

إقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

The Influence of Surface Coating Materials In Reducing The Corrosion of Steel Reinforcement in Concrete

تأثير مواد الطلاء الأوكسية في تقليل صدأ الحديد في الخرسانة

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The Influence of Surface Coating Materials In Reducing The Corrosion of Steel Reinforcement in Concrete

تأثير مواد الطلاء الأوكسيلية في تقليل صدأ الحديد في الخرسانة

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ محمد زياد محمد النيرب لنيل درجة الماجستير في كلية الهندسة قسم الهندسة المدنية- تصميم وتأهيل المنشآت وموضوعها:

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The Influence of Surface Coating Materials In Reducing The Corrosion of Steel Reinforcement in Concrete

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق،،،

مساعد نائب الرئيس للبحث العلمي والدراسات العليا

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.....
أ.د. فؤاد علي العاجز



ABSTRACT

This study examines the impact of Epoxy materials to minimize the corrosion of steel reinforcement through test program within three types of Epoxy materials that have been painted on the rebar and choose the best type of surface coating in minimizing the corrosion rate of steel reinforcement. It also studies of the impact of this surface coating on the bonding strength between the rebar and the concrete on the one hand, as well as their impact on the flexural strength on the other hand.

The study seeks to fill the gap mentioned by suggesting more methods to improve the bonding between steel reinforcement and concrete.

Testing program was set up on the two main phases. The first phase included tests to choose the best material from surface coating within three types of materials are used and the most prevalent market, while the second one covered making the necessary improvements to increase the flexural strength in addition to increasing the bending forces.

The corrosion rate result for reinforcement in beams without surface coating after 70 days was more than 50% from its weight. However, the corrosion rate result for reinforcement in beams with surface coating type (C) "Polyurethane resin" after 70 days was 1.6 % from its weight that is the best surface coating. Experiments show the need to use surface coating and admixture to minimize the corrosion rate and improve the flexural strength and bonding between concrete and steel reinforcement.

ملخص البحث:

تبحث هذه الدراسة في تأثير المواد الأوكسية على التقليل من صدأ الحديد من خلال برنامج تجارب للعديد من العينات ضمن ثلاثة أنواع من المواد الأوكسية التي تم طلائها على حديد التسليح واختيار أكثر الأنواع نجاعة في التقليل من نسبة حدوث صدأ الحديد وكذلك دراسة تأثير هذه المادة على قوى الترابط بين حديد التسليح وبين الخرسانة من جهة وكذلك تأثيرها على قوى الانحناء من جهة أخرى.

تسعى هذه الدراسة لسد الفجوة المذكورة عن طريق اقتراح أكثر من طريقة لتحسين قوى الترابط بين الحديد وبين الخرسانة.

تم انشاء برنامج الفحوصات على مرحلتين اساسيتين حيث شملت المرحلة الاولى الفحوصات لاختيار أفضل مادة أوكسية من ضمن ثلاثة مواد تم استخدامها والاكثر انتشارا بالسوق أما المرحلة الثانية فشملت اجراء التحسينات اللازمة لزيادة قوى الترابط بين الحديد وبين الخرسانة وكذلك زيادة قوى الانحناء.

دلت النتائج على أن معدل صدأ الحديد في العينات بدون استخدام دهان المواد الأوكسية على الحديد بعد 70 يوم كانت أكثر من 50% من وزنها بالرغم أن معدل صدأ الحديد في العينات مع استخدام نوع (C) من المواد الأوكسية بعد 70 يوم كانت 1.6% من وزنها والتي تدل على أن هذا النوع هو أفضل أنواع المواد الأوكسية استخداماً كما وأكدت النتائج على ضرورة استخدام طريقة المواد الأوكسية مع الاضافات للتقليل من صدأ الحديد وتحسين قوى الانحناء وقوى الترابط بين الخرسانة وحديد التسليح.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL BACHGROUND

Reinforced concrete is considered the most frequently used structural material, not only it has good mechanical proprieties after hardening, easy to use, etc. but also its dominant advantage that it is considered as an economic structural material.

In recent years, the common point view about concrete as a durable maintenance-free construction material has been changed. The insufficient consideration of durability during the design process, the inadequate execution and maintenance are some reasons that reinforced concrete structures did not perform as well as it was expected (**Kovacs, 2000**).

Corrosion of concrete reinforcing steel is considered one of the most serious problems facing the reinforced concrete structures. More than 80% of reinforced concrete structural damages around the world are caused by the corrosion of steel (**Franciskovic et al, 2006**).

The problem of reinforced concrete corrosion is consider also as an economical problem, some countries like U.S. and U.K. spent hundreds of millions of dollars yearly for repairing structural damages resulting from reinforced concrete corrosion problem. This problem is clearly manifested in many other courtiers, especially in the Middle East Area (**El-Reedy, 2008**).

1.2 PROBLEM STATEMENT

Gaza strip is costal area which has 40 Km coastline on the Mediterranean Sea. This location with the associated environmental conditions may have a considerable influence on the deterioration of existing concrete structures, especially steel corrosion.

Although the problem of reinforced concrete corrosion common appears in Gaza Strip buildings, few researches had studied this problem. Some factors like inadequate concrete cover, quality of water or admixtures uses in the mix design of concrete, seashore climate affects, etc. may be some factors causing this problem.

A survey of forty case studies for assessment of existing damaged structures in Gaza Strip showed that the main cause of defects in existing buildings was reinforcement corrosion, with about 31% of the causes (**Abu Hamam, 2008**).

1.3 RESEARCH AIM AND OBJECTIVES

The main aim of the current study is to minimize the corrosion of the reinforcement by using surface coating materials on bars of steel reinforcement. The objectives of this research are:

1. Identify the effects of several surface coating materials on the mechanical properties of concrete such as flexural capacity, tensile strength of steel and bonding between surface coating materials and concrete materials.
2. Identify the effects of several surface coating materials on the physical properties of concrete such as corrosion rates.
3. Identify the best surface coating which can effectively be used to minimize the corrosion of steel reinforcement.

1.4 METHODOLOGY

To achieve the research objectives the following methodology was followed:

- **Literature review.**

In this section previous research works related to the subject of the undertaken research were reviewed to identify main concern aspects of the problem.

- **Select different types of surface coating to be used in steel reinforcement**

We use three types of surface coating (Acrylic polymers, Epoxy polymers, Polyurethane resin) for decreasing corrosion rate .

- **Conduct experimental program**

The experimental program is developed based on full understanding of the problem. It is designed to achieve the research problem.

- **Obtain the best surface coating which minimizes the corrosion of steel reinforcement.**

Regarding to the test program we will choose the best type of surface coating which minimize the corrosion rate in steel reinforcement.

- *Studying the effect of surface coating material on the bonding between concrete and steel reinforcement.*

After choosing the best surface coating we examine the type of surface coating and its effects on bonding between the concrete and steel reinforcement.

- *Studying the effect of surface coating material on the flexural strength of concrete.*

After choosing the best surface coating we examine the type of surface coating and its effects on the flexural strength of concrete.

- *Improve the flexural with surface coating.*

We use different methods for improving the flexural strength in concrete.

- *Improve the bonding between concrete and reinforcement with surface coating.*

We use different methods for improving the bonding between the surface coating and steel reinforcement.

1.5 THESIS ORGANIZATION

The thesis contains five chapters organized as follows:

Chapter 1(Introduction)

This chapter gives a general background about the reinforced concrete structures Corrosion problem, research problem and scope, objectives and methodology used to achieve the research objectives. Also it describes the structure of the thesis.

Chapter 2 (Literature Review)

This chapter discusses the concept of corrosion of steel in concrete, its mechanism, types, causes and structural effects.

Chapter 3 (Materials and Experimental Investigation)

This chapter reviews the experimental investigation, characterization of concrete materials, surface coating materials and corrosion initiation set up.

Chapter 4 (Test Results and Analysis)

This chapter discusses the results of first stage of test program regarding to corrosion rate and bonding test results and discusses the results of second stage of test program regarding to the flexural and bonding tests.

Chapter 5 (Conclusion and Recommendation)

This chapter includes the concluded remarks, main conclusions and recommendations drawn from this research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Corrosion is an electrochemical process where a metal undergoes a reaction with chemical species in the environment to form a compound. The chemical species are principally oxygen and water. The corrosion of steel is the process that steel is oxidized at the anode and the electrons are released and flow to the cathode for the oxygen reduction reaction (Zhang and Mailvaganam, 2006).

In the case of steel embedded in concrete, the concrete is a porous material containing water in the voids due to the process of curing or because of rainy weather or any weather with high relative humidity. Thus, the concrete will contain humidity, which is a common cause of corrosion. Although, it is not necessary that steel bars embedded in concrete to be corroded, this happens because concrete has a high concentration of the oxides calcium, sodium, and magnesium. These oxides produce hydroxides that have a high alkalinity when water is added (pH 12–13). This alkalinity will produce a passive layer on the steel reinforcement surface; consisting of oxides and hydroxides for iron and part of cement. This layer is dense and prevents the occurrence of corrosion (El-Reedy, 2008).

This passive layer is, however, can be broken when carbon dioxide enters the concrete and reaches the steel-concrete interface. This is called carbonation. Another powerful destroyer of the steel passive layer is the present of chloride salt in concrete. Chloride ions are introduced into the concrete by marine spray, industrial brine, deicing agents, and chemical treatments. These chloride ions can reach the reinforcing steel by diffusing through the concrete or by penetrating cracks in the concrete (Al-Ostaz, 2004).

After the passive layer is broken down, rust will appear instantly on the steel bar's surface. The chemical reactions are the same in cases of carbonation or of chloride attack. During the corrosion process, current flows in a closed loop. In addition to electrons flowing through the steel, an external current is carried through the pore solution of the concrete by the movement of charged ions to complete a closed loop. The external current consists of negatively charged hydroxyl ions moving from the cathode to the anode, and positively

charged ferrous ions moving from the anode to the cathode (Kepler, 2000). Figure 2.1 shows a diagram of rust formation on steel reinforcement in concrete (Al-Ostaz, 2004).

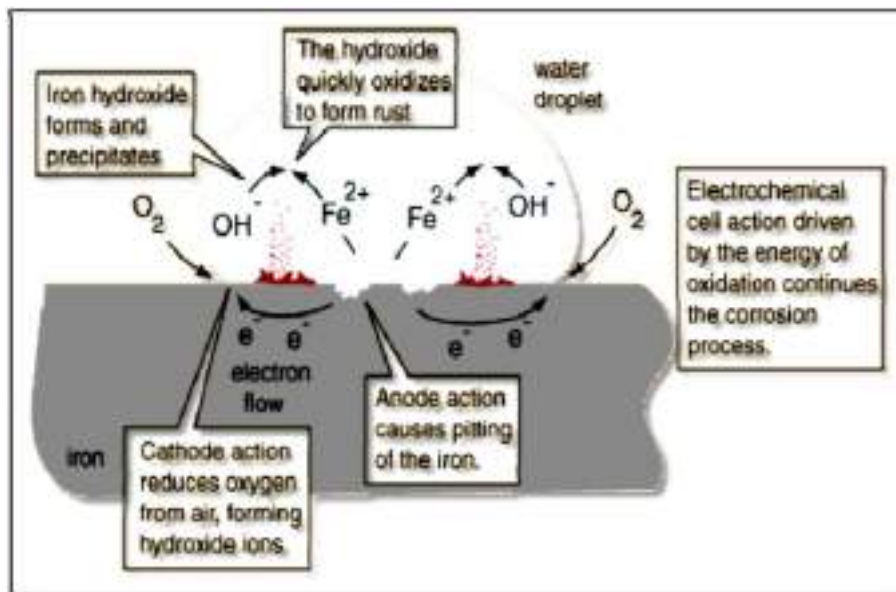


Figure 2.1 Diagram of rust formation on steel reinforcement in concrete (Al-Ostaz, 2004).

2.2 CORROSION ELECTROCHEMISTRY

The terms ‘anode’ and ‘cathode’ discussed in this chapter come from electrochemistry which is a basic of Daniell cell. Daniell cell illustrate how chemical reaction produce electricity. The cell is composed to two “half cells” copper in copper sulphate and zinc in zinc sulphate. The total voltage of the cell is determined by the metals used and by the nature and composition of the solutions (Broomfield, 1997).

What is happening is that in each half cell the metal is dissolving and ions are precipitating. Copper is more resistant to this reaction than zinc so when connect the two solutions by a semi-permeable membrane (which allows charge to be exchanged through it but the ions cannot pass through). When connecting the two metals with a wire, the zinc goes into solution and the copper from the copper sulphate solution plates out (is deposited) on the copper electrode.

Half-cell potentials are a function of concentration as well as the metal and the solution. A more concentrated solution is generally more corrosive than a dilute one, so a current will flow in a cell made up of a single metal in two different concentrations of the same solution (Broomfield, 1997).

When a metal such as steel is in an electrolyte (this is an aqueous solution which can carry ions such as water with some rock salt in solution) then a corrosion cell can be formed. A part of the steel in the electrolyte forms the anode and another part of the steel also in the same electrolyte forms the cathode. Corrosion in this would be occurring at all the anode points which are dispersed around the steel. This gives the appearance of general or uniform corrosion (**Chess, 1998**).

It can be considered the corrosion of steel in concrete as a concentration cell. That is the co-existence of passive and corroding areas on the same reinforcement bar forming a short-circuited galvanic cell with the corroding area as the anode and the passive surface as the cathode. The voltage of such a cell can reach as high as 0.5V or more, especially where chloride ions are present. The resulting current flow (which is directly proportional to the mass lost by the steel) is determined by the electrical resistance of the concrete and the anode and cathode reaction resistance (**Newman, 2003**).

Figure 2.2 is a schematic of micro-corrosion cells on steel's surface, regions labeled (A) are the anodic areas where metal is dissolving, regions labeled (C) are cathodic areas where no corrosion is occurring. The arrows represent the current flow (**Chess, 1998**).

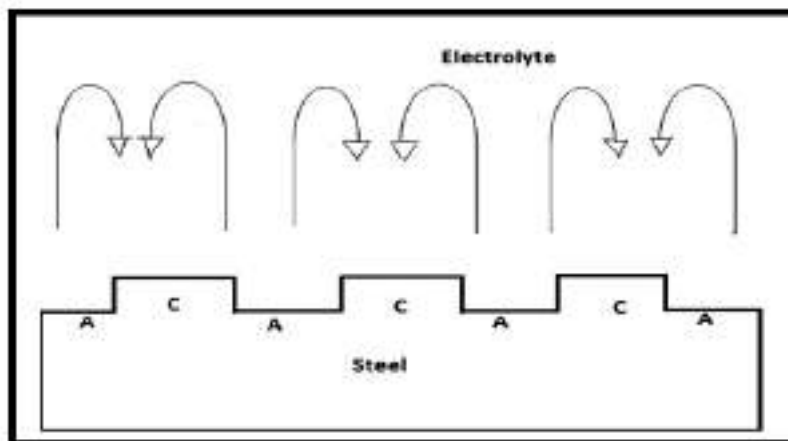


Figure 2.2 Schematic of Micro- Corrosion in Steel Reinforcement (**Chess, 1998**).

2.3 TYPES OF CORROSION

2.3.1 Black Rust

This type of corrosion occurs when there is a large distance between anode and cathode locations and also if oxygen is not available. This usually occurs in cases of buildings immersed in water or when a protective layer prevents presence of oxygen (**Chess, 1998**).

In this type of corrosion (known as ‘black’ or ‘green’ rust due to the color of the liquid seen on the rebar when first exposed to air after breakout) the iron as Fe^{+2} stay in solution. This means that there will be no expansive forces to crack the concrete so corrosion may not be detected by cracking and spalling of the concrete and the reinforcing steel may be severely weakened before corrosion is detected (**Broomfield, 1997**).

2.3.2 Pit Formation

Corrosion in steel bars starts by forming a small pit, after that, the number of pits will be increased with time and then the combination of these pits causes a uniform corrosion on the surface of the steel bars. This is obvious in the case of a steel reinforcement exposed to carbonation or chloride effects. The uniform corrosion and pitting corrosion are illustrated in Figures 2.3- 2.4.

Many chemical reactions describe the formation of pits and, in some cases, these equations are complicated. But the general principle of pit corrosion is very simple, especially in cases of chloride attacks(**Newman, 2003**).



Figure 2.3 Uniform Corrosion (**Newman, 2003**).

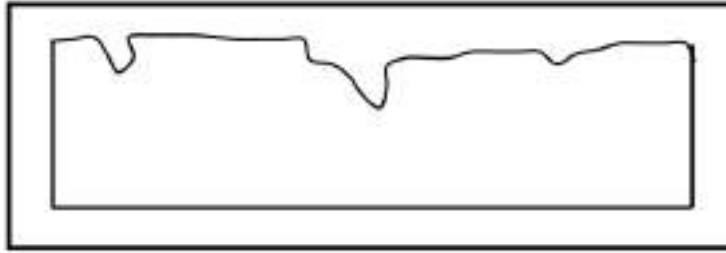
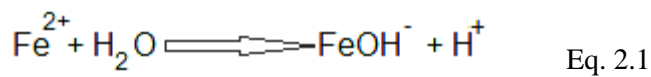


Figure 2.4 Pitting Corrosion (**Newman, 2003**).

At some suitable site on the steel surface (often thought to be a void in the cement paste or a sulphide inclusion in the steel), the passive layer is more vulnerable to attack and an electrochemical potential difference attracts chloride ions. Corrosion is initiated and acids are formed; hydrogen sulphide from the sulphide (MnS) inclusion and HCl from the chloride ions if they are present. Iron dissolves and the iron in solution reacts with water (Equations 2.1-2.2).



Eq. 2.2

A pit forms, rust may form over the pit, concentrating the acid (H⁺), and excluding oxygen so that the iron stays in solution preventing the formation of a protective oxide layer and accelerating corrosion (**Broomfield, 1997**).

2.3.3 Bacterial Corrosion

Bacteria are another cause of corrosion. Because bacteria exist in soil, the foundation is considered the main element exposed to this type of corrosion. These bacteria will convert sulfur and sulfides to sulfuric acid. The acid will attack the steel and then cause initiation of the corrosion process. Other bacteria that attack the sulfide exist in the steel reinforcement FeS due to reactions. This type of corrosion is often associated with a smell of hydrogen sulfide (rotten eggs) and smooth pitting with a black corrosion product when steel bars are exposed to soil saturated with water (**Newman, 2003**).

2.3.4 Stay Current Corrosion

Stray current corrosion (such as a nearby pipeline or DC electric railway lines) is a type of localized corrosion caused by the electrical circuits to the steel reinforcement. Corrosion takes place at the anode, the point where the current leaves the metal to return to the power source or to ground. Stray current corrosion is difficult to diagnose since the point of corrosion does not necessarily occur near the current source (**Singley, 1985**)

2.4 CAUSES OF CORROSION

There are two main reasons for corrosion of steel in concrete: chloride attack and carbon dioxide penetration, which is called the carbonation process. There are also other reasons, such as the presence of certain chemicals inside the concrete and voids that affect the steel. Moreover, some acids, such as sulfate, will attack the concrete and cause concrete deterioration and corrosion of steel and then break the concrete alkalinity around the steel bars (**Newman, 2003**). However, significant corrosion does not occur for steel in concrete that is either very dry or continuously saturated, because both air and water are necessary for corrosion to be initiated. Steel will remain corrosion-resistant in concrete if the concrete cover prevents air and water from reaching the embedded reinforcement (**Kepler, 2000**).

2.3.1. Chloride Attack

Chlorides can attack concrete from more than one source. The first source is from inside the concrete during the casting process, the second is to move to concrete from outside to inside. When casting takes place, chlorides exist in concrete as a result of the following: (**Kepler, 2000**).

1. Using seawater in the concrete mix.
2. Aggregate that contains chlorides that can be washed well.
3. Using additives that have higher chloride content than that defined in the specification.
4. Water used in the concrete mix that has a higher number of chloride ions than that allowed in the specifications.

Also chlorides can propagate inside concrete from the external environment by:

- 1- Concrete exposed to seawater spray or continuous exposure to salt water.

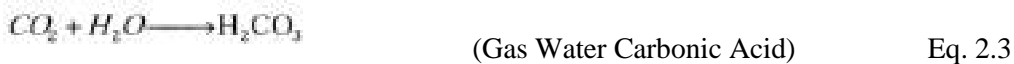
2- Using salt to melt ice.

3- Presence of chlorides in chemical substances that attack the concrete structure, such as salt storage.

The effect of chloride salts depends to some extent on the method of addition. If the chloride is present at the time of mixing, the calcium aluminates (C3A) phase of the cement will react with the chloride to some extent, chemically binding it as calcium chloroaluminate. In this form, the chloride is insoluble in the pore fluid and is not available to take part in damaging corrosion reactions. The ability of the cement to complex the chloride is limited, however, and depends on the type of cement. Sulfate resisting cement, for example, has a low C3A content and is therefore less able to complex the chlorides. In any case, experience suggests that if the chloride exceeds about 0.4% by mass of cement, the risk of corrosion increases. This does not automatically mean that concretes with chloride levels higher than this are likely to suffer severe reinforcement corrosion. This depends on the permeability of the concrete and on the depth of carbonation in relation to the cover provided to the steel reinforcement

2.3.2. Carbonation

Carbonation is the result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Like many other gases carbon dioxide dissolved in water to form an acid. Unlike most other acids the carbonic acid does not attack the cement paste, but just neutralizes the alkalis in the pore water, mainly forming calcium carbonate that lines the pores as given in Equation 2.3 and 2.4



Calcium hydroxyl exists in the concrete and increases the concrete alkalinity that maintains a pH level of 12–13; after carbonates attack inside the concrete and spread, it will form calcium carbonate. As seen in equation 2.3 and 2.4 the value of pH will be reduced to the level that causes the corrosion to the steel reinforcement (**Zhang and Mailvaganam, 2006**). Carbonation damage occurs most rapidly when there is small concrete cover over

the reinforcing steel. Carbonation can occur even when the concrete cover depth to the reinforcing steel is high. This may be due to a very open pore structure where pores are well connected together and allow rapid CO₂ ingress. It may also happen when alkaline reserves in content, high water cement ratio and poor curing of the concrete (**Broomfield, 1997**).

2.5 CORROSION RATE

The corrosion rate is considered the most important factor in the corrosion process from a structural-safety perspective and in the preparation of the maintenance program for the structure. This factor is considered an economic factor of structural life, when the corrosion rate is very high, the probability of structure failure will increase rapidly and structural safety will be reduced rapidly (**Zhang and Mailvaganam, 2006**).

During the last decades, many physical and mathematical models have been introduced to estimate the time of corrosion initiation and propagation. The first numerical model of this kind was developed by Collepardi, in which he employed the

Fick's second law of diffusion and indicated that diffusion coefficient is one of the most important parameters in service life prediction. Tutti's model was one of the first attempts to predict the service life of RC structures.

As shown in Figure 2.5 the concept of this model is to divide the service time of the structure into T_0 (t_{init}), as the time to corrosion initiation, and T_i (t_{prop}), as the time of corrosion propagation until failure occurs.

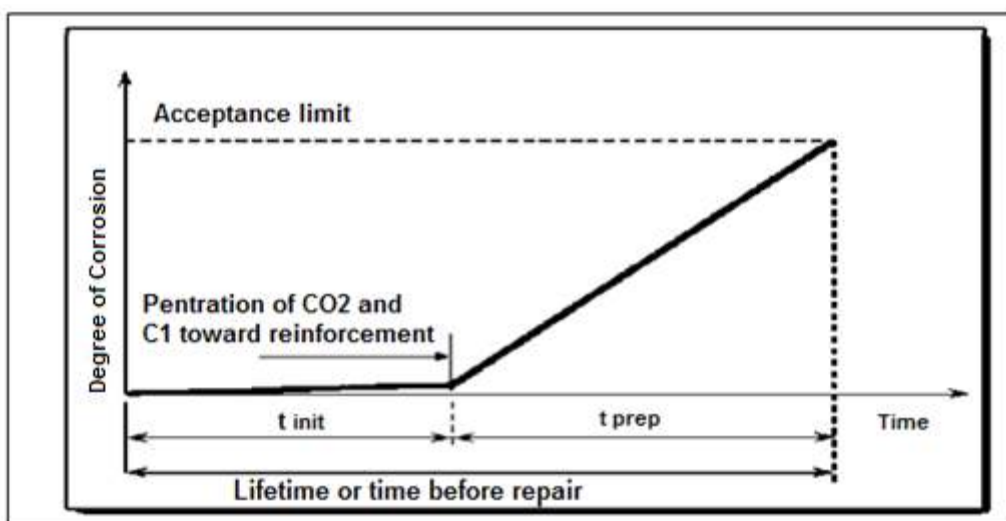


Figure 2.5 Tutti's Model for Corrosion Process of Steel in Concrete (**Broomfield, 1997**).

On the other hand, typical corrosion rates of steel in various environmental situations have been reported in recent years. The average corrosion rate, Cr, for passive steel in concrete attacked by chlorides is about 100µm/year. The typical corrosion rate, Cr, is a time-invariant random variable described by a lognormal distribution with mean Cr of 50 µm/year, and coefficient of variation Vcr of 50%.

Because the corrosion rate changes with environment, no accurate data are available to predict the real corrosion rate. However, there are many empirical formulas to calculate the corrosion rate, these formulas changes according to the corrosion reasons, for example in the case of carbonation attack. Table 2.1 gives values of the corrosion rate according to the relative humidity.

Table 2.1: Corrosion Rate According to Relative Humidity (**Broomfield, 1997**).

Cement Content (c), ^a CR, ^b and t _p ^c									
Relative Humidity (%)	40	50	60	70	80	90	95	98	100
C (CEM1b)	460	460	460	460	485	535	570	595	610
C (CEM2b)	360	360	360	360	380	420	445	465	480
C (CEM3b)	340	340	340	340	355	395	420	440	450
C (CEM4b)	230	230	230	230	240	265	285	295	305
CR	0.3	0.3	0.3	2	5	10	20	50	10
t _p	330	330	330	50	20	10	5	2	10

a Kilograms per cubic meter.
b Micrometers per year
c Year

The corrosion rate depends on different factors, so if it possible to control these factors, the corrosion rate will be low. The main factor that affects the corrosion rate is the presence of water and oxygen, especially in the cathode zone shown in the Figure 2.6 (**Zhang and Mailvaganam, 2006**).

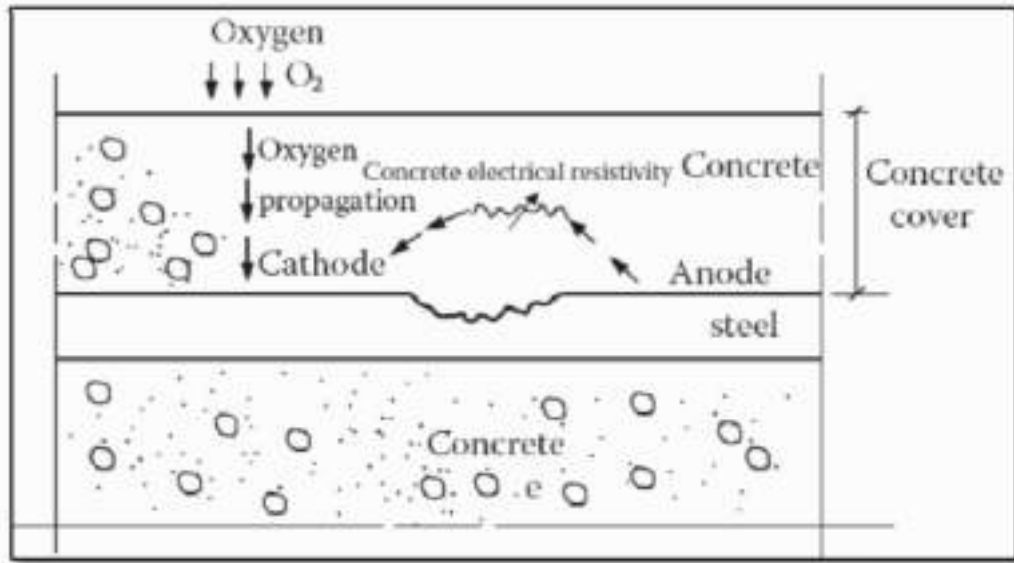


Figure 2.6: Factors Affecting Corrosion Rate (Abu-Hamam, 2008).

The second important factor affecting the corrosion rate is the moving of the ions inside the concrete voids around the steel reinforcement. If the speed of moving ions is very slight or prevented, the corrosion rate will be very slow also or, in the ideal case, prevented. This case may happen when the concrete around the steel bars has a high resistance to electrical conductivity between a node and cathode. The measurement of electrical resistivity to the concrete surrounding the steel reinforcement can give us an assumption of the corrosion rate and the chemical reaction rate (Abu-Hamam, 2008).

2.6 CORROSION STRUCTURAL EFFECTS

Among the different deterioration mechanisms occurring in concrete structures, the corrosion of reinforcement is the most detrimental one. Their consequences, whether due to concrete carbonation or to an excessive chloride content in the concrete, can be classified into three main groups as seen in Figure 2.7

- 1- Those, which affect the reinforcement section, reducing the effective area and ductility.
- 2- Those, which are related to concrete integrity.
- 3- Those, which affect the interaction concrete – reinforcement due to the bond reduction.

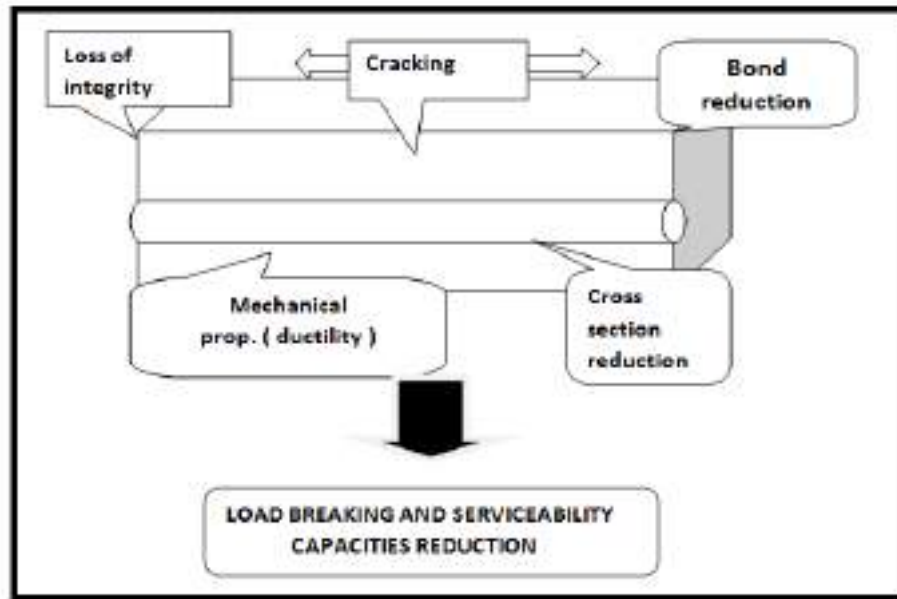


Figure 2.7: Reinforcement Corrosion Effects on Concrete Structures

However, the most problems that occur because of corrosion of steel in concrete are due not only to the shortage in the steel section but also to fall of the concrete cover. Many studies and much research have been conducted to calculate the amount of corrosion occurring and causing the concrete cover to fall. It has been found that cracks may occur in cases of reduction of 0.1 mm from steel reinforcement sections and, in some cases, much less than 0.1 mm, depending on the distribution of oxides and the ability of concrete to withstand the stresses, as well as the distribution of steel (**Abu-Hamam, 2008**).

The reason of concrete cover failing refer to the fact that the rust occupies a much larger volume than the original steel and causes the buildup of bursting forces at the surface of the reinforcement. Because concrete is weak in tension these bursting forces quickly cause the concrete to crack parallel to the reinforcement direction and eventually, to spall away from rebars. However, corrosion is a complex mixture of oxides, and hydroxides and hydrated oxides of steel have a volume ranging from twice to about six times that of the steel consumed to produce it. The magnitude of the rust incremental are various according to various steel oxides generated as shown in Figure 2.8 (**Al-Ostaz, 2004**) . Note that the concrete cover in the corner is more prone to falling because it is a largely exposed area for the penetration of carbon dioxide or exposure to chlorides, as well as oxygen. Therefore, concrete cracks often happen faster in this situation (**Al-Ostaz, 2004**)

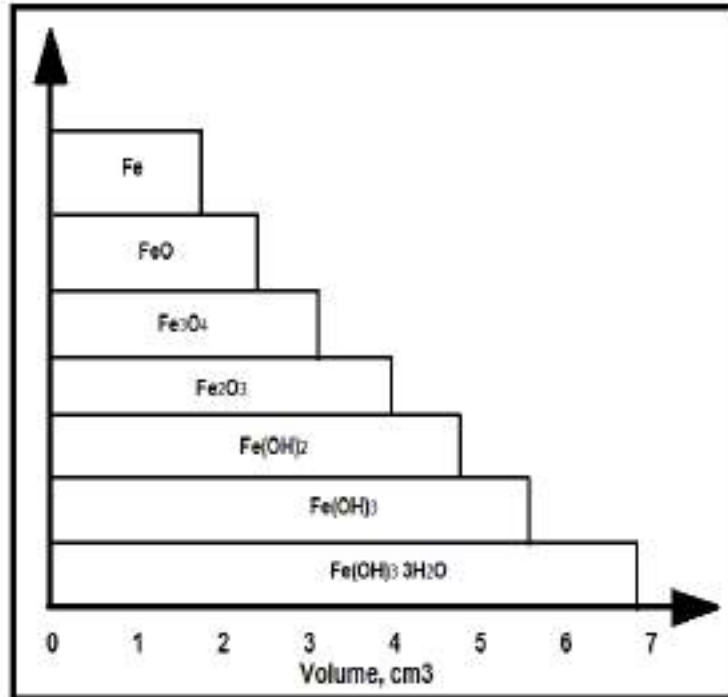


Figure 2.8: The Volume Change for Various Steel Oxides in Comparison With Original Volume of Fe Equal to 1 cm³

However, in the last decades many empirical formulas were integrated to calculate the following parameter:

1. The losses in the steel reinforcement due to corrosion.
2. The crack width of the concrete cover due to corrosion.
3. The pond between the concrete and steel reinforcement in the present of corrosion.

These parameters are mainly affected with the corrosion rate, corrosion cause (carbonation and or chlorides attack) and environmental situation surrounding the concrete.

2.5.1. Losses in Steel Reinforcement Due to Corrosion

Weight-loss of the reinforcing steel could be calculated based on the current going through rebar. According to Faraday's Law, the total weight loss of a reinforcing steel bar that is oxidized by the passage of electric charge can be expressed in Equation 2.5 as follows:

$$W_{\text{loss}} = [TC] \times \frac{EW}{F} \quad \text{Eq. 2.5}$$

Where, W loss is the total weight loss of reinforcing steel (grams), TC is the total electric charge (amp-sec or coulombs); EW is the equivalent weight, indicating the mass of metal (grams) that is oxidized. For pure elements, the EW is given by $EW=W/n$; here W is the atomic weight of the element, and n is the valence of the element. For carbon steel, the EW is approximate 28 (grams). F is Faraday's constant in electric charge ($F=96490$ coulombs, or amp-sec)

Equation 2.6 presents the losses of steel bars in electrolyte, in the case of reinforcement embedded in concrete the reduction in steel cross section can be expressed in equations 2.7 and 2.8 as follows

$$\phi = \phi_0 - \alpha P_x$$

Eq. 2.6

Where ϕ is the reduction in cross section area of steel bar (cm^2), ϕ_0 is the cross section area of steel reinforcement before corrosion (cm^2), α is the "pitting factor", the α values are different if the corrosion is homogeneous ($\alpha = 2$) than for pitting corrosion ($5 < \alpha < 10$), P_x is the corrosion rate (mm/year) which can be expressed in equation 2.11 as follow:

$$P_x = I_{\text{corr}} \times t$$

Eq. 2.7

The determination of I_{corr} depends on the environment evolution. Thus, several strategies may be used for the determination of I_{corr} and the loss of section with time P_x , anyhow Table 2.2 gives values of I_{corr} by means of the wetness time.

Table 2.2: Averaged Corrosion Currents (I_{corr}) and Wetness Periods (wt)

Exposure class		I_{corr} ($\mu\text{A}/\text{cm}^2$) (mean value)	W_t [-]
0	No risk of corrosion, very dry	0	0
Carbonation			
XC1	Dry or permanent wet	0	0
XC2	Wet rarely dry	0.4	1
XC3	Moderate humidity	0.2	0.5
XC4	Cyclic wet dry	0.5	0.75
Chloride ambients			
XD1	Moderate humidity	0.4	0.5
XD2	Wet, rarely dry	3.0	1
XD3	Cyclic, wet and dry	3.0	0.75
XS1	Airborne salt conditions	3.0	0.5
XS2	Submerged	Not present	
XS3	Tidal, splash and spray zones	7.0	1

2.5.2. Modeling of reinforcement corrosion in concrete

Corrosion of steel reinforcement has been considered the most prevalent form of deterioration of reinforced concrete structures, potentially seriously compromising the service life of these structures. Service life prediction and enhancement of concrete structures under corrosion attack are therefore of significant importance. In recent years, in addition to laborious experimental investigations, numerical methods that are capable of simulating the corrosion processes of reinforcing steel and thus reliably predict the service life of concrete structures have gained increasing attention.

The modeling of steel corrosion in concrete structures involves solving the governing equation in Laplace form that satisfies the two boundary conditions of potential and current density at the steel concrete interface . Currently available models often adopt only one of the above two boundary conditions, with the other satisfied by iteration to convergence (**The Ngoc Dao, 2010**).

2.7 PRVIOUS STUDIES ON CORROSION OF STEEL REINFORCEMENT

J.G. Cabrera (2005) presents the deterioration of concrete due to steel reinforcement corrosion. He used laboratory data to investigate the effects of corrosion rate on cracking and bond strength loss. He also examined the influence of fly ash on the rate of reinforcement corrosion. The laboratory data is used to develop numerical models to predict the rate of corrosion from the width and intensity of cracking, bond stress from corrosion rate, and serviceability loss from corrosion rate.

P. Garces et al, (2006) discuss the results of addition different types of carbonaceous materials to concrete mixes and their effect on the corrosion of embedded steel has been studied. Using a constant water/cement ratio of 0.42 and different amounts of carbonaceous materials and different curing periods the evolution of the corrosion process in the embedded reinforced bars has been determined. The addition of small quantities of carbonaceous materials to the mixture produces a reduction of the concrete permeability. Tests demonstrate that a decrease of the corrosion level occurs when the content ratio of carbon material addition is increased.

Hanifi Binici et al (2007) presents the results of corrosion resistance for pumice collected from pyroclastic exposure in the Van, Kayseri, Nevsehir and Osmaniye regions of Turkey. The corrosion resistance of reinforced steel (RS) and mass losses of concrete specimens were investigated. The specimens were exposed to 5 and 10% sodium sulphate solutions. Reinforced steel mass losses and compressive strengths of concrete were measured. Improvements of the compressive strength and corrosion resistance were observed for specimens with the increasing layers of coating. The corrosion rates of pumice coated specimens were lower than the control specimens. There was a close relationship between type of pumice coating and reinforcement corrosion. Corrosion ratio decreased with increasing amounts of reactive SiO₂. The alkalinity of the concrete, permeability of the concrete cover, the quality of the concrete and the corrosion environment were crucial factors in influencing the effectiveness of the concrete cover for corrosion protection of reinforced steel. All pumice concretes offered excellent resistance to corrosion, where Osmaniye pumice (OP) best increased corrosion resistance of reinforced steel.

El-Ebweini Mohammed (2009) presents the results of a laboratory investigation of the flexural capacity such as strength, deflection and steel mechanical properties for both corroded and repaired corroded beams. Examination of the behavior of crack development was also examined. It was concluded that the flexural capacity of the corroded beams reduced by about 28 % compared with the control beams and showed a noted reduction in its ductility behavior during the flexural test. The flexural capacity of the repaired beams increased by about 47 % compared with the control beams. They showed good ductility behavior during the flexural test and performed as sound constructed beams regarding their flexural capacity, crack development and deflection. It also concluded that types of repairing materials used for applying a new layer to corroded beams did not affect the flexural performance of repaired beams, in spite of that it may be important to inhabit the corrosion process in the future.

Mike Otieno (2013) discuss a critical review of some of the available corrosion rate prediction models focusing mainly on chloride-induced corrosion. In addition, proposals for the improvement of these models are made. . However, it has not been assigned the level of importance it deserves especially with respect to its prediction. In most cases, instantaneous measurements or constant predicted corrosion rate values are used in damage prediction models hence neglecting its time-variant nature while in some cases, salient

factors that affect corrosion rate such as cover cracking and concrete quality and not taken into consideration during the model development. The direct consequence of this may be under- or overestimation of the severity and the time to corrosion-induced damage such as for example cover cracking, and hence service life of the structure.

CHAPTER 3

MATERIALS AND EXPERIMENTAL INVESTIGATION

3.1 INTRODUCTION

Corrosion of reinforcing steel is considered as one of the most serious problems facing the reinforced concrete structures. More than 80% of reinforced concrete structural damages around the world are caused by the corrosion of steel (**The Ngoc Dao, et al, 2010**).

The problem of reinforced concrete corrosion is considered also as an economical problem, some countries such as U.S. and U.K. spent hundreds of millions of dollars yearly for repairing structural damages resulting from reinforced concrete corrosion problem. This problem is clearly manifested in many other countries, especially in the Middle East Area (**Abu Hamam, 2008**). The main objective of the performed experimental investigation is to investigate the effect of three surface coating materials on the reinforced concrete beams. The test program consists of two stages, the first stage included choosing the best surface coating according to the corrosion rate and bonding. The second stage is concerned with using the best surface coating to improve flexural and bonding.



Figure 3.1 Steel Reinforcement of beam

3.2 EXPERIMENTAL INVESTIGATION

The main objective of the experimental investigation is to apply three surface coating materials (*Acrylic polymers, Epoxy polymers and Polyurethane resin*) on the reinforcement of concrete beams. We use these types of surface coating because these types are available in Gaza markets and suitable for the coastal areas. The proposed testing program in figure 3.2 includes testing of 56 reinforced beams that are to be designed, constructed, and tested under flexure to achieve the research objectives. Three of the beam samples are considered as control beams for each step. The test program consists of two phases. The first phase is concerned with choosing the best surface coating materials based on the corrosion rate and bonding strength as shown in figure 3.2. The second phase is concerned with using the best surface coating with improve flexural and bonding.

In the first phase, three types of surface coating materials are used to measure its effects on the corrosion rate on steel bar of reinforced concrete. In addition, these types of surface coating are used to measure the bonding strength between the reinforcement and concrete.

The main aim of the first phase is determining the best type of surface coating that reduce the corrosion rate without affecting bonding strength between reinforcement and concrete.

For determining the best surface coating, 20 samples are prepared for testing with 5 levels of testing in different times to measure the corrosion rate regarding to the time factor. Steel reinforcement bars painted with the three types of surface coating and prepare the samples with connect the electrical cell during the NaCl solution with concentrate 5% to accelerate the corrosion process.

Four sample were tested in the first week, each sample for each type of surface coating and one sample as control sample for comparison. Four samples were tested each week with measuring the corrosion rate for five weeks and specifying the best type for surface coating.

For bonding strength, reinforcement bars were painted with the three types of surface coating with one control sample for comparison, these samples tested after 28 days of curing using pull out test machine for choosing the best type of surface coating.

Finally we can specify the best type of surface coating that reduces the corrosion rate and conserve the bonding between reinforcement and concrete and we can transform to the second phase.

In the second phase, samples were tested to further in prove of the performance of the best surface coating from the first phase. First of all, 3 samples were prepared without surface coating to measure the flexural and compare the results with control sample. The second level of testing is to prepare another 3 samples painted with the best type of surface coating and measure the flexural strength at 28 days and comparing the results with control sample.

The third level of testing is to prepare another 3 samples with surface coating and sand and tested after 28 days to measure the flexural strength and compare the results with control sample. The fourth level of testing is to prepare 3 samples with best surface coating and admixture of 3% of cement weight at the mix and test after 28 days comparing the results of flexural with control sample.

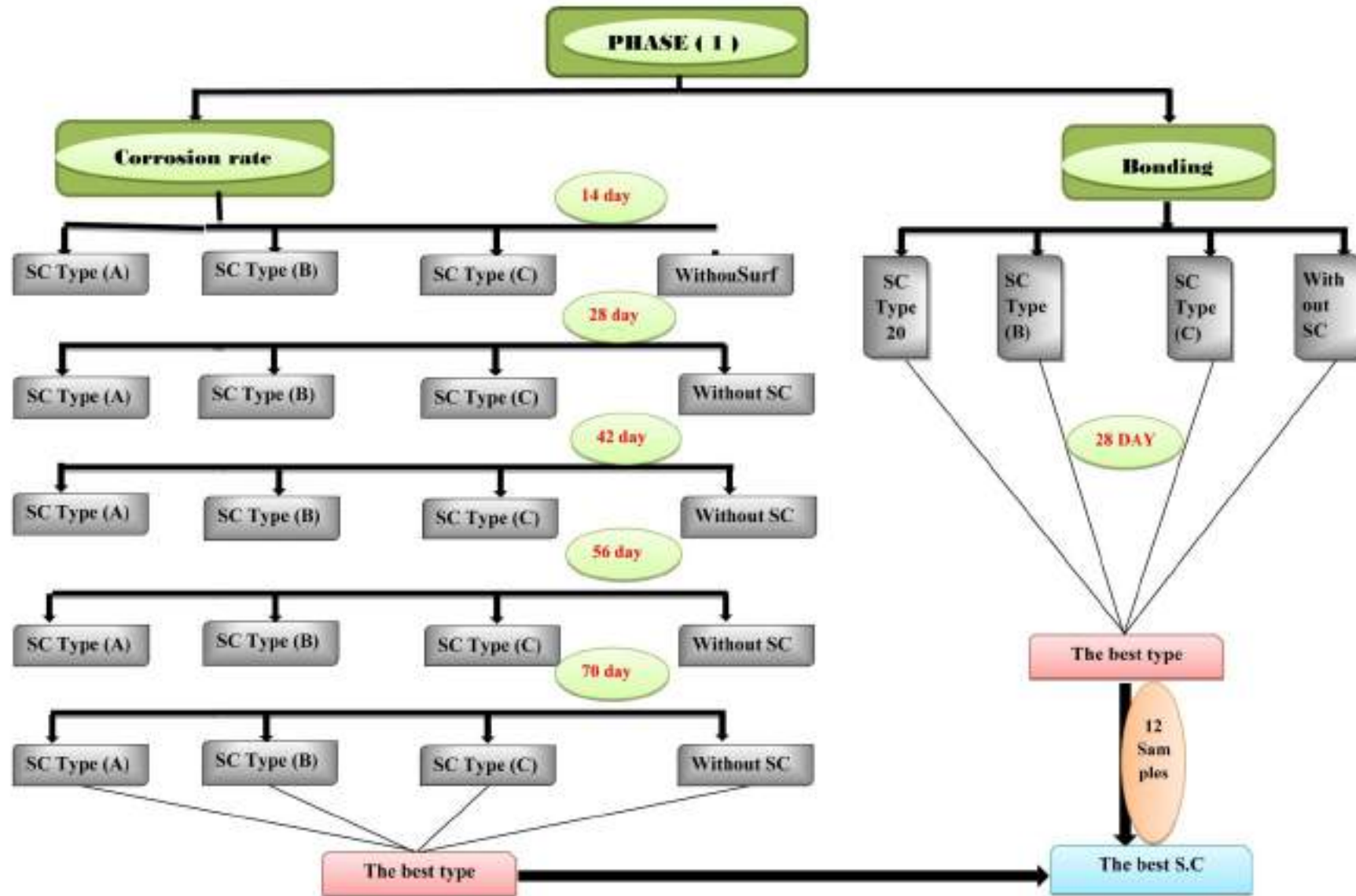
The final level of testing is to prepare 3 samples with best surface coating and sand and admixture with 3% of cement weight and test these samples after 28 days to measure flexural strength and comparing the results with control sample, with these levels of testing we improve the flexural strength.

Regarding to the bonding, 3 samples prepared without painting surface coating on steel bars of reinforced concrete to measure the bonding after 28 days, but for improve the bonding, steel bars of reinforcement painted with surface coating and spread the sand on the surface coating before drying on bars to increase the bonding between concrete and steel bars then tested with pull out device and compare the result with control sample. The second level of testing is painting steel bars of reinforcement with surface coating and add admixture with percentage of 3% of cement weight to the concrete mix and test the bonding after 28 days comparing the results with control sample.

Finally, steel reinforcement bars painted with surface coating and sand and admixture with 3% of cement weight and tested with pull out device to measure bonding and comparing the results with control sample after 28 days of curing, with these procedures we can specify the most effective way for improve flexural and bonding and reducing the corrosion rate.

Figure 3.2 shows the detailed steps of the main two phases.

Fig. 3.2 Testing program Flow Chart



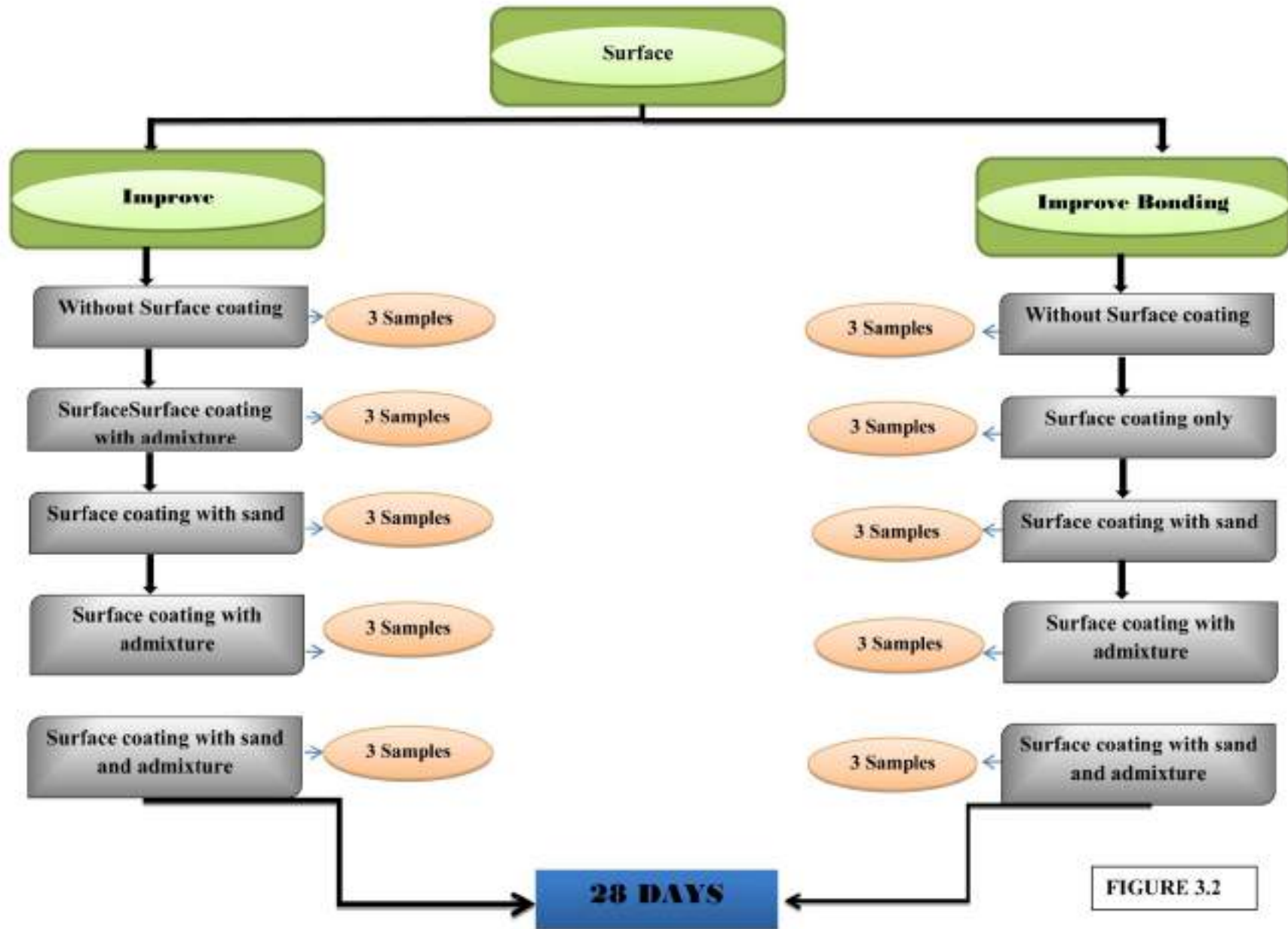


FIGURE 3.2

3.3 PROPERTIES OF CONCRETE CONSTITUENTS

The following section presents material properties which used in the experimental investigation such as concrete and steel discussed as follow:

3.3.1 Aggregate

Aggregate is relatively inexpensive and strong making material for concrete. It is treated customarily as inert filler. The primary concerns of aggregate in mix design used are gradation, maximum size, and strength. Providing that concrete is workable, the large particles of aggregate, it is important to ensure that the aggregates are clean, since a layer of silt or clay will reduce the cement aggregate bond strength, in addition to increasing the water demand.

According to the local market surveying, three types of coarse aggregate were found. Table 3.1 illustrates the sieve analysis and the properties of these types.

Table 3.1: Coarse Aggregate Types, Sieves and Properties

Sample Description	Type 1	Type 2	Type 3
Sieve Size	% Passing	% Passing	% Passing
(mm)			
37.5	100	100	100
25.0	100	100	100
19.0	46.74	99.2	100
12.5	3.33	56.3	100
9.5	1.42	13.22	94.3
4.75	1.06	3.41	25.24
2.63	1.06	2.03	6.63
Dry Unit weight (kg/m³)	1436	1506	1486
Dry Specific Gravity	2.68	2.65	2.63
Saturated Specific Gravity	2.71	2.65	2.63
Absorption %	1.12%	2.42%	3%

To achieve the ASTM C33-03 standard requirements for coarse aggregate, a mix design of these three types was prepared as shown in Table 3.2 and Figure 3.3.

Table 3.2: Coarse Aggregate Sieve and Analysis According To ASTM C33-03

	Aggregate Kind	Type 1	Type 2	Type 3
	% Percent	7.00%	68.00%	25.00%
Sample Description	Coarse Aggregate		ASTM C 33-03	
	Mix of type (1&2&3)		Min	Max
Sieve Size (mm)	% Passing	% Passing	% Passing	
37.5	100.0	100.0	100.0	
25.0	100.0	100.0	100.0	
19.0	95.7	90.0	100.0	
12.5	63.5			
9.5	32.7	20.0	55.0	
4.75	8.7	0.0	10.0	
2.63	3.1	0.0	5.0	
Unit weight(kg/m3)	1496			
Dry Specific Gravity	2.65			
Moisture Content%	0.14			
Absorption %	2.47			

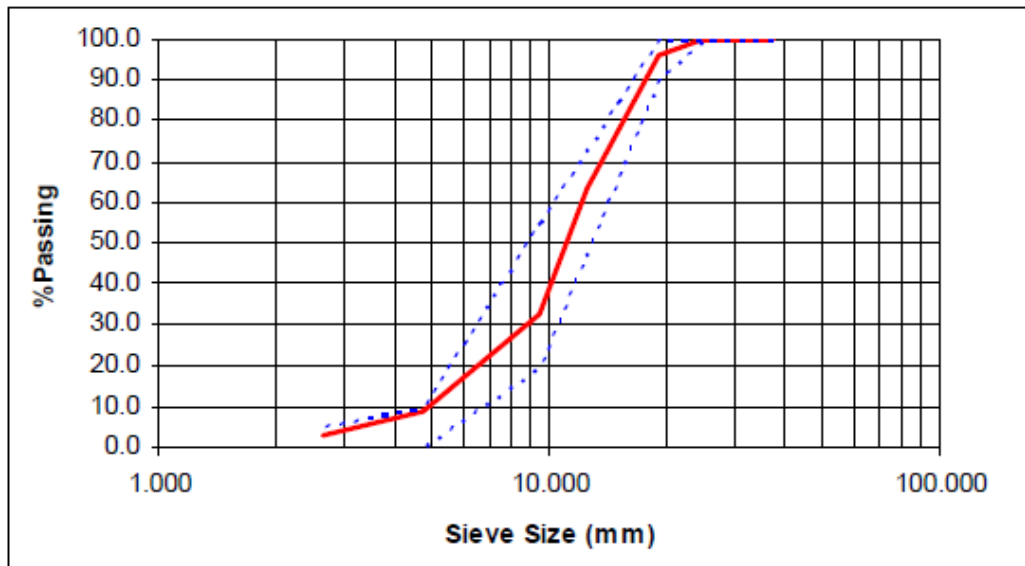


Figure 3.3: Coarse Aggregate Sieve Analysis According To ASTM C33-03 Limitation

According to the local market surveying, two types of fine aggregates were found, Table 3.3 illustrates the sieve analysis and the properties of these types

Table 3.3: Fine Aggregate, Sieve Analysis

Sample Description	Type 1 (Crushed Stone Sand)	Type 2 (Natural Sand)
Sieve Size	% Passing	% Passing
(mm)		
9.50	99.91	100
4.750	99.03	100
2.360	81.92	100
1.180	45.93	100
0.600	22.30	99.6
0.300	6.97	47.8
0.150	4.15	2.04
0.075	3.26	0.34
Dry Specific Gravity	2.65	2.60

To achieve the ASTM C33-03 standard for fine aggregate, mix design of these two types was prepared as shown in Table 3.4 and Figure 3.4.

Table 3.4: Fine Aggregate Sieve and Analysis According To ASTM C33-03

	Type 1	Type 2		
Percent	70.00%	30.00%		
Sample Description	Mix of type 1&2		ASTM C 33-03 Fine AGG	
			Min	Max
Sieve Size (mm)	% Passing		% Passing	% Passing
9.500	99.94		100.0	100.0
4.750	99.32		100.0	100.0
2.360	87.34		90.0	100.0
1.180	62.15			
0.600	45.49		20.0	55.0
0.300	19.22		0.0	10.0
0.150	3.51		0.0	5.0
0.075	2.38			
Dry Specific Gravity	2.635			
Moisture Content%	0.20			
Absorption %	1.80			

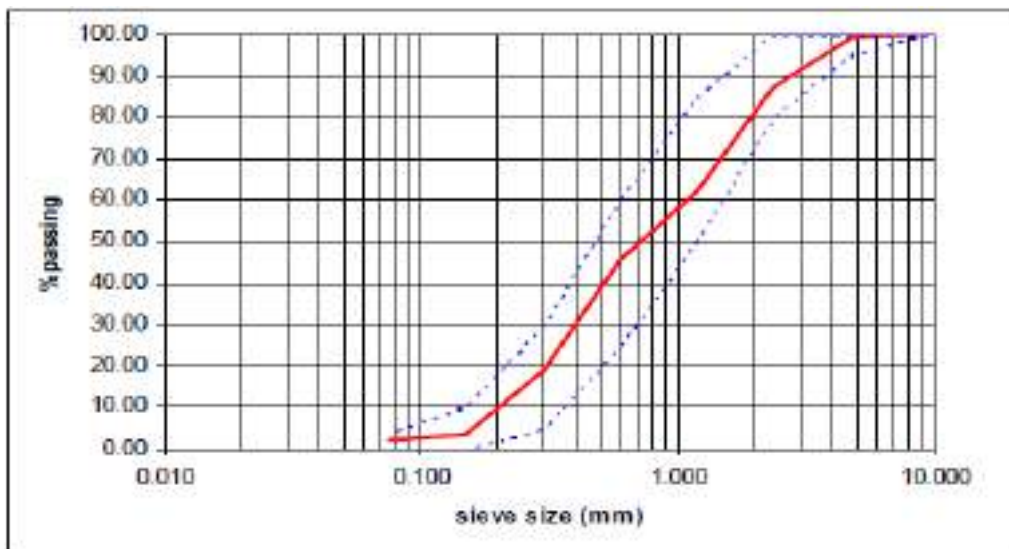


Figure 3.4: Fine Aggregate Sieve Analysis According To ASTM C33-03 Limitation

3.3.2 Cement

Portland cement type I was used. The cement was obtained from local market and kept in dry location. The cement source was Silo Nisher. Ordinary/Normal Portland cement is one of the most widely used type of Portland cement. Portland stone is white grey limestone in island of Portland, Dorset.

3.3.3 Water

Tap water, potable without any salts or chemical was used in the study. The water source was the soil and material lab in Islamic University of Gaza.

3.3.4 Admixtures

Concrete admixtures are used to improve the behavior of concrete under a variety of conditions. Chemical admixtures used to improve the quality of concrete during mixing, transporting, placement and curing such as **a hard dispersible polymer powder based on vinyl acetate and ethylene** for very good tensile adhesion strength on inorganic surfaces combined with good workability.

Table 3.5: Specification data to admixtures .

Property	Inspection Method	Value
Bulk density	DIN EN ISO 60	490.0 - 590.0 kg/m ³
Particle size	DIN EN ISO 4610	Max. 4 % over 400 µm
Ash content (1000 °C)	specific method	Max. 13.0 %
Solids content	DIN EN ISO 3251	min. 98.0 %

3.4 PROPERTIES OF SURFACE COATING MATERIALS

Three types of surface coating used in this study to minimize the corrosion of the reinforcement and to identify their effects on the mechanical and physical properties of concrete. These types are **Acrylic polymers, Epoxy polymers and Polyurethane resin.**

3.4.1 *Acrylic polymers*

Acrylics are esters of acrylic acids that is they are the products formed by the reaction of an acrylic acid and alcohol. The esters of acrylic acid polymerise readily to form exceptionally clear plastics. These are widely used in applications requiring clear durable surfaces, e.g. in the aircraft and automobile industries. In more common use are surface coatings involving acrylics. The physical properties of the acrylics (such as gloss, hardness, adhesion and flexibility) can be modified by altering the composition of the monomer mixture used in the polymerisation process. **(Kinloch et al, 1983)**

Acrylics are used in a wide range of industries, and the list below is simply a selection of some of the more common examples:

- Adhesives
- The textile industry (e.g. making the sponge fill used in padded jackets)
- Paper coatings
- The paint industry (particularly in paints used for road markings)

The polymerisation process proceeds readily in the presence of catalysts and may be carried out in any one of four different ways: in emulsion, in bulk, in solution or in suspension.

- Emulsion polymerisation occurs in a water / monomer emulsion using a water-soluble catalyst. Emulsion polymerisation is the main process used in NZ for the production of acrylic polymers.
- Bulk polymerisation is carried out in the absence of any solvent. The catalyst is mixed in with the monomer and the polymerisation is then left to occur with time. This is the method commonly used to manufacture acrylic sheets.
- Solution polymerisation is carried out in a solvent in which both the monomer and subsequent polymer are soluble. Only low molecular weight polymers can be manufactured by this process, as high molecular weight polymers cause very high viscosities.
- Suspension polymerisation is carried out in the presence of a solvent (usually water) in which the monomer is insoluble and in which it is suspended by agitation.

To prevent the droplets of monomer from coalescing and also to prevent the polymer from coagulating, protective colloids are added. Suitable colloids include bentonite, starch, polyvinyl alcohol and magnesium silicate. In contrast to emulsion polymerisation the catalyst is monomer-soluble and is dissolved in the suspended droplets (**Kinloch et al, 1983**)

3.4.2 Epoxy polymers

Epoxy resins are polyether resins containing more than one epoxy group capable of being converted into the thermoset form. These resins, on curing, do not create volatile products in spite of the presence of a volatile solvent. The epoxies may be named as oxides, such as ethylene oxides (epoxy ethane), or 1,2-epoxide. The epoxy group also known as oxirane contains an oxygen atom bonded with two carbon atoms

Applications for epoxy resins are extensive: adhesives, bonding, construction materials (flooring, paving, and aggregates), composites, laminates, coatings, molding, and textile finishing. They have recently found uses in the air- and spacecraft industries.

The curing of the epoxy group takes place either between the epoxide molecules themselves or by the reaction between the epoxy group and other reactive molecules with or without the help of the catalyst. 20-24 the former is known as homopolymerization, or corrective curing; and the latter is an addition or catalytic curing reaction (**Yee et al, 1984**).

3.4.3 Polyurethane resin

Polyurethanes are a highly variable family of polymers, materials that result from the linking of a chain of simple, repetitive molecules. These materials can be seen in many forms and can be put to numerous uses, depending upon how their properties are manipulated. Polyurethane resin, which is a synthetically produced sticky substance, is one of those forms.

Polyurethane resin is an industrial product that is used in the production of many other products, such as rubbers and medicines. To understand this material, it is best to have a basic understanding of how polyurethanes are made (**D.Howell, 1999**).

An isocyanate is a compound composed of nitrogen, carbon, and oxygen. When it's exposed to a hydroxyl, a compound that contains hydrogen, it will form a urethane

linkage. A diisocyanate is a compound that contains two isocyanates, so these are, therefore, also reactive to hydrogen. They are mostly produced for the role they play in making polyurethane, which is a reaction that involves more than one urethane linkage.

Polyols are basically alcohols that contain more than one hydrogen atom. Producing polyurethane resin generally involves allowing a reaction between a polyol, such as polyether polyol, and a diisocyanate, such as toluene diisocyanate. Heat or catalysts are also necessary to complete the process, and when they are added, the resin will generally take a final and irreversible form. This means it may be impossible to reform them even if heat is added again (**D.Howell, 1999**)

3.5 SET UP OF CORROSION INITIATION

3.5.1 Calculation of corrosion rate

Electrochemical methods provide an alternative to traditional methods used to determine the rate of corrosion. Direct and quantitative determination of corrosion rates can be determined from simple electrochemical measurement. The simplest way of measuring the corrosion rate of a steel is to expose the sample to the test medium (e.g. sea water) and measure the loss of weight of the material as a function of time. Although these tests are simple, there is no simple way to extrapolate the results to predict the lifetime of the system under investigation.

The concept of accelerating the corrosion was to force steel reinforcement to act as anode in galvanic cell. That can be done by immerse beams in aqueous solution and connecting the steel reinforcement bars with positive DC current generator to act as anode while connecting the negative power supply to external steel rods immersed in the aqueous solution to act as cathode. This consists electric circuit and force steel ions to translate from anode to cathode as discussed previously.

Before finalizing the corrosion system setup, a pilot study was done, different current values were applied to four specimens, and the steel embedded in the concrete were visually inspected weekly for each different current.

The following is a list of the equipment used for the electrochemical test set-up:

- Seven water basins with dimension (0.6x 0.5 x 0.4) m as shown in figure 3.5



Figure 3.5 Casting molds

- Electric wires and electric clamps as shown in figure 3.6



Figure 3.6 electric clamps

- Multimeter as shown in figure 3.7



Figure 3.7 Multimeter device

- AC 300 Watt computer power supply as shown in figure 3.8



Figure 3.8 computer power supply

A basin filled with a sodium chloride solution (5 percent NaCl by weight of water) was prepared. The solution covered 30mm of the beams height (in which the flexural reinforcements exist). The electric wires were attached to the reinforcement bars with the help of a garden hose clamps. It was used to impress the necessary voltage for the corrosion process to proceed. The beams were connected in parallel to +5 Volts with a capacity of 25 Amperes electric DC current generated by power supply, which impressed an equal voltage on each beam. The negative power supply terminal was

connected to twelve 10 mm steel rods immersed in the aqueous solution between the beams in order to facilitate the opening and closing of the electric circuit as shown in figure 3.9.

To ensure that enough oxygen needed for the corrosion mechanism exists just 30mm of the beam height were immersed in the solution on the other hand the sodium chloride solution was replaced twice every week as shown in figure 3.10.

During the electrochemical corrosion process, the current passing through each beam was measured by the Multimeter every 10 days. The physical changes and crack development of beams during the corrosion process were obtained. the standby beams were used to check the statues of flexural steel bars embedded in concrete.



Figure 3.9 Connection of reinforcement with electrical cell



Figure 3.10 Connection of samples with electrical cell

3.6 MIX DESIGN

A concrete mix was designed to obtain 28-day compressive strength f_c' cubic = 25MPa, 70-100 mm slump, a maximum aggregate size of 19 mm, and w/c ratio of 0.61. Table 3.1 illustrates the results of the mix design proportions for each cubic meter of concrete regarding to ACI 211.1.

Table 3.6 Mix design proportion for each cubic meter of concrete

No	Material kind	Weight/m ³ (kg)	Notes
1	Coarse Aggregate	930	Coarse Aggregate consists of the following: <ul style="list-style-type: none"> • 65.1(kg) type 1 • 632.4(kg) type 2 • 232.5(kg) type 3
2	Fine Aggregate	892	Fine Aggregate consists of the following: <ul style="list-style-type: none"> • 624.4(kg) type 1 • 267.6(kg) type 2
3	Cement	336	Portland cement type 1
4	Water	241	Potable water

Normal weight concrete with the mix design proportions illustrated in table 3.2

was used. Three 10x10x10 mm concrete cubes from this mix design were tested to determine the compression strength of concrete, Table 4.7 illustrates these results.

3.6.1 Preparation of samples

The beam dimensions (30cm x 15 cm x 10 cm) are designed in accordance with ACI 318-08, preventing shear failure through using $\phi 8\text{mm}$ stirrups @50mm and $2\phi 10$ in the bottom of beam and $2\phi 10$ on the top of beam as shown in figures 3.11.

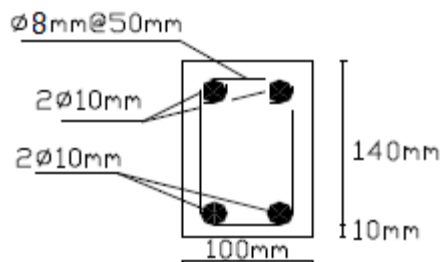


Figure 3.11 Section Details of beam

Table 3.7 Sample concrete cubes compression strength results

Sample No	Dimension (mm)			Weight (g)	28 days failure load (kN)	Stress (MPa) Cube	Stress (MPa) Cylinder
	Length	Width	High				
1	101	99	100	2380	351	35.5	28.4
2	101	100	100	2465	353	35.0	28.0
3	100	100	100	2430	347	34.7	27.8
Average	100.7	99.7	100	2425	350.3	35.1	28.1

3.7 TESTING OF SPECIMENS

3.7.1 Pull out strength

This test method follows the ASTM C-900-06 procedure and covers the determination of the pullout strength of hardened concrete by measuring the force required to pull an embedded 12 mm diameter corrugated steel bar inserted into fresh concrete mix specimen. This test method does not provide procedures to estimate other strength properties.



Figure 3.11 Pull out test machine

3.7.2 Flexural strength

The flexural test measures the force required to bend a beam under three point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed. This test method follows the ASTM C-78 procedure where the 10×10×50 cm³ hardened concrete specimen lies on two 40 cm apart supporting spans and the load is applied to the center by the loading nose producing three points bending at a specified rate till failure.



Figure 3.12 Flexural test machine

All concrete samples were placed in curing basin in the first stage with 3 cm height of NaCl solution. All samples remained in the curing at the second stage basin up to time of testing at 28 days as shown in figure 3.13



Figure 3.13 curing samples

CHAPTER 4

TEST RESULTS AND ANALYSIS

The main objective of this chapter is to present and analyze the results obtained from the experimental program.

The experimental data reported are classified under the following categories:

1. **First phase of test program:** includes Corrosion rate and bonding.
2. **Second phase of test program:** includes improvement of flexural and bonding.

4.1 RESULTS OF FIRST STAGE OF TEST PROGRAM

The first phase is concerned with choosing the best surface coating according to the corrosion rate and bonding tests, in this phase, three types of surface coating used to measure the corrosion rate and the role of each type to reduce the corrosion. In addition these types used to study the bonding between the reinforcement and concrete and determining the best type of surface coating that reduces the corrosion rate without side effects at bonding between reinforcement and concrete.

4.2 CORROSION RATE RESULTS

Twenty samples prepared with 5 levels of testing in different times to measure the corrosion rate regarding to the time factor. Steel reinforcement bars painted with the three types of surface coating and prepare the samples with connect the electrical cell with NaCl solution of 5% concentrate on to accelerate the corrosion process.

Table 4.1 illustrates the standard weight of steel reinforcement for control sample.

Table 4.1: Standard Weight of Reinforcement in control samples

Standard weight of reinforcement		
Type of Surface Coating	Name of surface coating	Weight (gm)
Type (A)	Acrylic polymers	755
Type (B)	Epoxy polymers	755
Type (C)	Polyurethane resin	755
Without surface coating	NA	755

4.2.1 Test results of corrosion rate after 14 days

Table 4.2: Corrosion rate results after 14 days

Test results of corrosion rate after 14 days				
Type of surface coating	Control weight(gm)	Actual weight(gm)	Losses(gm)	Losses(%)
Type (A) Acrylic polymers	755	737	18	2.4
Type (B) Epoxy polymers	755	742	13	1.7
Type (C) Polyurethane resin	755	753	2	0.3
Without surface coating	755	640	115	15.2

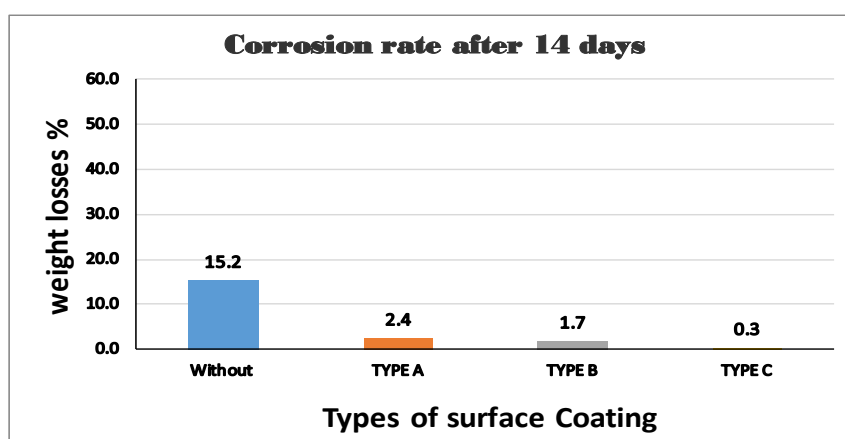


Fig 4.1: Corrosion rate results after 14 days

The above figure illustrates that samples tested without surface coating after 14 days loss 15.2% of its weight, however samples tested with surface coating type (C) (Polyurethane resin) with loss 0.3% but the types (A) and (b) loss 2.4% and 1.7% respectively. This indicates that type (C) of surface coating is the most effective type of the three surface coating in minimizing the corrosion rate.



Fig 4.2: Corrosion process in the first phase of test program.

4.2.2 Test results of corrosion rate after 28 days

Table 4.3: Corrosion rate results after 28 days

Test results of corrosion rate after 28 days				
Type of surface coating	Control weight(gm)	Actual weight(gm)	Losses(gm)	Losses(%)
Type (A) Acrylic polymers	755	702	53	7.0
Type (B) Epoxy polymers	755	692	63	8.3
Type (C) Polyurethane resin	755	749	6	0.8
Without surface coating	755	590	165	21.9

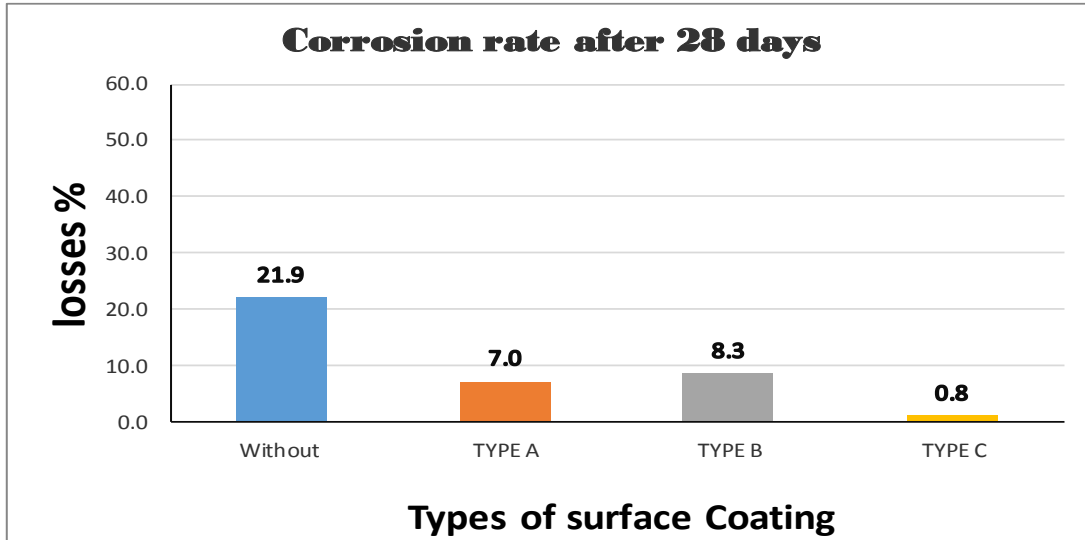


Fig 4.3: Corrosion rate results after 28 days

The above figure illustrates that samples tested without surface coating after 28 days loss 21.9 % of its weight, however samples tested with surface coating type (A) and (B) loss 7.0% and 8.3% of its weight respectively but type(C) (Polyurethane resin) loss 0.8% which indicate that type (C) of surface coating is the most effective type of the three surface coating in reducing the corrosion rate.

Figure 4.4 indicates the procedures of this phase.



Fig 4.4: Corrosion of reinforcement in the first stage of test program.

4.2.3 Test results of corrosion rate after 42 days

Table 4.4: Corrosion rate results after 42 days

Test results of corrosion rate after 42 days				
Type of surface coating	Control weight(gm)	Actual weight(gm)	Losses(gm)	Losses(%)
Type (A) Acrylic polymers	755	659	96	12.7
Type (B) Epoxy polymers	755	673	82	10.9
Type (C) Polyurethane resin	755	745	10	1.3
Without surface coating	755	512	243	32.2

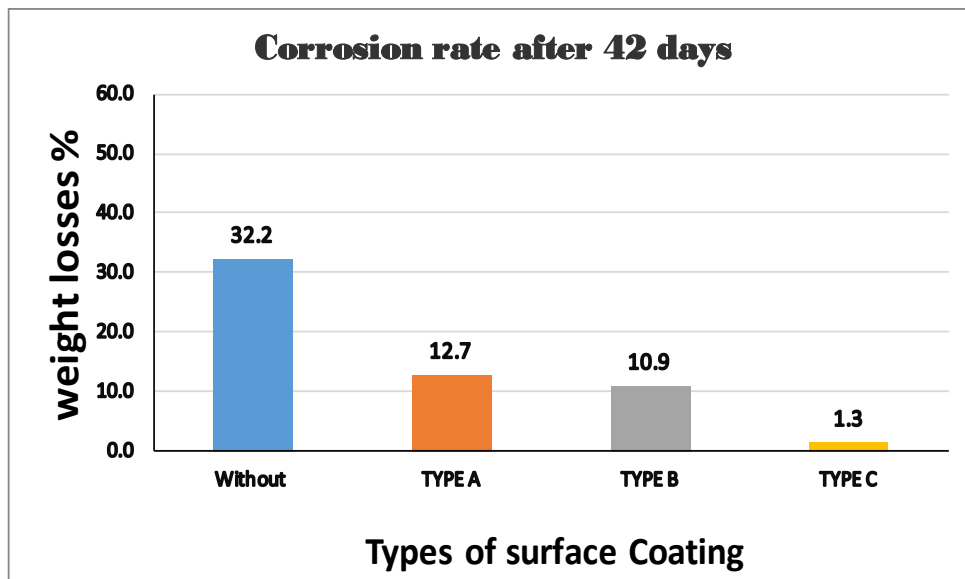


Fig 4.5: Corrosion rate results after 42 days

The above figure illustrates that samples tested without surface coating after 42 days loss 32.2% of its weight, however samples tested with surface coating types (A) and (B) loss 12.7% and 10.9% of its weight respectively but type (C) (Polyurethane resin) loss 1.3% which indicate that type (C) of surface coating is the most effective type of the three surface coating in minimizing the corrosion rate.



Fig 4.6: Corrosion of reinforcement in the first phase of test program.

4.2.4 Test results of corrosion rate after 56 days

Table 4.5: Corrosion rate results after 56 days

Test results of corrosion rate after 56 days				
Type of surface coating	Control weight(gm)	Actual weight(gm)	Losses(gm)	Losses(%)
Type (A) Acrylic polymers	755	641	114	15.1
Type (B) Epoxy polymers	755	657	98	13.0
Type (C) Polyurethane resin	755	743	12	1.6
Without surface coating	755	390	365	48.3

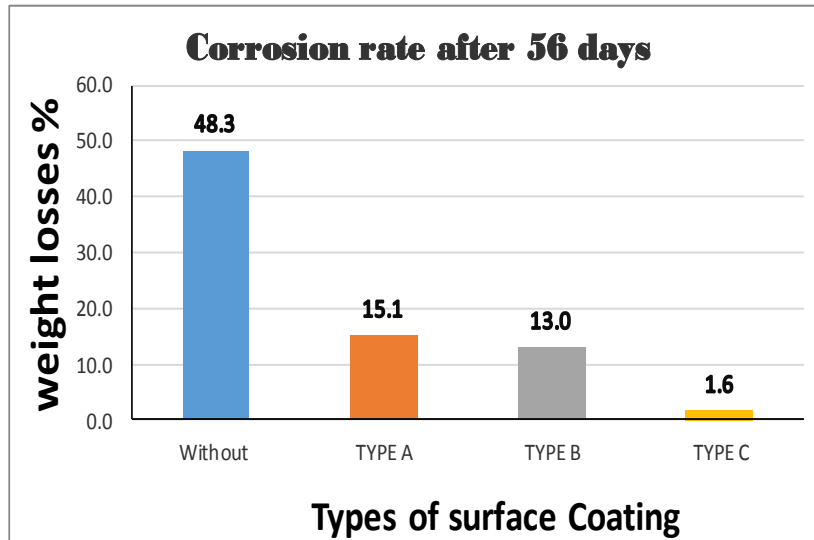


Fig 4.7: Corrosion rate results after 56 days

The above figure illustrates that samples tested without surface coating after 56 days loss 48.3% of its weight, however samples tested with surface coating type (A) and (B) loss 15.1% and 13.0% of its weight respectively but type (C) (Polyurethane resin) loss 1.6% which indicate that type (C) of surface coating is the most effective type of the three surface coating in reducing the corrosion rate.

4.2.5 Test results of corrosion rate after 70 days

Table 4.6: Corrosion rate results after 70 days

Test results of corrosion rate after 70 days				
Type of surface coating	Control weight(gm)	Actual weight(gm)	Losses(gm)	Losses(%)
Type (A) Acrylic polymers	755	612	143	18.9
Type (B) Epoxy polymers	755	647	108	14.3
Type (C) Polyurethane resin	755	743	12	1.6
Without surface coating	755	367	388	51.4

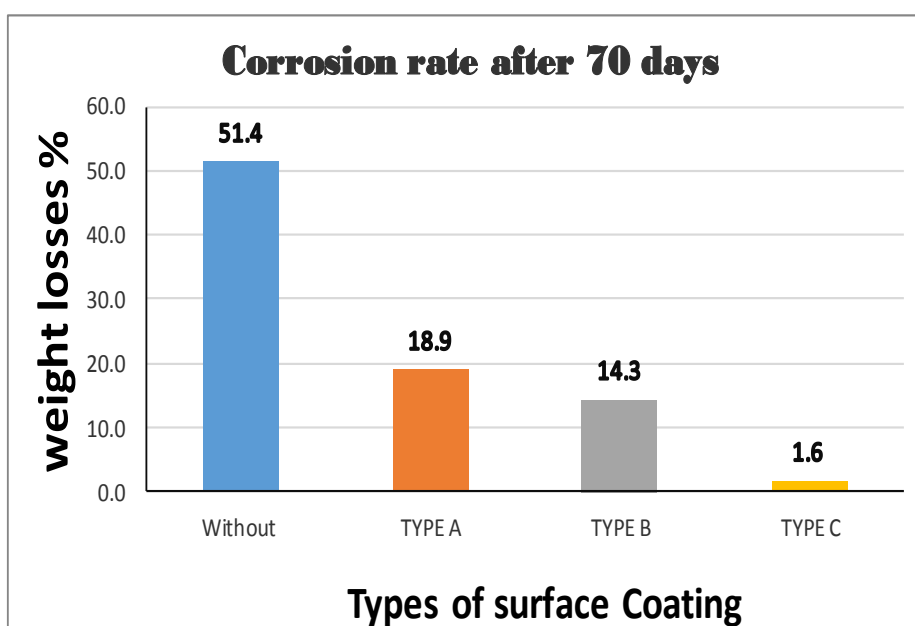


Fig 4.8: Corrosion rate results after 70 days

The above figure illustrates that samples tested without surfacing coating after 70 days loss 51.4% of its weight, however samples tested with surface coating type (A) and (B) loss 18.9% and 14.3% of its weight respectively but type (C) (Polyurethane resin) loss 1.6% which indicate that type (C) of surface coating is the most effective type of the three surface coating in minimizing the corrosion rate.

4.2.6 Comparison between types of S.C according to the corrosion rate

Table 4.7: Comparison between types of S.C according to the corrosion rate

Types of S.C	14 Days	28 Days	42 Days	56 Days	70 Days
without	15.2	21.9	32.2	48.3	51.4
Type(A) Acrylic polymers	2.4	7.0	12.7	15.1	18.9
Type(B) Epoxy polymers	1.7	8.3	10.9	13.0	14.3
Type (C) Polyurethane resin	0.3	0.8	1.3	1.6	1.6

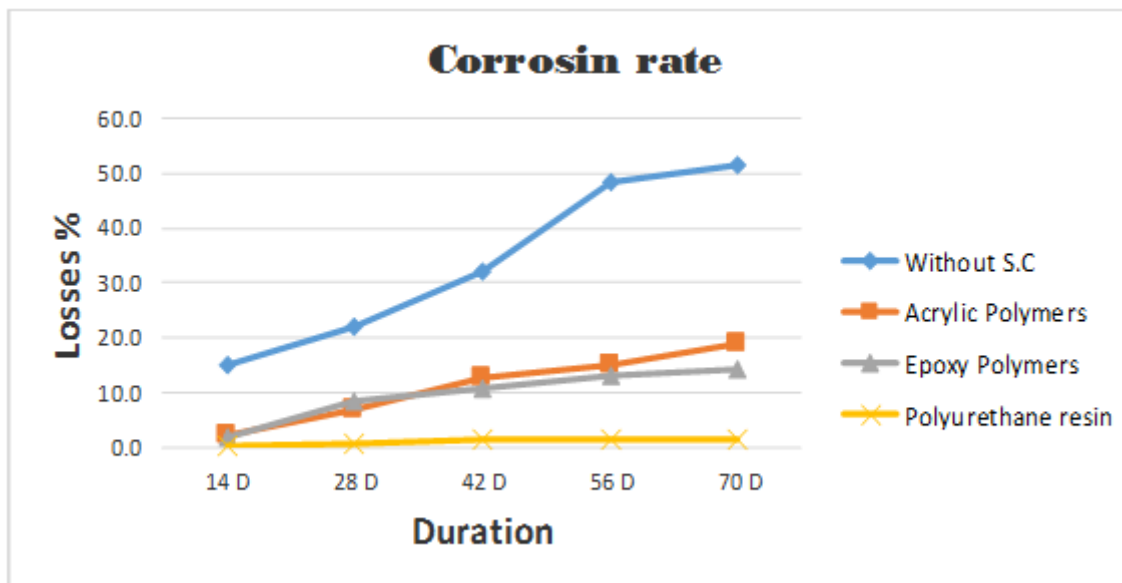


Fig 4.9: Comparison between types of S.C according to the corrosion rate.

The above figure illustrates that samples tested without surfacing coating after 70 days loss 51.4% of its weight, however samples tested with surface coating type (A) and (B) loss 18.9% and 14.3% of its weight respectively, however type (C) loss 1.6% of its weight which indicates that type (C) of surface coating is the most effective type among three surface coating in minimizing the corrosion rate. However the existence of same current, treatment condition and percentage of salts solution for accelerate of corrosion rate.

It is noticed that types (A) and (B) of surface coating have approximately the same efficiency to minimize the corrosion rate. To examine the exact difference the bonding strength test was carried out to specify the bonding strength between the steel reinforcement and concrete.

4.3 BONDING TEST RESULTS

For bonding check, reinforcement bars were painted with the three types of surface coating with one control sample for comparison, these samples tested after 28 days of curing using pull out test machine for choosing the best type of surface coating.

4.3.1 Bonding test results after 28 days

Table 4.8: Bonding test results after 28 days

Bonding test results after 28 days, KN				
Type of surface coating	Sample (1) KN	Sample (2) KN	Sample (3) KN	Average KN
Type (A) Acrylic polymers	57	54	50	53.67
Type (B) Epoxy polymers	55	53	54	54.00
Type (C) Polyurethane resin	53	55	55	54.33
Without surface coating	68	67	59	64.67

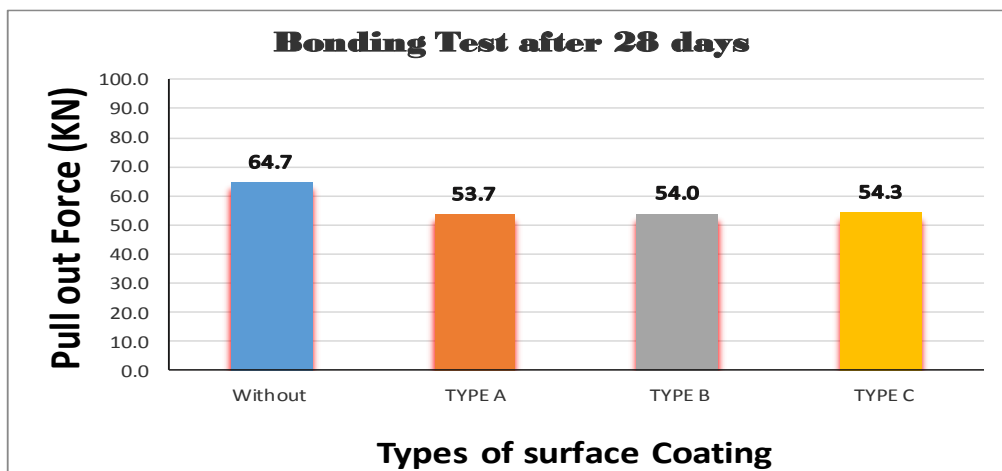


Fig 4.10: Bonding test results after 28 days.

The above figure illustrates the bonding strength results after 28 day. The sample which were tested without surface coating after 28 days was 64.7KN. However samples which were tested with surface coating type (A) , (B) were 53.7KN and 54.0KN respectively but type (C) was 54.3 KN.

It is notice that using surface coating in concrete decrease the bonding between steel bars and concrete. Types (B) and (C) have the same effects in decreasing the bonding however type (A) showed the worst effect for decreasing bonding. Admixtures needed to improve the bonding between steel bars of reinforcement and concrete.



Fig 4.11: Bonding Tests in the first phase of test program.



Fig 4.12: Samples in Pull out Force test.

4.4 SECOND PHASE OF TEST PROGRAM

In the first stage of test program, we selected the best surface coating according to the decreasing corrosion rate which was Type (C) (**Polyurethane resin**) of surface coating. It was found that the use of surface coating decreases the bonding between concrete and steel reinforcement.

In the second phase of test program we improved the bonding between the concrete and steel reinforcement then we improved the flexural capacity of samples.

4.4.1 Test results of bonding improvement after 28 days.

Table 4.9: Bonding improvement results after 28 days

Bonding improvement results after 28 days				
Methods of Improvement	Sample (1) KN	Sample (2) KN	Sample (3) KN	Average KN
Without S.C	68	67	59	64.67
S.C only	53	55	55	54.33
S.C and sand	37	40	33	36.67
S.C and admixture	66	67	69	67.33
S.C, sand and admixture	41	43	46	43.33

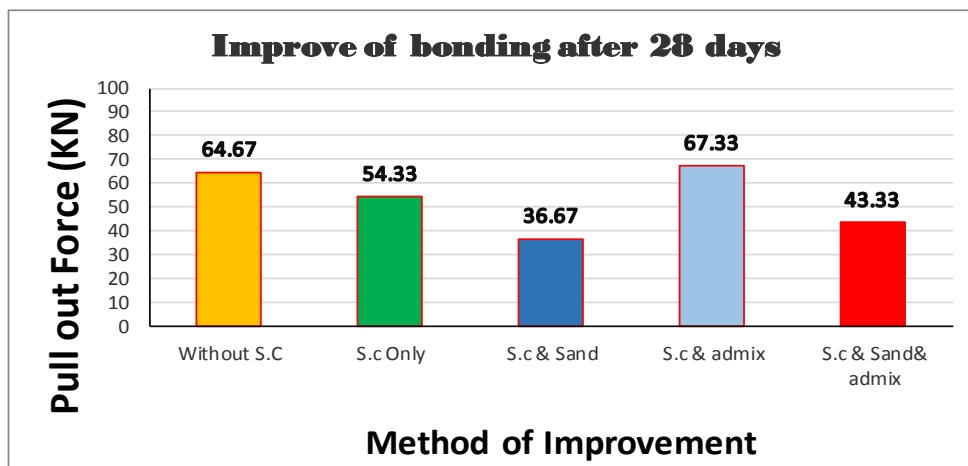


Fig 4.13: Bonding improvement results after 28 days.

The above figure illustrates the methods of improvement of bonding after 28 day, the samples tested without surface coating after 28 days were 64.67KN, however samples tested with surface coating only were 54.33KN, the samples tested by surface coating and sand were 36.67KN, the samples tested by surface coating and sand and admixture were 43.33KN but samples tested by surface coating and admixture were 67.33KN which is the best method of improvement.

Figure 4.14 and 4.15 illustrate these procedures of this phase.

It is noticed that painting surface coating on the steel reinforcement bars without any admixture for 3 samples reduce, the bonding with 16% comparing with control sample.

Spread the sand on the bars reinforcement after painting it with surface coating reduce the bonding between steel reinforcement and concrete with 43.3%.

Adding admixture with 3% of cement weight to the concrete increase the bonding between steel reinforcement and concrete with 5.1%.

The final method of spread the sand on the bars with surface coating and adding admixture with 3% of the cement weight to the concrete reduce the bonding between the steel bars and concrete with 32.9% so the best method for improve bonding is by adding an admixture.



Fig 4.14: Samples in Bonding test at second phase.



Fig 4.15: Samples in Bonding test at second phase.

4.4.2 Test results of flexural improvement after 28 days.

Table 4.10: Flexural improvement results after 28 days

Flexural improvement results after 28 days				
Methods of improvement	Sample (1) KN	Sample (2) KN	Sample (3) KN	Average KN
Without S.C	58.3	57.6	55.5	57.13
S.C only	37.8	36.2	35.4	36.46
S.C and sand	28.4	25.9	32.8	29.04
S.C and admixture	65.4	65.2	65.9	65.48
S.C , sand and admixture	42.	42.9	42.6	42.65

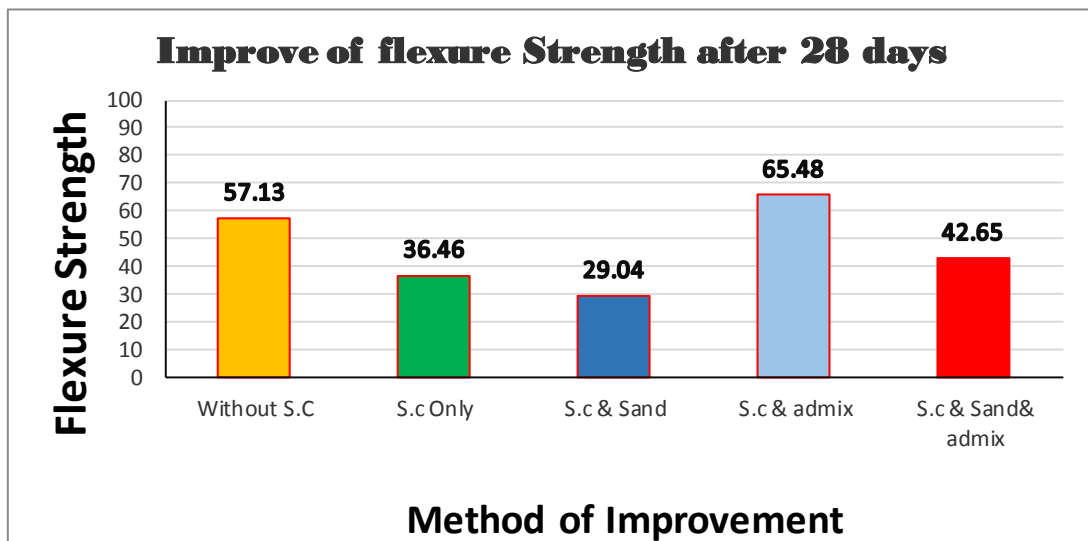


Fig 4.16: Flexural improvement results after 28 days.

The above figure illustrates the methods of improvement of flexural after 28 day, the samples tested without surfacing coating after 28 days were 57.13KN, however samples tested with surface coating only were 36.46KN, the samples tested by surface coating and sand were 29.04KN, the samples tested by surface coating and sand and admixture were 42.65KN but samples tested by surface coating and admixture were 65.48KN which is the best method of improvement for flexural test.

It is noticed that painting surface coating with type (C) on the steel reinforcement bars without any admixture for 3 samples reduces the flexural strength with 36.1% comparing with control sample.

Spread the sand on the bars reinforcement after painting it with surface coating with type (C) reduces the flexural strength with 43.3%.

Adding admixture with 5% of cement weight to the concrete increase the flexural strength with 14.6% comparing with control samples.

The final method of spread the sand on the bars with surface coating and adding admixture with 3% of the cement weight to the concrete reduces the flexural strength with 25.3% so the best method for improve flexural strength is adding admixture only. Figure 4.17 and 4.18 illustrate these procedures.



Fig 4.17: Flexural Tests in the second phase of test program.



Fig 4.18: Flexural Tests in the second phase of test program.

4.4 CONCLUSION REMARKS

1. In the first phase of test program the results show that the best surface coating which reduces corrosion rate after 70 days is surface coating type (C) (Polyurethane resin).
2. In the first phase, using surface coating only minimizes the corrosion rate specially in using type (C) of surface coating but using this type reduces the flexural strength and bonding between steel bars and concrete.
3. In the second phase of test program the results show that the best method of bonding improvement after 28 days is surface coating with admixture 3% of cement weight to the concrete which improved the bonding between concrete and steel reinforcement with 5.1% comparing with control sample.
4. In the second phase of test program the results show that the best method of flexural improvement after 28 days is surface coating with admixture 3% of cement weights which improves flexural strength with 14.6% comparing with control samples.
5. In the second phase of test program the worst method for improving bonding and flexural.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

Several parameters were investigated in the undertaken research to understand the influence of the corrosion process on the flexural capacity of corroded beams, and the structural performance for the surface coating on the samples. An experimental test program consisted of two phases was applied. The first phase is concerned with choosing the best surface coating regarding to the bonding tests and corrosion rate. In this phase, three types of surface coating used to measure the corrosion rate and the role of each type to reduce the corrosion. In addition these types used to study the bonding between the reinforcement and concrete and determining the best type of surface coating that reduce the corrosion rate without side effects at bonding between reinforcement and concrete. In the second phase of test program we improved the bonding between the concrete and steel reinforcement then we improved the flexural capacity of samples.

5.2 CONCLUSION

In order to accelerate the corrosion process, an electrochemical system which depends on the concept of Faraday's second law was used. The aim of accelerating the corrosion was to force steel reinforcement to act as anode in a galvanic cell. which can be done by immersing beams in an aqueous solution and connecting the steel reinforcement bars with positive DC current generator to act as anode while connecting the negative power supply to external steel rods immersed in the aqueous solution to act as cathode. This consists electric circuit and force steel ions to translate from anode and to cathode.

Samples of the reinforcing bars were tested using the standard tension test to determine the properties of the corroded bars. The following conclusions are drawn:

5.2.1 Effect of surface coating on corrosion of steel reinforcement.

1. Several longitudinal cracks formed parallel to the flexural reinforcement along both bottom and sides of corroded beams due to corrosion process.

2. The corrosion rate result for reinforcement in beams without surface coating after 70 days was more than 50% from its weight.
3. The corrosion rate result for reinforcement in beams weight loss with surface coating Type (A) "**Acrylic polymers**" after 70 days was 18.9% from its weight.
4. The corrosion rate result for reinforcement in beams with surface coating Type (B) "**Epoxy polymers** "after 70 days was 14.3% from its weight.
5. The corrosion rate result for reinforcement in beams with surface coating type (C) "**Polyurethane resin**" after 70 days was 1.6 % from its weight which is the best surface coating.

5.2.2 Effect of surface coating on bonding strength between concrete and steel reinforcement.

1. The bonding improvement result after 28 days was 67.33 KN in the method of surface coating with admixture with is the best method used to improve the bonding between reinforcement and concrete with 5.1% comparing to control samples.
2. Using sand in bonding improvement decrease the bonding between steel bars and concrete with 43.3%.
3. We need to use surface coating and admixture to minimize the corrosion rate and improve the flexural strength and bonding between concrete and steel reinforcement.

5.2.3 Effect of surface coating on flexural strength of concrete

1. The flexural strength improvement result after 28 days with 14.6% comparing to control samples.
2. Using sand in flexural strength improvement decreases the flexural strength with 49.1%.

5.3 RECOMMENDATION FOR FUTURE RESEARCH

1. Very few experimental investigations are available on the behaviour of reinforced concrete corroded beams subjected to bending action. More experimental investigations are necessary to monitor and assess the structural condition in corroded concrete beams and investigating a repairing techniques to deal with the corrosion problem from structural point of view.
2. A more detailed study of the composite interaction between the steel and the concrete and the bond deterioration are required to understand the action of the expansion of the corrosion products and the reduction of the reinforcing bar section.
3. A larger number of specimens should be tested with the improvement of the electrochemical set-up to increase the corrosion rate and to decrease the corrosion time.
4. Further future research is needed to investigate the durability of the applied techniques and how to prevent the future corrosion process.
5. Find best method for painting the steel bars to save at the same depth of painting layer.
6. Find another methods for improving bonding and flexural strength .

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