EFFECT OF CONCRETE COVER AND EXTERNAL CHLORIDE CONCENTRATION ON CORROSION RATE OF LOADED REINFORCED CONCRETE BEAMS

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Abstract— Corrosion of the steel reinforcement plays a vital role in the determination of durability and service life for many of the concrete structures. Corrosion of reinforcing steel is an economically expensive problem since it could lead to unanticipated, premature failure of concrete structures. In most cases, water-soluble chlorides induce the corrosion of the reinforcing steel. Extensive research work has been done on the corrosion behavior of the embedded steel reinforcement and also on the different protective measures that are available for corrosion control. However, little work has been done to identify the performance and predict the behavior of the stressed steel subjected to corrosive environment with time.

The main aim of this research is to evaluate the corrosion rate of loaded reinforced concrete (R.C.) beams subjected to corrosive environment taking into account two main parameters affecting this rate, namely, the concrete cover and the concentration of the external chlorides

Test results have showed that the corrosion rate is affected by concrete cover more than by the percentage of external chlorides. Decreasing the concrete cover from 50 to 20mm will increase the average corrosion rate 62% .Increasing the external chlorides concentration from 1% to 5% will increase the corrosion rate 52%

1.1 INTRODUCTION

Corrosion of steel reinforcement is considered one of the major causes of reinforced concrete deterioration. Corrosion can be defined as the loss of useful properties due to chemical or electrochemical reactions. Causes of corrosion are attributed to the reinforcing steel itself, its constituting, or to the surrounding environment. Steel surface can have adjacent areas with different potentials due to presence of impurities from other materials, non-uniform cooling during the manufacturing process or different concentrations of ions surrounding the steel surface. Concrete may contains some ions such as chloride ions either intentionally, as a concrete admixture, or unintentionally, also as those present in concrete materials. The surrounding environment may be corrosive such as the case of industrial buildings, marine structures, foundations, etc. [1, 2, 3, 4, 5].

In fact, little work has been performed to quantitatively describe how the behavior of RC elements change in the presence sustained loading. The application of cyclic or static loads shifts the corrosion potential to more negative values. This shift seems to increase with the increase in the amount of load. A possible cause of this behavior could be due to stress concentration on the reinforcement [6]. The presence of a sustained load and the associated flexural cracks significantly reduce the time to corrosion cracking and slightly increase the corrosion crack width. The presence of flexural cracks during corrosion process causes the increased steel mass loss rate and, consequently, the reduction in the beam strength [7]. The loading history and loading level have significant effects on both corrosion initiation and the rate of corrosion propagation. The failure mode of the reinforced concrete beams also changes from a shear failure of concrete to bond splitting as the degree of corrosion increased [8].

The corrosion rate provides information on the rate at which reinforcing steel is being oxidized. The higher the rate, the sooner concrete cracking and spalling will appear. Therefore, this information can be useful in estimating the time to additional damage and in selecting cost-effective repair and long-term corrosion-protection systems, [8]. The corrosion rate is measured in terms of the percentage of the weight loss which is calculated using Faraday equation

1.2 OBJECTIVE

The main objective of this research work is to study the effect of concrete cover and percentage of external chlorides on corrosion rate of reinforcing bars in loaded R.C. beams

Three values of concrete cover were considered; 20mm, 35mm and 50mm. Three values of external chloride concentrations were considered 1%, 3% and 5%.

1.3 MATERIALS

1.3.1 Concrete and concrete materials

The cement used was ordinary Portland cement that complies with the requirement of the Egyptian standard specifications, [9]. The coarse aggregate was crushed stone. The used sand was natural sand with fineness modulus of 2.47. Table 1 gives the sieve analysis test results for the used sand and crushed stone. Table 2 gives physical properties of the used sand, crushed stone. The concrete mix was designed to achieve cube compressive strength after 28 days of 30 MPa as given in Table 3. The steel reinforcement used was high tensile steel with oblique ribs of grade 36/52 and a nominal diameter 12 mm. The average measured 7 and 28 days cube compressive strength were 29 and 37.5 MPa respectively. Test specimens were cast and cured by wet burlaps until the test date.

Table 1: Sieve Analysis Test Results for Fine and Coarse Aggregates

Fine Agg.	Sieve size (mm)	4.75	2.36	1.18	0.60	0.30	0.15
	% passing	99.0	96.8	88.8	59.7	14.1	1.6
Coarse Agg.	Sieve size (mm)	37.5	31.5	28.0	20.0	10.0	5.0
	% passing	100	100	100	100	97.5	2.50

Table 2: Properties of Fine and Coarse Aggregates

Property	Fine Agg.	Coarse Agg.
Specific gravity	2.56	2.61
Unit weight (t/m^3)	1.53	1.58
Crushing value (Los Anglos)	---	23.6%
% Fine materials (by volume)	2.00	---
% Absorption	---	1.8%

Table 3: Mix Proportions (By weight) of One Cubic Meter of Concrete

Cement (OPC) (Kg)	Sand (Kg)	Crushed Stone (Kg)	Water (Liter)
350	630	1120	210

1.3.2 Loaded R.C. beams

Nine specially designed R.C. beams were used in the experimental program, [10]. Figs (1 & 2) present the dimensions and reinforcement details of loaded R.C. beams. The test specimen was divided into three parts: The first part of the specimen had dimensions 150 mm wide, 200 mm high, 400 mm long. This part was reinforced with one deformed steel bar as a top reinforcement having the length of 1000 mm. To avoid excessive corrosion at the ends of the main reinforcing bar, all reinforcement bars were coated with epoxy except the mid part of the main bar of length 400 mm.

During the test, load was applied to the middle part of the beam by the second and third parts of the specimen. These two parts had dimensions 150 mm wide, 100/200 mm high and 380 mm long, and were reinforced by 2Ø10 mm deformed steel bars as a top and bottom reinforcement. The shear reinforcement consisted of 3Ø8 mm plain mild steel reinforcing bars as stirrups at 40 mm above the external post-tension force location and 2Ø8 horizontally stirrups, as shown in fig. (2). The main bar was welded to the reinforcement of part two and three to transfers the applied load to the main bar, as shown in fig. (2).

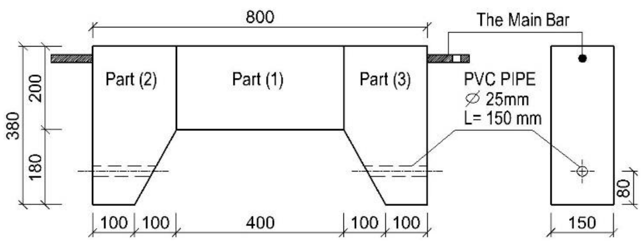

Figure (1) Concrete Dimensions of loaded R.C. Beams used in Phase(I) (all dimensions are in mms)

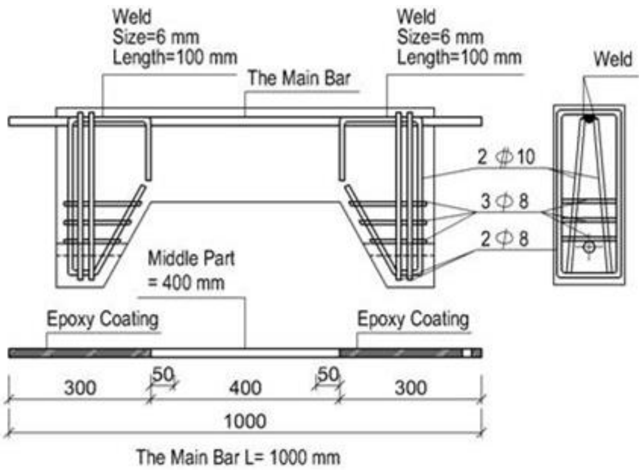

Figure (2) Reinforcement Details of loaded R.C. Beams used in Phase(I) (all dimensions are in mms)

1.3.3 Details of Prestressing System

The method of applying a constant sustained load to the specimens is shown schematically in fig. (3). The load was applied and kept constant on the test specimens until failure. The load was applied using a portable 90 KN hydraulic Jack and 16 mm diameter steel bar. The load-deflection behavior of parts "2" and "3" was monitored by the use of a dial gauge placed between part "2" and the part "3", as shown in fig. (3). In this configuration, the right side of the steel rod was connected to a steel nut that rested on a steel plate. On the left side, the steel rod was connected to the portable hydraulic Jack by the steel rod and a steel coupler. After applying the load, the left nut was tightened by a wrench and was controlled by the measuring crack width. The range of crack widths was kept between 0.2 - 0.25 mm. It should be noted that the crack width was controlled to a certain value as accurately and practically as possible, but the crack width increased over time due to creep and shrinkage. Thus, the crack width mentioned was actually the initial (instantaneous) width.

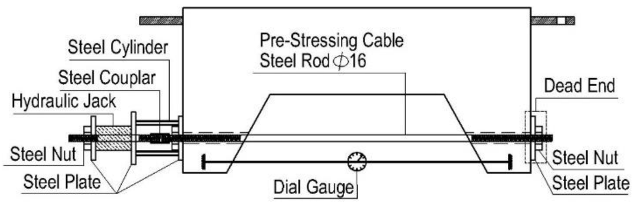

Figure (3) Schematic Diagram of Prestressing System

1.4 TEST METHODOLOGY AND RESULTS

The test specimens (loaded R.C. beams) 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 (the main reinforcing steel bar) and an external cathode (a steel plate). An electronic voltmeter was used to measure the current intensity in the circuit by recording the potential difference between a fixed resistances 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 1%, 3% and 5% sodium chloride (NaCl) solution at the room temperature and was connected to a constant 5 Voltage power supply. The steel plate was submerged in the solution and was cleaned periodically to prevent depositing of salt on the surface. The details of the corrosion cell are shown in fig. (4). During the progress of the accelerated corrosion test, the potential difference values "V" were automatically recorded every one hour for a total time of 1440 hours using a specially designed data acquisition system.

The following equations were used to calculate the corrosion current intensity in the circuit:

$$I = V/R \qquad \text{eq. (1)}$$

Where

I = Corrosion current intensity

V = Potential difference, across 100Ω resistance.

R = Resistance (100 Ω).

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

$$Mt = [M/Z{*}F][\int I.dt] \qquad \text{eq. (2)}$$

Where

Mt = Total weight loss (gm)

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

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

Z = Ionic charge (2 for iron).

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

Table 4 gives the calculated total mass loss (Mt) for all the test specimens. All specimens were labeled as (1)/(2) where: (1) is the value concrete cover and (2) the value of external chlorides concentration.

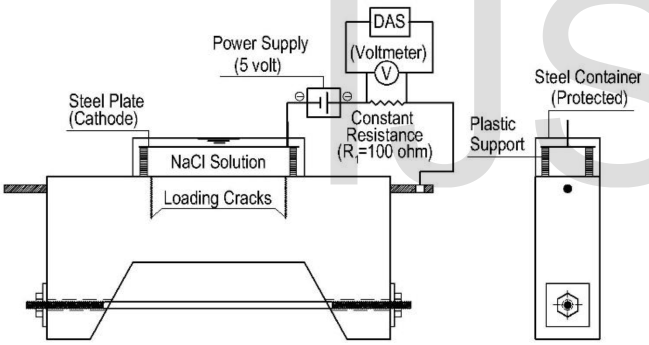

Figure (4): Schematic Diagram of Corrosion Acceleration Technique.

Table 4: Total Mass Loss for Test Specimens

Code of Specimen	Weight Loss *(gm)	%Weight Loss *	Corrosion Cracks
20/1	30.41	8.37	One longitudinal crack
20/3	33.14	9.12	
20/5	39.28	10.81	
35/1	18.50	5.09	
35/3	25.73	7.08	
35/5	28.85	7.94	
50/1	15.15	4.17	No corrosion cracks
50/3	24.35	6.7	
50/5	25.98	7.15	

*The total weight loss after twelve weeks

1.5 Discussion of Test Results

1.5.1 Effect of Concrete Cover on the Percentage of Weight Loss (Based on Faraday's, Equation)

The percentage of weight loss of all beams was calculated using Faraday's, equation. The percentage of weight loss values were calculated weekly for a total time of twelve weeks. Figs. (5) to (7) represent the calculated percentage of weight loss for all beams along the 12 weeks. Fig. (8) shows bar chart for the total percentage of weight loss after twelve weeks for all concrete covers for different external chlorides concentrations. The values of 50 mm cover were taken as a reference value (i.e. 100%). The percentage of weight loss measurements of 20 and 35 mm covers were compared to those of 50mm cover.

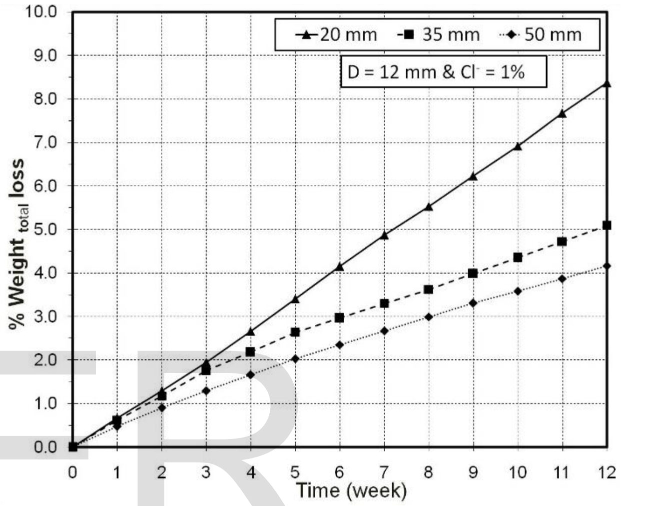

Figure (5): The % Weight Loss vs. Time for different concrete covers and external Chloride concentration 1%

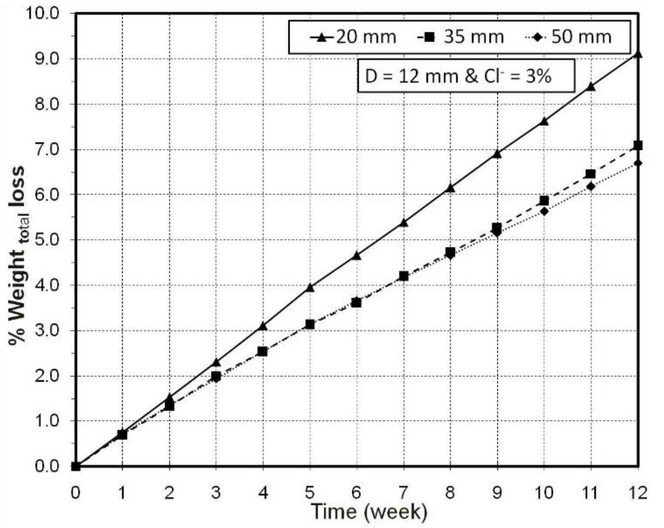

Figure (6): The % Weight Loss vs. Time for different concrete covers and external Chloride concentration 3%

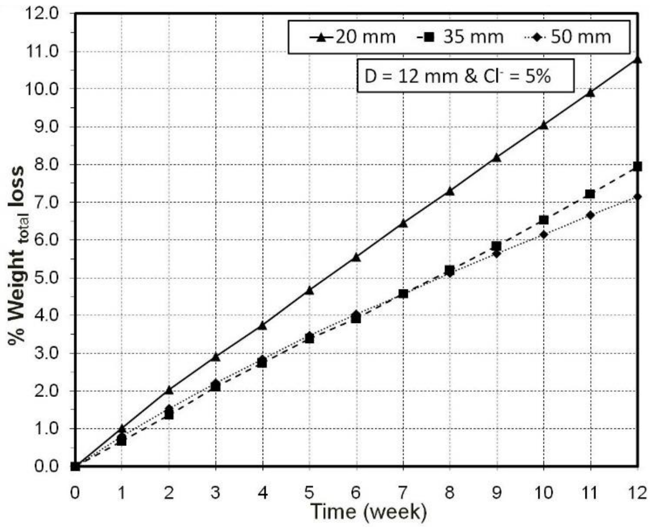

Figure (7): The % Weight Loss vs. Time for different concrete covers and external Chloride concentration 5%

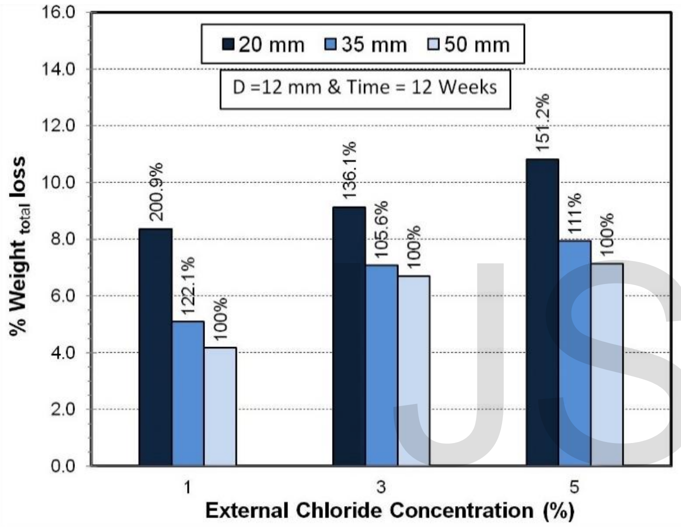

Figure (8) The % Weight Loss for Different Concrete Covers, Different External Chloride Concentrations

Based on the calculated values of percentage of weight loss, which are represented graphically in figs. (5) to (8), the following points were observed:

- For the loaded R.C. beams (1% chlorides), the percentage of weight loss of 20 mm and 35 mm covers are 100.9% and 22.1% respectively higher than that of 50mm cover. This means that for all chlorides content 1% there is a big difference between corrosion rates of different values of concrete covers. In other words, it can be said that for low chlorides content, the concrete cover has a remarkable effect on corrosion rate.
- For medium chlorides content (3%), the percentage of weight loss is almost the same value for 35 and 50mm covers, while for 20 mm cover, it was 36.1% higher than that of 50 mm cover. For high chlorides contents (5%), percentage of weight losss of 20 and 35 mm covers are 51.2% and 11% higher than that of 50 mm cover respectively

1.5.2 EFFECT OF CHLORIDE CONCENTRATIONS ON THE PERCENTAGE OF WEIGHT LOSS (BASED ON FARADAY'S, EQUATION)

Figs. (9) to (11) represent the calculated percentage of weight loss for all beams along the twelve weeks. Fig. (12) shows bar chart for the total percentage of weight loss after twelve weeks for all chloride concentrations for different concrete covers and bar diameters. The values of 1% chlorides were taken as a reference value (i.e. 100%). The percentage of weight loss measurements of 3% and 5% chlorides were compared to those of 1% chlorides.

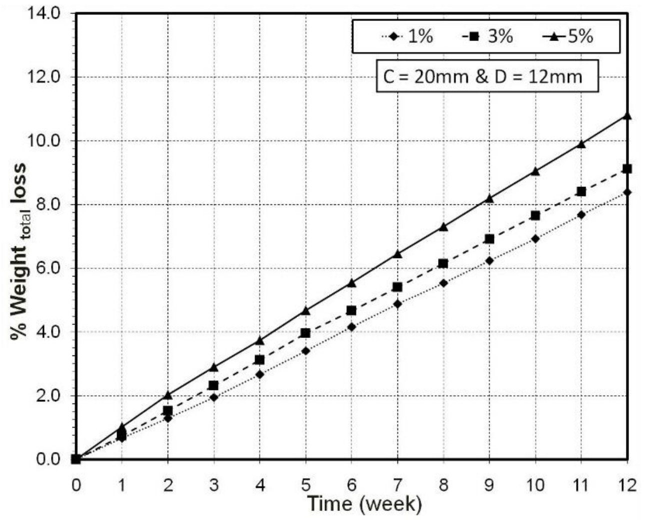

Figure (9) The % Weight Loss vs. Time for Different External Chloride Concentrations, Concrete cover 20mm

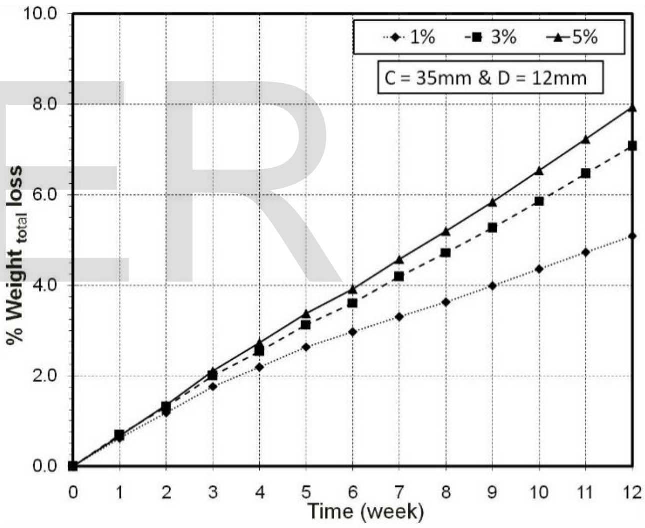

Figure (10) The % Weight Loss vs. Time for Different External Chloride Concentrations, Concrete cover 35mm

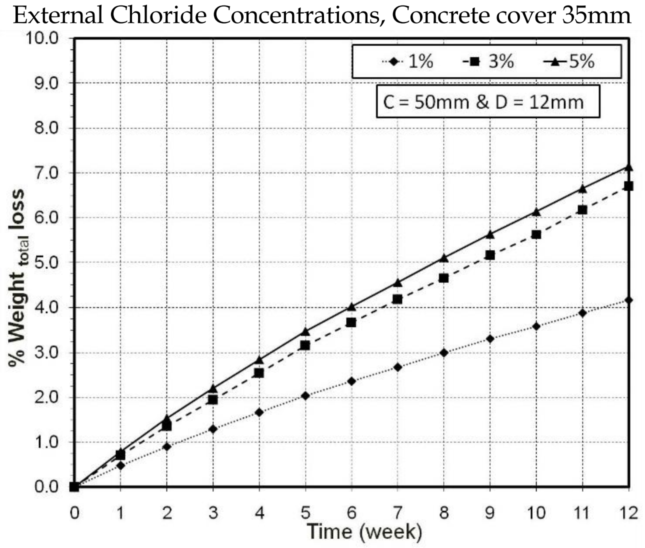

Figure (11) The % Weight Loss vs. Time for Different External Chloride Concentrations, Concrete cover 50mm

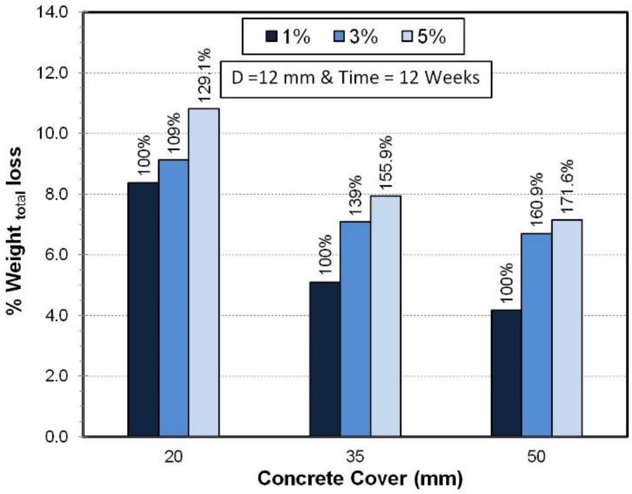

Figure (12) The % Weight Loss for Different External Chloride Concentrations, Different Concrete Covers

Based on the calculated values of percentage of weight loss, which are represented graphically in figs. (9) to (12), the following points were observed. For the loaded R.C. beams (20mm cover), the % Weight losses of 3 and 5% chlorides contents are 9% and 29.1% higher than that of 1% chlorides contents respectively. For medium chlorides concrete cover (35mm), the % Weight losses of 3 and 5% chlorides contents are 39% and 55.9% higher than that of 1% chlorides contents respectively. For large concrete cover (50mm), the % Weight losses of 3 and 5% chlorides contents are 60.9% and 71.6% higher than that of 1% chlorides content respectively.

1.6 Conclusions

In case of different degrees of aggressiveness of the outside environment 1%, 3% and 5% (external chloride concentration), decreasing the concrete cover from 50mm to 20mm will increase the corrosion rate by 100.7%, 36.1% and 51.2% respectively.

In general, it may be stated that:

- The small concrete cover of (20mm) does not offer any degree of protection for all levels of external chloride attack. So, it is strongly recommended to use a minimum value of concrete cover equal of 30mm in the Egyptian code of practice [11] instead of the current value of (20mm) for the cases of structures subjected to the second and the third categeory of extenal attack.
- Corrosion rate of the worst case (case of the highest degree of external attack and the smallest value of concrete cover) is almost 2.5 times that of the case of the lowest degree of external attack and the largest value of concrete cover.

1.7 Acknowledgement

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1.8 References

1. Nasr, E.A., Abdel-Wahab, M.M. and Khalaf, M.A. (2003),"Corrosion Resistance Of Reinforced Concrete Using different Protection Method" ICSGE conference, Faculty of Eng., Ain Shams University.
2. Khalaf, M.A. (2004), "Evaluation of the Effectiveness of Wrapping Reinforced Concrete surface with FRP Sheets as an Indirect Protection Method", Scientific bulletin of faculty of Eng., Ain Shams University.
3. Ismail, T. (1989), "Corrosion Prevention of Steel Reinforcement in Concrete," M.SC. Thesis, Faculty of Engineering, Ain- Shams University.
4. 3rd International Conference (1989), "Deterioration and Repair of Reinforced Concrete in the Arabian Gulf," Bahrain, Proceedings; Volume 1, pp. 21-24.
5. Elnouhy, H. A. (1996), "Corrosion Inhibitors for Reinforcing Steel in Concrete," Master of Science, the American University in Cairo.
6. Mendoza, A.R. (2003), "Corrosion of Reinforcing steel in Loaded Cracked Concrete Exposed to De-icing Sltes", Master of Applied Science, University of Waterloo, Waterloo, Ontario, Canada.
7. El Maaddawy, T., Soudki, K. and Topper, T. (2005), "Long-Term Performance of Corrosion-Damaged Reinforced Concrete Beams", ACI Structural Journal, vol. 102, No. 5, Sep. –Oct. 2005, pp 649-656.
8. ACI Committee (222R-01), (2001), "Protection of Metals in Concrete Against Corrosion", ACI JOURNAL.
9. ES (4756-1/2006), "Specification for Portland Cement CEMI", Egyptian Standardization Authority.
10. Rashad, A. (2003), "Improving the Performance of Reinforced Concrete Elements Using Fiber Reinforced Plastics", Master of Science, Faculty of Engineering, Ain Shams University, Cairo, Egypt.
11. Egyptian Code of Practice, (ECCS 203), (2007), "Egyptian Code for Design and Construction of Concrete Structure", 8th Edition, Ministry of Building Construction, Egypt.