

# Effect of Wet Curing Duration on Long-Term Performance of Concrete in Tidal Zone of Marine Environment

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**Abstract:** A proper initial curing is a very simple and inexpensive alternative to improve concrete cover quality and accordingly extend the service life of reinforced concrete structures exposed to aggressive species. A current study investigates the effect of wet curing duration on chloride penetration in plain and blended cement concretes which subjected to tidal exposure condition in south of Iran for 5 years. The results show that wet curing extension preserves concrete against high rate of chloride penetration at early ages and decreases the difference between initial and long-term diffusion coefficients due to improvement of concrete cover quality. But, as the length of exposure period to marine environment increased the effects of initial wet curing became less pronounced. Furthermore, a relationship is developed between wet curing time and diffusion coefficient at early ages and the effect of curing length on time-to-corrosion initiation of concrete is addressed.

**Keywords:** curing, diffusion, chloride, silica fume, service life, durability.

## 1. Introduction

The chloride-induced corrosion of the embedded steel has become the most common cause of loss of integrity and failure in concrete structures and infrastructures placed in the marine environment (Swamy 1988; Neville 2000; Radlińska et al. 2014; Pritzl et al. 2014; Ghassemzadeh et al. 2011). Hence, the chloride permeability has been recognized to be a critical intrinsic property of the concrete (Guneyisi et al. 2005, 2009), and a lot of research has been conducted to enhance concrete resistance to chloride permeability (Shekarchi et al. 2009).

From durability point of view, concrete cover quality plays significant role in blocking of aggressive substance ingress such as chloride ions into the reinforced concrete (Thomas 1991; Bonavetti et al. 2000). There are several methods to improve the quality of the concrete cover such as use of supplementary cementitious materials, reduction in water-to-cementitious materials ratio (w/cm), and appropriate initial

curing regimes (Neville and Brooks 1990; Ghassemzadeh et al. 2010). Although it is a very simple and inexpensive procedure, proper initial curing, prior to exposure to marine environment, has an important influence on improving concrete cover quality so that the concrete acting as a fine barrier to the access of aggressive species and accordingly extend the service life of reinforced concrete structures exposed to chloride (Alizadeh et al. 2008; Khatib and Mangat 2002; Khatib 2014; Radlinski and Olek 2015).

The objective of curing is considered by the duration of providing concrete with sufficient humidity and appropriate temperature conditions to reduce the loss of moisture to ensure the progress of hydration reactions causing the filling and segmentation of capillary voids by hydrated compounds (Guneyisi et al. 2005, 2009). On the contrary, drying of concrete particularly at the concrete surface, caused by a poor curing regime, leads to a restricted hydration and thus higher porosity and permeability in the surface layers which form covers for the reinforcement protections (Mangat and Limbachiya 1999; Khanzadeh-Moradllo et al. 2009).

The matter would be more critical in the case of concrete containing silica fume replacement because the pozzolanic reaction is, in general, very sensitive to the curing procedure (Toutanji and Bayasi 1999; Atis et al. 2005). According to the ACI 308 Recommended Practice (ACI Committee 308 1998), the curing period should be extended to 14 days when the cement contains supplementary cementitious materials, owing to the slow hydration reactions between supplementary cementitious materials and the calcium hydroxide. In addition, curing condition also could be an important parameter in controlling durability of the reinforced concrete in a harsh condition of the marine tidal zone

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prior to exposing to sea water, where the concrete cover is subjected to wetting–drying cycles.

A considerable volume of research has been conducted on different curing regimes and related effects on concrete properties. However, the effect of curing conditions on the chloride penetration into the concrete in real field condition at long term has not been well studied. Also, despite the importance of this object in Persian Gulf region, which is one of the high aggressive environments in the world, a few investigations were conducted in this region in long-term (Neville 2000; Shekarchi et al. 2009; Khanzadeh-Moradllo et al. 2012). In this regard, a comprehensive effort is accomplished in Construction Material Institute (CMI) to examine the short and long-term effect of curing regimes on durability of concretes located in Persian Gulf marine environment. The objective of this study is to investigate the effect of wet curing duration on chloride penetration in plain and blended cement concretes with 7.5 % silica fume which subjected to tidal exposure condition in Persian Gulf for 5 years.

## 2. Experimental Program

### 2.1 Materials and Mixture Proportions

The cementitious materials used in this study were Portland cement (PC) equivalent to ASTM Type II with a specific gravity of 3.14 and a fineness of 290 m<sup>2</sup>/kg, and silica fume (SF) obtained from Azna ferro-silicon alloy manufacture with a specific gravity of 2.20 and a specific surface area of 20,000 m<sup>2</sup>/kg. The chemical and physical properties of these materials are given in Table 1. The aggregates used were crushed limestone from Metosak plant and were graded according to ASTM C 33. The coarse aggregate had maximum size of 12.5 mm and specific gravity and absorption values of 2.79 and 1.9 %, respectively. The fine aggregate had specific gravity and absorption values of 2.59 and 3.2 %, respectively. The fineness modulus of fine aggregates was 3.2. Polycarboxylate ether polymer superplasticizer was used for the mixes in order to improve the workability of fresh concrete.

The concrete mixture proportions detailed in Table 2 were used to study the effect of curing on both normal Portland cement and silica fume concrete (labeled as NPC and SFC, respectively); w/cm ratio is 0.5 and cementitious material content 400 kg/m<sup>3</sup>.

The concrete mix proportions used in this study were not specifically chosen to meet the durability requirements given in Iranian National Code for concrete durability in Persian Gulf for the conditions of exposure used, but to provide concretes which would undergo a measurable amount of chloride penetration and deterioration in the short exposure periods used. Therefore, the results of this study may not be generalized for concrete made with a low w/cm. In addition, silica fume content of 7.5 % by weight of cement was used, because a previous study (Shekarchi et al. 2009) showed that there is an optimum silica fume content of 7.5 % by weight of cement beyond which additional silica fume does not produce additional benefits in line with the additional costs.

### 2.2 Casting and Curing of Concrete Specimens

The concrete mixture was prepared in the laboratory using a 0.1 m<sup>3</sup> countercurrent pan mixer. The fresh concrete was tested for air content (ASTM C 231), slump (ASTM C 143) and unit weight (ASTM C 138). Cubes of 150 × 150 × 150 mm and prisms of 150 × 150 × 600 mm in dimension were casted in steel molds and were compacted using a vibrating table. The 150 mm cubes were used for the determination of the compressive strength in accordance with DIN 1048, while the prisms were used to be tested for chloride penetration in the field. Properties of fresh and hardened concrete are summarized in Table 3. Five different curing procedures were applied on both cube and prism concrete specimens. All molds were covered with wet burlap for the first 24 h after casting. Concrete specimens were demolded after 24 h. Four of the five concrete prisms and their cube specimens were cured in water for 1, 3, 6, and 27 days labeled 1-D, 3-D, 6-D, and 27-D, respectively. The other one remained in ambient conditions of laboratory without moist curing at 40–50 % RH and 19–23 °C until exposure to seawater called 0-D for no-curing.

**Table 1** Chemical properties of binders.

Oxide composition % by mass	Cement	Silica fume
CaO	62.25	–
SiO <sub>2</sub>	21.22	93.16
Al <sub>2</sub> O <sub>3</sub>	4.68	1.13
Fe <sub>2</sub> O <sub>3</sub>	3.68	0.72
MgO	3.63	1.6
Na <sub>2</sub> O	0.25	–
K <sub>2</sub> O	0.75	–
SO <sub>3</sub>	1.74	0.05
L.O.I.	1.37	1.58

**Table 2** Details of the concrete mixtures.

code	Cement (kg/m <sup>3</sup> )	Silica fume (kg/m <sup>3</sup> )	w/cm	Water (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )	Fine aggregate (kg/m <sup>3</sup> )	Plasticizer (%)
NPC	400	0	0.5	200	956	778	1.2
SFC	370	30	0.5	200	959	784	1.2

**Table 3** Properties of fresh and hardened concrete.

Code	Density (kg/m <sup>3</sup> )	Air content (%)	Slump (mm)	Curing	Compressive strength (MPa)	
					7 days	28 days
NPC	2370	2.7	80	0-D	26.0	31.3
				1-D	30.0	36.6
				3-D	30.8	37.9
				6-D	33.5	39.0
				27-D	33.5	39.8
SFC	2355	1.6	65	0-D	26.0	37.1
				1-D	29.9	45.3
				3-D	32.9	51.4
				6-D	34.4	53.6
				27-D	34.4	55.2

### 2.3 Exposure Condition

Next, the investigated prism specimens which were located in Bandar-Abbas coast in south of Iran are sealed on four sides using epoxy polyurethane coating to ensure one-dimensional diffusion. The performance of this type of coating has been confirmed by previous studies (Khazadeh-Moradllo et al. 2012). Specimens were then subjected to tidal zone exposure condition in Persian Gulf for the entire period of investigation (60 months). Tidal exposure was situated at the about 2.2 m from sea level, so that concrete specimens were in contact with sea water for 12 h per day then they were exposed to dry condition (air) for rest of the day, simulating the tidal zone condition.

The Persian Gulf water is highly saline (Table 4) due to its enclosed condition (mostly surrounded by lands of Iran and Arabian Peninsula) and the high evaporation rate. Also, there are large fluctuations in daily and seasonal temperature and humidity regimes. Temperature can vary by as much as 30 °C during a typical summer day and relative humidity can range from 40 to 100 % within 24 h (Al-Amoudi and Bader 2001).

### 2.4 Sampling and Testing

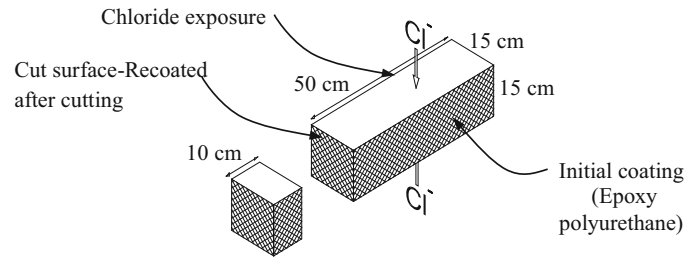
Sampling is carried out at the ages of 3, 9, 36, and 60 months of exposure in tidal zone. Each time, 100 mm

long prisms are cut from the end of the prism specimens (Fig. 1). The cut surface of the remaining part is coated and moved back to the exposure condition for future sampling. The 150 × 150 × 100 mm slices are taken to the laboratory in order to determinate the chloride penetration.

In the laboratory, a nominal 45 mm diameter core is taken from each slice to provide chloride concentration profiles. Each core is grinded in eight increments from the finished surface to an estimated depth of chloride penetration. The method used to estimate the chloride penetration depth was according to the procedure described by NordTest NT Build 492, which involves measuring the depth of color change of a freshly cut concrete surface in the direction of the chloride flow using 0.1 M AgNO<sub>3</sub> aqueous solution. Fine particles for chloride analysis are collected using a profile grinder parallel to the exposed surface according to NordTest NT Build 443 method with the accuracy of 0.5 mm at eight different depths. The first 1 mm fine particles are not included in calculations as it might be affected by actions such as washout, etc. The profile grinder and a grind hole are cleaned between depth increments to reduce the possibility of cross-contamination of samples from different depths. For each sample of concrete, fine particles are collected, the depth below the exposed surface is calculated as the average of six uniformly distributed measurements using a slide

**Table 4** Concentration of various ions in seawater at Persian Gulf.

Ion type	K <sup>+</sup>	Ca <sup>++</sup>	Mg <sup>++</sup>	SO <sub>4</sub> <sup>--</sup>	Na <sup>+</sup>	Cl <sup>-</sup>	Total salt
Concentration (ppm)	470	480	1600	3300	12600	23,400	41,850



**Fig. 1** Initial concrete prism specimens + cuts for laboratory tests.

caliper. The fine particles from each layer is collected and pulverized so that all the material will pass a 850- $\mu\text{m}$  (No. 20) sieve. At each depths, a sample having a mass of approximately 10 g is selected to the nearest 0.01 g and then analyzed for acid-soluble chloride content by the potentiometric titration of chloride with silver nitrate according with ASTM C 1152, and ASTM C 114, part 19. The cross-sectional area of a 45 mm diameter core is large enough to represent the concrete so that there is no need to be concerned about variations from sample to sample due to varying aggregate contents.

## 2.5 Chloride Diffusion Coefficient ( $D_c$ ) and Surface Chloride Content ( $C_s$ ) Calculation

The chloride penetration rate as a function of depth from the concrete surface and time can reasonably be represented by Fick's second law of diffusion according to following expression (Crank 1975):

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \quad (1)$$

The solution for Eq. (1):

$$C_{(x,t)} = C_s \left( 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D_c t}} \right) \right) \quad (2)$$

$$C_{(x,0)} = 0 \quad x > 0 \quad C_{(0,t)} = C_s \quad t \geq 0$$

where  $x$  is distance from concrete surface;  $t$  denotes time;  $D_c$  is diffusion coefficient;  $C_s$  is surface chloride concentration;  $C_{(x,t)}$  represents chloride concentration at the depth of  $x$  from the surface after time  $t$ ; and erf is the error function.

Fick's second law for one-dimensional diffusion, as shown in Eq. (1), is a special case of a more generalized model of diffusion where concrete is assumed to be a homogenous material; chloride concentration at the exposure surface is considered constant; no chemical or physical binding between the diffusing species and material occurs; and the effect of co-existing ions is constant. In other words, these limitations of analysis may be neglected as measured data are used for comparison purposes within the same set of exposure conditions. Also, the effect of other mechanisms of chloride ion penetration such as a capillary suction or sorption mechanism is not considered in this study.

Using a computer statistical analysis program, the non-linear regression is carried out on the experimental data and by curve fitting of solutions of Fick's second law of

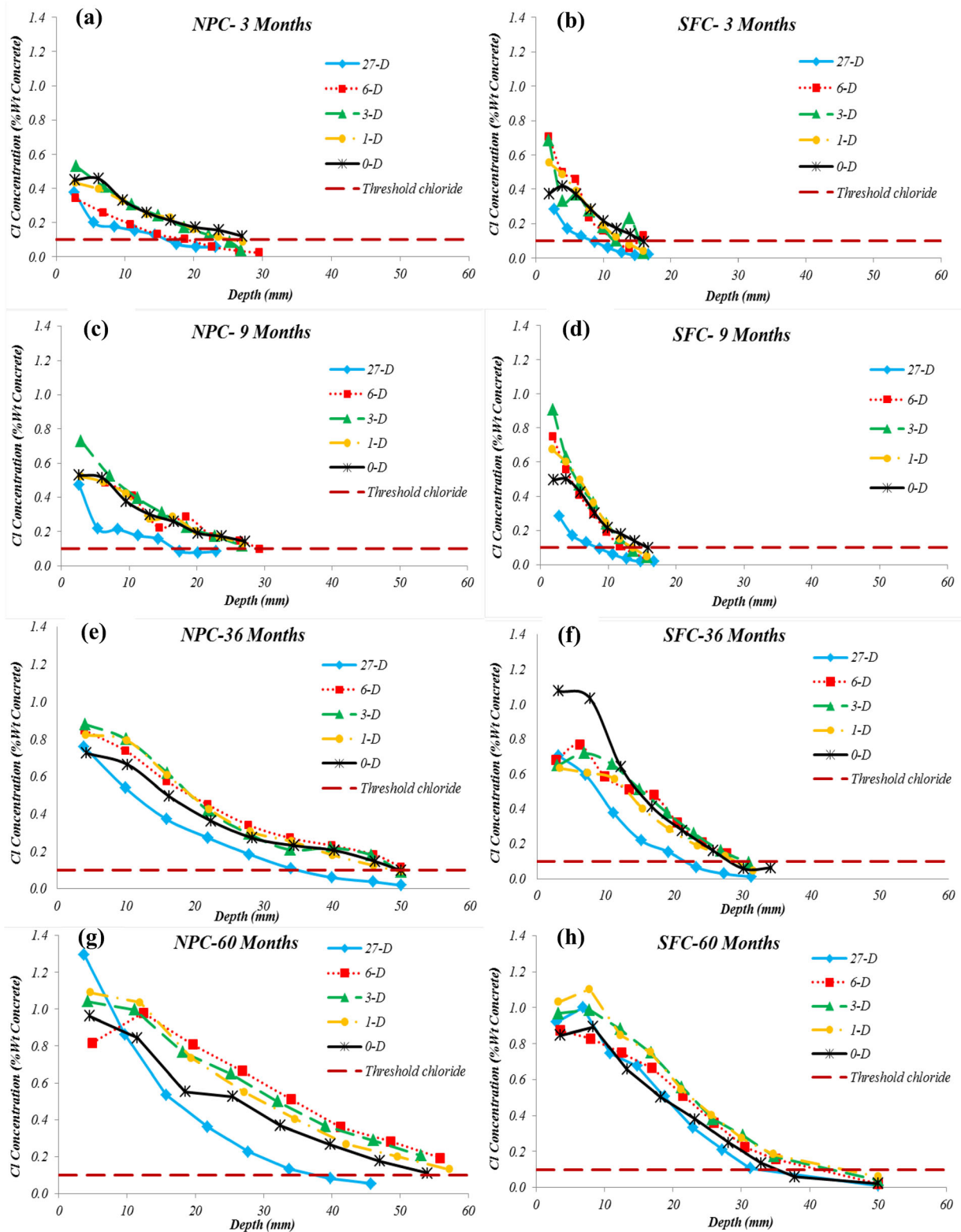
diffusion, the values of  $D_c$  and  $C_s$  in the Eq. (2) are determined. The curve fitting has been done in such a way that the chloride profiles are fitted where the correlation between the measured and fitted profiles has a maximum. Curve fitting has been performed in accordance with a procedure described in NordTest NT Build 443 and resulted in two regression parameters; Namely a diffusion coefficient and surface chloride content. For each specimen, at the time of testing, a single measurement of chloride concentration at each specified depth has been done and the diffusion coefficient and surface chloride build-up have been calculated accordingly.

## 3. Results and Discussion

### 3.1 Chloride Profiles at Varying Exposure Time

Chloride concentration profiles of the concrete specimens with different curing regimes which were placed in tidal zone at varying exposure time (3, 9, 36, and 60 months) are presented in Fig. 2. Based on Fig. 2a, it can be concluded that the 27-D and 6-D curing regimes present better performance to prevent chloride transmission into the concrete for NPC sample after 3 months exposure. While by a visual judgment it seems that extending the wet curing period till 3 days have not significantly improved the NPC sample performance against the chloride uptake. It is obvious from chloride profiles that there is a noticeable improvement in reducing chloride concentration is seen in 27 days wet cured SFC sample in comparison with the other curing regimes, especially in early ages. The less pronounced effect of wet curing in SFC until 6 days could be due to the micro filling or particle packing effect of silica fume which conceal the wet curing influence on chloride penetration. From Fig. 2b, d, it is noticeable that wet cured samples of SFC show a higher surface chloride concentration than the uncured sample at early ages which could be due to the higher level of chloride binding and sorptivity. Because, it is suggested that the higher hydration rate for the the pozzolanic action of silica fume results in the formation of a higher content of C-S-H phases. This, in turn, increases the physical chloride binding due to the relatively high surface area of the C-S-H (Beaudoin et al. 1990; Luping and Nilsson 1993; Dousti et al. 2011).

It is obvious from chloride concentration profiles during exposure time (Fig. 2) that the wet curing effect is time-dependent and its influence on chloride resistance diminishes in long-term irrespective of the concrete mixture. Further



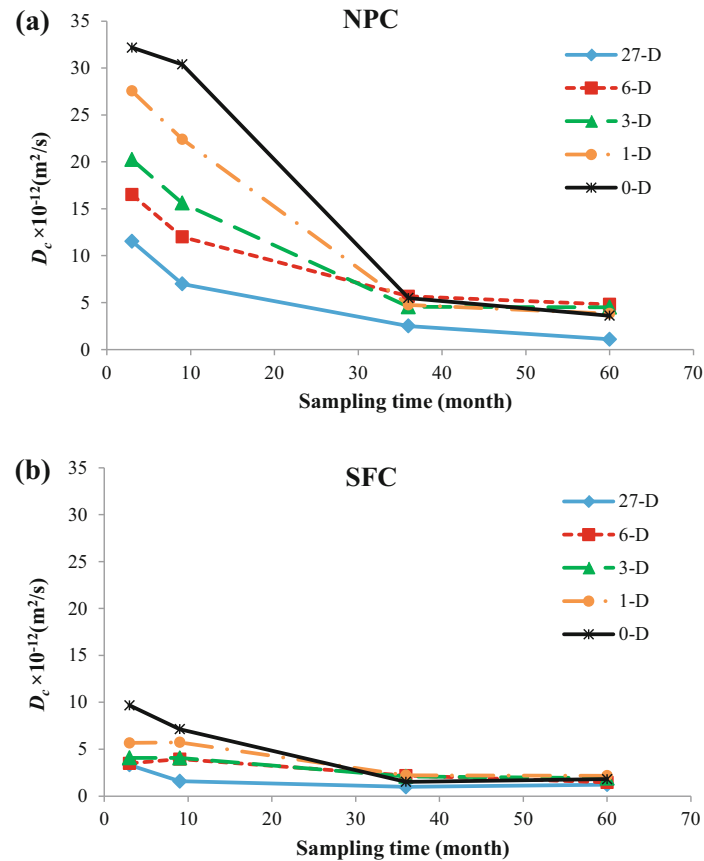
**Fig. 2** Chloride concentration profiles of concrete specimens with different curing regimes placed in tidal zone of Persian Gulf region at varying exposure time. *Note* chloride threshold value is assumed 0.1 % by weight of concrete for corrosion initiation (Thomas 1996; Pargar et al. 2007).

analysis is provided in following sections based on calculated diffusion coefficient and surface chloride content.

### 3.2 Chloride Diffusion Coefficient ( $D_c$ )

Diffusion coefficient changes, over time for different curing periods in tidal zone are presented in Fig. 3. From

results, it can be seen that extending the wet curing period has reduced the diffusion coefficient in comparison with no-cured sample in plain and blended specimens at early ages (3 and 9 months) as the same as previous studies (Guneyisi et al. 2007) that indicated long-term curing results in higher resistance to chloride permeability. But as the time goes on,



**Fig. 3** Diffusion coefficient values versus sampling time for different curing regimes in tidal zone: **a** NPC specimens, **b** SFC specimens.

this discrepancy reduces and the rate of diffusion coefficient diminishes too. This is thought to be due to the curing effects of the seawater masking initial differences (Thomas and Matthews 1990). Mohammed et al. (Mohammed et al. 2002, 2004) found that seawater causes a reduction in the pore volume or shifts the pore size to smaller pores at concrete surface.

According to Fig. 3, the differences in value of diffusion coefficient in various ages, especially between early and long-term ages, were notable in short-term curing regimes and non-curing, but this is not the case in 27 days curing. Indeed, as the curing time increases, the decreasing rate of diffusion coefficient upon time reduces while the microstructure of concrete improves and the ingress of chloride ions into the concrete diminishes in early ages. This reduction in early age diffusion preserves the concrete against high rate of chloride penetration at early ages. So the initiation time of reinforcement corrosion will delay and the service life of the structure will increase.

As it is shown in Fig. 3, with comparison of silica fume and plain specimens, it is found that the silica fume specimens have lower diffusion coefficient in all curing times which confirms that concretes containing silica fume exhibit improved chloride penetration resistance compared to those of plain Portland cement concretes.

With regard to the time dependent variation of chloride diffusion coefficient, following equation was employed to express the  $D_c$  as a function of exposure time:

$$D_c = at^b \quad (3)$$

where  $D_c$  is the diffusion coefficient ( $\text{mm}^2/\text{s}$ ),  $t$  is the exposure time (s), “ $a$ ” and “ $b$ ” are the regression parameters presented at Table 5.

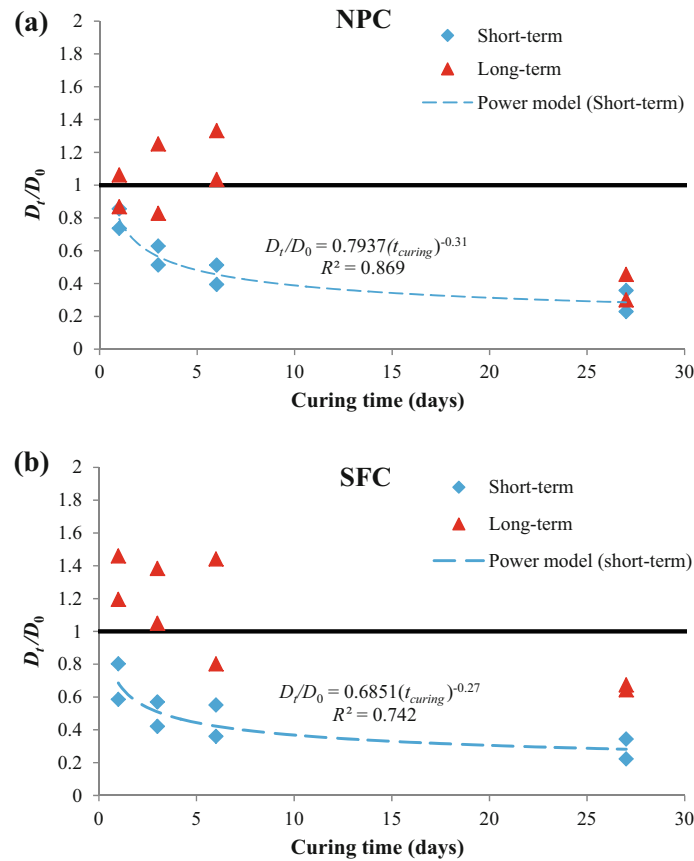
Based on Table 5, good correlation between  $D_c$  and exposure time is observed for all NPC and SFC samples with regression coefficients varying from 0.78 to 0.99. The model introduced in Eq. (3) can be employed to estimate the variation of chloride diffusion coefficient with time for different curing regimes. The fitted equation has also been incorporated in estimating the time-to-corrosion initiation which will be discussed in following sections.

### 3.3 Relationship Between Diffusion Coefficient and Curing Time

From the modeling point of view, the effect of curing conditions on the chloride diffusion coefficient has not been studied well (Alizadeh et al. 2008). To understand better the relationship between the curing time and a diffusion coefficient in short-term and long-term exposure periods,  $k_{curing} = D_t/D_0$  versus curing times are plotted in Fig. 4 for NPC and SFC samples in tidal zone, where  $D_0$  is the diffusion coefficient of no-cured concrete,  $D_t$  is the diffusion coefficient of wet cured specimen, and  $k_{curing}$  is the curing factor. As it is seen from Fig. 4, there is a power functional relationship between curing factor ( $k_{curing}$ ) and time of wet curing ( $t_{curing}$ ) at early ages:

**Table 5** Modeling the chloride ion diffusivity versus exposure time.

Curing	NPC			SFC		
	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
27-D	2.2991	-0.760	0.95	0.0008	-0.357	0.83
6-D	0.0165	-0.432	0.99	0.0005	-0.296	0.78
3-D	0.1863	-0.568	0.94	0.0004	-0.286	0.89
1-D	3.5321	-0.728	0.93	0.0026	-0.378	0.87
0-D	13.688	-0.797	0.90	0.3849	-0.659	0.91



**Fig. 4** Curing factor values versus curing time for different concrete mixtures in tidal zone: **a** NPC specimens, **b** SFC specimens.

$$k_{curing} = \alpha \times t_{curing}^{-m} \quad (4)$$

where “ $\alpha$ ” and “ $m$ ” are coefficients varying with concrete mixture design, which are determined for different concrete mixtures with implementing the nonlinear regression on the experimental data. The curing factor decreases with increasing the wet curing time for NPC and SFC samples in short-term ages (3 and 9 months), which represents the efficiency of wet curing period in reducing the diffusion coefficient. This decrease in diffusion coefficient is very sharp until curing time of 6 days, especially for SFC, while the curing factor decreasing rate significantly diminishes from 6 days to 27 days curing time.

Based on Fig. 4, there is no distinct relationship between  $k_{curing}$  and  $t_{curing}$  in long-term (36 and 60 months) and some of the curing regimes are not any more effective in reducing

the diffusion coefficient. A “ $k_{curing} = 1$ ” is considered as a efficiency boundary of curing regimes, where the wet cured sample acts similar to no-cured sample. According to results in long-term ages, a 27 days wet curing is the only curing regime which preserves its efficiency in reducing diffusion coefficient in both of NPC and SFC mixtures. As mentioned, this might be due to the curing effects of the seawater masking initial differences.

The results of long-term ages also imply that there is a slight increase in diffusion coefficient from a 0-D curing condition to the 6-D and 3-D in NPC and SFC samples ( $k_{curing} > 1$ ). William F. Perenchio observed the same trend between initial curing period and long-term drying shrinkage (Perenchio 1997). According to Perenchio’s suggestion (Perenchio 1997), it is possible that there is a pessimum initial curing time with respect to drying shrinkage or other

parameters which produces the greatest value for that parameter. This higher drying shrinkage might cause micro-cracks and respectively an increase in diffusion coefficient. More work is needed to further understand this behavior.

According to the European Union RC structures durability design guideline (The European Union 2000), it has been suggested to include a coefficient for curing in RC structures service life design in order to take into the account the effect of curing regime on concrete diffusion coefficient and service life. The European Union suggested values for curing factor are compared to observed values from this study in early age in Table 6. Based on Table 6, the European Union suggested values are about 20 % higher than the calculated values for NPC samples. This difference can be due to the variations in concrete mixture proportions and environmental factors.

### 3.4 The Influence of the Curing Time on Surface Chloride Content ( $C_s$ )

The time-dependent characteristic of the chloride content at a concrete surface is another significant parameter in predicting the chloride ingress at the depth of steel and the concrete structures service life (Ann et al. 2009). Therefore, the influence of curing conditions on surface chloride content is addressed in current study.

The surface chloride content versus an exposure time is plotted in Fig. 5 for different curing regimes in tidal zone. Surface chloride content data were scattered with increment of the curing time, there is no regular trend observed. The general trend of surface chloride shows its increment as the time goes on. The SFC specimens have more surface chloride content in comparison with NPC specimens in early ages as shown in Fig. 5, presumably due to the higher level of chloride binding and sorptivity. With increased chloride binding capacity, total chloride contents increase nearer the surface of the concrete, but decrease deeper in the concrete (Glass and Buenfeld 2000; Song et al. 2008). As discussed earlier, it is suggested that the higher hydration rate for the the pozzolanic action of silica fume results in the formation of a higher content of C-S-H phases. This, in turn, increases the physical chloride binding due to the relatively high surface area of the C-S-H (Beaudoin et al. 1990; Luping and Nilsson 1993; Dousti et al. 2011). As the time goes, the rate of surface chloride content increment is lower in SFC specimens in contrast to NPC specimens.

In addition, it has been observed that the linear build-up model can express the time dependent nature of the  $C_s$

(Khanzadeh-Moradillo et al. 2012; Sadati et al. 2015). The following equation was employed to express the  $C_s$  as a function of exposure time:

$$C_s = k \times t + C_0 \quad (5)$$

where  $C_s$  is the surface chloride content (% weight of concrete),  $t$  is the time (s), “ $k$ ” is the regression coefficient, and  $C_0$  is the earliest available measurement on surface chloride concentration; i.e. the measurement at 3 months.

Table 7 summarizes the regression coefficients. Based on Table 7, good correlation between  $C_s$  and exposure time is observed for all NPC and SFC samples with regression coefficients varying from 0.76 to 0.99. This indicates that a linear regression with the initial value is good representatives of the surface chloride ion build-up in tidal zone. This equation is proposed for further investigating the time-to-corrosion initiation of structures at following section.

### 3.5 The Influence of the Wet Curing Time on Time-to-Corrosion Initiation of Concrete Structures

The efficiency of the curing condition in preventing the ingress of chloride can be further emphasized by estimating time-to-corrosion initiation of concrete structures which subjected to different curing regimes. It is worth to mention that the concrete structure corrosion occurs in two steps, corrosion initiation time and corrosion propagation time (Morga and Marano 2015). The latter step is not considered in this study. The time-to-corrosion initiation is considered to be the time required for chloride ion concentration to reach to a certain threshold value at reinforcement cover depth. The regression results obtained for predicting the chloride ion diffusion and surface chloride build-up (Eqs. (3) and (5)) were incorporated to calculate the corrosion initiation time based on Fick’s second law of diffusion (Crank 1975):

$$C_{(x,t)} = (C_0 + kt) \left( 1 - \operatorname{erf} \left( \frac{x}{2 \times \sqrt{(at^b) \cdot t}} \right) \right) \quad (6)$$

where “ $a$ ”, “ $b$ ”, “ $C_0$ ”, and “ $k$ ” are the regression parameters presented at Tables 5 and 7. In this study the chloride threshold value is supposed to be 0.1 % weight of the concrete, based on previous studies (Thomas 1996; Pargar et al. 2007), and the thickness of concrete reinforcement cover is considered to be 50 mm. Therefore, Eq. (6) was solved for

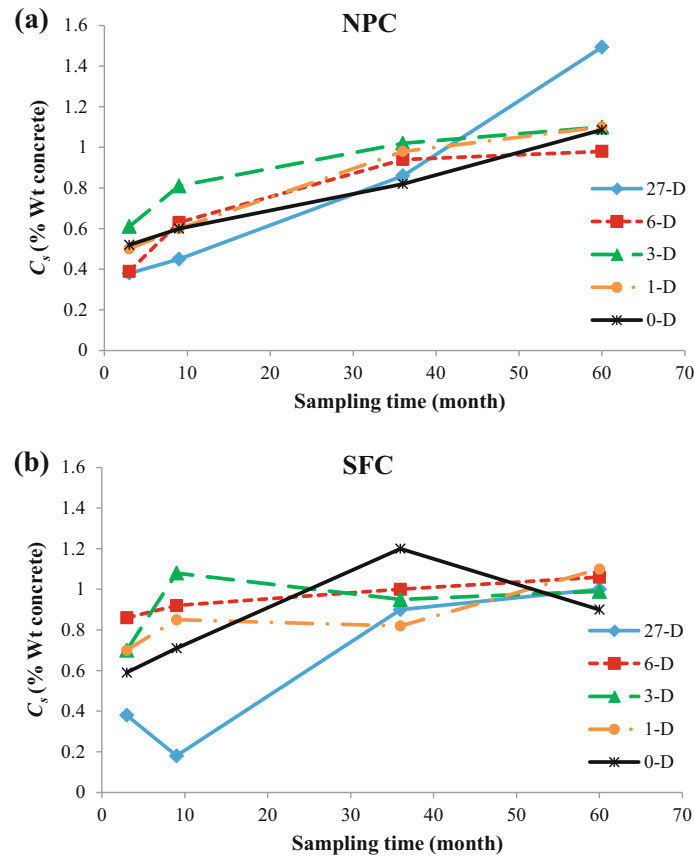
**Table 6** Curing factor for different curing conditions.

Curing condition	$k_{c,cl}$ * (NPC)	$k_{c,cl}$ (SFC)	$k_{c,cl}$ (The European Union 2000)
1 day wet curing	1.77	1.54	2.08
3 days wet curing	1.26	1.10	1.50
7 days wet curing**	1.00	1.00	1.00
28 days wet curing**	0.64	0.68	0.79

\*  $k_{c,cl}$  (curing factor for different curing regimes) =  $D_c$  (for correspondence curing)/ $D_c$  (7 days wet curing).

\*\* To compare curing factors, 6-D and 27-D curings are assumed equal to 7 and 28 days wet curings, respectively.





**Fig. 5** Surface chloride content values versus sampling time for different curing regimes in tidal zone: **a** NPC specimens, **b** SFC specimens.

**Table 7** Modeling the surface chloride concentration versus exposure time.

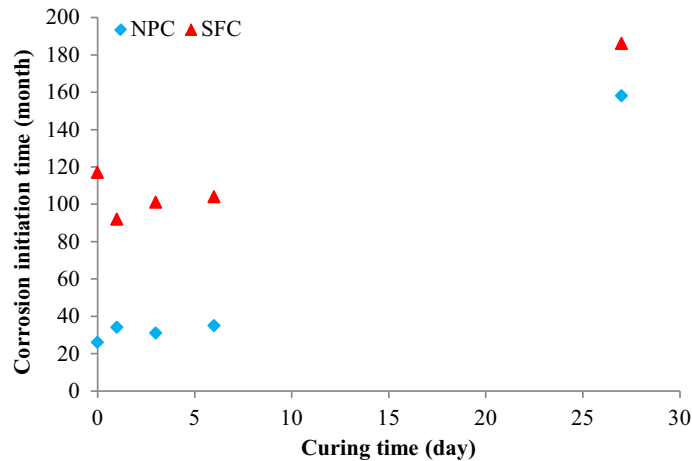
Sample	Curing	$k$	$R^2$
NPC	27-D	7.00E-09	0.95
	6-D	4.00E-09	0.79
	3-D	4.00E-09	0.83
	1-D	4.00E-09	0.95
	0-D	4.00E-09	0.99
SFC	27-D	4.00E-09	0.77
	6-D	1.00E-09	0.95
	3-D	2.00E-09	0.91
	1-D	2.00E-09	0.76
	0-D	6.00E-09	0.98

finding time-to-corrosion initiation ( $t$ ) corresponding to  $C_{(x,t)} = 0.1$  at  $x = 50$  mm for different samples.

An estimated time-to-corrosion initiation versus curing time for different mixtures are plotted in Fig. 6. Both plain and silica fume specimens show that 27 days wet curing causes tangible increase in time-to-corrosion initiation. It seems that no difference is observable between the time-to-corrosion initiation values of the curing times less than 6 days in both silica fume and plain specimens based on time dependent results from field. It might happen because of the availability of continuous capillary pores in concrete

specimens with less amount of wet curing (Shamim Khan et al. 1993; Zhang et al. 1999). Based on Powers et al. (1959), the approximate time required to produce maturity at which capillaries become discontinuous is approximately 14 days for concrete with w/c of 0.50. As explained earlier, microcracks due to drying shrinkage can also cause this phenomenon.

According to results, it seems that longer wet curing (27 days) provides high quality skin layer in concrete surface, and accordingly it plays significant role as a barrier to concrete inner depths in controlling chloride ions penetration



**Fig. 6** An estimated corrosion initiation time vs curing time for different concrete mixtures.

into the concrete specimens. These results are for the materials, mixtures, environmental conditions, and specifications used on this study.

#### 4. Conclusion

This study was conducted to investigate the effect of wet curing duration on chloride penetration in plain (NPC) and blended cement concretes with 7.5 % silica fume (SFC) and water-to-cement ratio of 0.5 which were subjected to tidal exposure condition in Persian Gulf for five years. Based on the test results, the major conclusions of this study could be summarized as follows:

- A wet curing extension decreases difference between initial and long-term diffusion coefficients due to improvement of concrete cover quality and blocking the ingress of aggressive substance in initial ages. This reduction in early age diffusion preserves concrete against high rate of chloride penetration at early ages.
- As the length of exposure period to marine environment increased the effects of initial wet curing became less pronounced. This might be due to the curing effects of the seawater which compensate for the differences observed in early age diffusion coefficient due to the duration of initial wet curing. In long-term ages, a 27 days wet curing is the only curing regime which preserves its efficiency in reducing diffusion coefficient in both of NPC and SFC mixtures.
- A power functional relationship is derived between curing factor ( $k_{curing} = D_t/D_0$ , where  $D_0$  is the diffusion coefficient of no-cured concrete,  $D_t$  is the diffusion coefficient of wet cured specimen) and time of wet curing ( $t_{curing}$ ) at early ages.
- The general trend of surface chloride shows its increment as the time goes on. The SFC specimens have more surface chloride content in comparison with NPC specimens in early ages presumably due to the higher level of chloride binding and sorptivity. But as the time

goes, the rate of surface chloride content increment is lower in SFC specimens in contrast to NPC specimens.

- Both plain and silica fume specimens show that 27 days wet curing causes tangible increase in time-to-corrosion initiation and service life of concrete structures. It seems that no difference is observable between the time-to-corrosion initiation values of the curing times less than 6 days in both silica fume and plain specimens based on time dependent results from field. It might happen because of the availability of continuous capillary pores in concrete specimens (w/c of 0.50) with less amount of wet curing.

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