Comparison Between Effectiveness Of Corrosion Protection Methods Commonly Used In Egypt

Ibrahim Abdel-Latif

Abstract: From early sixties there has been a growing awareness that reinforced concrete structures can suffer severe deterioration in advance of its design life as a result of corrosion of the reinforcing steel. Generally, 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 reinforcing steel corrosion, 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. Many articles had been studied in details different causes of corrosion, corrosion mechanism, corrosion assessment and different protection methods. The main target of this research work is to investigate and compare between effectiveness of the protection methods most commonly used in Egypt. This will be done by comparing the results of corrosion resistance measured for the reinforced concrete specimens protected by each method individually with those of similar specimens without any protection. The used protection methods are:
1)　Steel Coating with four different types of coatings (most commonly used in Egypt) with a varied number of layers.
2)　Concrete Coating with a varied number of layers.
3)　Concrete Admixture.
4)　Combined method (Concrete Admixture + Concrete Coating).
Corrosion resistance was measured by using accelerated corrosion technique where an external electric power combined with a highly concentrated sodium chloride solution were used to accelerate the corrosion process.

Index Terms: Corrosion, Concrete, Carbonation, Chloride, Corrosion Protection, Steel Coating, Concrete Coating, Corrosion Inhibitor.

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1 INTRODUCTION

Corrosion of steel reinforcement is considered one of the major causes of reinforced concrete deterioration (1). Corrosion can be defined in many ways but the most commonly one is the loss of useful properties due to chemical or electrochemical reactions. Causes of corrosion are attributed to the reinforcing steel itself, to concrete and concrete materials, or to the surrounding environment (1). 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 (1). Concrete may contain some ions such as chloride ions either intentionally, as a concrete admixture, or unintentionally like those present in concrete materials. Surrounding environment may be corrosive such as the case of industrial buildings, marine structures, foundations, …etc. (1). The mechanism of corrosion process is known as an electrochemical reaction occurs at the surface of the steel due to presence of a potential difference between two adjacent points of the steel surface. This potential difference occurs because of any of the aforementioned causes. At anode point the electrochemical oxidation takes place and at cathode point the electrochemical reduction occurs where the steel bar acts as an electric conductor and concrete acts as an aqueous medium (2,3). 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_2) 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 ($CaCl_2$) still found in concrete admixtures, can result in the free passage of chloride ions through the concrete cover and de-passivation 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.
Different techniques with variable effectiveness are used to protect the steel reinforcement from corrosion. The choice of the most suitable protection method depends on many factors as cost, nature of the structure, and the required level of protection (1,2,3). The protection level varies from a relative reduction of the corrosion rate to a complete prevention. Generally, there are four categories of protection methods:
1. Steel coating.
2. Concrete coating.
3. Concrete Admixtures (corrosion inhibitors).
4. Cathodic protection (Sacrificial anode, Impressed current and hybrid)
In Egypt, the first three methods are considered the most commonly used for reinforcing steel while the fourth one is used for steel pipes and tanks. Steel coatings, Concrete coatings and

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• *Assistant Professor, Structural Engineering Department, Ain Shams University, Egypt. E-mail: ibrahim.yousif@eng.asu.edu.eg*

Concrete Admixtures are extensively used now for that purpose in Egypt.

2 CONCRETE & 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 lime stone. Natural sand was used with fineness modulus of 2.30. The concrete mix was designed to achieve275 Kg/cm^2 cube compressive strength after 28 days. The used reinforcing steel bars were high tensile steel with oblique ribs of grade 400/600 and of nominal diameter 13 mm. The average measured 7 and 28 days cube compressive strength were 245 and 315 Kg/cm^2 respectively.

3 PROTECTION METHODS

A total of 17 specimens were used in this study. The protection methods used for these 17 specimens are as follows:
1. Control specimens: 2 specimens designated as (C1 and C2) were used without any protection for comparison purpose.
2. Steel Coating: 8 specimens designated as (SC11, SC12, …SC42) were protected by coating of the steel surface with four different types of coating (The most commonly used coatings in Egypt designated as 1,2,3 and 4 produced by four different companies). For each type of coating (first number in designation) two specimens were used; the first with one layer coating and the other with two layers coating (second number in designation).
3. Concrete Coating: 3 specimens designated as (CC1, CC2 and CC3) were protected by coating of the concrete surface with bitumen with one, two, and three layers of bitumen respectively.
4. Concrete Admixture: two specimens designated as (CA1 and CA2) were protected by adding an admixture as a corrosion inhibitor to the concrete (The most commonly used admixtures in Egypt).
5. Mixed (Combined) protection (Concrete admixture + concrete coating): 2 specimens designated as (M1 and M2) were protected by adding an admixture as a corrosion inhibitor to the concrete in addition to concrete coating.

Table 1 gives the details for the test specimens, used protection method and the identification for each specimen individually.

TABLE 1: DETAILS AND DESIGNATION OF TEST SPECIMENS

| No.	Protection method	Designation	No. of layers	Code
1	Without Protection	Control	---	C1
2			---	C2
3	Steel Coating	SC1	1	SC11
4			2	SC12
5		SC2	1	SC21
6			2	SC22
7		SC3	1	SC31
8			2	SC32
9		SC4	1	SC41
10			2	SC42
11	Concrete Coating	CC	1	CC1
12			2	CC2
13			3	CC3
14	Concrete Admixture	CA	---	CA1
15			---	CA2
16	Mixed Protection: Concrete Admixture + concrete coating	CC + CA	1	M1
17			1	M2

4 TEST SPECIMENS AND METHODOLOGY

Test specimens are called "Lollipop" specimens; they are 100 mm diameter and 200 mm length concrete cylinders with a 10 mm 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 Fig. 1.
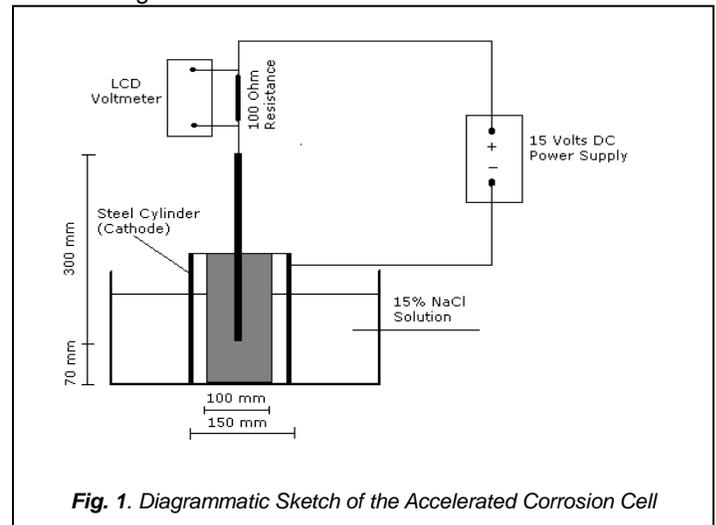
Fig. 1. Diagrammatic Sketch of the Accelerated Corrosion Cell
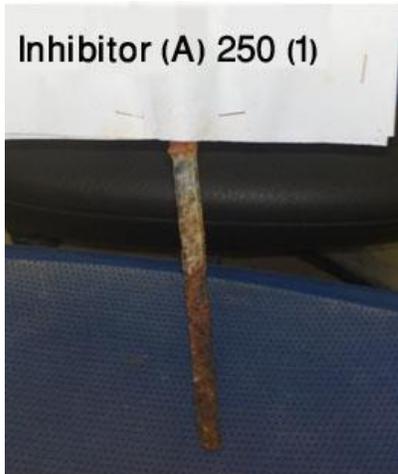
5 TEST RESULTS

During the progress of the accelerated corrosion test, the resulting current values "I" are manually recorded every 2 hours up to 250 hours (approximately 10 days) and the cracking of the specimen is observed by visual inspection as shown in Figs. 2, 3, 4 and 5. Test results for test specimens are shown in Figs. 6, 7, 8, 9 and 10 as a relationship between the corrosion current "I" and corrosion time "t". Fig. 6 shows this relationship for the control specimens, Figs. 7 and 8 show typical relationships for steel coated specimen and concrete coated specimen respectively. Fig. 9 shows this relationship for specimens protected by using concrete admixture and Fig. 10 for specimens protected by using concrete admixture and concrete coating in the same time.
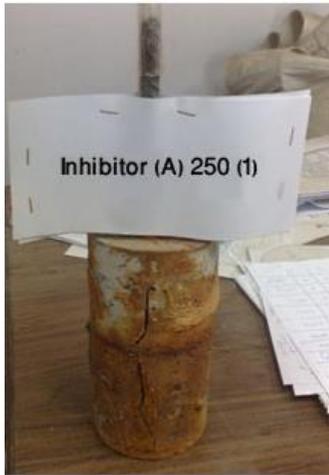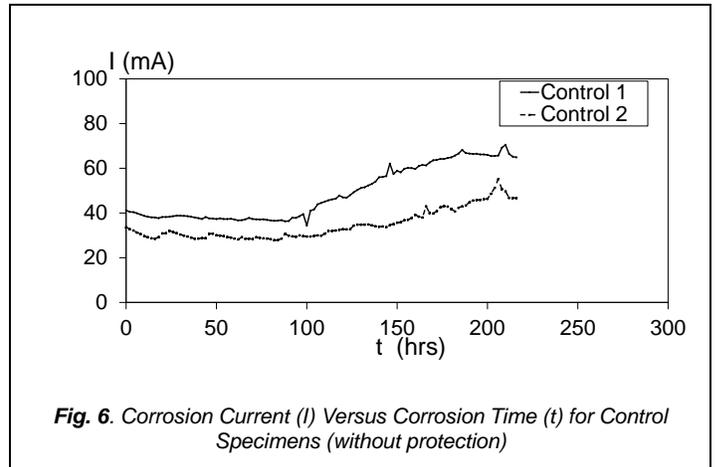
Fig. 2. Crack Pattern of Cylinder (CA1)

Fig. 3. Bar after corrosion for Cylinder (CA1)
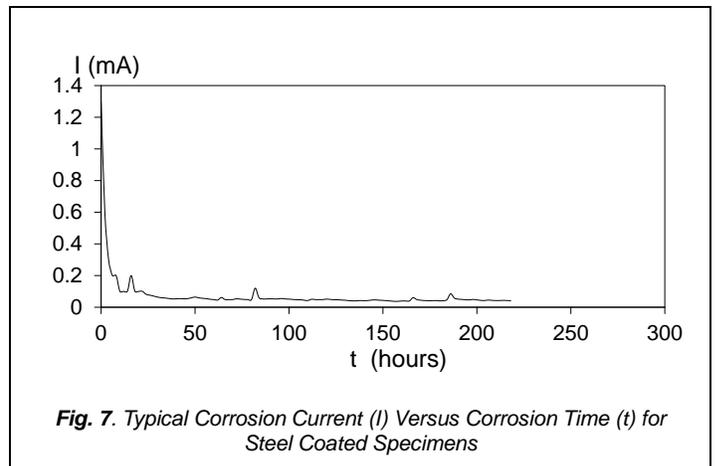

Fig. 4. Crack Pattern of Cylinder (C1)

Fig .5. Bar after corrosion for Cylinder (C1)

Fig. 6. Corrosion Current (I) Versus Corrosion Time (t) for Control Specimens (without protection)

Fig. 7. Typical Corrosion Current (I) Versus Corrosion Time (t) for Steel Coated Specimens
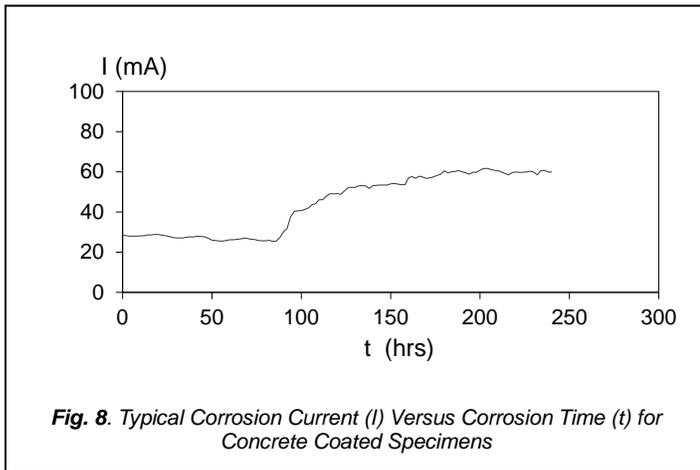
Fig. 8. *Typical Corrosion Current (I) Versus Corrosion Time (t) for Concrete Coated Specimens*
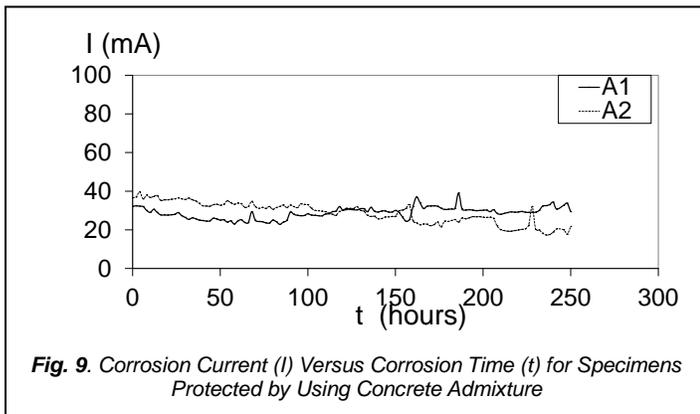

Fig. 9. *Corrosion Current (I) Versus Corrosion Time (t) for Specimens Protected by Using Concrete Admixture*
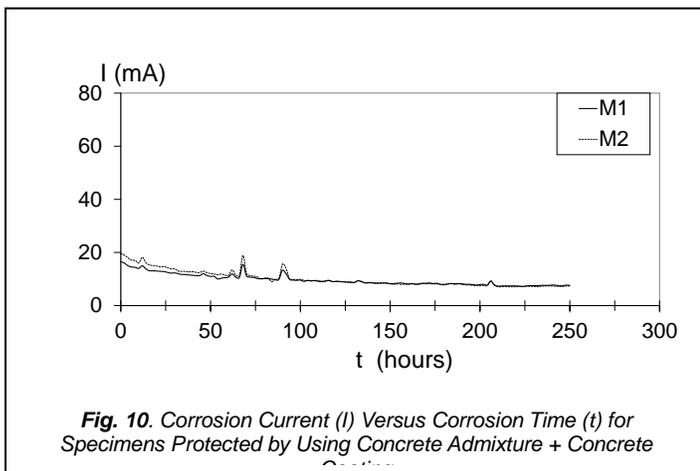

Fig. 10. *Corrosion Current (I) Versus Corrosion Time (t) for Specimens Protected by Using Concrete Admixture + Concrete Coating*

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

$I = V/R$ (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:

$M_t = [M/Z*F][\int I.dt]$ (2)

Where

  M_t = Total mass 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 2 gives the calculated total mass loss (Mt) for all the test specimens. The value ($\int I.dt$) was calculated using the area under the curve starting from time (0) (i.e. starting of the experiment) until certain time (250 hours).

TABLE 2: TOTAL MASS LOSS FOR THE 17 TEST SPECIMENS

No.	Protection method	Designation	No. of layers	Code	Total mass loss (gm)*
1	Without Protection	Control	---	C1	11.03
2			---	C2	9.34
3	Steel Coating	SC1	1	SC11	0.15
4			2	SC12	0.06
5		SC2	1	SC21	0.07
6			2	SC22	0.03
7		SC3	1	SC31	0.07
8			2	SC32	0.14
9		SC4	1	SC41	0.05
10			2	SC42	0.01
11	Concrete Coating	CC	1	CC1	7.11
12			2	CC2	7.21
13			3	CC3	6.12
14	Concrete Admixture	CA	---	CA1	8.38
15			---	CA2	7.91
16	Mixed Protection: Concrete Admixture + concrete coating	CC + CA	1	M1	5.44
17			1	M2	5.25

*Total mass loss calculated from equation (2)

6 DISCUSSION OF TEST RESULTS

1. Comparing the total mass loss for the test specimens protected by steel coatings with one and two layers as shown in Fig. 11, it can be seen that using two layers is more effective than one layer; the average total mass loss for one layer case is between two and five times that of the two layers. However, one layer provides a very satisfactory level of protection, two layers is usually preferred to avoid any local defect that can be easily happen in the case of one layer. Local defect of the protective layer causes a pitting corrosion (i.e. a concentrated corrosion) at the location of the defect.

2. Concrete Coating by bitumen is not effective enough to protect the steel reinforcement from corrosion; however, it may provide a reasonable level of protection for concrete itself. It is known that such method is commonly used in Egypt for foundations. As shown from Fig. 12 that using only one protective layer of bitumen reduces the total mass loss by about 30% only compared to the control case; however, two or three layers can cause about 40% reduction. In practice, as in the foundations case, the steel surface that is not embedded in concrete is usually coated by bitumen to avoid corrosion at these locations.

3. The chemical admixture used as a corrosion inhibitor reduces the total mass loss by about 20% compared to the control case. This result shows clearly that depending only on admixtures to resist corrosion is not quite effective. Admixtures can be used in addition to another method as coating of concrete surface or steel surface or both.

4. Using of chemical admixture and coating of concrete surface in the same time (specimens M1 and M2) reduces the total mass loss by about 48% compared to the control case. This

level of protection considered good compared to using the admixtures only.

5. Comparing the results of the total mass loss for all the test specimens protected by different methods as shown in Fig. 13, it can be seen that the most effective protection method is coating of the steel surface. The values of the total mass loss for the steel coated test specimens are almost negligible compared with those protected by other methods of protection. Special care must be taken during the coating process since any defect of the protective layer can cause a pitting concentrated corrosion as mentioned earlier.
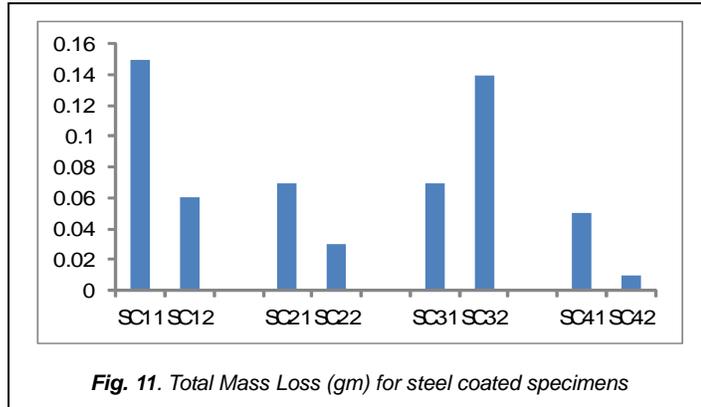

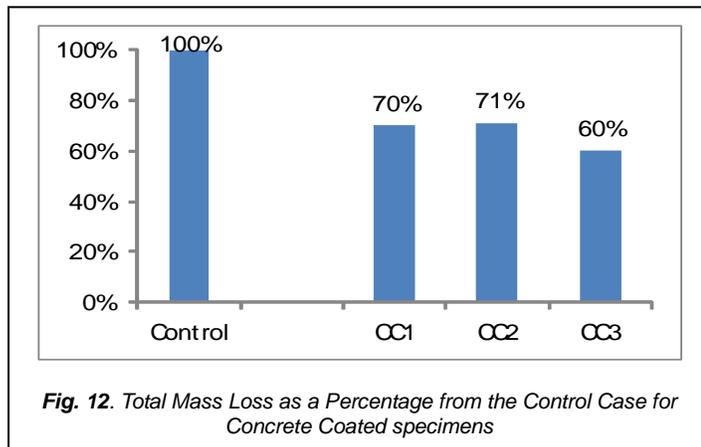**Fig. 11**. *Total Mass Loss (gm) for steel coated specimens*

Fig. 12. *Total Mass Loss as a Percentage from the Control Case for Concrete Coated specimens*
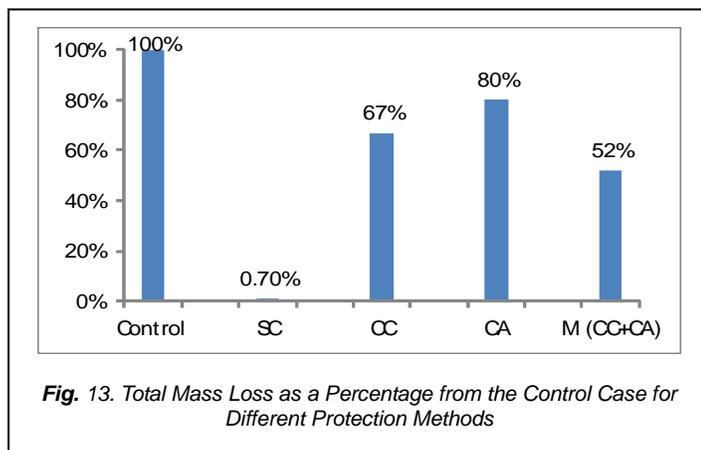

Fig. 13. *Total Mass Loss as a Percentage from the Control Case for Different Protection Methods*

7 CONCLUSIONS

Based on the obtained test results and the discussion of these results, the following points can be easily concluded:

- Steel Coating (SC) is considered the most effective protection method. This high protection level is suitable for the aggressive environments.
- Concrete Coating (CC) using 1,2 or 3 layers of bitumen, which is commonly used in the concrete footings, cannot provide a reasonable level of protection unless it is combined with other protection method.
- Concrete Admixtures (CA) do not provide suitable protection especially in aggressive environments.
- Combined protection (Chemical admixture + Concrete coating) provides a relatively reasonable level of protection. However, this protection level is still very far from the protection level given by the steel coating.

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