages (60 and 90 days) with increasing ; in compressive strength of 12% for dosage 2% and 14% for dosage 3% at age of 90 days, in splitting tensile strength of 21% and 30% respectively, in flexural strength of 19% and 29% respectively, with a reduction of 42% and 48% respectively in absorption. Also this admixture is active to protect the steel reinforced wires against corrosion for 90 days of partial immersing in 3.5% NaCl solution with inhibitor efficiency of 98% and 92% respectively.

6. The SBR (Styrene -Butadiene –Rubber) admixture in dosages of 10% and 15% by vol. of water has an awful effect on corrosion process because it works as corrosion accelerator not as corrosion inhibitor.
7. The SBR (Styrene -Butadiene –Rubber) admixture in dosage 25% is the superior in enhancing most concrete properties. It increases; compressive strength by about 8%, 11% and 7% for ages 28, 60, and 90 respectively, 37% in splitting tensile strength, 37% in flexural strength and with a maximum reduction of 77% in percentage absorption. It also yields a reduction of 97% in corrosion rate after 12 weeks of partial immersing in 3.5% NaCl solution with a reduction in economical cost of 13%.

## 5.3 Recommendations

**The researcher recommends the following :**

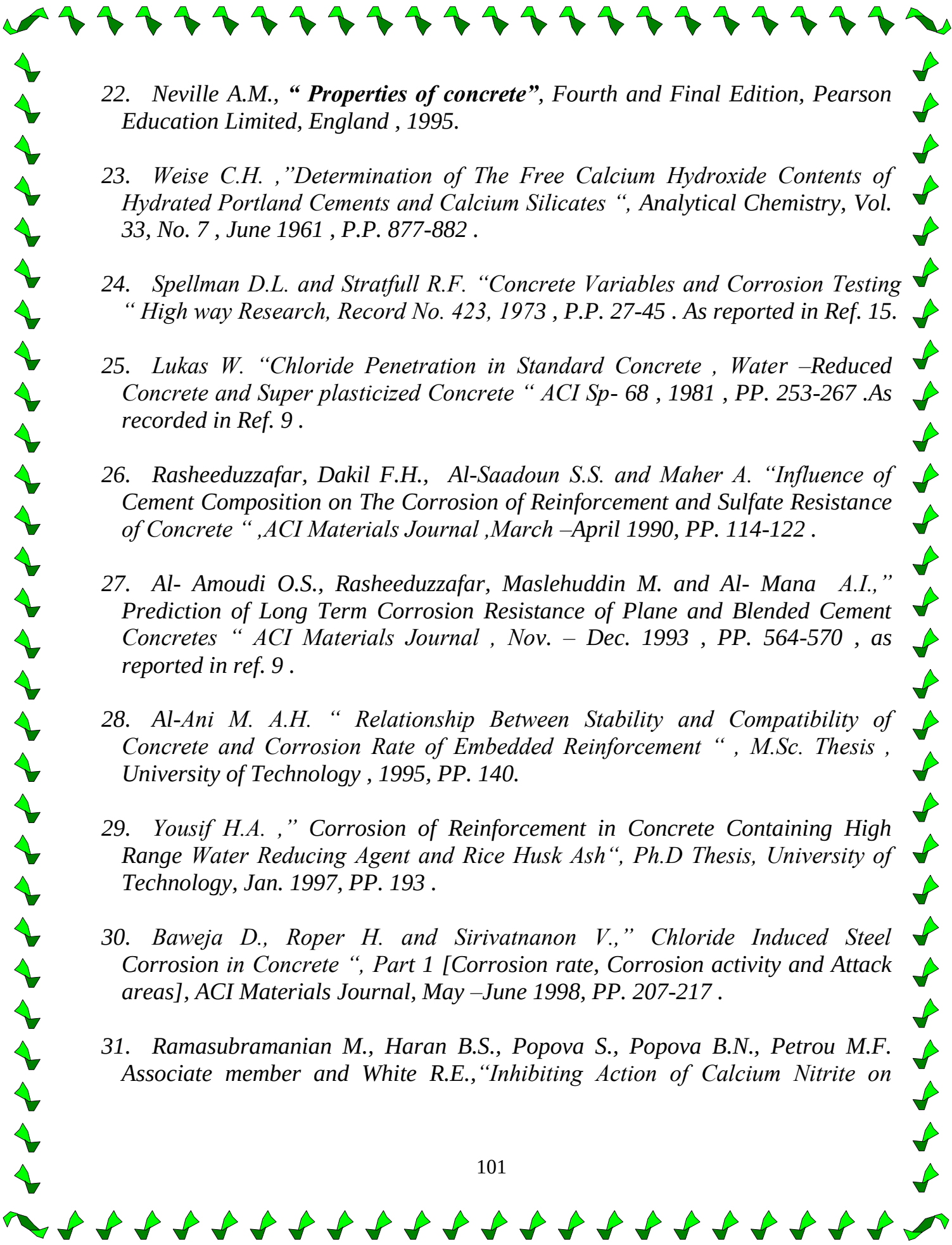
1. Using sodium benzoate in a concentration 2% by weight of cement as a corrosion inhibitor in reinforced concrete. This dosage is preferable to protect the steel reinforcement against corrosion and for the economical cost if the mixing ratio is 1:1.8:2.5 and may be more for the mixing ratio 1:2:4.
2. Using potassium dichromate as a corrosion inhibitor in concentration 2% by weight of cement in reinforced concrete. This dosage is preferable to protect the

3. steel reinforcement against corrosion and for the economical cost if the mixing ratio is 1:1.8:2.5 and may be more for the mixing ratio 1:2:4.
4. Using the SBR (Styrene – Butadiene – Rubber) admixture in concentration 25% by vol. of water or 12% by weight of cement, it is preferable in improving concrete properties and reducing corrosion rate with efficiency of 97%.
5. Mixing two types or more of corrosion inhibitors together in different concentrations and using them as one admixture added to the concrete mix, the cost of mixing depends on the cost of each inhibitor, availability and the action phase (cathodic inhibitor + anodic inhibitor) like MCI (migrating corrosion inhibitor).
6. Corrosion of steel in concrete is one of the biggest problems that face the civil engineering especially in the southern of Iraq and that affects the durability of constructions, because of the few studies in this regard in Babylon university / civil engineering department, the researcher recommends to investigate more in this regard .

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'ON ERROR GOTO 1
CLS
2 PRINT " "
3 PRINT " "
4 PRINT "
***
5 PRINT "  *** Program To Calculate Corrosion Current  ***
6 PRINT                                and Corrosion Rate
***

No. of Data = 154
FOR j data = 1 TO No. of Data
FOR I = 1 TO 6
12 READ I(I): PRINT I, I(I): I(I) = I(I) * .000001: NEXT
15 'PRINT I1, I2, I3, I4, I5, I6
16 READ V1, V2, V3
17 PRINT "V1="; V1, "V2="; V2, "V3="; V3
20 R1 = I(3) / I(1)
21 R2 = I(1) / I(4)
25 Ic1 = I(1) / (R1 + (4 * R2)) ^ .5
30 PRINT "Ic1="; Ic1
35 R1 = I(1) / I(4)
40 R2 = I(6) / I(4)
45 Ic2 = I(1) / ((R1 * R2) ^ 2 + (4 * R1)) ^ .5
50 PRINT " Ic2="; Ic2
51 Iav. = (Ic1 + Ic2) / 2
52 PRINT "Iav. ="; Iav.
53 C.R = Iav * .10189
54 PRINT "C.R="; C.R
55 M = V3 / V1
60 Rp1 = 2 * M * ((M ^ 2) - 1) * V1 / ((2 * M ^ 2) * (I(1) + I(4)) - (I(3) + I(6)))
65 PRINT "Rp1="; Rp1
70 M = V2 / V1
75 Rp2 = 2 * M * ((M ^ 2) - 1) * V1 / ((2 * M ^ 2) * (I(1) + I(4)) - (I(2) + I(5)))
80 PRINT "Rp2="; Rp2
REM
'1 RESUME NEXT
SLEEP
NEXT
N
DATA 0.4,0.8,1,0.1,0.5,1,0.06,0.09,0.12
DATA 0.5,0.6,1,0.6,0.9,1.5,0.06,0.09,0.12
DATA 0.2,0.6,1,1.6,3,6,0.06,0.09,0.12
DATA 1.1,1.5,1.8,0.3,0.9,2.5,0.06,0.09,0.12
DATA 0.8,1,1.3,0.3,1.1,2.2,0.06,0.09,0.12

```

**DATA 0.8,0.9,1.2,0.3,1.1,2.4,0.06,0.09,0.12**  
**DATA 1.5,2.2,5.2,2.3,2.6,0.06,0.09,0.12**

**N\***

**DATA 0.3,1,1.5,0.8,1.5,2.5,0.06,0.09,0.12**  
**DATA 0.8,1,1.6,0.8,1,2.5,0.06,0.09,0.12**  
**DATA 1,1,1.6,0.6,1.1,2.4,0.06,0.09,0.12**  
**DATA 0.9,1.3,2,1.1,1.7,2.5,0.06,0.09,0.12**  
**DATA 10,11,13.1,18.7,21.2,28,0.06,0.09,0.12**  
**DATA 14,13.5,15.8,13.5,20,25.5,0.06,0.09,0.12**  
**DATA 22,25,27.5,14,15.5,23,0.06,0.09,0.12**

**SB1 \***

**DATA 0.3,0.4,0.5,0.5,0.6,0.9,0.06,0.09,0.12**  
**DATA 0.8,1,1.1,0.9,2.7,4.8,0.06,0.09,0.12**  
**DATA 0.6,1.2,1.4,0.4,0.8,1.7,0.06,0.09,0.12**  
**DATA 0.8,1,1.2,0.7,1.7,3.5,0.06,0.09,0.12**  
**DATA 0.5,0.9,1.1,0.4,1.2,2,0.06,0.09,0.12**  
**DATA 0.5,0.9,1.7,0.3,1,1.3,0.06,0.09,0.12**  
**DATA 0.7,1.1,1.5,0.6,1.2,1.5,0.06,0.09,0.12**

**SB1**

**DATA 0.7,0.9,1.5,0.6,1.5,4,0.06,0.09,0.12**  
**DATA 0.9,1,1.3,0.8,1.5,2,0.06,0.09,0.12**  
**DATA 0.9,1,1.5,0.9,1.2,2.4,0.06,0.09,0.12**  
**DATA 0.9,1.2,2,0.2,1.2,2,0.06,0.09,0.12**  
**DATA 0.2,0.6,0.9,0.3,0.8,1.3,0.06,0.09,0.12**  
**DATA 1.5,2,2.6,1.2,2.6,3.5,0.06,0.09,0.12**  
**DATA 1.3,1.7,2.5,1,2.1,2.5,0.06,0.09,0.12**

**SB2\***

**DATA 2,2.5,3,0.3,0.7,2,0.06,0.09,0.12**  
**DATA 0.3,1.5,2.5,0.5,0.7,1.4,0.06,0.09,0.12**  
**DATA 0.9,1.5,2.6,1,2.5,5,0.06,0.09,0.12**  
**DATA 1.2,1.6,2.3,0.5,1.9,2.2,0.06,0.09,0.12**  
**DATA 0.4,0.8,1.5,0.4,0.6,1.3,0.06,0.09,0.12**  
**DATA 1,1.9,2.5,0.7,1.1,2.2,0.06,0.09,0.12**  
**DATA 0.9,1.5,2.7,0.6,1.5,2.5,0.06,0.09,0.12**

**SB2**

**DATA 0.8,2.6,4,0.9,1,2,0.06,0.09,0.12**  
**DATA 0.8,2.1,3,0.9,1,2,0.06,0.09,0.12**  
**DATA 0.7,1.5,2,0.5,0.9,1.5,0.06,0.09,0.12**

DATA 0.7,1.7,2,0.5,0.9,1.8,0.06,0.09,0.12  
DATA 1.1,2.1,2.5,0.6,0.8,1.2,0.06,0.09,0.12  
DATA 0.9,1.5,2.6,0.6,1.5,2.5,0.06,0.09,0.12  
DATA 0.7,1.9,2.5,0.5,1.1,2.3,0.06,0.09,0.12

**SB3 \***

DATA 0.6,1,2,0.4,0.8,1,0.06,0.09,0.12  
DATA 0.7,1.3,2,0.6,1,1.3,0.06,0.09,0.12  
DATA 0.8,1.2,1.8,0.7,1.1,1.5,0.06,0.09,0.12  
DATA 0.7,1.2,1.7,0.7,1,1.2,0.06,0.09,0.12  
DATA 0.9,1.3,1.9,0.8,1.3,1.5,0.06,0.09,0.12  
DATA 0.8,1.2,1.7,0.6,1.1,1.6,0.06,0.09,0.12  
DATA 1,1.5,2.1,0.7,1.2,1.6,0.06,0.09,0.12

**SB3**

DATA 0.6,1,2,0.9,1.2,1.9,0.06,0.09,0.12  
DATA 0.6,0.9,1,0.6,1.1,1.9,0.06,0.09,0.12  
DATA 0.7,0.9,1,0.4,0.8,1.8,0.06,0.09,0.12  
DATA 0.2,0.5,0.8,0.2,0.9,2.1,0.06,0.09,0.12  
DATA 0.5,0.9,1.5,0.2,0.6,1.6,0.06,0.09,0.12  
DATA 0.5,0.9,1.1,0.2,0.8,1.8,0.06,0.09,0.12  
DATA 0.5,0.8,1.5,0.4,0.9,1.9,0.06,0.09,0.12

**PD1 \***

DATA 0.5,0.9,1.2,0.3,0.5,1.2,0.06,0.09,0.12  
DATA 0.6,0.9,1.2,0.4,0.8,1.5,0.06,0.09,0.12  
DATA 0.9,1.1,1.4,1.6,1.8,2.6,0.06,0.09,0.12  
DATA 0.9,1.5,1.8,1,1.9,2.3,0.06,0.09,0.12  
DATA 70,80,90,30,32,39.1,0.06,0.09,0.12  
DATA 45.4,55.8,65,35,32.5,38.3,0.06,0.09,0.12  
DATA 55.3,57.5,75,37.5,38,39,0.06,0.09,0.12

**PD1**

DATA 0.8,1,1.8,1.5,2,2.5,0.06,0.09,0.12  
DATA 0.8,0.9,1.5,0.9,1.8,2.8,0.06,0.09,0.12  
DATA 0.8,0.9,1,0.4,0.7,1,0.06,0.09,0.12  
DATA 0.9,1.15,1.8,0.5,1.5,4,0.06,0.09,0.12  
DATA 0.7,1.3,1.8,0.5,0.9,1.5,0.06,0.09,0.12  
DATA 0.9,1.3,1.6,0.3,0.9,2.1,0.06,0.09,0.12  
DATA 0.8,1.5,1.9,0.4,1.1,2.1,0.06,0.09,0.12

**PD2 \***

DATA 1,2,2.7,0.8,2,2.8,0.06,0.09,0.12  
DATA 0.9,1.5,2.1,0.7,1,1.5,0.06,0.09,0.12

DATA 0.8,1.1,1.3,0.8,1.2,2.3,0.06,0.09,0.12  
DATA 1.4,1.8,2.1,0.8,1.1,2.3,0.06,0.09,0.12  
DATA 0.5,0.6,1.8,0.4,0.7,0.9,0.06,0.09,0.12  
DATA 0.7,1,1.5,0.3,0.5,0.7,0.06,0.09,0.12  
DATA 0.9,1,1.6,0.2,0.4,0.6,0.06,0.09,0.12

**PD2**

DATA 0.7,0.9,1.1,0.8,1.2,2,0.06,0.09,0.12  
DATA 0.6,0.9,1.5,0.9,1.2,1.5,0.06,0.09,0.12  
DATA 0.9,1.3,1.6,1,1.2,1.6,0.06,0.09,0.12  
DATA 0.7,1,1.2,0.6,1,1.8,0.06,0.09,0.12  
DATA 0.5,1.7,1.9,0.5,1.3,2.4,0.06,0.09,0.12  
DATA 0.3,0.5,0.7,0.3,0.7,2.5,0.06,0.09,0.12  
DATA 0.6,1.3,1.7,0.5,1.5,1.9,0.06,0.09,0.12

**PD3 \***

DATA 0.8,1.5,2,0.1,0.6,1,0.06,0.09,0.12  
DATA 0.8,1.7,2,0.6,2.2,2.5,0.06,0.09,0.12  
DATA 1,2.5,2.8,0.5,1,1.5,0.06,0.09,0.12  
DATA 2,2.4,3,1.2,2,2.5,0.06,0.09,0.12  
DATA 2,2.6,3,1,2,3.2,3.5,0.06,0.09,0.12  
DATA 1.5,2,3.5,2,2.5,3.1,0.06,0.09,0.12  
DATA 1.5,2.2,3,1.5,2.2,3.5,0.06,0.09,0.12

**PD3 \***

DATA 0.8,1.7,2.1,0.9,1.5,2,0.06,0.09,0.12  
DATA 0.6,0.9,1.5,0.5,1,2.5,0.06,0.09,0.12  
DATA 0.8,0.9,1.1,0.3,0.8,2.2,0.06,0.09,0.12  
DATA 1.8,2.1,2.7,0.8,1.8,3.4,0.06,0.09,0.12  
DATA 0.8,1,1.5,0.6,1.3,2.5,0.06,0.09,0.12  
DATA 1,1.7,1.9,0.8,2.3,3.5,0.06,0.09,0.12  
DATA 1,1.9,2.3,0.8,2.5,3.2,0.06,0.09,0.12

**SBR10 \***

DATA 0.4,0.5,0.6,0.4,0.8,1,0.06,0.09,0.12  
DATA 0.4,0.5,1.5,0.4,1.2,2.5,0.06,0.09,0.12  
DATA 40.2,50.2,55.37,40.9,46.5,0.06,0.09,0.12  
DATA 40,45,55.7,38,41.1,45.4,0.06,0.09,0.12  
DATA 38.2,43,55.5,31,32.5,35,0.06,0.09,0.12  
DATA 25.9,28.8,29.5,20.6,21.5,25.8,0.06,0.09,0.12  
DATA 23.5,25.5,26.5,20,21.5,21.9,0.06,0.09,0.12

**SBR10**

DATA 0.4,1.1,2,0.8,1.1,1.7,0.06,0.09,0.12  
DATA 1.2,1.4,2,0.9,1.3,1.8,0.06,0.09,0.12  
DATA 19,26,30.7,1.5,3.5,0.06,0.09,0.12  
DATA 26,40.5,49.8,9,45,51.5,0.06,0.09,0.12  
DATA 9,18,25,10.5,23.5,38.3,0.06,0.09,0.12  
DATA 5.5,16.8,20,11,15.5,26.8,0.06,0.09,0.12  
DATA 6.5,12.3,25,6,15.5,31.5,0.06,0.09,0.12

**SBR15 \***

DATA 3,3.3,3.6,0.6,1.7,2,0.06,0.09,0.12  
DATA 1.5,1.9,2.3,0.8,1.4,4.2,0.06,0.09,0.12  
DATA 2.2,2.4,3,1.5,2.2,10.6,0.06,0.09,0.12  
DATA 4.5,5.5,8,3.5,4.2,5,0.06,0.09,0.12  
DATA 2,2.5,5.7,1.6,1.9,5.2,0.06,0.09,0.12  
DATA 1.9,2.7,4,3.5,10,18.5,0.06,0.09,0.12  
DATA 2.5,3.7,4.5,4,15,16.5,0.06,0.09,0.12

**SBR15**

DATA 1,1.8,2.4,0.5,1.1,3,0.06,0.09,0.12  
DATA 2.5,3.2,4.2,0.5,1.4,4,0.06,0.09,0.12  
DATA 11,13,13.5,4.4,7,19,0.06,0.09,0.12  
DATA 8,9.3,10.5,2.7,4,12.8,0.06,0.09,0.12  
DATA 9.5,9.8,13.5,5.4,6.5,13,0.06,0.09,0.12  
DATA 13,14.3,15,13.5,15,19,0.06,0.09,0.12  
DATA 12.5,15,16.5,14,15.5,28.5,0.06,0.09,0.12

**SBR25 \***

DATA 0.5,1,2.1,0.3,0.9,2,0.06,0.09,0.12  
DATA 0.9,1,1.5,0.3,0.8,2,0.06,0.09,0.12  
DATA 1.5,2.8,3.2,0.7,0.9,1.8,0.06,0.09,0.12  
DATA 0.9,1.3,1.5,0.3,0.9,1.5,0.06,0.09,0.12  
DATA 0.8,1,1.3,0.2,0.9,1.8,0.06,0.09,0.12  
DATA 0.5,0.7,1,0.3,0.6,1.3,0.06,0.09,0.12  
DATA 0.6,0.9,1.1,0.5,0.8,1.5,0.06,0.09,0.12

**SBR25**

DATA 0.9,1.5,2.2,0.1,0.3,0.4,0.06,0.09,0.12  
DATA 1.1,1.6,2.3,0.4,0.5,0.6,0.06,0.09,0.12  
DATA 0.7,0.9,1.2,0.3,1.2,2,0.06,0.09,0.12  
DATA 0.2,0.4,1,0.3,0.8,1.2,0.06,0.09,0.12  
DATA 0.2,0.4,0.6,0.3,0.9,1.8,0.06,0.09,0.12  
DATA 0.2,0.8,2.5,0.3,0.8,1.4,0.06,0.09,0.12  
DATA 0.3,0.7,1.7,0.5,0.9,1.5,0.06,0.09,0.12

\*\*\*\*\*

### Calculation sample :

To calculate the average of corrosion current ( $I_{corr.av.}$ )

#### **Note:**

$I_1$ : the current in Amp. at  $\Delta E_1 = 0.060$  volt ,  $V_1$

$I_2$ : the current in Amp. at  $\Delta E_2 = 0.090$  volt ,  $V_2$

$I_3$ : the current in Amp. at  $\Delta E_3 = 0.120$  volt ,  $V_3$

$I_4$ : the current in Amp. at  $\Delta E_4 = -0.060$  volt

$I_5$ : the current in Amp. at  $\Delta E_5 = -0.090$  volt

$I_6$ : the current in Amp. at  $\Delta E_6 = -0.120$  volt

$I_{corr}$  : corrosion current (Amp.)

C.R: corrosion rate (Kg/sec.m<sup>2</sup>)

$R_p$  : polarization resistance (volt/Amp.)

### Barnart Method:

A)  $2\Delta E = 120$  mv ,  $\Delta E = 60$  mv ,  $-\Delta E = -60$

$R_1 = I_3 / I_1$  ,  $R_2 = I_1 / I_4$

$$I_{corr.1} = I_1 / (R_1 + 4R_2)^{0.5}$$

B)  $\Delta E = 60$  mv ,  $-2\Delta E = -120$  mv ,  $2\Delta E = 120$  mv

$R_3 = I_1 / I_4$  ,  $R_4 = I_6 / I_4$

$$I_{corr.2} = I_1 / ((R_3 * R_4)^2 + 4R_3)^{0.5}$$

$$I_{corr.av.} = (I_{corr.1} + I_{corr.2}) / 2$$

Corrosion Rate (C.R) =  $I_{corr.av.} * eq. wt. / (96500 * A)$

***A : surface area of the steel wire(0.5 cm in diameter) that imbedded in concrete (m<sup>2</sup>)***

***eq. wt. : equivalent weight of steel (kg)***

***96500 : faraday constant***

$$Rp_1 = \frac{2 * M_1 * (M_1^2 - 1) * V_1}{2 * M_1^2 * [I_1 + I_4] - [I_3 + I_6]} \quad \text{where } M_1 = \frac{V_3}{V_1} = 2$$

$$Rp_2 = \frac{2 * M_2 * (M_2^2 - 1) * V_1}{2 * M_2^2 * [I_1 + I_4] - [I_2 + I_5]} \quad \text{where } M_2 = \frac{V_2}{V_1} = 1.5$$

### **For example:**

***The data of sample N (without micro cracks )at age 12 weeks of immersing in 3.5% NaCl solution.***

***I<sub>1</sub> = 1.5 \*10<sup>-6</sup> Amp. at ΔE<sub>1</sub>= 0.06 volt. , V<sub>1</sub>***

***I<sub>2</sub> = 2.0 \*10<sup>-6</sup> Amp. at ΔE<sub>2</sub>= 0.09 volt. , V<sub>2</sub>***

***I<sub>3</sub> = 2.5 \*10<sup>-6</sup> Amp. at ΔE<sub>3</sub>= 0.12 volt. , V<sub>3</sub>***

***I<sub>4</sub> = 2.0 \*10<sup>-6</sup> Amp. at ΔE<sub>4</sub>= -0.06 volt.***

***I<sub>5</sub> = 2.3 \*10<sup>-6</sup> Amp. at ΔE<sub>5</sub>= -0.09 volt.***

***I<sub>6</sub> = 2.6 \*10<sup>-6</sup> Amp. at ΔE<sub>6</sub>= -0.12 volt.***

***I<sub>corr.1</sub> = 6.7 \*10<sup>-7</sup> Amp. calculated by the QB program***

***I<sub>corr.2</sub> = 7.5 \*10<sup>-7</sup> Amp.***

***I<sub>corr.av</sub> = 7.24 \*10<sup>-7</sup> Amp.***

$$A = (0.005 * 22/7 * 0.18) + (0.0025)^2 * 22/7$$

$$A = 0.002847 \text{ m}^2$$

$$\text{Eq. wt. for steel} = 56/2 = 28$$

$$C.R = 7.24 * 10^{-7} \text{ Amp.} * (28 / (96500 * 0.002847))$$

$$C.R = 7.24 * 10^{-7} \text{ Amp.} * 0.10189$$

$$C.R = 7.382 * 10^{-8} \text{ kg / sec.m}^2$$

$$Rp_1 = 31441.05 \text{ volt/amp. at } m=2$$

$$Rp_2 = 19650.66 \text{ volt/amp. at } m=1.5$$



جمهورية العراق  
وزارة التعليم العالي والبحث العلمي  
جامعة بابل  
كلية الهندسة  
قسم الهندسة المدنية

# تأثير استخدام مثبطات التآكل على خواص الخرسانة و مدى فاعليتها

رسالة مقدمة  
إلى كلية الهندسة في جامعة بابل  
كجزء من متطلبات نيل درجة الماجستير  
في علوم الهندسة المدنية

من قبل  
**عبيد محمد عبد الأمير الأسدي**  
بكالوريوس هندسة مدنية 1998 / جامعة بابل  
دبلوم عالي سيطرة نوعية على مواد البناء 2001 / الجامعة التكنولوجية

بإشراف  
أ.م.د. مهدي صالح عيسى  
م.د. فلاح كيمي مطلوب

# الخلاصة

إن التآكل في حديد تسليح الخرسانة بتأثير أملاح الكلوريدات يعتبر من القضايا الرئيسية المهمة التي تواجه الهندسة المدنية والمتعلقة بديمومة الخرسانة، وعلى الرغم من وجود العديد من الطرق المختلفة المستخدمة لحماية حديد التسليح من التآكل إلا أنه لا يزال التآكل يشكل مشكلة كبيرة بسبب كلفة إعادة تأهيل المنشأ.

وجد إن استخدام مثبتات التآكل أو مستحلب SBR في إنتاج خرسانة الاسمنت البورتلاندي الاعتيادي يحسن من مقاومة الخرسانة المسلحة ضد التآكل من خلال تفاعل المثبط مع المحيط وتشكيل طبقة من نواتج التفاعل تحمي حديد التسليح من التآكل إضافة إلى فاعلية هذه المواد في تقليل النفاذية والامتصاص للخرسانة.

وفي هذا البحث تم دراسة استخدام كل من بنزوات الصوديوم ودايكرومات البوتاسيوم كمثبتات انودية بثلاث نسب ( 1% , 2% , و 3% من وزن الاسمنت) إضافة إلى استخدام محلول SBR (ستايرين- بيوتا دين- مطاط) بثلاث نسب أيضاً (10% , 15% , و 25% من حجم ماء الخلطة) و مدى تأثيرها على خواص الخرسانة : كمقاومة الانضغاط، مقاومة شد الانشطار، مقاومة الانثناء و الامتصاص. كما وتم دراسة تأثير هذه المواد بهذه النسب على منع أو تأخير حصول التآكل لحديد التسليح في الخرسانة المسلحة من خلال فحص مقاومة الاستقطاب بطريقة النقاط الثلاثة للحديد ومعرفة نسب التآكل وفحص المقاومة الكهربائية للخرسانة .

تم تهيئة 220 نموذج متضمناً 99 مكعب بإبعاد (15\*15 سم) , 33 مكعب بإبعاد (10\*10 سم), 33 اسطوانة بإبعاد (15\*10 سم) , 33 منشور بإبعاد (10\*10\*40 سم) و 22 نموذج خرساني مسلح مستخدمين أنواع مختلفة من الخلطات الخرسانية مع نسبة خلط 1: 1.8 : 2.5 و

نسبة الماء الى الاسمنت 0.48 . جميع النماذج الخرسانية تم إنضاجها في الماء الاعتيادي لمدة 28 يوم بعدها تم وضع النماذج الخرسانية المسلحة فقط الـ 22 في محلول مائي حاوي على أملاح كلوريدات الصوديوم NaCl بتركيز 3.5% (مقارب لتركيز ماء البحر) لمدة ثلاثة أشهر. نصف عدد هذه النماذج تم تعريضه إلى 10% من الحمل الأقصى لكل خلطة بعد ستة أسابيع من الغمر في المحلول الملحي لغرض عمل تشققات شعرية في النماذج الخرسانية المسلحة لتسريع عملية التآكل.

نتائج الفحوص جاءت بالاستنتاجات التالية : استخدام بنزوات الصوديوم ودايكرومات البوتاسيوم بتركيز 2% من وزن الاسمنت سبب انخفاض في مقاومة الانضغاط بعمر 28 يوم بمقدار

15% و 4% على التوالي , لكن في الاعمار المتأخرة كانت هناك زيادة في مقاومة الانضغاط حوالي 7% و 11% بعمر 90 يوم على التوالي (عملت كمبطين للتفاعلات). وأعطى هذان المضافان تحسن وزيادة في كل من الخواص التالية: مقاومة شد الانشطار بمقدار 17% لبنزات الصوديوم و 21% لدايكرومات البوتاسيوم, زيادة في مقاومة الانتشاء بمقدار 18% و 20% على التوالي, كذلك سببت هذه المضافات انخفاض كبير في خاصية الامتصاص بمقدار 38% و 42% على التوالي مع انخفاض بالكلفة الاقتصادية بمقدار 12% لكل منهما وكانت كفاءة المثبط 98% لكل منهما أيضاً .

أما نتائج استخدام مستحلب الـ SBR بتركيز 25% من حجم ماء الخلط فقد أعطى تحسن كبير في جميع الخواص الميكانيكية حيث كانت الزيادة في : مقاومة الانضغاط بمقدار 8%, 11% و 7% للأعمار 28, 60 و 90 يوم على التوالي, مقاومة شد الانشطار ومقاومة الانتشاء بمقدار 37% كما وسجل أعلى انخفاض في الامتصاص بمقدار 77% مع انخفاض في الكلفة بمقدار 13% وكانت كفاءته كمثبط 97%.

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2008/ 6 / 5