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Enhancing the Life Cycle of RC Structures and Validating Service Life Prediction Models

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ABSTRACT: Chloride-induced corrosion of reinforcing steel bars is the main durability factor controlling the life cycle of reinforced concrete structures. As the environment in the UAE is one of the most corrosive in the world, chloride-induced corrosion is considered to be the main reason for the fast deterioration of reinforced concrete structures. A long-term experimental program is currently underway to study and optimize the performance of highly corrosion-resistant reinforced concrete products (high-performance concrete reinforced with corrosion-resistant steel). In this study four concrete mixes containing different levels of supplementary cementing materials as well as corrosion inhibiting admixtures are used. A total of thirty nine ASTM G109 specimens with normal and corrosion-resistant steel were prepared and are monitored for corrosion activity. The standard durability tests currently used in the UAE, namely water permeability, RCPT, migration coefficient, and diffusion coefficient were conducted for each mix. Semi-destructive testing of some of the G109 specimens was performed to validate the current service life prediction models. This paper presents the currently available results.

1 INTRODUCTION

Chloride-induced corrosion of reinforcing steel is the main cause of deterioration of reinforced concrete structures. It is the main durability feature controlling the service life of structures in the Gulf region (Nagi and Kilgour 2008). In general, service life is the period of time during which a structure meets or exceeds the minimum requirements set for it. The parameters limiting the service life can be technical, functional or economical (Vesikari 1988). The technical service life is the time in service until a defined unacceptable state is reached, such as cracking, spalling of concrete, or failure of elements. Service life methodologies have applications in the design phase of a structure as well as in the operation phase where inspection and maintenance strategies can be developed in support of life-cycle cost analysis (ACI 365). The environment in the Gulf is considered one of the most corrosive in the world. Marine exposure, chloride contaminated soil, and ground water are the main sources of chloride ions. Chloride ions penetrate through the concrete cover and finally reach the surface of the steel. When the amount of chlorides exceeds a certain threshold value, the passive layer around reinforcing steel in concrete is destroyed and corrosion is initiated. Corrosion product formed on the steel surface is about two to six times larger in volume than the original steel (Broomfield

1997). As a result, the extra volume creates tensile stresses in the concrete around the steel bars. When these stresses exceed the tensile strength of concrete, cracking and spalling of the concrete cover starts. Such damage reduces the service life of the structure and increases its life cycle cost.

Major research has been conducted on corrosion in the U.S., Europe and elsewhere (Broomfield 1997, Nagi and Whiting 1993). Past research always focused on improving either the concrete or the reinforcing steel. More research was conducted on reinforcing steel. For example, epoxy coated bars and galvanized steel are some of the options that have been studied and used (Yeomans 1991). Epoxy coated bars have been widely used in bridge decks in North America and performed relatively well in areas where deicer salts are used. However, its performance in marine and humid environment was not satisfactory (Clear et al. 1995). Another example of methods used to improve the service life of the structure by reducing the possibility of steel corrosion is the Cathodic Protection System (CPS) (Whiting et al. 1995). CPS protects the steel by applying an external DC current through external metallic anodes placed in the structure. The system is very good in theory as well as in practice, but it is costly since it requires continuous monitoring during the whole life of the structure.

Corrosion resistance steel has been developed in recent years. It has higher strength than normal steel and four to five times higher corrosion resistance compared to carbon steel (Clemeña 2003). Such steel is currently available in the UAE market. In addition, high-performance concrete has been introduced to the UAE construction field. This type of concrete has very low permeability and significantly reduces the penetration of chloride ions into concrete, therefore delaying the corrosion initiation. In addition, corrosion inhibitors are used with such materials to enhance their corrosion resistance and extend their service life. The proposed product of combining both materials (corrosion-resistant steel and high-performance concrete) will be the ideal choice to reduce corrosion and to extend the service life of the structures which is the main objective of this research study.

2 RESEARCH OBJECTIVES

Most of the structures built and currently being built in the Gulf region utilize reinforced concrete as the main construction material. As a result, there is an increasing demand among private and public owners to extend the service life of structures and to assess the remaining service life of existing structures. The main objective of this research program is to develop a maintemance-free reinforced concrete product (high performance concrete with corrosion-resistant steel) that has the potential to produce at least 75-100+ years of maintenance-free structures. This can be achieved by first identifying accurate chloride corrosion threshold parameters for various combinations of such concrete product and then validating service life prediction models using the collected data.

3 EXPERIMENTAL PROGRAM

The experimental program utilized four different concrete mix designs. The control mix consists of only Ordinary Portland Cement (OPC). The other three mixes contain, in addition to OPC, Ground Granulated Blastfurnace Slag (GGBFS), Fly Ash, and Microsilica (MS). For each of the three mixes containing the cementing materials two mixes were prepared, one mix with organic (amine carboxylate-based) corrosion inhibitor and the other without it. Two of the mixes used were similar to concrete mixes used lately in some of the iconic projects in the UAE. One mix contains OPC as well as all other cementitious materials making it a quadruple blend. Although this mix is not commercially used it was felt that it is important to monitor its performance in comparison to the other mixes. Details of all main mixes used are shown in Table 1.

Table 1: Concrete mix designs used in the experimental study

		C40/10 Control	C50/10	C60/10	C80/10
OPC	(kg)	400	167	162	400
GGBFS	(kg)	-	251	135	-
Fly Ash	(kg)	-	-	135	95
MS	(kg)	-	22	18	55
Total Cement	(kg)	400	440	450	550
Water	(kg)	200	150	145	150
w/c free		0.5	0.34	0.32	0.27
Glenium 119	(Lt.)	-	5	7	-
Glenium Sky 504	(Lt.)	-	-	-	2.75
Slump	(mm)	130	205	225	230

Since chloride-induced corrosion is the main durability parameter controlling the service-life of concrete structures in the Gulf region, the experimental program focused on assessing the corrosion-preventing characteristics of the tested mixtures. Slightly modified ASTM G109 test was used in the study. ASTM G109 is a reliable laboratory test used to assess the corrosion resistance of concrete system based on macroscopic corrosion cell. In the test, two reinforcing steel layers are placed in a concrete prism as shown in Figure 1. One bar is placed at the top near the surface and two bars at the bottom of the prism. All other faces of the prism are coated with epoxy coating to control the influx of chlorides. The specimens are ponded with 15% sodium chloride solution for two weeks and dried for another two weeks. Macrocell current and half-cell potential readings are taken at the first day of the second week of ponding. As the chloride ions reach the top bar and when the corrosion threshold is reached, the passivated layer around the bar is destroyed (depassivated) and becomes anodic (Virmani 1987). A corrosion cell is formed, which produces an electrical potential difference between the top bar and the bottom bars, which remain cathodic (chloride free concrete). This potential difference produces a flow of an electric (corrosion) current. The top and bottom bars are externally connected through a 100-ohm resistor used to measure the macrocell corrosion current. The measured current is related to the corrosion activity at the top bar. The modification in the test from the ASTM G109 is the use of variety of mixes and a higher concentration of NaCl (15% instead of 3%).

For all mixes, except for the control one, a similar mix was prepared but with corrosion inhibitor. The corrosion inhibitor used is organic (amine carboxylate-based) with a constant dosage of 0.6 liter/m^3. Two types of steel bars were used in this study, carbon steel ASTM A615 Grade 60 and corrosion-resistant high strength steel ASTM 1035 Grade 100. Combining two types of steel with high-performance concrete with and without corrosion inhibitor is done to compare the corrosion activity (time to initiation of corrosion and chloride threshold) among other parameters in order to provide guidelines as to which combination of materials should be selected in design to achieve a certain service-life. A total of 39 prisms were prepared as shown in Table 2. Figure 2 shows a view of one set of the specimens in the lab during a wetting cycle.

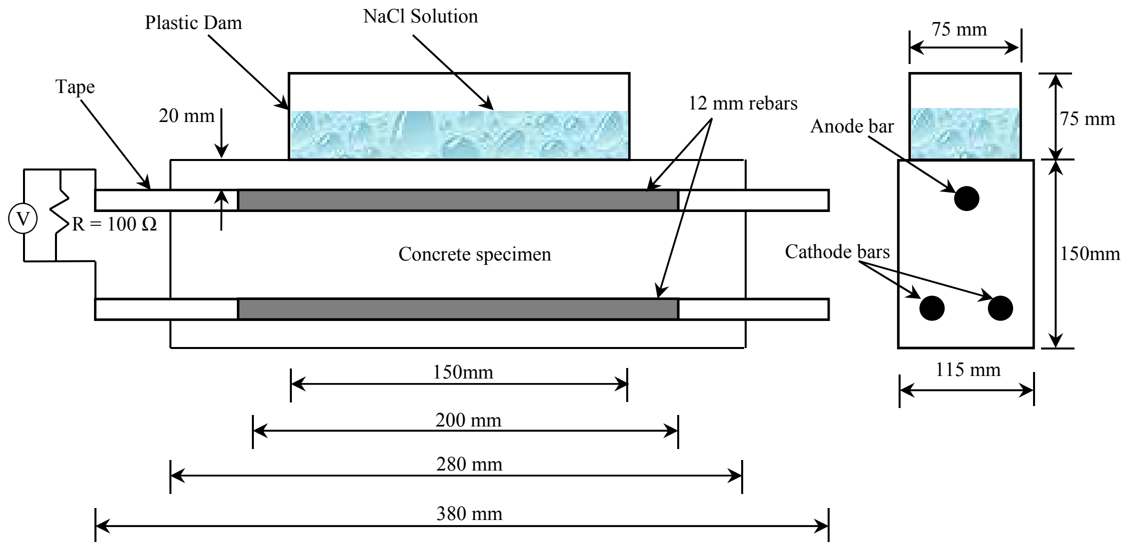

Figure 1: Test setup

Table 2: Number of ASTM G109 specimens used in the experimental study

	Carbon steel	Corrosion-resistant steel	
C40/10 Control	3	2	
C50/10	3	2	
C50/10 w/CI*	3	2	
C60/10	3	3	
C60/10 w/CI	3	3	
C80/10	3	3	
C80/10 w/CI	3	3	
Total	21	18	39

*CI: Corrosion Inhibitor

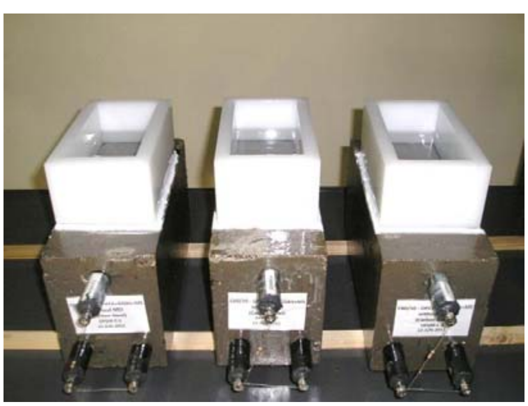

Figure 2: Picture of the specimens in the laboratory during a wetting cycle

4 PRILIMINARY RESULTS

For each mix, twenty four standard cubes (150 mm) were prepared. The cubes were used for compressive strength and durability tests. Compressive strength was measured at 28 and 56 days and the results are shown in Table 3. The first number in the mix designation is the 28-day design strength and the second number is the maximum aggregate size used. The data shows that all mixes including those that contain supplementary cementing materials (SCM's) achieved their compressive design strength at 28 days. All mixes achieved on average an additional 12% increase in strength at 56 days.

Table 3: Compressive strength and durability parameters tests results

		C40/10 Control	C50/10	C50/10 w/CI	C60/10	C60/10 w/CI	C80/10	C80/10 w/CI
Casting Date		5/6/2011	7/6/2011	9/6/2011	12/6/2011	14/6/2011	16/6/2011	20/6/2011
Compressive Strength (N/mm^2)	28 Days	40.9	73.4	77.1	69.2	74.3	94.2	88.8
	56 Days	46.2	81.1	83.5	80.5	85.0	100.2	99.6
Water Absorption (%) BS 1881	28 Days	4.2	1.1	1.1	0.7	0.8	0.8	1.2
RCPT (Coulombs) ASTM C1202	28 Days	5279	475	476	506	476	561	534
	56 Days	5362	190	192	166	178	178	168
Chloride Migration Coefficient $x\ 10^{-12}$ (m^2/sec) NT Build 492	28 Days	17.94	1.12	1.57	1.32	1.72	0.86	1.96
	56 Days	16.21	0.82	1.04	0.75	0.65	0.7	0.89
Effective Chloride Transport Coefficient $x\ 10^{-12}$ (m^2/sec) NT Build 443	28 Days	19.8	2.16	1.72	2.12	1.84	1.51	1.73

Water absorption (BS 1881 Part 122), and rapid chloride permeability (RCP) test (ASTM C1202) were also performed for each of the mixes and the results are shown in Table 3. As shown in Table 3, for all mixes utilizing SCM the RCP values were less than 1000 coulombs indicating low permeability. Chloride migration coefficient (NT Build 492) and effective chloride transport coefficient (NT Build 443) were also performed at 28 and 56 days and at 28 days, respectively, and data for all mixes are presented in Table 3. It should be noted that the diffusion coefficient must be used when performing service life analysis. However, since the diffusion coefficient requires on average 45 days to complete compared to 24 hours required for the rapid migration coefficient test, and since the rapid migration coefficient test results compare well with the diffusion coefficient test results as can be seen in Table 3, the rapid migartion coefficients may be used at the mix design stage. This finding is in-line with previous studies done by Tang and Sorensen (2001) and Nagi et al. (2011). It must be noted that microsilica has the most effect on durability parmeters. This can be seen in Table 3 where the diffusion coefficient of mix C80/10 is the lowest among all three mixes due to the use of higher quatities of microsilica.

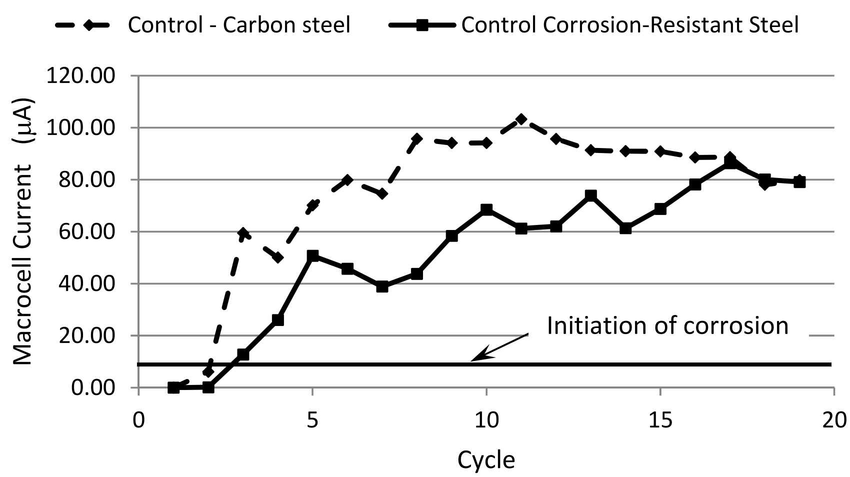

Figure 3: Macrocell current vs. wetting-drying cycle

Preliminary current readings of G109 specimens up to the 19th cycle indicate no corrosion activities in all specimens except the control specimens which have both carbon and corrosion-resistant steel. Figure 3 shows the macrocell current vs. time (each cycle is four weeks). Chloride profile analysis was conducted on one of the control specimens with carbon steel at the end of the fifth cycle. Chloride concentration at the level of the steel was found to be 0.21% by weight of concrete which is about four times higher than the carbon steel corrosion threshold of 0.05% and higher than the ASTM A1035 steel corrosion threshold of 0.18%. This is in agreement with the macrocell current readings shown in Figure 3 which imply that at the fifth cycle both types of steel used in the control concrete specimens have macrocell current readings higher than 10μA indcating corrosion activitiy in the specimen (ASTM G109). Corrosion was also verified visually by opening the specimen after the chloride analysis was done.

Macrocell current readings will continue to be taken for all specimens. Whenever a specimen in a set reaches a reading of 10μA, chloride analysis will be performed in order to determine the level of chloride concentration in the vicinity of the steel bar at the onset of corrosion. The purpose of this process is to come up with corrosion threshold values for the various concrete and steel combinations with and without corrosion inhibitor to be used later in service life analysis models. Other specimens in the set will continue to be monitored (macrocell readings) in order to study and compare the rate of corrosion among the different combinations after corrosion initiation.

5 SERVICE LIFE MODELS

ACI Life 365 model is used to predict the service life of reinforced concrete structures based on chloride-induced corrosion. The main parameters considered in the model are concrete mix design, specifically diffusion coefficient and diffusion decay index, concrete cover, surface chloride content, and corrosion threshold. In order to validate the ACI Life 365 model, the service life of some of the ASTM G109 specimens were predicted. Since 15% NaCl solution is used in the study, the surface chloride content was found to be relatively high (3% by weight of concrete). The threshold for the control mixes used in the analysis was 0.05% by weight of concrete while for concrete with corrosion inhibitor a value of 0.18% was used based on manufacturer's literature. Findings of the predicted service life for all mixes are shown in Table 4.

Table 4: Predicted service life and observed time of corrosion initiation

Mix	Diffusion Coefficient $x10^{-12}$ (m^2/sec)	Predicted Service Life (months)	Initiation of Corrosion (Lab monitoring) (months)
C 40/10 w/CS*	19.8	2.4	2
C40/10 w/CRS**	19.8	4.8	4
C50/10 w/CS	2.16	27.6	No corrosion yet
C50/10 w/CS+CI+	1.72	74.4	No corrosion yet
C60/10 w/CS	2.12	36.0	No corrosion yet
C60/10 w/CS+CI	1.84	98.4	No corrosion yet
C80/10 w/CS	1.51	24.0	No corrosion yet
C80/10 w/CS+CI	1.73	34.8	No corrosion yet

* Carbon Steel
** Corrosion-Resistant Steel
\+ Corrosion Inhibitor

Ruling about corrosion activitiy in the monitored specimens is based on the ASTM G109 criteria, which suggests that corrosion initiation occurs when the average macorcell current reaches 10μA. At this stage of the test (19 cycles), only the control mix with both types of steel has reached this current. For the cases where the corrosion-resistant steel was used with the corrosion inhibitor the corrosion threshold is estimated to be 0.36% by weight of concrete. The predicted service life of Mix C80/10, for example, where both corrosion-resistant steel and corrosion inhibitor were used, will be 54 months. However, the estimated threshold value will have to be verified based on the results of this experimental program as well as another research program which is already in progress using different testing methods.

6 SUMMARY AND CONCLUSIONS

Thirty nine ASTM G109 specimens were prepared using four different concrete mix designs and two types of corrosion-preventive technologies, namely corrosion-resistant steel and organic corrosion inhibitor. These specimens are currently being subjected to cycles of wetting and drying using 15% NaCl solution. In order to assess the role of concrete in extending the service-life of structures, chloride permeability, migration, and diffusion coefficients were measured at 28 and 56 days. All mixes containing SCM yielded low values for the measured durability parameters. Macrocell current readings are taken every four weeks and readings indicate that corrosion activity is taking place only in the control mix specimens. ACI Life 365 model was used to predict the service life of all concrete mixes. Data showed good agreement between the predicted service life and actual corrosion activities. It must be noted that the diffusion decay index given by ACI Life 365, which is based on the mix design, has a very significant effect on the predicted service life. This parameter needs to be further verified based on the final experimental results. All specimens will continue to be subjected to cycles of wetting and drying and final results will be used to further assess currently available service-life computer models and recommendations will be given to optimize service-life of concrete structures in the Gulf region.

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