



Field evaluation of corrosion mitigation on reinforced concrete in marine exposure conditions

Ahmed Abd El Fattah^{a,*}, Ibrahim Al-Duais^a, Kyle Riding^b, Michael Thomas^c

^a King Fahd University of Petroleum and Minerals, P.O. Box 215, Dhahran 31261, Saudi Arabia

^b University of Florida, Gainesville, FL 32611, USA

^c University of New Brunswick, H-126b, Old Head Hall, University of New Brunswick, Fredericton, New Brunswick, Canada

HIGHLIGHTS

- Corrosion inhibitors decreased steel corrosion rate with cover greater than 25.4 mm.
- Caltite did not reduce chloride ingress rates.
- Caltite reduced steel corrosion rate when the cover was greater than 12.7 mm.
- FA & SC performed better than corrosion inhibitors and SF in reducing chloride ingress.
- FA & SC performed better than corrosion inhibitors and SF in preventing corrosion.

ARTICLE INFO

Article history:

Received 6 May 2017

Received in revised form 10 January 2018

Accepted 13 January 2018

Available online 20 February 2018

Keywords:

Marine exposure site

Durability

Chloride diffusion coefficient

Linear polarization resistance

Chloride bulk diffusion

Supplementary cementitious materials

Corrosion inhibitors

Hydrophobic materials

ABSTRACT

The Arabian Gulf is one of the most unfriendly environments for concrete structures due to the harsh chloride attack to reinforcing steel. Durability of concrete is improved by the addition of Supplementary Cementitious Materials (SCMs) and/or chemical agents to concrete mixtures. A marine exposure site was constructed on the west coast of the Gulf in order to study the influence of SCMs and chemical admixtures on corrosion activities in reinforced concrete. Plain and reinforced concrete blocks made from eight mixes, containing cement Type I and Type V with different SCMs and corrosion inhibitors (MCI, CNI, and Caltite), were subjected to natural marine weathering process in exposure zones; tidal, splash and atmospheric for twelve months. Eight blocks, four plain and four reinforced with four black steel bars with various cover depth, were made from each mix. The blocks were monitored and their performance were evaluated in terms of chloride ingress and steel corrosion activity. Corrosion inhibitors showed better effectiveness with cover depth increase. Fly ash and slag cement showed the best performance of corrosion mitigation. Caltite showed marginal reductions in chloride concentrations and a slight improvement in corrosion rates compared to control blocks. The atmospheric-exposed samples showed marginal increase in chloride surface concentration unlike the tidal-exposed ones. The results illustrate the importance of ensuring adequate cover depth for achieving a long service life in harsh environment.

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1. Introduction

One of the main factors that leads to the deterioration of concrete structures is reinforcing steel corrosion. Corrosion is caused mainly by the ingress of chloride from the surface. When the chloride concentration reaches a threshold limit at the surface of the reinforcement depassivation occurs and corrosion is initiated. This salt ingress through the concrete is dependent on both the con-

crete internal porosity system and the surrounding environmental conditions. Corrosion in high chloride environments usually manifest in the form of localized (pitting) corrosion in which a local area of the reinforcement becomes the cathode in the corrosion cell and adjacent passive layer becomes the anode [1]. In most studies the marine environment is divided into four main zones in relation to the interaction between concrete and seawater as shown in Fig. 1.

Numerous supplementary cementitious materials (SCMs) and chemical additives have been used in the construction industry to enhance reinforcing steel corrosion resistance, such as silica

* Corresponding author.

E-mail address: ahmedmohsen@kfupm.edu.sa (A. Abd El Fattah).

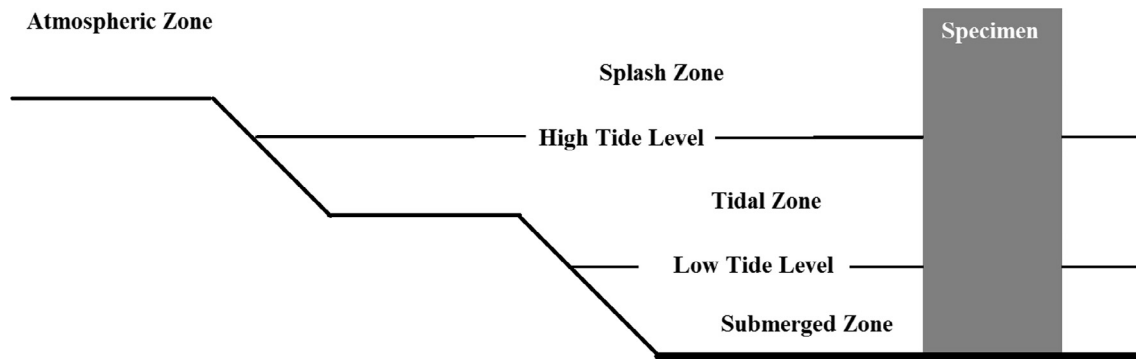


Fig. 1. Exposure zones breakdown.

fume, pulverized fly ash (FA), slag cement (SC), natural pozzolan, Calcium Nitrite Inhibitor (CNI), Migrating Corrosion Inhibitors (MCI) and caltite. The effectiveness of such materials have been the main focus of numerous studies [2–10] where the diffusion is studied and the corrosion activity is monitored.

Several marine exposure sites have been constructed in different parts of the world that have harsh or severe weather to evaluate concrete behavior under real environmental condition [5,8,10–24]. For instance, Cheewaket et al. [5] studied the effect of varying the replacement ratio of fly ash and water-to-binder ratio on the chloride binding capacity of samples exposed in the tidal zone of the Gulf of Thailand and concluded that binding capacity was not affected by the water-to-binder ratio as much as it was significantly affected by the fly ash percentage [5]. Another study was conducted by Roy et al. [12] where they studied the effect of the type of exposure on the minimum cover depth and diffusion coefficient (Da) of samples exposed in the Gulf of Singapore [5].

The Arabian Gulf with its high salinity levels, high humidity and temperature is considered to be one of the harshest environments in the world for concrete exposure [16,23,25,26]. Seawater in the Arabian Gulf has higher concentrations of salt than that found in most other bodies of water around the world. For example, the Arabian Gulf has a salt concentration of 4.4% and sulfate concentration of 4696 ppm, whereas the Caribbean Sea has a salt concentration of just 3.8% and sulfate concentration of 3864 ppm [27]. In this study, eight different concrete mixes were subjected to the natural marine weathering process in three exposure zones; tidal, splash and atmospheric for twelve months. This paper illustrated the findings from exposure in terms of chloride diffusion and corrosion current rate that was calculated using the linear polarized resistance method. In addition, this study compared the different exposure zones and different materials impact in terms of their effects on concrete durability.

2. Materials

This study used eight different mixes in order to understand the impact of cementitious materials and chemical admixtures on

reinforcing steel corrosion. Concrete mixture proportions used in this study are shown in Table 1. A common fixed water-to-cementitious materials ratio (w/cm) of 0.40 was used. ASTM C150 type I and V cements were used in order to quantify the impact of the cement aluminates content and consequent chloride binding amount on the chloride ingress rate. Three different supplementary cementitious materials (SCMs) were used in this project: an ASTM C1240 silica fume (SF), an ASTM C618 fly ash (FA) class F and an ASTM C989 slag cement (SC). Table 2 shows the cement and SCM chemical composition and physical properties. In addition, mixtures were made with the Type I cement and a migrating corrosion inhibitor (MCI), calcium nitrate corrosion inhibitor (CNI), or Caltite. An ASTM C494 high-range water reducing admixture was used in all mixtures. Mixes 1,2,6,7 and 8 contained MIRA110 (5 L/m³) [28], whereas mixes 3, 4 and 5 contained WRDA8 (2 L/m³) [29] and Viscocrete-SM4110 (1 L/m³) (1.6 L/m³ for Mix 3) [30].

Table 2 shows the chemical composition and physical properties of cementitious materials used in this study.

3. Methodology

3.1. Site condition

The exposure zone was chosen at a private beach belonging to King Fahd University for Petroleum and Minerals on the Half-Moon bay located in the city of Khobar in the Eastern province of the Kingdom of Saudi Arabia. The location chosen is part of a semi-enclosed body of the Arabian Gulf as illustrated by Fig. 2.

The Eastern Province has been labeled by the Saudi Building Committee as one of the most aggressive environments for concrete in Saudi Arabia and in the Gulf region due to its closeness to the Arabian Gulf, its high-temperature and high-humidity weather. The salinity and temperature gradient are quite high in the gulf as illustrated in Figs. 3 and 4 with an average rate of evaporation of almost 28.8 mm per day. The exposure site has local temperature ranging from 10 to 45 °C. The average relative humidity usually fluctuates between 10% and 80%. Periods of high rainfall

Table 1
Mix proportioning.

Mix	HRWR	Cement (kg/m ³)	Coarse Aggregate (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)	Silica Fume (kg/m ³)	Fly Ash (kg/m ³)	GGBS (kg/m ³)	Notes
1	0.4	340	1070	775	136	–	–	–	Type I
2		340	1070	775	136	–	–	–	Type V
3		320	1100	735	136	21	–	–	SF
4		255	1090	735	136	–	85	–	FA
5		100	1095	735	136	–	–	240	SC
6		340	1070	775	136	–	–	–	MCI at 0.6 L/m ³ of concrete
7		400	1070	775	136	–	–	–	CNI at 20 L/m ³ of concrete
8		400	1070	775	136	–	–	–	Caltite at 30 L/m ³ of concrete

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