CONCRETE REPAIR AND CATHODIC PROTECTION OF CORRODED REINFORCED CONCRETE STRUCTURE

Adel ElSafty, Ph.D., P.E., P.Eng., Assistant Professor, School of Engineering, University of North Florida, Jacksonville, FL, USA
Khalid M. Yousri, Ph.D., Associate Professor, Housing & Building National Research Center, Cairo, Egypt
Hosam EL-Din H. Seleem , Ph.D., Associate Professor, Housing & Building National Research Center, Cairo, Egypt

ABSTRACT

The corrosion of reinforcing steel in reinforced concrete (RC) structures and bridges is a wide-spread and persistent problem. Different repair methods and materials are available to repair concrete structures suffering steel corrosion damage. However, the initial corrosion problem remains in untreated chloride contaminated concrete areas and may lead to subsequent deterioration. The use of cathodic protection (CP) addresses the electrochemical nature of corrosion and provides corrosion protection. This paper provides the design and details of the installation techniques of a cathodic protection system applied to a structure with corroded steel caused by chloride attack. Visual examination, reinforcement inspection, measurements of cement and alkali contents, hammer tapping survey, half-cell potential survey, and measurement of Cl^- content by weight of cement and concrete were performed for columns and other structural members in the defected building of this study. This paper presents the CP system made up of expanded zinc mesh and a stay-in-place reinforced concrete jacket applied to several columns of the studied building. Monitoring was conducted for the RC structure treated with CP that involved passing a small electric current through the reinforcement layer. The paper presents the results of performed tests and reviews the long-term monitoring of impressed current CP system. It also provides the practical aspects of delivering the CP remedial solution from the technical aspects of repair. From the presented case study, the paper shows the feasibility and effectiveness of using CP method for RC columns in bridges and buildings. It also presents the advantage of requiring only minimal monitoring and maintenance over the extended lifetime of structures.

Keywords: Concrete, Beam, Corrosion, Cathodic Protection

INTRODUCTION

There is a corrosion problem in both constructed and repaired RC structures. The repaired concrete suffers severe steel corrosion only after a few years of being repaired. The migration of chloride ions from chloride-contaminated concrete to the new repair material results in a continuing corrosion that causes cracking and spalling of concrete.

In reinforced concrete structures, the alkaline nature of the hydrated cement phases leads to the formation of a passive oxide layer on the steel reinforcement surface. That effectively protects the steel and significantly reduces its corrosion. Yet, the concrete permeability allows the ingress of chemical agents that lead to a breakdown in the protective passive layer and subsequent corrosion of steel reinforcement[1,2]. The two most common processes causing steel corrosion are chloride attack and carbonation where carbon dioxide action reduces the pH in the concrete pore solution[1]. These two processes lead to breakdown of the passive oxide layer and subsequent formation of expansive corrosion products, which can lead to cracking and spalling of concrete surface. Chloride attack on reinforcing steel can be as a result of chloride salts which have diffused in from the external surface, for example, wind-blown sea salt, or from cast-in chloride salts. Above a certain chloride level threshold, steel corrosion is initiated. Initiation is followed by a propagation period, which eventually leads to cracking and spalling of the concrete.

The techniques employed in concrete repair have developed over the past few decades, and a variety of solutions to the problem of reinforcement corrosion now exist[2,3,4,5]. More recently, an improved understanding of the corrosion process has led to the development of electrochemical techniques, which attempt to address the actual cause of the problem rather than the symptoms. There are several electrochemical techniques to treat chloride-contaminated concrete and solve or reduce the problem. Cathodic protection CP methods control steel corrosion by providing a small direct electrical current passed from an anode to reinforcing steel in affected regions[2,3]. The CP methods include impressed current and sacrificial (galvanic) cathodic protection. The impressed-current system uses an external electric power source to provide a current flow from an externally placed anode to the corroding reinforcing steel. The galvanic system uses dissimilar metals coupled together in a common environment forming a battery cell to supply current to the corroding steel. Maintenance procedures are different for the two CP methods. There is little need for post-installation maintenance and monitoring for a galvanic system as it provides its own power and regulates its current output according to the changing environmental conditions. Impressed-current system requires more effort maintaining rectifier currents and making adjustments to changing conditions.

The sacrificial anode cathodic protection system has an expanded zinc mesh (sacrificial anode) and a stay-in-place reinforced concrete jacket if remedial work is needed. It creates a galvanic cell that provides enough electrical current to stop corrosion of the original embedded steel and protect the newly added one. It has been widely for protecting steel in submerged reinforced concrete. Sacrificial anode was also used for cathodic protection of above ground reinforced concrete.

While impressed current cathodic protection systems have been widely used in cathodic protection of steel reinforced concrete structures, such systems require an external direct current (DC) power supply or rectifier. A sacrificial system does not require such power supply, but instead relies on the oxidation potential of the particular anodic alloy in a particular environment. When the anodic alloy is electrically connected to the steel, both in the concrete as an electrolyte, a galvanic cell is established. With the proper selected anodic alloy a potential difference between the anode and steel results, establishing a current flow between the anodic alloy and the steel (cathode). If adequate current density is obtained to polarize the steel, it will either prevent or decrease the rate of corrosion to a minimal acceptable level. Recently, a method of Galvashield discrete sacrificial anodes was developed to protect localized areas around surface repair[4]. There are also other methods to extract chlorides from concrete[5].

PROPOSED RESEARCH

In our study, a zinc mesh was installed to create a sacrificial zinc anode incorporated at the whole repair area and coupled to the steel reinforcement. The zinc mesh is believed to corrode preferentially and thus provide a protection to the surrounding steel. As the zinc corrodes, it releases a supply of electrons and this electrical current travels through the steel wires into the surrounding reinforcing steel to reduce new corrosion activity on the steel. There are several factors affecting the output from the anodes depending on the concrete resistivity, moisture content, temperature, permeability, chloride content, pH, conductivity, and reinforcing steel density. Therefore, fluctuations in the current output of the anode varied with corrosion activity of the steel and the conditions that exist within the concrete.

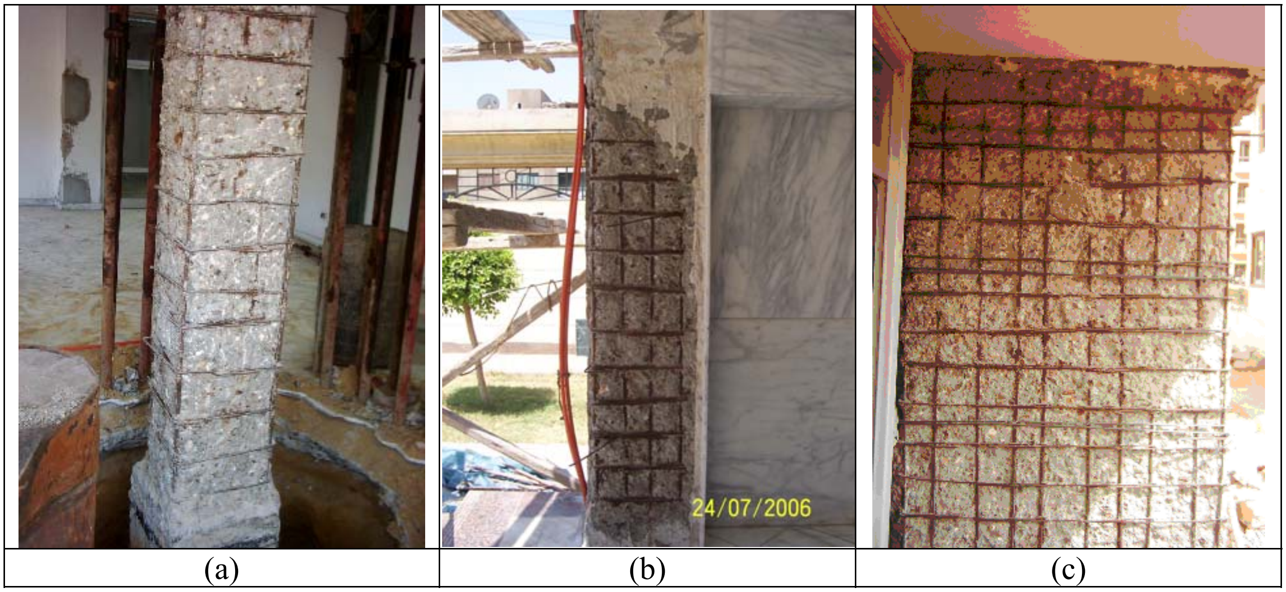
The chloride threshold to develop depassivation and corrosion of steel reinforcement depends on several factors, such as concrete mix proportions, cement type, C_3A content of cement, water/cement ratio, steel surface conditions, temperature, relative humidity, and source of chloride penetration among others. Moreover, there is a lack of accordance for the definition of the chloride threshold itself, either on the determining parameters (visual observation, corrosion potential or corrosion current) or on the expression of the threshold (as Cl^-/OH^- ratio or by weight of cement or concrete). Several researchers studied these effects[6,7,8].

Previous investigations on chloride thresholds were studied in mortar based on corrosion measurements and expressed as total, free, and Cl^-/OH^- ratio. Chloride thresholds were indicated in the range of (1.24 – 3.08%) and (0.39 – 1.16%), by weight of cement, for total and free chlorides, respectively. Active corrosion was considered when, in a small exposed area, the rebar corrosion rate is higher than 0.1 $\mu A/cm^2$.

In this presented case study of a defected building, cast-in chloride salts were present in its fresh concrete constituents while mixing. That eventually caused deterioration due to its reinforcing bar corrosion. Visual inspection of the repaired contaminated areas has been routinely performed and the half-cell potential readings were recorded. The readings were pulled down significantly and the sacrificial anodes continue to function after several years. Experimental studies and field investigation were conducted into the critical chloride ion concentration, corrosion weight loss of reinforcing bars, pH value, and visual examination of spalled and/or delaminated surfaces. Within the limits of the conducted experiments, it was verified that the critical chloride ion concentration was 1.5 kg/m^3 at the depth of the reinforcing bar and that concrete started to crack at a corrosion weight loss of 170 mg/cm^2 per unit corrosion area of the reinforcing bar surface. This paper describes a number of electrochemical treatments for protecting reinforced concrete structures, with examples of installations and supporting data obtained.

INVESTIGATION PROCEDURE AND TESTS

The initial survey of visual inspection was conducted to identify the extent or the repair work prior to any decision of repair. Moreover, a more extensive concrete investigation was conducted to accurately identify the cause of deterioration and potential damages. The initial building inspection revealed serious defects; thus an extensive concrete investigation was conducted. The investigation included visual examination, hammer tapping survey of the structures, covermeter survey, half-cell testing, depth of carbonation, steel reinforcement inspection, cement/alkali, and chloride content. The investigation showed concrete and steel damage and corrosion-related problems, as shown in Figures 1(a), (b), and (c).



(a) (b) (c)

Fig. 1 Corroded Steel reinforcement (a) interior column, (b) exterior column, and (c) exterior column

For corroded steel reinforcement, the average corrosion and the average loss of yield stress were almost 30% of the steel area in several areas in the columns. Table 1 shows the average elongation loss of about 55%. Table 2 indicates the Cl- ion concentration in columns.

Table 1: Tension test of corroded steel rebar samples (1st floor)

Samples	Nominal Diameter (mm)	Actual Diameter (mm)	Actual Area (mm^2)	Yield Stress (N/mm^2)	Tensile Stress (N/mm^2)	Elongation %
Sound Steel	16	15.7	129	400	600	20 %
Corroded Steel	16	13.2	90	290	430	9%

*Note: calculations are based on the nominal diameter

Table 2: Chemical analysis of concrete samples in RC columns as percentage of the cement weight

Sample Locations	Cl^- %
Ground Floor	2.75
1st Floor	0.67
2nd Floor	0.8
Limits of Egyptian Code	0.3

Core samples were extracted from defected columns to determine the condition of the concrete as shown in Table 3. The visual inspection and hammer tapping survey on the concrete columns found areas of delamination, spalling, and exposed corroded reinforcement on columns and slab areas. The percentage of the approximate delaminated surface area and spalling ranged from 5% to 30% in columns, as shown in Table 4.

Table 3: Compressive strength of the extracted core specimens

Sample Locations	Compressive strength, MPa
Ground Floor	23.6
2nd Floor	29.2

Table 4: Area of defected concrete

Sample Locations	Approximate Surface area spalling (%)
Ground Floor	5% to 30%
2nd Floor	5% to 20%

The covermeter survey showed that the average cover depth was about 25 mm. The half-cell potential readings indicated a high risk of corrosion in several areas; where readings were less than -350 mV (less negative) with respect to electrode of copper- copper sulphate half-cell. The depth of carbonation measurements were done with no significant signs of carbonation. The carbonated areas were limited only to the surface within maximum of 5 mm. The reinforcement inspection was carried out for all the affected columns, showing moderate to severe pitting corrosion in several locations and slight to moderate general corrosion in the rest. Concrete pieces were broken and tested to determine cement and alkali content. The tests showed that the alkali contents were within normal limits. Chloride content testing showed extensive chloride contamination in all the columns with values exceeding the threshold limit of 0.4% of the cement weight. The depth of the tested samples ranged from 5 mm to 150mm, which was way beyond the steel reinforcement.

REPAIR PROCEDURE

Based on the performed tests, it was clear that the problem is not superficial and that the chloride penetration/content problem would cause further damage and possible structural failure. It was decided that patch repair and concrete replacement were not suitable for this case due to the extent of damage involved, inability to treat the remaining chloride contaminated areas which can accelerate steel corrosion adjacent to repair areas due to incipient anode effect. Besides, the demolition and rebuilding option was quite expensive. Therefore, the repair option of CP was chosen as it stops the corrosion from reoccurring even while some contaminated concrete may still remain. The CP and repair involved removing only unsound concrete areas that are chloride contaminated. Since the design of CP system is individual to each structure, the CP installation to the treated building was integrated with the concrete repair. All the practical issues were discussed to lay out a feasible and effective repair work.

Work proceeded in two main stages. The first stage involved repair of columns according to the level of corrosion. The second stage involved electrochemical protection. The repair work ranged from just sand blasting the reinforcing steel and restoring the concrete cover for less corroded elements to adding a new reinforcement and concrete jacket for medium and highly corroded elements, as shown in Figure 2. In all cases, polymers were not allowed, and two steel stirrups were welded to the longitudinal reinforcement of each column, one leg of a stirrup is projected outside the column.

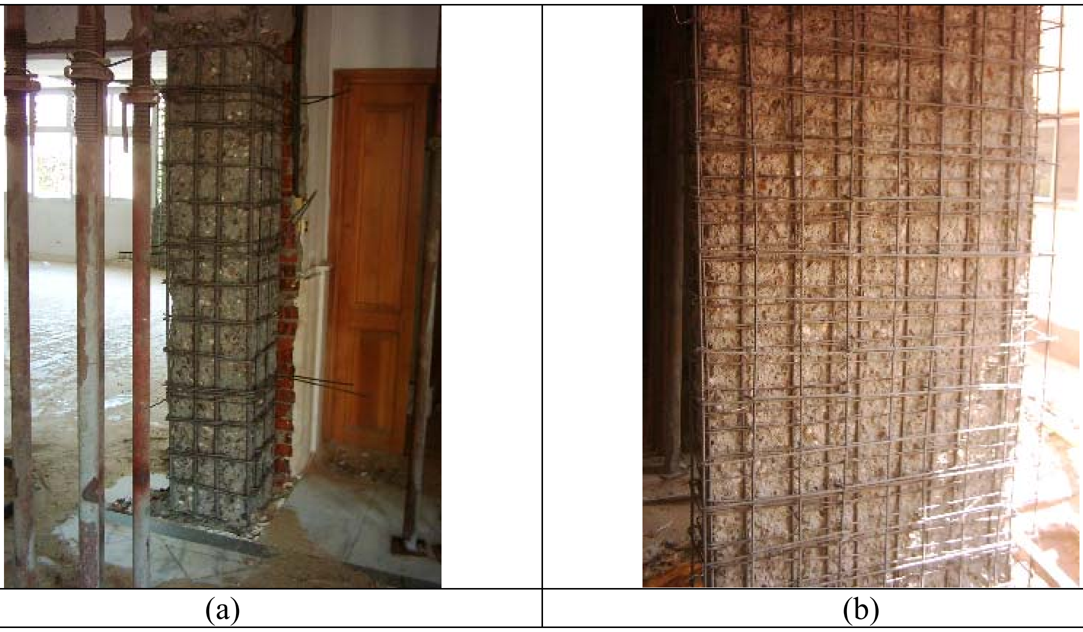

(a) (b)

Fig. 2 Sand blasted steel and new steel (a) interior column, (b) exterior column

In the second stage, a zinc mesh was installed at the surface of column, as shown in Figures 3, 4, and 5. A strip was bent to project outside the column. A plaster layer, 15 mm thick is applied over the zinc mesh. An impressed current was then applied; the zinc leg was connected to the positive pole and the stirrup leg to the negative pole of a DC power supply. The columns surfaces were held moist during current application for 7 days. The potential difference of the current flow was monitored using half-cell as shown in Figure 6c.

Installation of the anodes started with removal of all damaged concrete, including deteriorated concrete removal from around and behind the steel reinforcement of the columns in accordance with good concrete repair practice. All exposed steel reinforcement were cleaned to a bright condition and subjected to abrasive blasting. All steel reinforcing were routinely checked to be continuous to assure providing a good electrical connection. Additional electrical connections were used for loss of continuity. Connections were made through drilling concrete to a sound reinforcing rebar in the area requiring protection. Steel rebars were provided for the concrete jacket. The anode zinc mesh was installed on a grid basis throughout the entire surface of the columns and connected to the steel reinforcement. The electrical connection was verified using a multimeter. The cementitious repair mortar was sprayed with a shotcrete. A watertight junction box was used to house the connections and to serve as an access site for measuring current and voltage outputs, as shown in Figure 3. Monitoring of the performance was conducted through potential mapping at intervals starting from every week for the first 2 months to monthly readings. The current output from anodes was in the range of 235 to 500 μA.

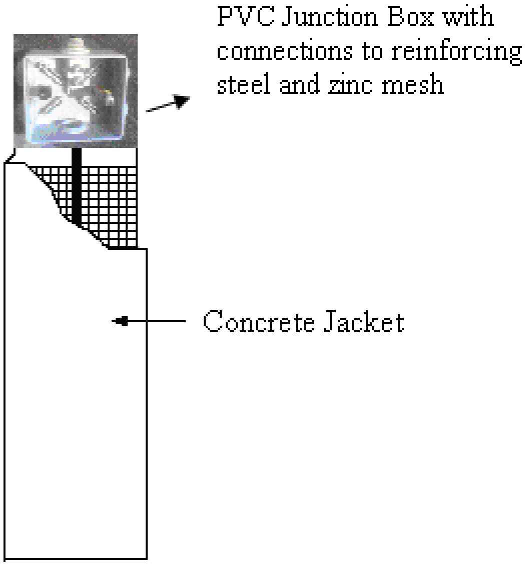
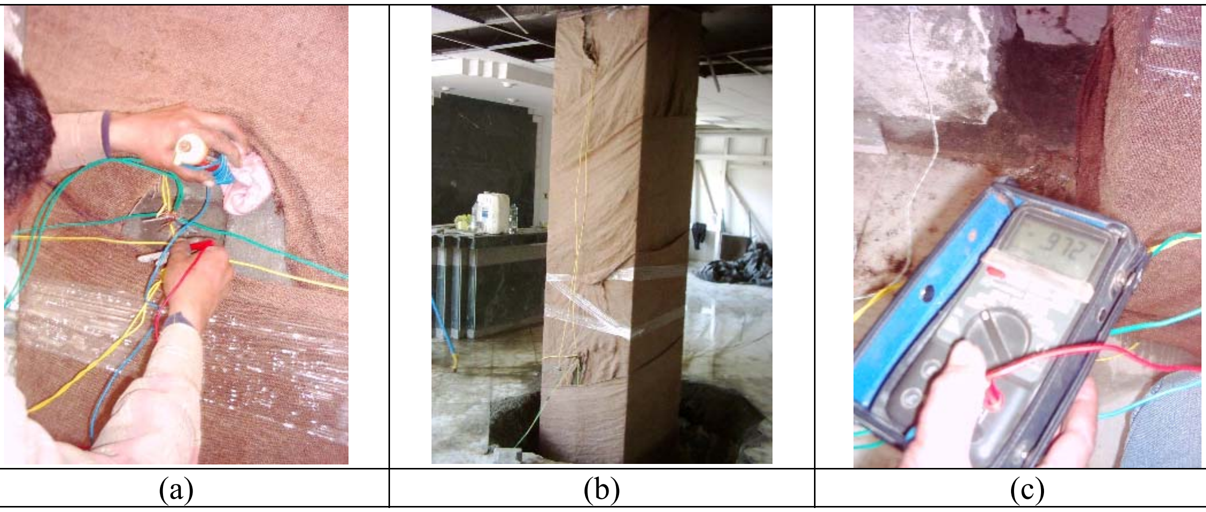


Fig. 3 Steel and zinc mesh for column repair

Fig. 4 Grout Spraying using Shotcrete

Fig. 5 Grouting and zinc mesh installation

After the period of impressed current flow, the steel leg was connected to the zinc strip leg into a junction box. Current flow from zinc to steel cage was checked at wet condition, as shown in Figure 6.



(a) (b) (c)

Fig. 6 Electric current (a) current connection, (b) treated Column, (c) voltmeter readings

The proposed repair system was designed to meet the performance requirements of BS12696: 2000. Impressed current cathodic protection, that required a permanent DC power supply, was used with a steel mesh and an installed anode system of a zinc mesh. The zinc mesh was an ASTM A-190 expanded sheet or ASTM B69-01a for A190 alloy. The zinc mesh was connected to the steel reinforcement with a connection box to provide the required protective current to the steel.

A cathode current density of $20mA/m^2$ was used for the steel. Each anode area was provided with a negative cable connection to the reinforcement. The anode design current density was $110mA/m^2$, which satisfied the 100mV potential shift requirement for effective 'Cathodic Protection' as specified under NACE (National Association of Corrosion Engineers) Standard RP 0290-90. In concrete repair areas, the reinforcement electrical continuity was routinely tested. The anode system and cabling were fixed to the concrete substrate. The effectiveness of negative connections was also verified. The selection of sprayed concrete instead of form-and-pour repair technique reduced the need for formwork and expedited the repair time. Dry spray technique with water added at the nozzle was used for sprayed concrete overlay.

Continuity testing was performed for exposed parts of the steel mesh in the concrete and measuring inter-steel voltage using a high impedance voltmeter. Monitoring of CP system was performed to ensure proper performance and that the system is switched on and operational. The monitoring was done weekly for the first 2 months and then the verification tests were carried out every two months for a year.

LIMITATIONS AND SERVICE LIFE

The galvanic anode service life depends on many factors including the zinc anode consumption and impact of alkalinity reduction. Some studies suggest that approximately 10% of the amount of zinc in the anode is consumed over 10 years if the system remains perfect with a nominal current output of 60 mA. The suggestion is based on the assumption that the provided amount of lithium hydroxide monohydrate ($LiOH \cdot H_2O$) exceeds the consumed one over the life of the anode. That maintains high pH value with a reasonable alkaline level for anode mortar. Also, since anode current is affected by moisture and RH, the anode was encased with a with high alkalinity concrete mortar to promote and sustain the anodic activity of zinc.

CONCLUSIONS

Premature failure of concrete repairs or concrete adjacent to repaired one is a major problem. The total chloride ion concentration in the concrete structure exceeded certain threshold and caused severe steel corrosion. The successful structural repair method was performed using a CP system that incorporate impressed current and anode zinc mesh installation. It protected the damaged structure suffering from corrosion related to chloride contamination. There were site constraints regarding space and accessibility that prompted the designed CP procedure outlines in this paper. Field data were collected and analyzed over two years. The cathodic protection repair is believed to continue extending the service life of the building and prevent future corrosion problems.

REFERENCES

1. ACI Committee 546, "Concrete Repair Guide (ACI 546R-04)," American Concrete Institute, Farmington Hills, Mich., 2004, 53 pp.

2. Varble, J. B., "Cathodic Protection of Reinforced Concrete Decks: Laboratory Phase," NCHRP Report No. 180, Transportation Research Board, Washington, D.C., 1977
3. Bertolini et al., "Cathodic Protection and Cathodic Prevention in Concrete: Principles and Applications," Journal of Applied Electrochemistry, 1998, V. 28, pp. 1321-1331.
4. Concrete Innovations Appraisal Service (CIAS), "Galvashield embedded galvanic anodes for repair of concrete", A Service of the Strategic Development Council (SDC) of the Concrete Research and Education Foundation (ConREF), CIAS Report: 01-1, July 2001
5. Glass, G.; Taylor, J.; Roberts, A.; and Davison, N., "The Protective Effects of Electrochemical Treatment in Reinforced Concrete," *NACE Paper* No. 03291, Corrosion 2003, 2003.
6. AASHTO (The American Association of State Highway and Transportation Officials) test method T-260 "Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials", American Association of State Highway Transportation Officials.
7. David A. Whiting, Peter C. Taylor, and Mohamad A. Nagi "Chloride Limits in Reinforced Concrete" Portland Cement Association, , Research & Development Information PCA R&D Serial No. 2438, Skokie, Illinois, USA, 2002.
8. - Karin, P. "Corrosion Threshold Value and Corrosion Rate in Reinforced Concrete" Swedish Cement & Concrete Research Institute, CIB Publication, Stockholm, 1992.