

# Effect of the size of uncoated area of reinforcing steel bars on corrosion rate

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**Abstract**— Durability issues associated with reinforced concrete structures are some of the biggest problems the civil engineering community is facing today around the world. One of the most significant durability issues is the corrosion of steel reinforcement, which leads to rust formation, cracking, spalling and degradation of structures. This is considered to be the main factor causing damage in bridges and other infrastructure [1, 2]. Many articles had been studied in details different causes of corrosion, corrosion mechanism, corrosion assessment and different protection methods. Most of corrosion studies done in the last few decades concentrated more on the different methods of protection.

Coating of steel bars is considered the most commonly used protection method. Uncoated parts of steel bars may be exist (especially in the case of one layer coating) due to many reasons such as bad quality painting, friction between bars, friction between bars and concrete forms, friction between bars and concrete, or due to any other reason (4).

The main objective of this research work is to study the effect of the size of uncoated parts on the corrosion rate. Corrosion rate of fully protected bars were compared with those of similar specimens having local defects of different sizes (ranging from 5 to 100 mm) and also were compared with uncoated bars as control specimens

## 1. INTRODUCTION

In reinforced concrete (RC) structures, concrete provides protection to the reinforcement bar. The dense and impermeable concrete provides the physical protection, whereas the alkalinity of the pore solution provides the chemical protection. The alkaline environment of concrete (pH 12-13) implies the formation of a passive film on the surface of the reinforcement bar that provides steel with corrosion protection [1, 2, 3]. However, the two main phenomena such as carbonation and chloride attack may lead to a breakdown in the surface layer of ferrous hydroxide that covers the steel in the alkaline concrete environment [39]. Carbonation characterized by the reaction between atmospheric carbon dioxide (CO<sub>2</sub>) and water in concrete pores to form insoluble carbonate which, with the reduction of the pH value of the pore solution of concrete, leads to the corrosion of reinforcing steel. In contrast, the chloride ions, for instance, sodium chloride found in sea water and salts used in the de-icing practices on the transportation network and calcium chloride (CaCl<sub>2</sub>) still found in concrete admixtures, can result in the free passage of chloride ions through the concrete cover and depassivation of the reinforcing bar. In reinforced concrete, corrosion affects the bond behavior of the reinforcement due to the loss of steel bar cross-section. The concrete bond strength does not solely depend on the properties of the concrete but also on other factors such as; spalling and cracking of the concrete cover.

1. Spalling is largely caused by the separation and disintegration of concrete. The main cause of spalling is growth of the corrosion products of the reinforcing bar leading to cracking and bulging of the concrete cover.
2. The corrosion of reinforcing steel or freezing and thawing can cause the separation of a coating from a substrate or the layers of coating from each other along a plane nearly parallel to the surface of concrete in a process known as delamination.

### 1.1 STEEL PROTECTIVE COATINGS

Protective coatings are probably the most widely used products for corrosion control. They are used to provide long-term protection under a broad range of corrosive

conditions, extending from atmospheric exposure to the most demanding chemical processing conditions. Protective coatings themselves provide little or no structural strength, yet they protect other materials to preserve their strength and integrity. The main function of a protective coating is to isolate structural reactive elements from environmental corrosives. A coating must provide a continuous barrier to a substrate, and any imperfection can become the focal point for degradation and corrosion of the substrate, [1].

From a corrosion point of view, a coating is rated on the resistance it provides against corrosion in a specific environment, and because there are many variations in environment aggressiveness, there is also a great variety of corrosion protective coatings. These can be broadly divided into metallic, inorganic and organic coating.

### 1.2 METALLIC COATINGS

Metallic coatings provide a layer that changes the surface properties of the work-piece to those of the metal being applied. The work-piece becomes a composite material exhibiting properties generally not achievable by either material if used alone. The coatings provide a durable, corrosion resistant layer, and the core material provides the load-bearing capability.

The deposition of metal coatings, such as chromium, nickel, copper and cadmium, is usually achieved by wet chemical processes that have inherent pollution control problems. Alternative metal deposition methods have been replaced some of the wet processes and may play a greater role in metal coating in the future. Metallic coatings are deposited by electroplating, electro-less plating, spraying, hot dipping, chemical vapor deposition, and ion vapor deposition. Some important coatings are cadmium, chromium, nickel, aluminum, and zinc, [1].

### 1.3 INORGANIC COATINGS

Inorganic coatings can be produced by chemical action, with or without electrical assistance. The treatments change the immediate surface layer of metal into a film of metallic oxide or compound that has better corrosion resistance than the natural oxide film. An example of applying these types of coatings is anodizing, which is an electrochemical

process during which aluminum is the anode. It involves the electrolytic oxidation of a surface to produce a tightly adherent oxide scale that is thicker than the naturally occurring film. The electric current passing through an electrolyte converts the metal surface to a durable aluminum oxide. The oxidized surface is hard and abrasion resistant, and it provides some degree of corrosion resistance.

Anodic coating provides an excellent surface both for painting and for adhesive bonding. Anodic coatings break down chemically in highly alkaline solutions ( $\text{pH} > 8.5$ ) and highly acidic solutions ( $\text{pH} < 4.0$ ). They are also relatively brittle and may crack under stress. Chromic acid anodizing is widely used with 7000 series alloys to improve corrosion resistance, [1].

## 1.4 ORGANIC COATINGS

High performance organic coatings were developed to protect metals from environmental damage. Of prime importance in the development of protective coatings was the petroleum industry, which produced most of the basic ingredients from which most synthetic resins were developed. The cracking of petroleum produced a multitude of unsaturated workable compounds that are important in the building of large resin polymers such as vinyls and acrylics. The building blocks for epoxies and modern polyurethane coatings are other derivatives produced by refining petroleum products.

## 1.5 EPOXY COATINGS

Epoxy-coated reinforcing steel (ECR) was developed and implemented in the mid-1970's to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. The epoxy coating is a barrier system intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel and to electrically insulate the steel to minimize the flow of corrosion current.

## 1.6 OBJECTIVES

The main objective of this research work is to investigate the effect of the size of the uncoated area of the steel bars on the corrosion rate. Three different cases are considered in this research:

1. Fully protected bars (with no defects in the protective coating)
2. Bars protected by the protective coating but with uncoated part of different sizes (ranging from 5 to 100 mm).
3. Completely non protected bars (with no coating).

## 2. MATERIALS USED

### 2.1 CONCRETE AND CONCRETE MATERIALS

The cement used was Portland cement of grade R42.5 that complies with the requirement of the Egyptian standard specifications ESS 4756/2007. The coarse aggregate was crushed stone. The used sand was natural sand with fineness modulus of 2.32. The concrete mix was designed to

achieve cube compressive strength after 28 days of 275  $\text{Kg/cm}^2$ . The steel reinforcement used was high tensile steel with oblique ribs of grade 400/600 and a nominal diameter 13 mm. The average measured 7 and 28 days cube compressive strength were 240 and 325  $\text{Kg/cm}^2$  respectively.

## 2.2 PROTECTIVE COATING

The used protective coating for the steel bars was Zinc rich epoxy which consisted of epoxy paint modified with zinc to provide protection against corrosion. The used product is considered the most widely used protective coating in the Egyptian market in the last few years.

## 3. TEST SPECIMENS IDENTIFICATION

Twelve test specimens were used in the experimental study. Two specimens were not protected and used as control specimens; these two specimens were denoted as NP1 and NP2. Two specimens were fully protected (i.e. without any local defect) one of them using one layer and the second using two layers; these two specimens were denoted as P1 and P2 respectively. Eight specimens were have local defects in the protective coating. The local defects were done by putting a tape around the steel bar before painting and removing it after that; the height of the defects were 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, 50mm, 100mm and specimens were denoted as D5, D10, D15, D20, D25, D30, D50 and D100 respectively. Table 1 shows all the test specimens and the identification of each specimen.

Table 1: Identification of test specimens

| Protection Case               | Details       | No. of Specimens | Ident. |
|-------------------------------|---------------|------------------|--------|
| No Protection (Control)       | No Protection | 2                | NP1    |
|                               |               |                  | NP2    |
| Protection with Local Defects | 5 mm defect   | 8                | D5     |
|                               | 10 mm defect  |                  | D10    |
|                               | 15 mm defect  |                  | D15    |
|                               | 20 mm defect  |                  | D20    |
|                               | 25 mm defect  |                  | D25    |
|                               | 30 mm defect  |                  | D30    |
|                               | 50 mm defect  |                  | D50    |
|                               | 100 mm defect |                  | D100   |
| Full Protection               | One layer     | 2                | P1     |
|                               | Two layers    |                  | P2     |

## 3.1 EXPERIMENTAL STUDY AND TEST RESULTS

Test specimens are called "Lollipop" specimens; they are 100 mm diameter and 200 mm length concrete cylinders with a 13 mm nominal diameter and 300 mm length steel bar was embedded in each specimen. The steel bar placed into the specimen keeping only 130 mm of its length embedded in concrete to make sure that the concrete cover is not less than 45 mm. Specimens were subjected to accelerated corrosion using the galvano-static method in which a current was impressed through the reinforcing steel bar by applying a fixed potential across the anode (reinforcing steel bar) and an external cathode (a steel

cylindrical pipe surrounds the specimen). An electronic voltmeter was used to measure the current intensity in the circuit by recording the potential difference between a fixed resistance of 100 Ohm. The circuit current was calculated as the product of the measured potential difference divided by the resistance. The concrete specimen was immersed in a 15% Sodium chloride (NaCl) solution at the room temperature and was connected to a constant 15 Voltage power supply. The steel cylindrical plate was submerged in the solution and was cleaned periodically to prevent depositing of salt on the surface. The dimensions of the test specimens and the corrosion cell are shown in Figure 1. During the progress of the accelerated corrosion test, the resulting current values "I" are manually recorded every 2 hours for a total time of 250 hours. Figures 2 and 3 show the obtained results for specimens D25 and D50 respectively. The following equations are used to calculate the corrosion current intensity in the circuit:

$$I = V/R \quad (1)$$

Where

I = Corrosion current intensity

V = Potential difference, across 100Ω resistance.

R = Resistance (100 Ω).

Then, the total mass loss will be calculated from the area under the curve of corrosion current versus time using Faraday's equation:

$$Mt = [M/Z \cdot F][\int I \cdot dt] \quad (2)$$

Where

Mt = Total mass loss (gm)

M = Atomic weight of metal (55.85 gm/mol for iron).

$\int I \cdot dt = Q$  = Electrical charge.

Z = Ionic charge (2 for iron).

F = Faraday's constant (96485.3 C/mole of e).

Table 2 gives the total calculated total mass loss (Mt) for all the test specimens. Figure 4 shows the total calculated total mass loss (Mt) for all the test specimens as a percentage from the control case (i.e. non protected case).

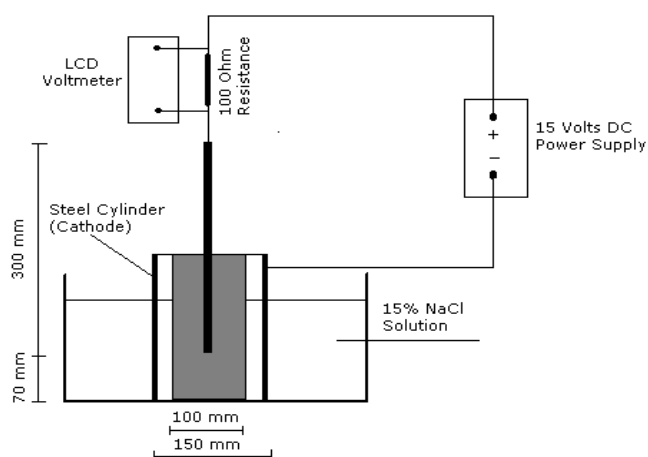


Figure 1 : Accelerated Corrosion cell

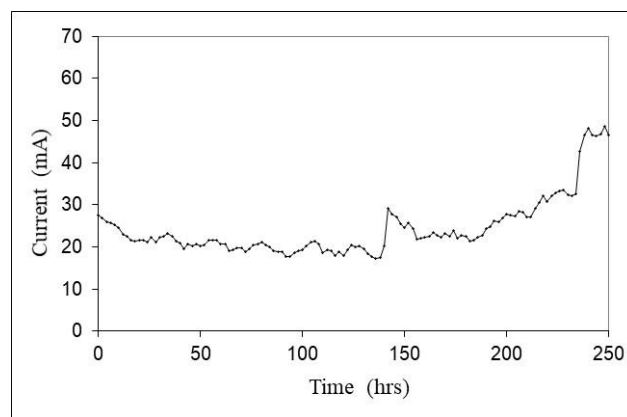


Figure 2 : Relationship between time (hrs) and corrosion current (mA) for specimen D25

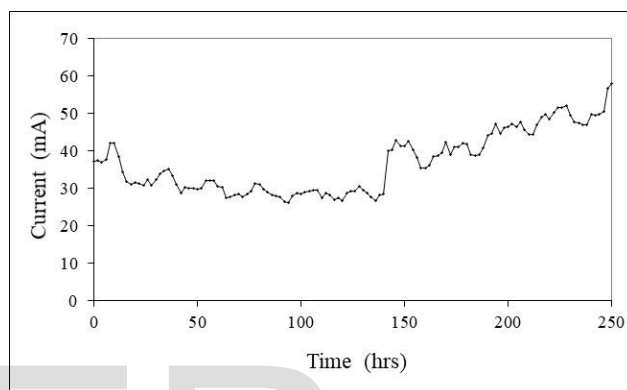


Figure 3 : Relationship between time (hrs) and corrosion current (mA) for specimen D50

Table 2: Total Mass Loss for Test Specimens

| Protection Case               | Specimen | Mass Loss (gm) | Av. Mass loss (gm) | % from control case |
|-------------------------------|----------|----------------|--------------------|---------------------|
| No Protection (Control)       | NP1      | 41.53          | 43.41              | 100                 |
|                               | NP2      | 45.29          |                    |                     |
| Protection with Uncoated part | D5       | 1.23           | 1.23               | 2.83                |
|                               | D10      | 4.76           | 4.76               | 10.97               |
|                               | D15      | 7.08           | 7.08               | 16.31               |
|                               | D20      | 7.67           | 7.67               | 17.67               |
|                               | D25      | 8.98           | 8.98               | 20.67               |
|                               | D30      | 14.54          | 14.54              | 33.50               |
|                               | D50      | 34.57          | 34.57              | 79.64               |
| Full Protection               | D100     | 41.43          | 41.43              | 95.55               |
|                               | P1       | 1.12           | 1.18               | 2.72                |
|                               | P2       | 1.24           |                    |                     |

#### 4. DISCUSSION OF TEST RESULTS

1. Comparing the total mass loss for the fully protected test specimens by one and two layers of the used protective coating, it can be seen that almost there is no difference between both cases as given in Table (2). However one layer provides a satisfactory level of protection, using of two layers is usually preferred to avoid any local defect that can be easily happen during handling of bars at site.

2. Local defect in the protective layer of size 5 mm which can be considered a relatively small size defect causes a mass loss below 3% compared to the control case. This is almost the same mass loss of the fully protected case. This means that defects below 5mm size have not any significant effect on the corrosion rate of steel bars. This is due to the protective field of the zinc rich coating which still protect the uncoated area due to its relatively small size.
3. Local defects in the protective layer of sizes between 10 to 30 mm which can be considered a relatively medium size defects causes a mass loss between 11% to 33% compared to the control case. These values are significant can not be neglected and a great care should be taken during the handling of coated bars in all stages of the construction process. The average diameter loss in this case is about 40%. This is considered a significant and dangerous reduction.
4. Local defect in the protective layer of size 50 mm which can be considered a large size defect causes a mass loss about 80% compared to the control case. The average diameter loss in this case is about 50%. This is considered a significant and dangerous reduction. These values are very high and can lead after a time of chloride exposure to a full diameter loss which affect the safety of the RC structure. This size of the defect is considered the worst one since there is no protective field available any more plus the high mass loss accompanied by only 50mm size, results in the highest diameter loss.
5. Local defect in the protective layer of size 100 mm which can be considered a very large size defect causes a mass loss about 95% compared to the control case. The average diameter loss in this case is about 25%. This is considered a significant and dangerous reduction but not as dangerous as the previous case of 50mm size defect.

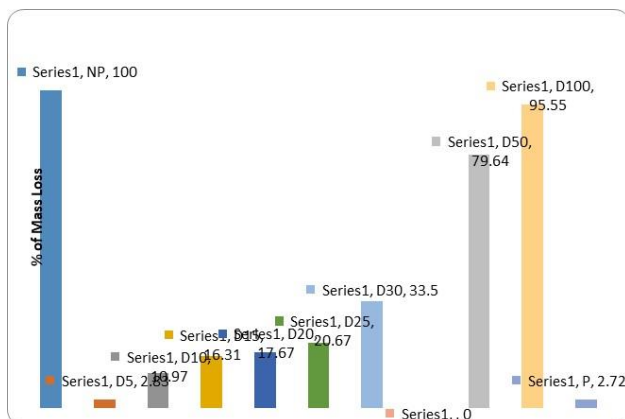


Figure 4 : % Mass Loss for different specimens compared To non-protected specimens (Control case)

## 5. CONCLUSIONS

Based on the results of the experimental study and above discussion, the following can be easily concluded:

1. For the Fully protected bars, there is no difference between one and two layers (both cases provides almost the same level of protection).
2. Small size local defects (of sizes smaller than 5 mm) did not have a significant effect on the corrosion rate test

results. This case almost has the same protection level of the fully protected bars.

3. Local defects of a relatively medium sizes (ranging between 10 to 30 mm) causes a significant drop in the protection level and can not be neglected.
4. Local defect of size 50 mm causes almost a complete loss of the protection level and can lead to a full diameter loss which can affect the safety of the RC structure. This size is considered the worst size of the uncoated area of the steel bar.
5. Local defects of a relatively large size of 100 mm causes a significant reduction of the protection level.

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