Structural Monitoring and Maintenance, *Vol. 2, No. 1 (2015) 35-48*
DOI: http://dx.doi.org/10.12989/smm.2015.2.1.035

Impact of aggressive exposure conditions on sustainable durability, strength development and chloride diffusivity of high performance concrete

Suad Al-Bahar* and A. Husain[a]

Construction and Buildings Materials Program, Energy and Building Research Center,
Kuwait Institute for Scientific Research, Safat 13109, Kuwait

(Received January 17, 2015, Revised March 8, 2015, Accepted March 10, 2015)

Abstract. The main objective of this study is to evaluate the long-term performance of various concrete composites in natural marine environment prevailing in the Gulf region. Durability assessment studies of such nature are usually carried out under aggressive environments that constitute seawater, chloride and sulfate laden soils and wind, and groundwater conditions. These studies are very vital for sustainable development of marine and off shore reinforced concrete structures of industrial design such as petroleum installations. First round of testing and evaluation, which is presented in this paper, were performed by standard tests under laboratory conditions. Laboratory results presented in this paper will be corroborated with test outcome of ongoing three years field exposure conditions. The field study will include different parameters of investigation for high performance concrete including corrosion inhibitors, type of reinforcement, natural and industrial pozzolanic additives, water to cement ratio, water type, cover thickness, curing conditions, and concrete coatings. Like the laboratory specimens, samples in the field will be monitored for corrosion induced deterioration signs and for any signs of failureover initial period ofthree years. In this paper, laboratory results pertaining to microsilica (SF), ground granulated blast furnace slag (GGBS), epoxy coated rebars and calcium nitrite corrosion inhibitor are very conclusive. Results affirmed that the supplementary cementing materials such as GGBS and SF significantly impacted and enhanced concrete resistivity to chloride ions penetration and hence decrease the corrosion activities on steel bars protected by such concretes. As for epoxy coated rebars applications under high chloride laden conditions, results showed great concern to integrity of the epoxy coating layer on the bar and its stability. On the other hand corrosion inhibiting admixtures such as calcium nitrite proved to be more effective when used in combination with the pozzolanic additives such as GGBS and microsilica.

Keywords: corrosion; deterioration; high performance concrete; marine and off shore structures; mineral admixtures; reinforced concrete

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 investigation of

---

*Corresponding author, Program Manager, E-mail: sbahar@kisr.edu.kw
[a] Research Scientist, E-mail: dhussain@kisr.edu.kw

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

concrete deterioration is instigated in this region, it often describes the extent of corrosion - induced deterioration that affects the concrete structures' integrity, and the leads to premature damages and degradation, which triggers unplanned repair works. Such unintended repairs are often ineffective, inadequate and repetitive. The region provides an extremely aggressive environment, which is characterized by high atmospheric temperature, 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 in structures of high performance concrete, which are relatively new (10-15 years of construction age). Investigations and survey studies conducted in Gulf area on premature deteriorated structures (Alhozaimy *et al.* 2012, Al-Bahar *et al.* 2002) concluded that repair and rehabilitation cost are often expensive, not highly effective in arresting the corrosion processes, and often repeated within few years. The study conducted in 1996 (Al-Matrouk *et al.* 1996), on impact of metallic corrosion on Kuwait economy, showed that the 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 the 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 initial cost of construction; nevertheless the increase is marginal compared to 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 (Shekarchi *et al.* 2009). As for the corrosion protection systems, such as supplementary cementing materials, corrosion inhibiting admixtures, and epoxy coated rebars, though they have been used for 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 (Abdul-Salam and Husain 2013). This can be attributed to the following:

- 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.
- There has been adoption of construction practices that do not necessarily guarantee high performance and durability of the reinforced concrete structures under the aggressive, hot environmental conditions.
- There has been 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.

Al-Bahar *et al.* (2002), was the first to carry out the large scale performance evaluation on the supplementary cement material. She 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. 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. In 2007 Haque *et al.*

utilized findings of Al-Bahar *et al.* (2002), to conduct research study to design durable concerete structures for the Arabian Gulf environment.

The corrosion protection systems investigated in this study are:

- 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 employed, as it is prevalent in the Arabian Gulf region. Damages of such nature could cause structure failure and detrimentally impact the durability of the reinforced concrete structure by corrosion induced deteriorations, (CSHRP 1990).
- Microsilica and Ground Granulated Blast furnace and 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 exceeded that of ordinary concrete and continue to rise after 56 days of curing (Alhozaimy *et al.* 2012). 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 beside the reduction in the resistance of concrete to salt weathering which is caused by crystallization of salts in the concrete pores (Kayali and Zhu 2005).
- 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 (Ann *et al.* 2006).

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:

- Strength development properties.
- Corrosion activities-related tests.
- Chloride ingress characteristics.

For specimen preparations, local building materials were used such as OPC Type I cement, sand, aggregates, and ordinary steel reinforcing bars. Chemical admixtures were provided by local suppliers, whereas local prominent 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 Corrosion rate
Time-to-Corrosion	Blocks : 300 x 300 x 200 mm	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

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, calcium silicate hydrate (C-S-H) is not sufficient to fill the capillary pores, which are mainly responsible for permeability of the cement paste and its vulnerability to chloride ingress.

4. Corrosion activities-related tests

4.1 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 (ASTM G 109, 2013). 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.

4.2 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.

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:

- The first involves taking incremental samples at different depths by drilling and measuring the chloride content at each increment.
- 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.
- In the third method, ionic diffusion is measured by the change in electrical properties that results from changes in concentration.

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

Fig. 2 Test setup of Corrosion Rate Test (Lollipop Test)

5.1 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.

5.2 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration ASTM C-1202-91)

This is a standard test method, designed to determine the electrical conductivity of concrete to provide a rapid indication of its resistance to the penetration of chloride ions (ASTM C 1202, 2012). 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.

5.3 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 (AASHTO T-259, 2002). 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.

6.1 Performance of GGBS concrete

Table 2 presents the concrete mix proportions of the ordinary concrete and the concrete with 50 % cement weight replacement by GGBS. The w/c ratio was selected to be relatively low to represent high performance concrete.

Results shown in Table 3 indicate the improvements achieved in the compressive 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. 3, and according to ASTM C-876, 2009, 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 occurring 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.

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 (Icorr) can be converted into penetration rates by the following equation (1), based on Faraday's law (Andrade and Martinez 2010)

Table 2 Concrete mix proportions

Ingredients	Ordinary Concrete	GGBS Concrete
Water-to-cementRatio (w/c)	0.36	0.36
Cement type (ordinary Portland cement OPC)	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

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

Properties / ConcreteType	Compressive Strength (kg/cm^2)				ASTM C-1202 (coulombs)		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

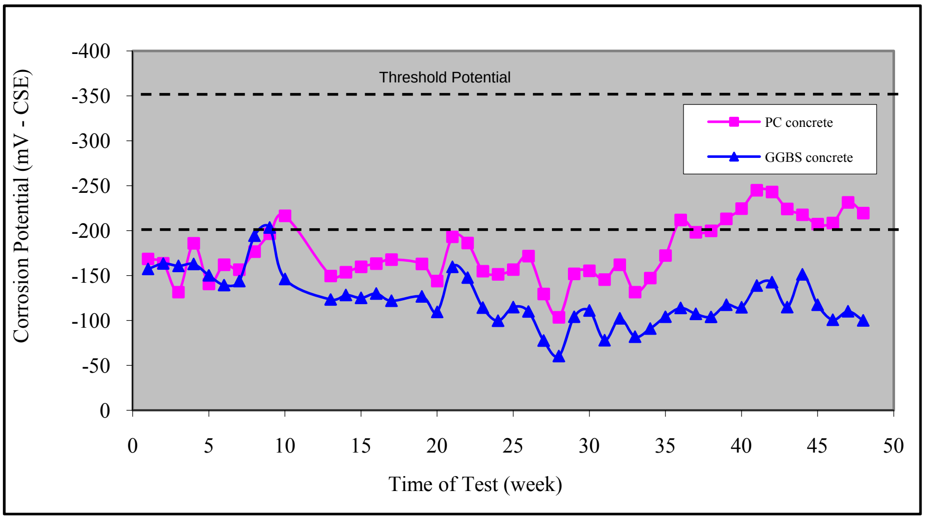

Fig. 3 Results of corrosion potential of steel reinforcing bars protected by ordinary concrete and GGBS concrete after time-to-corrosion test

$$\text{Corrosion penetration rate} = K\,(ai)/(nD) \quad (1)$$

where a = atomic weight of metal (55.8)
i = current density, μa/cm2
n = number of electrons lost, valence charge (2)
D = density of steel, 7.86 g/cm3
K =constant depending on the penetration rate desired (0.129 mpy (mils penetration per year), or 3.27 mm/y, or 0.00327 m/y

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 structures. The reason for this close values of OPC with respect to GGBS could be attributed to the high compactness and short aging of the OPC with respect to other sample, however there is an indication of some discrepancy between the two. Other parameters have indicated that GGBS outperformed the OPC concrete.

6.2 Performance of microsilica 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 absorption of concrete cover after 90 days of concrete surface ponding with 3% sodium chloride solution. Results showed substantial decrease in chloride ions absorption that ranged from 60 – 80% depending on the variation in the w/c ratio of the different concretes. The above results are in agreement with FHWA/RD-81-119 report (Whiting, D., 1981) for chloride ion penetration, which is presented in Table 6 and the results of ATSM C-1202 presented in Fig. 4 that indicated concrete resistivity to chloride ions penetration expressed as total charge passed through concrete in six hours. 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. 5 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 after AASHTO T-259

Concrete Code	Average Absorbed (%)		Maximum Absorbed (%)	
	1.6-13 mm	13 mm-25 mm	1.6-13 mm	13 mm-25 mm
* 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

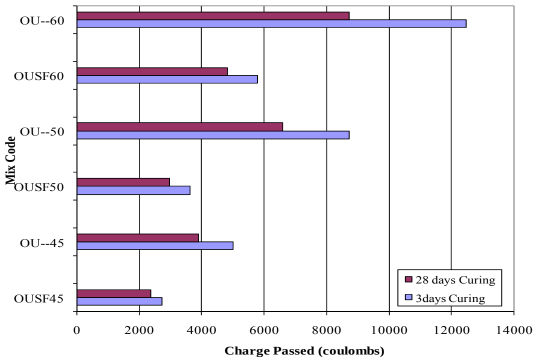

Fig. 4 Electrical indication of the ability of different mixes of concrete to resist chloride ion penetration, expressed in total charge passed in six hours after ATSM C-1202

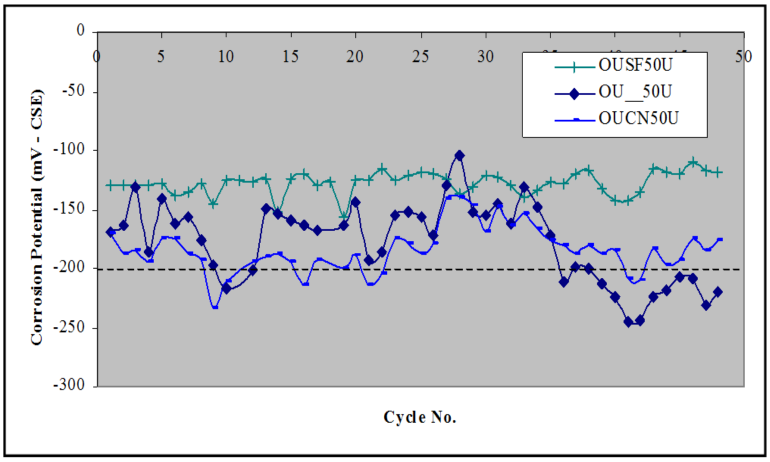

Fig. 5 Results of corrosion potential of steel reinforcing bars protected by different concretes after ASTM G-109

6.3 *Performance of epoxy coated rebars*

Results indicated 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 layer on the steel bar at the time of use. This study was conducted to evaluate the effect of damage to the surface of fusion bonded epoxy coating (FBEC) rebars on reinforcement corrosion in chloride contaminated environment. As the FBEC rebars normally experience damage due to mechanical transportation, for the study the damage has been purposely created by pinholes. Fig. 6 shows the effect of steel bar coating condition on the corrosion potential of the steel bar. It is clearly evident that the epoxy coating on the steel bar (OU-50C) has improved the resistance to corrosion activities compared to uncoated bars (OU-50U).Note that the rise in the potential readings of OU-50Cis an error that can be ignored as it could be attributed to electromagnetic noise of the linear polarization signal of the corrosion meter. Fig. 6 shows the negative impact when the epoxy coating is damaged (OU-50D), a sit reveals the increased corrosion activities indicated by the potential rise. Fig. 7 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 results above showed a cause for the concern when such rebars are used. It is quite known that due to the epoxy coating layer, the electrochemical monitoring signals will fail to detect any damages on the epoxy coated rebars, unless the steel bars are physically removed and visually examined. Fig. 8. Shows the extent of corrosion damage to the epoxy coating layer on the steel rebar. This is confirmed by studying the surface morphology of the steel bar under the optical microscope with a noticeable cavity formation, and the x ray analysis of the corrosion products which indicated the presence of chloride, the main cause of corrosion. The corrosion products when increase in size, it exerts internal stresses on the epoxy coating layer leading to its cracking and to the sudden failure of the reinforced concrete member.

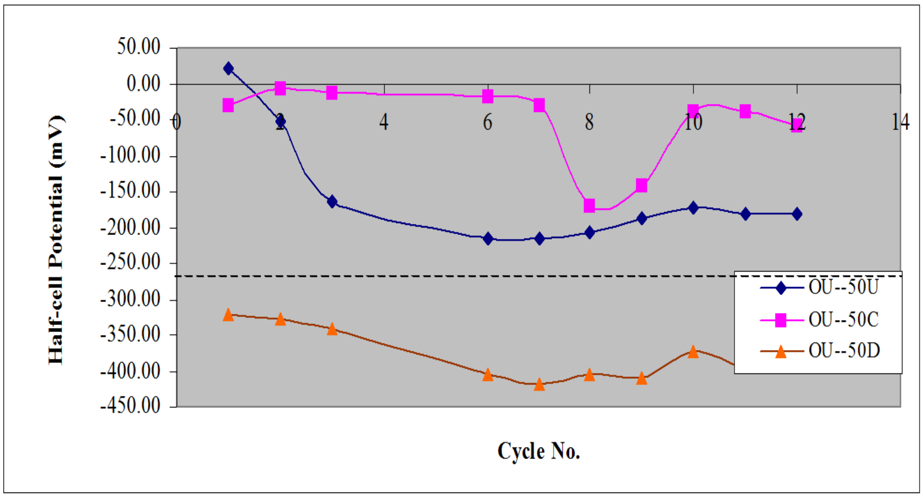

Fig. 6 Effect of epoxy coating condition on the corrosion potential of the steel reinforcing bars and its consequences on the corrosion activities

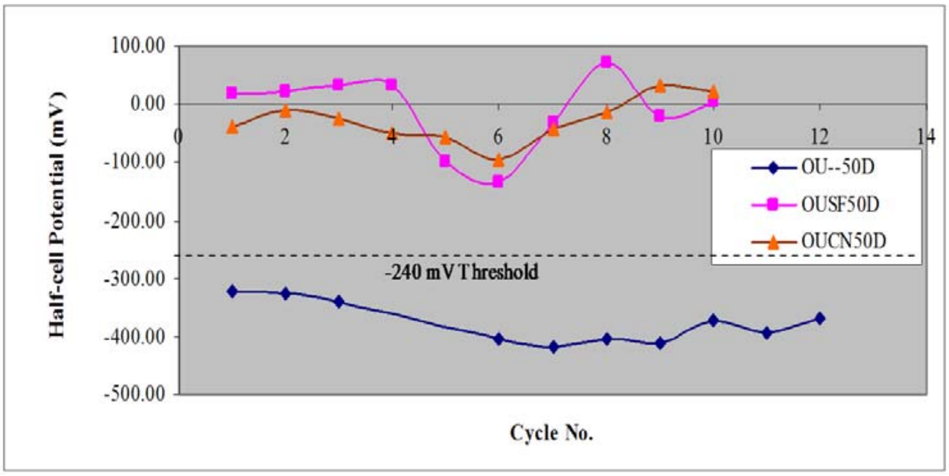

Fig. 7 Effectiveness of silica fume concrete and calcium nitrite in protecting and healing damaged epoxy coated rebars that delayed chloride ions attack on them

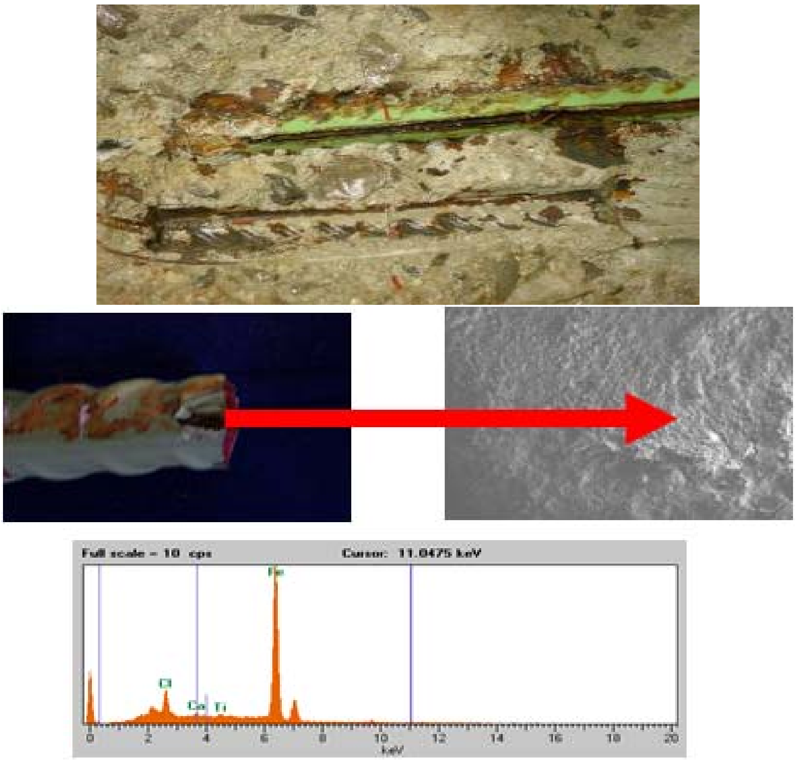

Fig. 8 The extent of corrosion occurred on epoxy coated rebar after time-to-corrosion test, confirmed by surface morphology of the steel bar under the epoxy coating layer and by the X- ray analysis that indicated the presence of chloride that instigated the corrosion process

7. Conclusions

As a summary to all above, its concluded that the supplementary cementing materials such as GGBS concrete and microsilica concrete when replace certain percentage of the cement by weight in the concrete mixture, 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 fusion bonded epoxy coating layer on the steel bar and on the use of FBEC rebars in high chloride laden environments. On the other hand it is proven that corrosion inhibiting admixtures such as calcium nitrite are more effective when used with other protection systems such as GGBS and microsilica. Accordingly conclusions can be drawn as following:

- Significant improvements in concrete performance when supplementary cementing materials are used, especially with respect to resistivity to chloride ions penetration and corrosion activities.
- Corrosion protections systems satisfy durability requirements of reinforced concrete structures in marine environment.
- Effectiveness of the epoxy coated rebars is reliant on the chloride concentration of the service environment, the quality of the concrete cover and the condition of the epoxy coating on the steel bar at the time of use.
- Effectiveness of corrosion inhibiting admixtures such calcium nitrite is highly reliant on their concentration with respect to chloride ion 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. Therefore corrosion inhibiting admixtures would work better in multi-protection system with other mineral admixture..
- 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.
- To validate the experimental results done 2002 (Al-Bahar *et al.* 2002), In the field research station there will be vast investigation under the actual severe and aggressive conditions to access the impact of marine and off shore industrial environments, (Abdul-Salam and Husain 2013) on the performance of reinforced concrete structures under variable atmospheric and weathering conditions, including atmospheric zone, high & low tide conditions, splash zone, submerged zone, underground zone, and above ground zone.

Acknowledgements

Gratitude and appreciation are extended to Kuwait Foundation for Advancement of Science, and Kuwait Institute for Scientific Research for their financial support. Also recognition and gratitude go to all the firms and companies which contributed to the research in-kind by provision of materials and services: KBRC Readymix Company, FOSROC Specialities, Gulf Consult - Engineering Consulting Office, and Al-Bahar & Bardawil Specialities.

References

AASHTO T-259. (2002), *Resistance of Concrete to Chloride Ion Penetration*, Standard Specification for Transportation Materials and Methods of Sampling and Testing, 14th Ed., Washington DC, USA: American Association of State Highway and Transportation Officials.

Abdul-Salam, S. and Husain, A. (2013), *Assessment Of The Durability And Corrosion Behavior Of Concrete Treated With Chemical Inhibitors For Kuwait Oil Company (KOC)*, Proposal, Kuwait Institute for Scientific Research, Kuwait.

Al-Bahar, S., Husain, A., Abdul-Salam, S., Abduljaleel, A., Karam, H. Al-Shamali, O. (2002*), Evaluation of Selected Corrosion Protection Systems for Reinforced Concrete Structures in Kuwait*, Final Report, KISR 6491, Kuwait Institute for Scientific Research, Kuwait.

Alhozaimy, A., Hussain, R.R., Al-Zaid, R. and Al-Negheimish, A. (2012), “Investigation of severe corrosion observed at intersection points of steel bars mesh in reinforced concrete construction”, *Constr. Build. Mater.*, **37**, 67-81.

Al-Matrouk, F., Al-Hashem , A., Al-Kharafi, F.M. and El-Khafif, M. (1996), “Impact of metallic corrosion on the Kuwait economy before and after the Iraqi invasion: A case study”. *In Industrial corrosion and Corrosion Control Technology: Proceedings of the Second Arabian Corrosion Conference*, Kuwait: Kuwait Institute for Scientific Research.

Andrade, C. and Martinez, I. (2010), *Techniques For Measuring The Corrosion Rate (Polarization Resistance) and the Corrosion Potential of Reinforced Concrete Structures*, Non-Destructive Evaluation of Reinforced Concrete Structures, Non Destructive Testing Methods , ISBN:978-1-84569-950-5, **2**, 284-316.

Ann, K.Y., Jung, H.S., Kim, H.S., Kim, S.S. and Moon, H.Y. (2006), “Effect of calcium nitrite-based corrosion inhibitor in preventing corrosion of embedded steel in concrete”, *Cement Concrete Res.*, **36**(3), 530-535.

ASTM C 876. (2009), *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete*, American Society for Testing and Materials, Philadelphia, Pennsylvania.

ASTM C 1202. (2012), *Electrical indication of concrete's ability to resist chloride ion penetration*, American Society for Testing and Materials, Philadelphia, Pennsylvania.

ASTM G 109. (2013), *Standard Test method for determining the effects of chemical admixtures on the corrosion of embedded steel reinforcement in concrete exposed to chloride environments*, American Society for Testing and Materials, Philadelphia, Pennsylvania.

ASTM C 856. (2014), *Standard Practice for Petrographic Examination of Hardened Concrete*, American Society for Testing and Materials, Philadelphia, Pennsylvania.

CSHRP. (1990), *Effectiveness of epoxy-coated reinforcing steel*, Canadian Strategic Highway Research Program, Final Report.

Haque, M.N., Al-Khaiat, H. and John, B. (2007), “A prelude to designing durable concerete structures in the Arabian Gulf”, *Build. Environ.*, **42**(6), 2410-2416.

Kayali, O. and Zhu, B. (2005), “Corrosion Performance of medium-strength and silica fume high-strength reinforced concrete in a chloride solution”, *Cement Concrete Compos.*, **27**(1), 117-124.

Shekarchi, M., Rafiee, A. and Layssi, H. (2009), “Long-term Chloride diffusion in silica fume concrete in harsh marine climates”, *Cement Concrete Compos.*, **31(**10), 769-775.

Whiting, D. (1981), *Rapid determination of chloride permeability of concrete*, Report No. FHWA/RD-81-119, Federal Highway Administration, Washington, D.C.