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Full-Scale Marine Exposure Tests on Treated and Untreated Concretes—Initial 7-Year Results

by Sreejith V. Nanukuttan, Lulu Basheer, W. John McCarter, Des J. Robinson, and P. A. Muhammed Basheer

An extensive chloride profiling program was undertaken on concrete pier stems erected in the vicinity of the Dornoch Bridge located at the Dornoch Firth in Northeast Scotland. The pier stems were 2 m (6.562 ft) high and octagonal in plan with 0.66 m (2.165 ft) wide faces. The piers were constructed in sets of three with the lowest of each set in the tidal zone and the highest in the atmospheric zone. The pier stems were placed in such a way that they would represent the exposure conditions of the actual bridge piers of the Dornoch Bridge. In all, six of the pier stems were made using plain ordinary portland cement (OPC) concrete (with three of these having the surface treated with silane); the remaining three pier stems had a concrete containing caltite as an additive. Three exposure zones were studied: the tidal zone, the splash zone, and the atmospheric zone. The tidal zone was further subdivided into two levels defined as low-level and high-level. Chloride profiles were obtained from the different regimes over a period of 7 years for all nine pier stems. This paper describes the nature of chloride ingress and the usefulness of diffusion parameters in classifying each exposure regimes. Furthermore, the effectiveness of silane and caltite in protecting concrete from chloride ingress in different exposure zones was studied.

Keywords: chloride profiles; chloride threshold; coefficient of diffusion; surface treatments.

INTRODUCTION

Chloride-induced corrosion of reinforcement is one of the major causes of the premature deterioration of reinforced concrete structures. This situation is exacerbated for structures that are close to, or located in, a marine environment. When chlorides accumulate within the surface layer of concrete, a concentration gradient of chloride ions is established within the concrete cover with the result that chloride ions migrate toward the reinforcement in the concrete. For structures subjected to cyclic wetting and drying, chloride ions can also be absorbed by capillarity or move in and out of concrete by convection.¹ In fact, only in saturated (that is, submerged) concrete is the transport of chlorides due to pure diffusion. In other zones, such as the tidal and the splash zones, absorption is an additional transport mechanism² that facilitates chloride ingress. Chloride ingress by absorption only takes place within the top 5 to 10 mm (0.2 to 0.4 in.) layer;³ however, diffusion is the dominant transport mechanism responsible for chloride movement to greater depths within the cover zone.

Although the submerged zone has the greatest chloride penetration, it does not necessarily mean that this zone is at most risk from reinforcement corrosion. There may not be sufficient oxygen within the concrete in the submerged region to promote corrosion. In general, concrete in the splash zone is considered to be at greater risk due to the availability of oxygen and the concrete is often subjected to

several deterioration processes such as chloride ingress, freezing-and-thawing damage, abrasion, and erosion.⁴

It is recognized that to reduce or negate the ingress of water, and water containing dissolved deleterious ions, the permeability of concrete must be decreased. Engineers adopt several different approaches to achieve this end. One approach is the use of mineral admixtures such as slag cement or pulverized fuel ash as a partial replacement to the portland cement; another approach is the use of chemical admixtures and surface treatments to prevent water and ionic ingress; yet another approach is the use of fusion-bonded epoxy-coated or stainless steel reinforcing bars, although this is not the focus of the current study.

The work reported in this paper uses both an admixture (caltite) and a surface treatment (silane). Caltite⁵ is an ingredient that reverses the capillary wicking action; it also causes a physical, hydrophobic pore blocking effect when the concrete surface is subjected to hydrostatic pressure. As a result of these processes, it is reported that a nonabsorptive and moisture-impervious, inherently dry concrete will be obtained that will offer permanent protection against soluble salt and acid attack.

Silane, on the other hand, is a hydrophobic pore liner for concrete and has been in use for over two decades.^{6,7} When silane is applied to the concrete, it reacts with the hydrated cement particles and forms a hydrophobic layer on the pore walls. The hydrophobic nature of the pores then prevents or slows down the ingress of water and water-born ions into concrete. Silane permits the movement of water vapor through the pores and, therefore, allows the concrete to breathe. This helps the drying out of the concrete. Because moisture is required in the concrete for the movement of chloride ions by diffusion, this drying process will help slow down or even stop the movement of chloride ions within the concrete and hence protects the reinforcement bars from corrosion.

Although the effectiveness of silane in preventing or slowing down chloride ingress has been proven under laboratory conditions, its performance on real structures subjected to natural environmental action is not clear, especially under long-term exposure. Also, the performance of caltite in a long-term exposure test warrants investigating. Based on this, an investigation was carried out as part of the construction of the Dornoch Bridge located at the Dornoch Firth in Northeast Scotland (North Sea). Concrete piers were exposed to this marine environment and chloride concentration profiles and

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diffusion coefficients were obtained during a 7-year period. This work is discussed in this paper.

RESEARCH SIGNIFICANCE

Most of the reported durability studies on concrete have been carried out in the laboratory, mainly due to the difficulty in obtaining an actual site for carrying out the test. Also, site investigations can be more difficult to carry out compared with laboratory studies due to the location of the structure. Often, traffic restrictions will have to be in place and scaffolding will have to be provided for access to the test location. Laboratory studies are often carried out under ideal conditions,



Fig. 1—Showing location of nine piers at marine exposure site; at this location, North Sea contains approximately 19.8 g/L (0.0436 lb/L) of chloride ions.

Table 1—Mixture details for pier stems

Mixture	Cement, kg/m ³ (lb/in. ³)	20 mm, kg/m ³ (lb/in. ³)	10 mm, kg/m ³ (lb/in. ³)	Fines, kg/m ³ (lb/in. ³)	Plasticizer, L/m ³ (gal./ft ³)	Caltite, L/m ³ (gal./ft ³)	w/c	F ₂₈ , MPa (lb/in. ²)
Plain	460 (28.65)	700 (43.60)	350 (21.80)	700 (43.60)	3.6* (0.027)	—	0.4	66 (1.378 × 10 ⁶)
Caltite	460 (28.65)	653 (40.67)	327 (20.37)	770 (47.96)	5.52 [†] (0.041)	30 (0.225)	0.4 [‡]	44 (0.919 × 10 ⁶)

*Naphthalene formaldehyde-based plasticizer.

[†]Includes 24 kg water from 83% by volume of caltite.

[‡]Naphthalene formaldehyde-based high-range water-reducing admixture 1.3% by weight of cement.

often varying one factor and controlling other factors. Also, laboratory studies are normally short-term studies, mainly because of the manpower required for long-term studies and the expenses involved in it. Depending entirely on the short-term studies, bearing in mind concrete structures have a life expectancy of several decades, is a big compromise. In this light, site investigations are valuable to substantiate the findings from the laboratory study. Long-term site investigation results are not that widely available for silane treated and caltite concretes. Because this paper reports a 7-year study on test samples exposed to sea-side conditions similar to that of the Dornoch Bridge, which is in the vicinity, the results reported will be valuable to the durability research on reinforced concrete.

EXPERIMENTAL INVESTIGATION

Two meter (6.562 ft) pier stems were fabricated from the formwork used in the construction of the piers for the Dornoch Bridge and placed such that they would replicate the conditions in which the actual bridge piers would be subjected. A total of nine pier stems were placed in different exposure environments. Six pier stems were made using plain ordinary portland cement (OPC) concrete, three of which were treated with silane. The remaining three piers were left untreated and acted as a reference. An additional three pier stems contained the additive caltite.

Pier stem details

The concrete piers were manufactured using the mixtures reported in Table 1 and were placed on the east side of the southern causeway leading to the Dornoch Bridge, as shown in Fig. 1. The mixture specification for the OPC mixture was that used in the bridge piers for the Dornoch Bridge. The tops of the pier stems were sealed by casting an in-place layer of a polymer-modified mortar used as a waterproof render. The bases of the piers were also bedded onto a similar mortar. By taking this measure to prevent water and chloride ingress through the tops and bases of the pier stems, comparisons could then be made of the performance of the continuous, full height of the piers.

The pier stems were octagonal in cross section with each face being 0.66 m (2.165 ft); the reinforcement is identical to that used in the Dornoch Bridge piers and comprised a combination of 32 and 40 mm (1.28 and 1.6 in.) reinforcing in the form of a circular cage. The cover to the reinforcement varies due to the circular cage arrangement and the pier stems having an octagonal shape; this gave a minimum cover of 65 mm (2.6 in.) at the center of each face.

The silane treatment on the concrete was applied in accordance with the specifications defined in Reference 9. The sides of the pier stems facing the sea are denoted as the front faces (FF) and those away from the direct sea exposure are considered as the back faces (BF). A schematic showing the positioning of the piers, classification of the exposure

zones, and face referencing is presented in Fig. 2. The temperature variation at a depth of 10 mm (0.4 in.) within the cover was measured for a period of 16 months and is presented in Fig. 3.

With reference to Fig. 2, concrete samples were collected from the FF (Faces 1 and 2) and BF (Faces 5 and 6) of piers for all of the four different exposure zones. The samples collected were analyzed for their chloride content (acid soluble) according to British Standard 1881: Part 124,¹⁰ and the results were expressed as chloride content per percentage weight of cement.

Dust was collected using a drilling tool (30 mm [1.18 in.]) with depth increments of 0 to 5, 5 to 15, 15 to 25, 25 to 35, 35 to 45, 45 to 55, and 55 to 65 mm (0 to 0.2, 0.2 to 0.6, 0.6 to 1, 1 to 1.4, 1.4 to 1.8, 1.8 to 2.2, and 2.2 to 2.6 in.) from the surface. The drilling tool and drill hole were cleaned between depth increments to reduce the possibility of cross-contamination of samples from different depths. After drilling, the drill-hole was plugged with a polymer-modified mortar used as a waterproof render. On average, 400 to 500 samples were collected every 6 months. The details about the duration of exposure is given in Table 2. Drilling locations are indicated in Fig. 2.

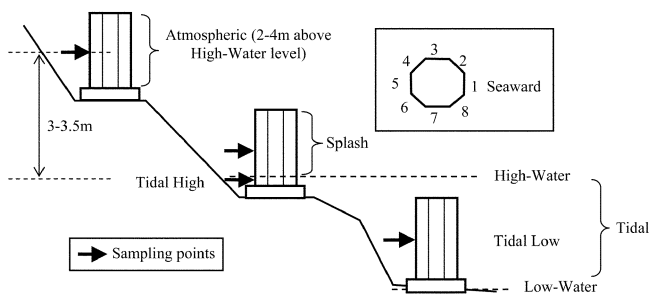


Fig. 2—Schematic figure showing positioning of piers.

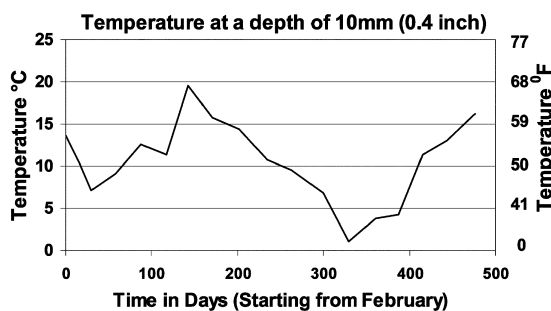


Fig. 3—Internal temperature recorded for 16 months.

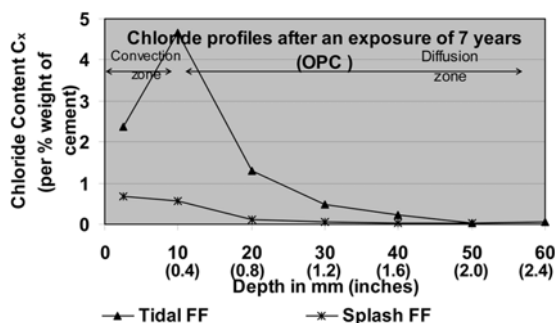


Fig. 4—Typical chloride profile for piers in tidal and splash zone.

RESULTS AND DISCUSSION

For each exposure condition, the total chloride content obtained from the dust samples was plotted against the corresponding depth to obtain a chloride profile that was later used for curve fitting (Fig. 4).

Andrade et al.¹¹ and Nilsson et al.¹² identify the curve fitting in two distinct zones: the convection zone and the diffusion zone. To obtain the parameters solely for diffusion, those points that are in the convection zone are eliminated from the fitting. Assuming the convection to be active only in the surface skin, all profiles were plotted with points starting from 10 mm (0.4 in.) deep onward. This should eliminate the effect of convection from the parameters obtained.

Table 2—Results from untreated OPC pier stems

Zone	Exposure duration, years	Front face		Back face	
		D_{ns} , $\times 10^{-12}$ m ² /s ($\times 10^{-12}$ ft ² /s)	C_s , % weight of cement	D_{ns} , $\times 10^{-12}$ m ² /s ($\times 10^{-12}$ ft ² /s)	C_s , % weight of cement
Tidal zone low level	1.17 (Year 1)	3.77 (40.56)	4.59	1.95 (21.98)	8.18
	1.67	1.67 (17.97)	6.77	2.52 (27.12)	6.64
	2.17	3.35 (36.05)	3.99	—	—
	2.67	2.07 (22.27)	4.82	—	—
	3.17	2.77 (29.81)	6.63	2.07 (22.27)	6.8
	3.67	2.24 (24.10)	4.28	1.9 (20.44)	5.61
	4.83	3.65 (39.27)	5.35	2.84 (30.56)	6.54
	6.17	2.21 (23.78)	7.19	2.78 (29.91)	7.09
	6.67	3.02 (32.50)	4.67	2.49 (26.79)	4.91
	7.17 (Year 7)	3.13 (33.68)	5.1	2.28 (24.53)	3.29
Tidal zone High level	1.17 (Year 1)	1.75 (18.83)	3.38	1.67 (17.97)	2.16
	1.67	1.29 (13.88)	5.27	2.47 (26.58)	3.14
	2.17	2.66 (28.62)	2.89	1.34 (14.42)	2.94
	2.67	1.37 (14.74)	3.96	3.05 (32.82)	2.37
	3.17	2.23 (23.99)	3.43	1.54 (16.57)	3.58
	3.67	0.56 (6.03)	2.86	0.84 (9.04)	1.32
	4.83	2.03 (21.99)	3.29	1.59 (17.11)	2.61
	6.17	0.93 (10.01)	4.28	1.94 (20.87)	3.19
	6.67	2.31 (24.86)	3.11	2.06 (22.17)	3.85
	7.17 (Year 7)	0.41 (4.41)	10.05	0.9 (9.68)	2.02
Splash zone	1.17 (Year 1)	5.41 (58.21)	0.16	1.64 (17.65)	0.32
	1.67	1.69 (18.18)	0.51	1.52 (16.36)	0.4
	2.17	1.28 (13.77)	0.61	1.19 (12.80)	0.31
	2.67	0.42 (4.52)	2.65	0.67 (7.21)	0.59
	3.17	1 (10.76)	1.38	0.79 (8.50)	0.9
	3.67	0.32 (3.44)	0.76	1.86 (20.01)	0.28
	4.83	0.83 (8.93)	1.44	1.02 (10.98)	0.78
	6.17	0.72 (7.75)	2	0.4 (4.304)	1.47
	6.67	2.04 (21.95)	1.73	1.08 (11.62)	1.12
	7.17 (Year 7)	0.29 (3.12)	1.5	0.37 (3.98)	0.42
Atmospheric zone	1.17 (Year 1)	—	0.06	—	0.05
	1.67	5.73 (61.65)	0.1	4.94 (53.15)	0.1
	2.17	1.31 (14.10)	0.29	2 (21.52)	0.13
	2.67	1 (10.76)	0.24	4.84 (52.08)	0.05
	3.17	0.62 (6.67)	0.68	1.4 (15.06)	0.2
	3.67	1.31 (14.10)	0.2	0.49 (5.27)	0.31
	4.83	0.32 (3.44)	0.53	0.38 (4.09)	0.21
	6.17	0.1 (1.076)	1.02	0.13 (1.4)	0.59
	6.67	0.88 (9.4688)	0.46	0.82 (8.82)	0.31
	7.17 (Year 7)	2.21 (23.78)	0.11	—	—

Both the surface chloride concentration C_s and the apparent diffusion coefficient D_{ns} were calculated from each of the modified profiles using the nonlinear curve fitting solution to Fick's Second Law (Eq. (1)) as described in NT-BUILD 443.¹³

$$C_C(x, t) = C_s - (C_s - C_i) \operatorname{erf}\left(\frac{x}{\sqrt{4D_{ns}t}}\right) \quad (1)$$

where $C_C(x, t)$ is the chloride concentration expressed in percentage weight of cement, measured at depth x at exposure time t ; C_s is the boundary condition at the exposed surface (surface chloride concentration); C_i is the background chloride concentration; x is the depth below the exposed surface (mm) (0.04 in.); D_{ns} is the apparent diffusion coefficient (m^2/s) ($10.76 \text{ ft}^2/\text{s}$); t is the exposure time in seconds (s); and erf is the error function.

A regression coefficient (R^2) was also obtained for each nonlinear curve fitting. This was later used to screen the reliability of the diffusion parameters, that is, if the R^2 value was ≤ 0.85 , results were not included for the study. Lower R^2 values were caused by two reasons. First, the lower level of

penetration of chloride in the splash and atmospheric zones results in lower C_C values compared with C_i values, and seemingly there can be fluctuation of data within a profile.

Chloride profiles

Spatial representation of the chloride content can be effectively used to compare the performance of different concretes in a given environment. Herein, the chloride profiles obtained in the case of two treated piers and an untreated pier are presented (Fig. 5 and 6).

For the silane and caltite pier stems, it is evident that the treatment had very little effect on the chloride penetration (Fig. 5) for piers in the tidal zone. Moreover, chloride penetration was higher for the silane treated concrete piers compared with the untreated piers after 7 years of exposure. The intermittent hydrostatic pressure induced by the seawater (a maximum head of approximately 2.0 m [6.56 ft] during each tidal cycle) would account for the ineffectiveness of silane at this location. Caltite, on the other hand, is an integral hydrophobic and pore-blocking ingredient that is dispersed throughout the entire volume of concrete. Whereas the hydrophobic action could, like silane, be rendered ineffective under hydrostatic pressure, the pore-blocking effect should

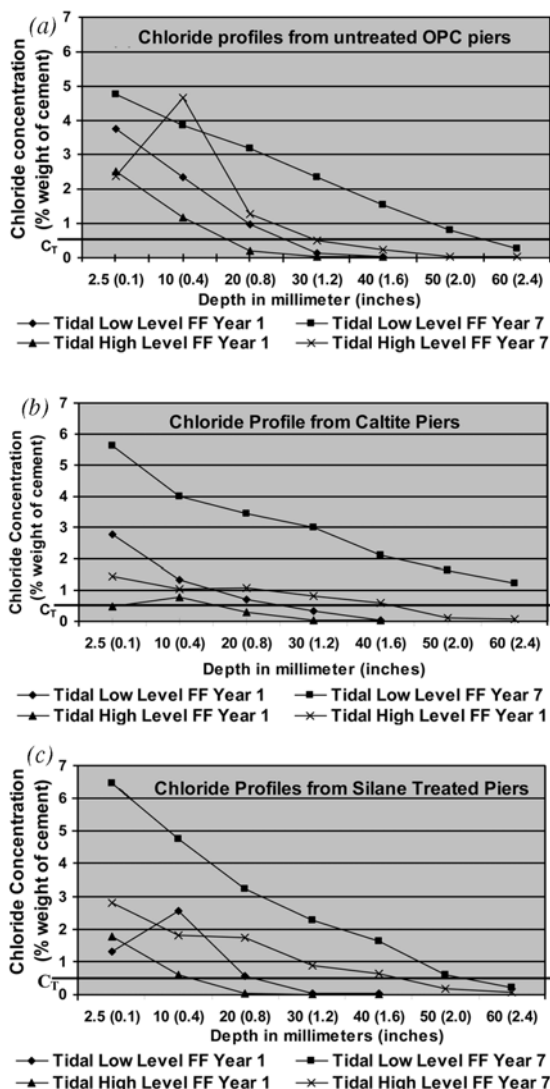


Fig. 5—Chloride concentration profiles for untreated and treated concrete in tidal zone.

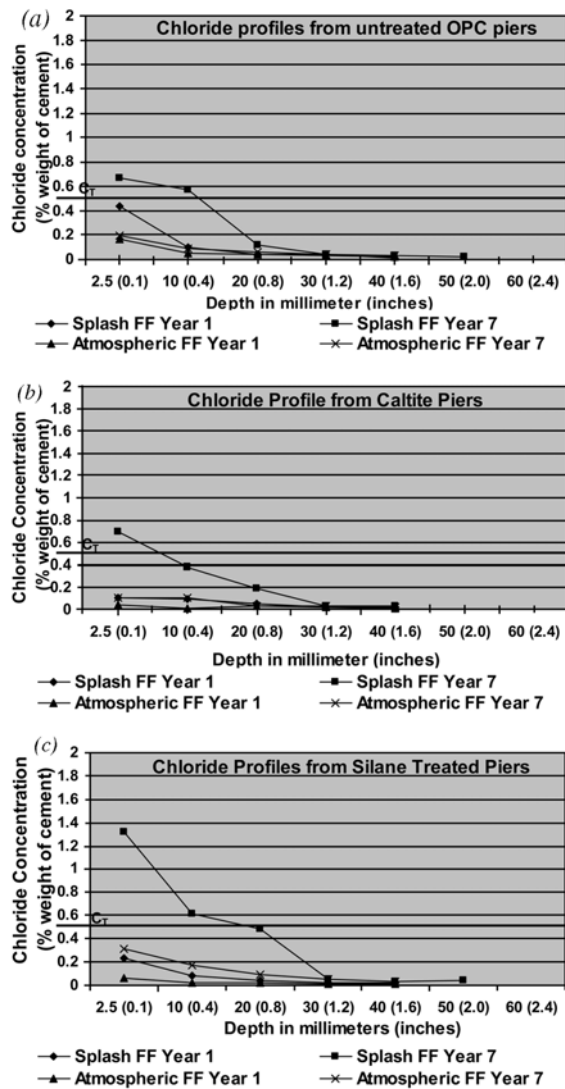


Fig. 6—Chloride concentration profiles for untreated and treated concrete in splash and atmospheric zone.

stop the ingress of seawater under pressure. Figure 5 clearly indicates that the latter mechanism is not working as chloride levels are similar to the untreated pier stem.

The case was different for pier stems in other zones (Fig. 6), where the penetration depth of chloride was lower and remained unchanged even after 7 years. The depth of penetration of chloride was more or less the same for treated and untreated piers at both splash and atmospheric zones. Although it seems that the caltite pier stems perform slightly better compared with both the silane and untreated piers.

Critical chloride level

The critical chloride level is defined as the chloride concentration occurring at the level of steel that results in depassivation, eventually leading to corrosion-induced deterioration. Critical chloride content or chloride threshold (C_T) is usually represented relative to the weight of cement.^{10,14} Other forms of expression such as chloride/hydroxyl ion ratios are also common.¹⁵⁻¹⁷ A review by Glass et al.¹⁸ revealed that the best way of expressing the chloride threshold is by total chloride content expressed relative to the

weight of cement. This represents all the potential chloride ions including those present in the bound form. For comparative purposes, a threshold value of $C_T = 0.5\%$ weight of cement is adopted in this paper¹⁹ as all the piers studied are either in an alternate wetting-and-drying cycle or in a moist environment.

The critical depth at which chloride concentration equals the threshold value is presented in Table 3. Piers in the tidal zone (low level and high level) recorded high levels of chloride concentrations compared with other exposure zones, irrespective of the treatments. As expected, the depth at which the critical chloride level was attained increased for the treated piers in the tidal zones after prolonged exposure.

For piers in the splash and atmospheric zones, chloride concentrations either failed to achieve the critical level or, if attained, it was limited to the surface skin (<20 mm [<0.8 in.] from the surface).

Diffusion parameters

The diffusion coefficients obtained during the exposure period for the different exposure regimes and types of concretes are shown in Fig. 7 and 8 (results related to the

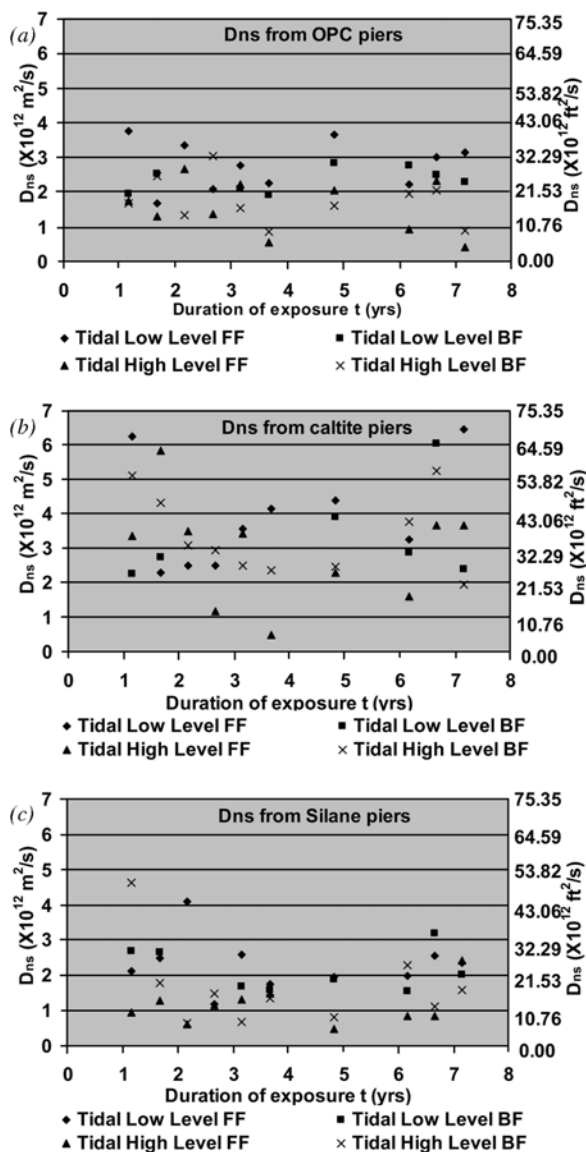


Fig. 7—Diffusion coefficients obtained from treated and untreated piers exposed to tidal condition (both front face [FF] and back face [BF]).

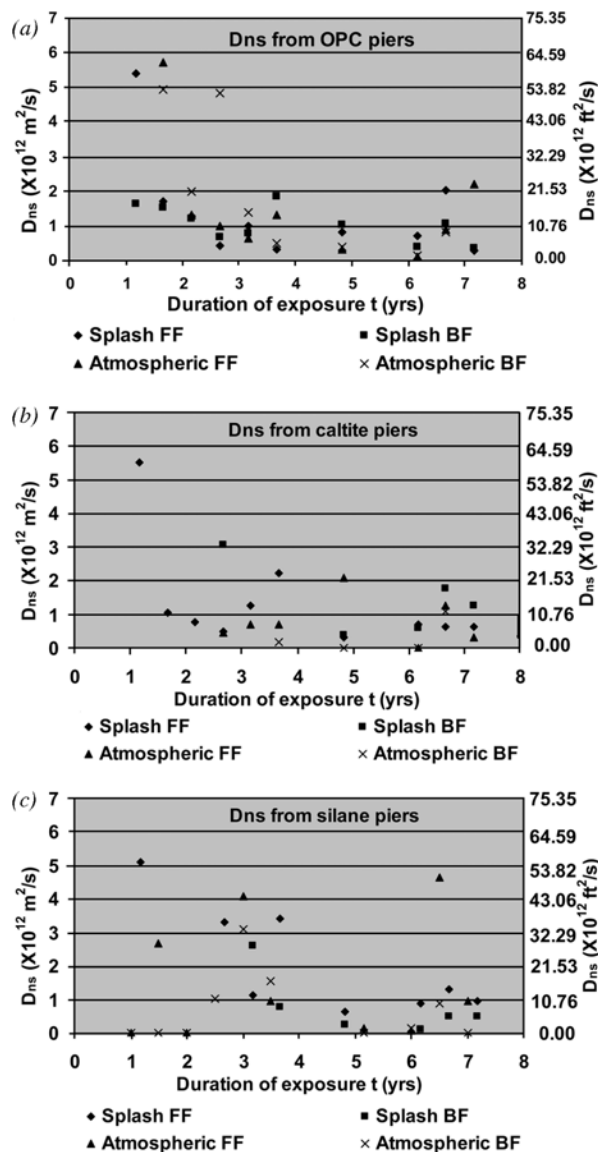


Fig. 8—Diffusion coefficients obtained from treated and untreated piers exposed to splash and atmospheric condition (both front face [FF] and back face [BF]).

untreated OPC pier stems are given in Table 2). Figure 7 presents the tidal zones, whereas Fig. 8 presents the splash and atmospheric zones. Considering Fig. 7, although the variations between diffusion coefficients at different periods are relatively high during the initial stages of the exposure, the trend becomes independent of the exposure duration after a period of time (Fig. 7(a) and (c)). Irrespective of the exposure

condition, the diffusion coefficient was similar, that is, in the range of $0.5 \times 10^{-12} \text{ m}^2/\text{s}$ ($1.6405 - 6.561 \times 10^{-12} \text{ ft}^2/\text{s}$) for untreated and silane treated concrete. In the case of the caltite pier stem, the coefficients followed a U-shaped trend (Fig. 7(b)) with time. For the pier stems in the tidal zone, the magnitude of the diffusion coefficients obtained were higher by a factor of 2 when compared with those obtained from the splash and atmospheric zones (Fig. 8).

Surface chloride concentrations obtained from the curve fitting are presented in Fig. 9. The amount of chlorides present at the surface is highest for tidal zone low level, followed by tidal zone high level, splash-zone, and atmospheric zone in decreasing order of magnitude. The magnitude of surface chloride concentrations were clearly dictated by the exposure conditions:

1. At the low level tidal zone, C_s was 4 to 6% weight of cement, which is six to ten times the concentration of the seawater. C_s values were similar for both treated and untreated piers.

2. At the high level tidal zone, C_s was 2 to 4% for the OPC pier stem and 1 to 3% for the silane treated and caltite pier stems.

3. In the splash and atmospheric zones, C_s was 0 to 2% for OPC pier stems and between 0 and 1% for the other pier stems.

For a given exposure environment, the surface chloride concentrations are relatively stable throughout the exposure period presented, irrespective of the surface treatments. This would appear to agree with results published by Bamforth et al.²⁰; however, 7 years of field study published by Andrade et al.²¹ reported an increase in surface chloride concentrations obtained. This cannot be the case, as there is always a specific maximum amount of chloride concentration that can be attained in a specific concrete. Exceptions can arise either due to climatic variations or due to temporary build-up by high tides.

CONCLUSIONS

Based on the results obtained from this case study, it can be concluded that:

1. The tidal condition, which is subjected to constant wetting and drying, recorded a high intensity of chlorides at every depth. The depth of penetration was negligible for piers in atmospheric zones where the presence of surface chlorides was relatively low;

2. Piers exposed to tidal conditions attained critical chloride threshold concentration throughout the skin layer (~50 mm [2 in.]) after 7 years of exposure;

3. The treatments studied did not perform well in cases where seawater continuously came in direct contact with the structure. Also, the treatments did not show any beneficial effect in either splash or atmospheric zone;

4. Diffusion coefficients followed a decreasing trend with duration of exposure, except for caltite piers in the tidal zone; however, the rate of decrease varied between the exposure conditions; and

5. Surface chloride levels increased steadily and then achieved a constant level for a given exposure regime and the magnitude of constant surface chloride levels was dependent on the exposure regime.

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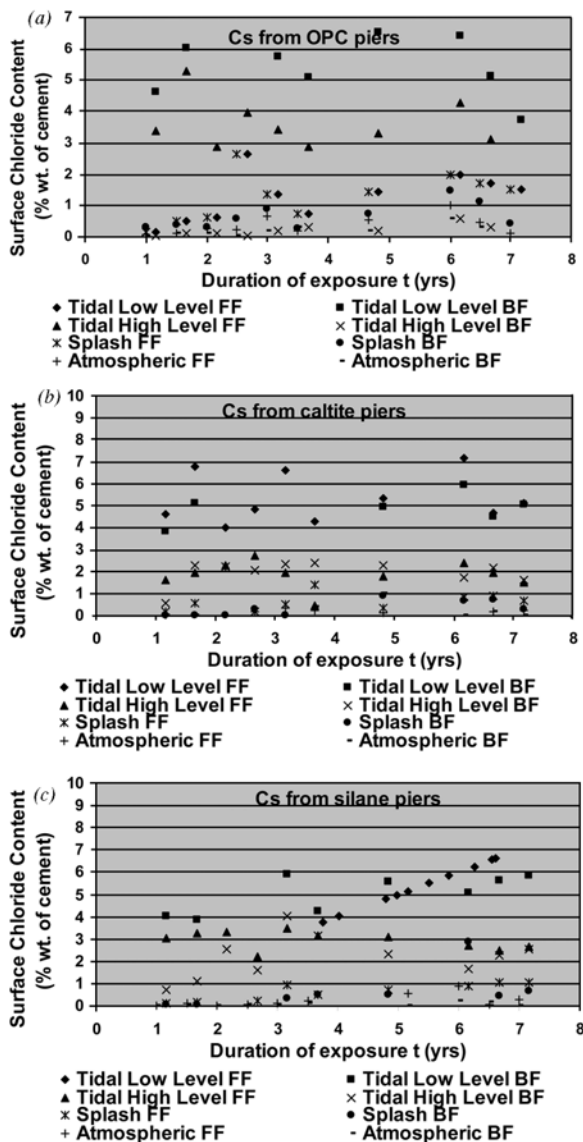


Fig. 9—Surface chloride concentrations obtained from treated and untreated piers exposed to all condition (both front face [FF] and back face [BF]).

Table 3—Depth at which chloride levels reached threshold concentration

Exposure regime		OPC, mm (in.)	Caltite, mm (in.)	Silane, mm (in.)
Tidal zone low level	Year 1	26 (1.04)	25 (1.00)	20 (0.80)
	Year 7	55 (2.20)	Higher	52 (2.08)
Tidal zone high level	Year 1	17 (0.68)	17 (0.68)	12 (0.48)
	Year 7	30 (1.20)	42 (1.68)	42 (1.68)
Splash zone	Year 1	Lower	Lower	Lower
	Year 7	12 (0.48)	7 (0.28)	20 (0.80)
Atmospheric zone	Year 1	Lower	Lower	Lower
	Year 7	Lower	Lower	Lower

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