Long-Term Research on High Performance Concrete in Natural Aggressive Exposure Conditions Prevailing in the Gulf Region

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Abstract

The main objective of this study is to evaluate the long-term performance of different concrete composites in natural aggressive exposure conditions of marine environment prevailing in the Gulf region. Durability assessment studies of such nature are usually carried out in humid environments that constitute seawater, chloride and sulfate laden soils, and groundwater conditions. These studies are very vital for sustainable development of marine and off shore reinforced concrete structures of industrial and petroleum installations. The study is in housed in a field test station that accommodates set up and number of specimens that are designed for assessment over 20 years. First round of testing and evaluation of the specimens will be carried out after three years of exposure. The study involves casting of high quality concrete specimens using different variables, including corrosion inhibitors, type of reinforcement, natural and industrial pozzolanic additives, water/cement ration, water type, cover thickness, curing conditions, and concrete coatings. The used reference control mix is prepared according to the ACI-318 specifications for marine exposure. Reinforced and plain concrete specimens are cast at the field test station, and cured onsite. After proper curing, the specimens are subjected to below ground and on ground exposure near seawater and tidal zone exposure. The specimens in the field will be monitored for corrosion and visually observed for any signs of failure or deterioration, such as cracking, spalling and delamination, at predetermined intervals over a period of 2 years. Samples and specimens will be retrieved for assessment at 28 days after casting, and at 12 and 24-month period throughout the duration of the exposure. The laboratory tests will be conducted to determine the chloride, sulfate, and alkalinity profiles, water permeability, chloride permeability, compressive strength, and carbonation. Some reinforced specimens will receive corrosion morphology and petrographic examination to assess the rebars condition and the integrity of the concrete matrix cover. Reinforced concrete elements such as columns and beams are fitted with remote data acquisition sensors for monitoring the health parameters of the structure including corrosion and carbonation induced related deteriorations.

Key words: Concrete, Reinforced Concrete, Deterioration, Corrosion, Marine, Off Shore.

1. INTRODUCTION

It is becoming increasingly obvious that aggressive environment and severe conditions pose great threat to reinforced concrete structures in Arabian Gulf region. Whenever concrete deterioration is investigated in this region, it is rarely goes without mentioning corrosion–induced deterioration inflicted on structures integrity, and the premature damages and degradation taking place that trigger unplanned repair works which often ineffective, inadequate and repetitive. The region provides an extremely aggressive environment, which is characterized by high ambient temperature and humidity conditions, and severe ground and ambient salinity with high levels of chlorides and sulfates in the soil and groundwater. Structures exposed to the marine environment, groundwater conditions and industrial pollution have suffered the most. Concrete corrosion is becoming inescapable phenomenon in this region even to structures of high performance concrete, which are relatively new (10-15 years of construction age). Recent survey study that took place in 1997 on premature deteriorated structures (1), concluded that repair and rehabilitation cost are often expensive, not highly effective in arresting the corrosion processes, and would have to be repeated within few years. The study conducted in 1992 (2), on impact of metallic corrosion on Kuwait economy, showed that cost of direct and indirect corrosion was 5.2% of the gross national product (GDP), out of which 17.4% was an avoidable cost that could have been saved by application of corrosion control technologies. The economical impact was estimated to be KD. 266 millions paid as unrecoverable cost of unavoidable corrosion. The study concluded that cost of corrosion in the construction industry was 0.5% of the GDP. That had demonstrated clearly the economical consequences of the corrosion-induced deterioration of reinforced concrete structures.

Corrosion protection systems reduce the risk of corrosion in reinforced concrete structures in many parts of the world. The use of these systems though might increase the cost of construction; the increase is marginal compared with the cost for repair of the structure as a result of premature deterioration. It is estimated that when these protection systems are used, the increase in construction cost is typically only 10 % of the cost for repair of the premature corrosion-induced deterioration that occurs in the absence of the protection systems (3). As for the corrosion protection systems, such as supplementary cementing materials, corrosion inhibiting admixtures, and epoxy coated rebars, though they have been used for building constructions in mega projects in the region, they have not been subscribed or standardized properly in a national building code of practices for the region. This can be attributed to the following:

1. No serious attempts have been made to report the performance of the various corrosion protection system, responsibly, to highlight their advantages and shortcomings to incorporate these experiences in a national construction guidelines and code of practices that address the environmental conditions prevailing in the region.

2. Adopting concrete construction practices that not necessary guarantee high performance and durability of the reinforced concrete structures under the aggressive, hot environmental conditions.

3. Lack of awareness and unfamiliarity with the use of these systems as well as the lack of comprehensive database on the long-term effectiveness of the systems under the environmental and service conditions prevailing in the region.

In 1997-2002 (1) Kuwait Institute for Scientific (KISR), supported by Kuwait Foundation for Advancement of Science (KFAS), and the major companies of material suppliers, ready mix concrete, and construction and consulting firms, have seized the opportunity to conduct this urgent study which aimed at identifying corrosion protection systems that are most suitable for application in reinforced concrete structures in Kuwait and to demonstrate enhancement achieved in concrete durability when these systems are used. Also among the main objectives are to establish performance data on the selected corrosion protection systems under typical local service conditions and to determine their economic benefits.

The corrosion protection systems that involved in the study are:

1. Epoxy coated reinforcing bar. Steel bars are protected with a coating of powdered epoxy that is fusion-bonded to the steel. The coating physically blocks chloride ions. Cracking and chipping of the coated bars may occur during transportation, storage and field handling, particularly where unskilled labors are used, as is prevalent in the Arabian Gulf region. Damages of such nature could be very detrimental to the integrity of these bars and the protection against corrosion (4).

2. Silica-fume (Microsilica) and Ground Granulated Blastfurnace Slag (ggbs). These are effective pozzolanic materials that significantly reduce concrete permeability and, thereby, reduce chloride ion ingress. The decreased permeability substantially increases resistance to chloride penetration and reduces the rate of steel corrosion and carbonation. Microsilica and ggbs concretes typically have low chloride diffusivity. On the other hand, though ggbs concrete has an early delay rate of hydration, it has lower heat of hydration and progressive compressive strength after 28 days, which superceded that of ordinary concrete and continue to rise after 56 days of curing (5). As for microsilica the concern includes the reduction in the pH value of the concrete which makes carbonation more likely and could cause bound chlorides to be liberated from the hydration products and reduction in the resistance of concrete to salt weathering which is caused by crystallization of salts in the concrete pores (6).

3. Calcium Nitrite Corrosion-Inhibiting Admixtures. It enhances the stability of the passivating layer on the surface of the reinforcing steel. In this concrete system chloride and nitrite ions compete for ferrous ions on the steel bar. If the chloride ion concentration is greater, the corrosion process will start. If, on the other hand, the nitrite ion concentration is greater, a passive layer will form to close off the iron surface. The effectiveness of the calcium nitrite admixture, therefore, is dependent on an accurate prediction of the chloride loading of the structure over its expected design life and, hence, on the selection of an appropriate dosage of the admixture (7).

2. TESTING PROGRAM

The testing program was designed to include standard and popular laboratory testing methods, accelerated and normal testing methods. The program also included field assessment studies, where specimens are prepared and placed in an exposure

site of multiple conditions. The corrosion test program covered three different evaluations:
1. Strength development properties.
2. Corrosion activities-related tests.
3. Chloride ingress characteristics.

For specimen preparations local building materials were used such as Type I & Type V cements, sand, aggregates, and ordinary steel reinforcing bars. Chemical admixtures were provided by local suppliers, whereas local promenant construction companies provided the research program with the required amounts of microsilica (from Elkem Microsilica), ggbs (from Falcon Cement), epoxy coated rebars (from Protech Dubai), and calcium nitrite (from Al-Gurg Fosroc Dubia). Table 1 presents test program summary designed for the study.

Table 1. Test Program Summary

Test	Specimen Size	Measurement
ASTM G-109	Beams: 279 x 152 x 114 mm	Macro-cell current Half-cell potential
Corrosion Rate (Lollipop)	Prism: 380 x 200 x 76 mm	Macro-cell current Half-cell potential
Time-to-Corrosion	Blocks : 300 x 300 x 200 mm	Corrosion rate Macro-cell current Half-cell potential
ASTM C-1202 (AASHTO T 277-86)	Cylinders: 100 x 200 mm	Total charge (conductivity)
AASHTO T 259-80	Slab: 300 x 300 x 75 mm	Chloride profile
Chloride Diffusivity	Cylinders: 100 x 50 mm	Chloride content
Outdoor Exposure	Beams: 120 x 120 x 350 mm With 2 bars With 1 bar Cylinders: 100 x 200 mm	Visual examination Half-cell potential Steel mass lost Chloride content

3. Strength Development Properties

This is presented in terms of compressive strength. Strength gain development is monitored and recorded at certain curing intervals. Any strength development with time can be related to change in permeability and chloride ingress characteristics. As hydration takes place and the curing process progresses, capillary pores are filled with hydration products. The capillary porosity of the paste depends on both w/c ratio of the

mix and the degree of hydration. The type of cement influences the degree of hydration achieved at a given age. At a high water/cement (w/c), ratio the volume of the formed cement gel is not sufficient to fill the capillary pores, which are mainly responsible for permeability of hardened cement paste and its vulnerability to chloride ingress.

4. Corrosion Activities-related Tests

Time-to-Corrosion Initiation (Modified ASTM G-109). This is a stringent testing method (Fig. 1), that evaluates the effectiveness of concrete in protecting embedded steel bars from corrosion when salts are applied externally (8). The test requires 48 weekly test cycles to complete. Measurement proceeds after 96 h of salt-water ponding, followed by vacuum removal of the salt water and immediate freshwater rinse and vacuum removal again. This is followed by 72 h of air-drying. The weekly measurements involve readings of half-cell potential, corrosion rate, and concrete resistivity, which are recorded with respect to a copper-copper sulfate reference electrode (CSE) of –350 mV.
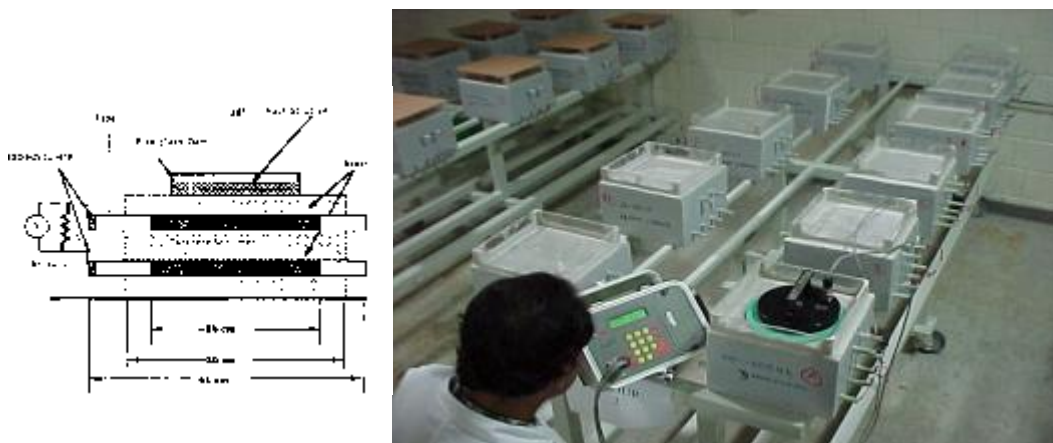

Fig.1. Test setup of Time-to-Corrosion Initiation (Modified ASTM G-109)

Corrosion Rate Test (Lollipop Test). This is a popular laboratory test method (Fig. 2), which demonstrates the effectiveness of corrosion protection systems exposed to the marine environment. The test takes its name from the shape of the test specimen. The test simulates the wicking of chlorides by concrete in seawater. The test studies the microcell corrosion current that occurs in a localized area on the steel rebar. Corrosion rate measurements are recorded every month, and involve half-cell potential and microcell corrosion current. This test takes at least one year for the initial results to appear. This test provides excellent chloride ingress profile indication, which qualifies the permeability characteristics of the different corrosion protection systems.
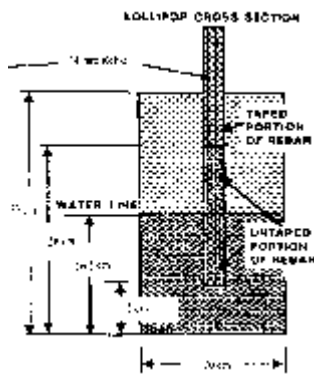
Fig.2. Test setup of Corrosion Rate Test (Lollipop Test)

5. Chloride Ingress Characteristics Tests

The rate at which ions, particularly chloride ions, can diffuse through concrete is important with regard to possible corrosion of steel reinforcement. Ions diffuse through concrete due to differences in ion concentration, which are often independent of hydraulic pressure gradient. Ion diffusivity is generally determined by measuring the time for the concentration at a given point to reach a particular value. There are at least three test methods to determine ionic diffusion rates:
1.   The first involves taking incremental samples at different depths by drilling and measuring the chloride content at each increment.
2.   The second involves measurement of ionic diffusion by concentration difference between two sides of a specimen after ponding with a chloride solution at one side for certain period of time.
3.   In the third method, ionic diffusion is measured by the change in electrical properties that results from changes in concentration.

Chloride Diffusivity. This is a popular long-term duration laboratory test method. This method is designed to assess the chloride ingress characteristics of cylindrical specimens; epoxy-coated on all surfaces, then cut at one end to expose the concrete. The exposed concrete surface provides access for one-dimensional diffusion of chloride ions of 3% NaCl solution. Chloride concentration profiles are developed by periodical assessment of chloride concentration at certain depths (0-10 mm, 10-25 mm, 25-30 mm, and 30-50mm). For certain concentrations, at each depth, the time will be recorded and compared.

Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration ASTM C-1202-91). This is a standard test method (Fig. 3), designed to determine the electrical conductivity of concrete to provide a rapid indication of its resistance to the penetration of chloride ions (9). The test consists of monitoring the amount of electrical current passed through 100 mm diameter by 50 mm long cores when one end of the core is immersed in sodium chloride and a potential difference of 60 V dc is maintained

across the specimen for 6 h. The total charge passed in coulombs is related to chloride permeability.

Fig. 3. Test setup of electrical indication of Concrete's Ability to Resist Chloride.

Resistance of Concrete to Chloride Ion Penetration (AASHTO T 259-80). This is a standard test method that evaluates the effect of variations in concrete properties on resistance to chloride ion penetration (10). The test results are correlated with findings of ASTM C1202 to confirm ionic diffusion by chloride ion concentration. Chloride diffusivity is measured by assessment of chloride concentration at different depths, after 90 days ponding with 3% NaCl solution.

6. RESULTS AND DISCUSSION

In this paper results and performance of each corrosion protection system will be compared to performance of ordinary concrete and the ability to arrest the corrosion process and control the corrosion activities within each system.

Performance of GGBS Concrete. Table 2 presents the concrete mix proportions of the ordinary concrete and the ggbs concrete as 50 % of cement weight was replaced by ggbs. The water- to- cement ratio was selected to be relatively low to represent high performance concrete.

Table 2. Concrete Mix Proportions

Ingredients	Ordinary Concrete	GGBS Concrete
Water-to-cement Ratio	0.36	0.36
Cement type	I	I
Cement (kg/m^3)	472	236
GGBS (kg/m^3)	-	236
Sand (kg/m^3)	550	550

* Aggregate 20 mm (kg/m^3)	770	770
* Aggregate 10 mm (kg/m^3)	380	380
Water (l/ m^3)	170	170
** Chemical Admixture (Caplast NE/EDS) (l/m^3)	5.5-8.5	5.5-8.5

* SSD = Saturated surface Dry , ** Super plasticizer water reducer

Results shown in Table 3 indicates the improvments achieved in the compessive strength at 28 and 56 days in spite of the delay in maturity in the third and seventh day of the curing period. Improvements occurred as a result of 50 % replacement of cement weight by ggbs have affected positively the concrete resistivity to chloride ions penetration and the corrosion activities on the protected steel reinforcing bars. In Fig. 4, and according to ASTM C-876-91 (11) for corrosion risk assessment of half-cell potential of steel bars in concrete, the half cell potential of the steel bar protected by the ggbs concrete was less than –200 mV-CSE after 48 cycles of testing according to modified ASTM G-109, which indicates that steel bar condition in the region described as 90 % probability no corrosion activity occuring on the surface of the steel bar. This is incomparable to results of steel bars protected by ordinary concrete, when its corrosion potential recorded –215 mV after 35 cycles of testing, which describe the steel bar condition as in the region of uncertain corrosion risk area. After 40 cycles of testing and at 280 day the onset of corrosion activities occurs at half-potential of –240 mV-CSE.
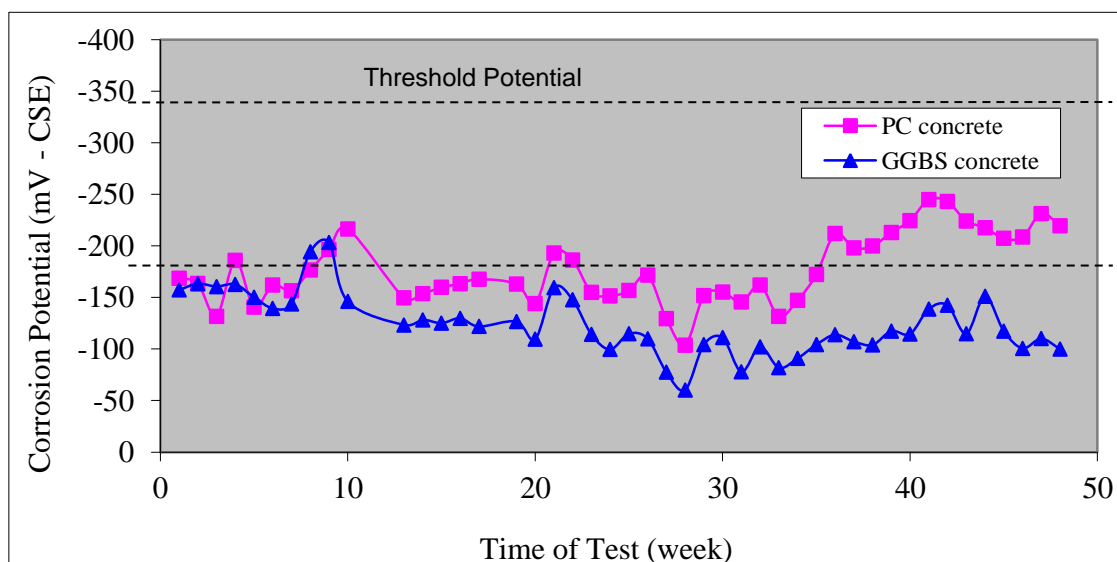

Fig. 4. Results of corrosion potential of steel reinforcing bars protected by ordinary concrete and GGBS concrete after time-to-corrosion test.

Table 4 shows results of the corrosion activities for both concretes represented as time-to-corrosion initiation, magnitude of corrosion activities, corrosion current density, concrete electrical resistivity, and corrosion penetration rate. Corrosion rate determined by linear polarization and other electrochemical techniques, expressed in terms of corrosion current density (I_{corr}) can be converted into penetration rates by the following expressions based on Faraday's law (12):

$$\text{Corrosion penetration rate} = K \frac{ai}{nD} \qquad (1)$$

where a = atomic weight of metal (55.8);
   i = current density, $\mu a/cm^2$;
   n = number of electrons lost, valence charge (2);
   D = density of steel, g/cm^3 (7.86);
   K = constant depending on the penetration rate desired with K = 0.129, mpy (mils penetration per year), K = 3.27 , mm/yr, and K = 0.00327 , m/yr

Table 3. Improvements in Mechanical and Physical Properties of Ordinary Concrete as 50% of Cement Weight Replaced by GGBS

Properties Concrete Type	Compressive Strength (kg/cm^2)				ASTM C-1202		AASHTO T-259 Percentage of chloride Absorption After 90 days	
	3 days	7 days	28 days	56 days	28 days	56 days	13 mm Depth	25 mm depth
Ordinary Concrete Type I	443	490	579	600	2590	1713	0.120	0.052
GGBS Concrete	356	440	632	780	1220	636	0.034	0.021

Table 4. Improvement in Concrete Permeability and Its Effect on Corrosion Activities on Steel Bars

Properties / Concrete Type	Time–to Corrosion (Modified ASTM G-109) (days)	Magnitude of Corrosion Activities (μA. day)	Corrosion Current Density (μA.cm^2)	Corrosion Penetration Rate (μm/year)	Concrete Electrical Resistively (kΩ. cm)
Ordinary concrete Type I	280	2081	0.166	1.927	70
GGBS Concrete	Corrosion Potential less than–200 mv	749	0.110	1.2	100

As results showed above there are significant improvements in concrete properties when 50% of cement replaced by ggbs, particularly with respect to chloride ions penetration and corrosion activities on steel bars, which qualify ggbs concrete for use in marine and off shore styructures.

Performance of Silica Fume Concrete in Comparison to Ordinary Concrete and Concrete with Calcium Nitrite

Results showed significant improvements in concrete properties with respect to chloride ions penetration, by 10% replacement of cement weight with microsilica, which had a direct effect on delaying the corrosion activities progress on steel reinforcement bars. According to AASHTO T-259 Table 5 presents results of chloride ions obsorption of concrete cover after 90 days of concrete surface ponding with 3% sodium chloride solution. Results showed substantial decrease in chloride ions obsorption that ranged from 60 – 80% depending on the variation in the water-to-cement ratio of the different concretes. The above results are in agreement with results of ATSM C-1202 presented in Fig. 5 that indicate concrete resistivity to chloride ions penetration expressed as total charge passed through concrete in six hours. According to FHWA/RD-81-119 report (13) for chloride ion penetration as presented in Table 6. The concrete classification has changed from high chloride ions penetration (>4000 coulombs) to low chloride ions penetration (2000 coulombs) when 10% of cement weight replaced by microsilica. As for the effectiveness of silica fume concrete in protecting the steel reinforcement, Fig. 6 clearly shows that it proceeded the capability of ordinary concrete and the concrete with calcium nitrite. According to modify ASTM G-109 test and the interpretation given by ASTM C-876 for corrosion risk assessment, results of the corrosion potential of the steel bars protected by the different concretes, indicated that after 48 cycles of drying and wetting with 15% sodium chloride solution, silica fume concrete continued to provide protection to the reinforcement while those protected by calcium nitrite concrete exhibited uncertain corrosion activities on their surfaces.

Table 5. Rate of Chloride Absorption at Different Depths of Concrete Surface

Concrete Code	Average Absorbed (%)		Maximum Absorbed (%)	
	1.6-13mm	13mm-25mm	1.6-13mm	13mm-25mm
* OU—50	0.161	0.118	0.186	0.177
**OUSF 50	0.089	0.049	0.111	0.111
*** OU –45	0.086	0.041	0.098	0.049
**** OUSF 45	0.069	0.006	0.096	0.009

  * Ordinary Concrete: w/c =0.5,   ** silica fume concrete: w/c = 0.5
*** Ordinary concrete: w/c = 0.45,   **** silica fume concrete: w/c = 0.45

Table 6. Chloride Permeability Based on Charge Passed

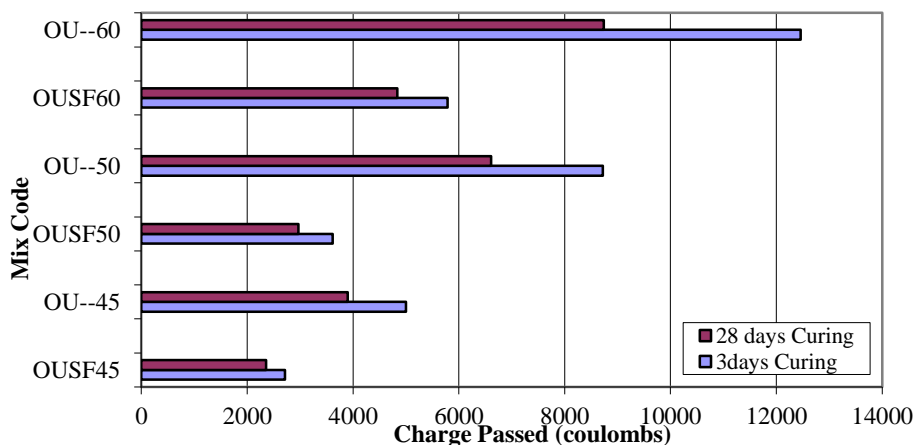| Charge Passed (coulombs)*	Chloride Ion Penetrability	Typical of
> 4,000	High	High w/c (>0.6). Ordinary concrete.
2,000 - 4,000	Moderate	Moderate w/c (0.4-0.5). Ordinary concrete.
1,000 - 2,000	Low	Low w/c (<0.4.) Ordinary concrete.
100 -1,000	Very Low	Latex modified concrete internally sealed concrete
< 100	Negligible	Polymer impregnated concrete. Polymer concrete.

*Reference 13

Fig. 5. Electrical indication of the ability of different mixes of concrete to resist chloride ion penetration, expressed in total charge passed in six hours.
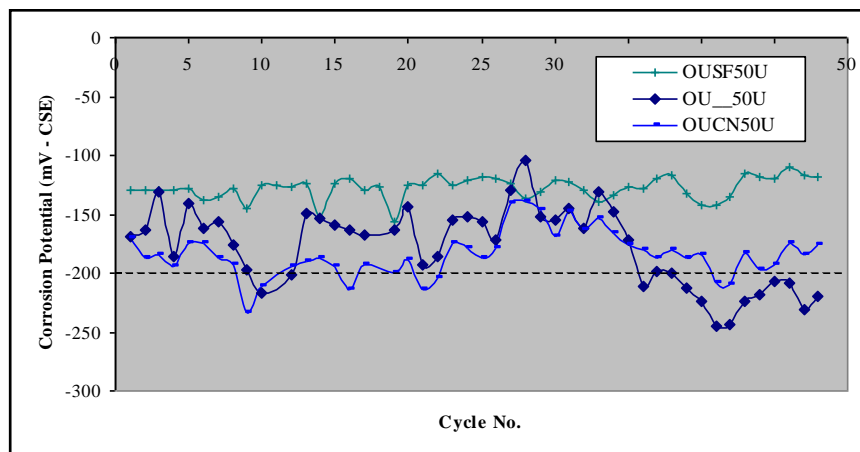
Fig. 6. Results of corrosion potential of steel reinforcing bars protected by different concretes after ASTM G-109 test.

Performance of Epoxy Coated Rebars

Results indicated in clearly that the effectiveness of the epoxy coated rebars is reliant on the quality of the concrete cover and the condition of the epoxy coating on the steel bar at the time of use. Fig. 7 shows the effect of steel bar coating condition on the corrosion potential of the steel bar. It is clearly evidant that the epoxy coating on the steel bar (OU-50C) has improverd corrosion activities resistance compared to uncoated bars (OU-50U). Also it shows the deterioration in the corrosion potential when the epoxy coating is damaged (OU-50D), it reveals the increased corrosion activities on the steel bar. Fig. 8 indicated the effectiveness of the silica fume concrete (OUSF50D) in delaying the penetration of the chloride ions and its attack on the damaged epoxy coating. It also shows the healing effect of the calcium nitrite when creating a passive layer on the damaged epoxy coated rebars to hinder chloride ions attack and hence corrosion activities from taking place. The discussion above has drawn the attention to the effectiveness of the epoxy coated rebars, nevertheless Fig. 9 is a cause for concern when such rebars are used. It is quite often that the electrochemical monitoring measurements used for investigating the corrosion activities, will fail to detect any damages on the epoxy coated rebars and hence overlook any change in the corrosion potential readings unless the steel bars are physically removed and visually examined. That was the reason behind the sudden failure and the deterioration which took place on 1986 in the state of Floride in USA, when application of epoxy coated rebars became very popular without precautionary measures or previous knowledge of such danger.
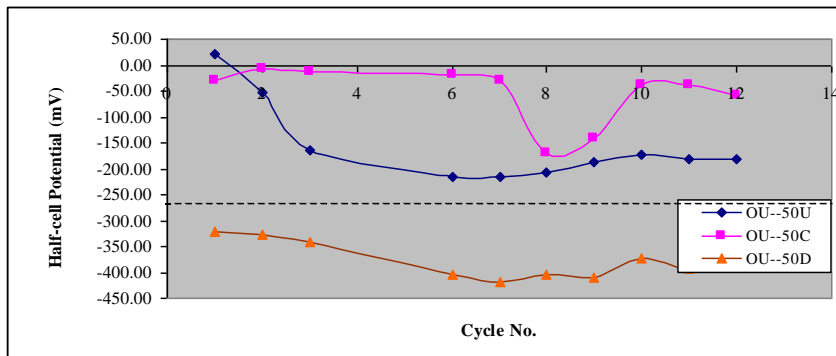
Fig. 7. Effect of epoxy coating condition on the corrosion potential of the steel reinforcing bars and its consequences on the corrosion activities
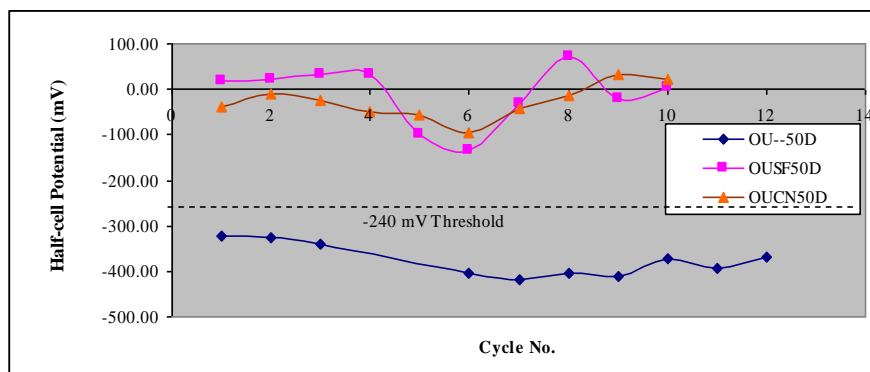

Fig. 8. Effectiveness of silica fume concrete and calcium nitrite in protecting and healing damaged epoxy coated rebars that delayed chloride ions attack on them.
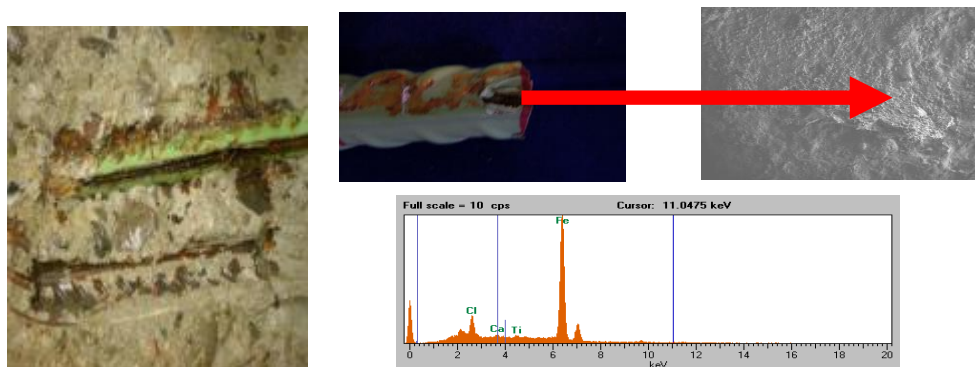

Fig. 9. Corrosion of epoxy coated rebar exhibited after time-to-corrosion test (Modified ASTM G-109)

7. SUMMARY AND CONCLUSIONS

As a summary to all above, its concluded that the supplementary cementing materials such as ggbs concrete and silica fume concrete when replace certain percentage of the cement weight in the concrete mixure, they have significant effect in enhancing concrete resistivity to chloride ions penetration and hence decrease the corrosion activities on steel bars protected by such concretes. As for the epoxy coated rebars results showed concerns related to the condition of the epoxy coating layer on the bar and to their application in high chloride laden environments. On the other hand it is proven that corrosion inhibiting admixures such as calcium nitrite are more effective when used with other protection systems such as ggbs and microsilica. Accordingly conclusions can be made as following:

1. Significant imrovements in concrete performance when suplementary cementing materials are used, especially with respect to resistivity to chloride ions petration and corrosion activities.

2. Corrosion protections systems satisfy durability requirements of reinforced conctere structures in marine environment.

3. Effectiveness of the epoxy coated rebars is reliant on the quality of the concrete cover and the condition of the epoxy coating on the steel bar at the time of use.

4. Effectivness of corrosion inhibiting admixtures such calcium nitrite is highly reliant on their concentration with respect to chloride ion concentration in the same environment. Any unaccounted for increase in the level of chlorides over the nitrite ions would lead to unexpected form of corrosion on the steel bars. That why such corrosion protection system would work better in multiprotection environment.

5. It is of great importance to conduct field research studies under the actual prevailing environmental to be able to conclude more realistic results that would make practical applications of such materials and systems more effective. Studies of that nature usually requires long time that spans to 5-10 years.

6. Kuwait Institute for Scientifc Research has extended and expanded the field research studies that were carried out in 2002 (1), Fig. 10, in marine and off shore research filed station that addresses the most severe and aggressive environmental conditions in the petroluem and industrial fields. The purpose is to carry out field investigation to assess the corrosion risk of two corrosion inhibiting admixtures under marine environment (14).

7. The field research station (RFS) will be accommodating similar exposure zones, Fig. 11, as previously accounted for; atmospheric zone, high & low tide zone, splash zone, submerged zone, underground zone, and above ground zone. The new RFS, will be supported by reinforced concrete elements such as columns and beams, which are fitted with remote data acquisition sensors for health monitoring parameters of the structures including corrosion and carbonation induced related deteriorations.

Fig. 10. Field Research Station of Kuwait Institute for Scientifc Research, 2002.

Fig. 11. Field Research Station of Kuwait Institute for Scientifc Research, 2014

8. ACKNOWLEDGEMENT

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