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Premature concrete degradation due to rebar corrosion has many socio-economic implications of great significance. These include the direct costs of maintaining and repairing structures in service, as well as the indirect costs resulting from production losses and diminishing economic growth. Insufficient cover quality and cover depths are major causes of premature deterioration on new structures, however hydrophobic impregnation in the form of silanes may be used to reinstate the durability of the affected structures. The silane product adheres to the capillary pores in the concrete cover, making the pore surface water-repellent. This reduces the ingress of dissolved deleterious species (chlorides) and subsequently minimises the risk of reinforcement corrosion initiation. Based on bulk diffusion testing of various concrete types, the objective of this study was to evaluate and quantify the influence of silane impregnation as a remedial measure for poor quality or insufficient cover depth in newly constructed structures and ultimately predict the service life extension possible for specific cover depths. The treated concrete samples showed suppressed chloride ingress, and lower chloride surface concentration (C_S) and apparent chloride diffusion coefficient (D_a) were recorded. The overall results indicate that the time to corrosion initiation in reinforced concrete structures with inadequate cover depth and quality, of any binder type, can be functionally extended using hydrophobic (silane) impregnation, provided proper surface preparation and application methods are employed.

Keywords: Concrete durability; Chloride ingress; Bulk Diffusion; Silane impregnation; Corrosion initiation.

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Premature concrete degradation due to rebar corrosion has many socio-economic implications of great significance. These include the direct costs of maintaining and repairing structures in service, as well as the indirect costs resulting from production losses and diminishing economic growth. Insufficient cover quality and cover depths are major causes of premature deterioration on new structures, however hydrophobic impregnation in the form of silanes may be used to reinstate the durability of the affected structures. The silane product adheres to the capillary pores in the concrete cover, making the pore surface water-repellent. This reduces the ingress of dissolved deleterious species (chlorides) and subsequently minimises the risk of reinforcement corrosion initiation. Based on bulk diffusion testing of various concrete types, the objective of this study was to evaluate and quantify the influence of silane impregnation as a remedial measure for poor quality or insufficient cover depth in newly constructed structures and ultimately predict the service life extension possible for specific cover depths. The treated concrete samples showed suppressed chloride ingress, and lower chloride surface concentration (C_s) and apparent chloride diffusion coefficient (D_a) were recorded. The overall results indicate that the time to corrosion initiation in reinforced concrete structures with inadequate cover depth and quality, of any binder type, can be functionally extended using hydrophobic (silane) impregnation, provided proper surface preparation and application methods are employed.

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1. INTRODUCTION

Over the last few decades, premature degradation of reinforced concrete structures due to reinforcement corrosion resulting from chloride ingress has become a worldwide concern. With increasing demand for infrastructure and subsequent expansion of the built environment, there is greater need for new concrete structures to withstand and perform in corrosive environments. It is for this reason that designing for durability has gained significant attention from Engineers and other stakeholders in the construction industry [1].

The capacity for concrete to resist the penetration of deleterious species such as the water-soluble chlorides depends on the quality and depth of the concrete cover. Concerning cover quality, mix composition and construction procedures have a major influence and need to be carefully controlled [2]. There are various protective methods for reinforced concrete structures aimed at improving their durability properties. One of these methods relates to hydrophobic treatments, which assist in reducing capillary absorption of water, and thus reduce the diffusion of chloride ions and prolong the corrosion initiation phase [1, 3]. Hydrophobic (silane) impregnations provide water-repellent surfaces and are typically applied by spraying or brushing and are absorbed into the concrete by capillary action [4, 5]. Numerous studies have shown that silane impregnation can successfully be applied to reduce chloride ingress into the concrete cover, which is evident in a reduction of both chloride surface concentrations and chloride diffusion coefficients [6, 7, 8, 9, 10].

However, there is limited work on modelling the service life of silane treated concrete and the quantification of the effect that silane treatment has on chloride ingress. The motivation for this study was therefore to investigate by how much the time to corrosion initiation and hence the service life of reinforced concrete may be extended using hydrophobic impregnation. This included evaluating the performance of silane treatment as a remedial measure to inadequate cover depth or quality in aggressive environments. It must be noted that this study is applicable to newly constructed structures, on which the treatment is applied prior to chloride ingress; the repair of existing, already deteriorated structures was not considered explicitly. Furthermore, the effectiveness of silane impregnation can decrease with time due to UV radiation, thermal shocks, abrasion and carbonation [11,12]. Hence, the results presented in this paper are based on the presumption that the water repellent product is reapplied at regular time intervals (every 10-15 years) to ensure that the protective measure is sustained [5, 13].

2. METHODOLOGY

2.1. Mix composition and specimen manufacture

Concrete samples of two w/b ratios, 0.45 and 0.60 and four different binder types (CEM I 52.5N, Fly-ash (FA) at 30% replacement level, Ground granulated Corex slag (GGCS) at 50% replacement level, and CEM III/B 42.5N), resulting in 8 different mixes (Table 1) were cast. CEM III/B 42.5N, manufactured by ENCI Netherlands [14] and containing 66-

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Table 1:. Mix composition

Material (kg/m^3)	**Mix 1 CEM I**	**Mix 2 CEM I**	**Mix 3 30% FA**	**Mix 4 30% FA**	**Mix 5 50% GGCS**	**Mix 6 50% GGCS**	**Mix 7 CEM III/B**	**Mix 8 CEM III/B**
Water to binder ratio (w/b)	0.45	0.60	0.45	0.60	0.45	0.60	0.45	0.60
Cement (CEM III/B 42.5N)	-	-	-	-	-	-	411	308
Cement (CEM I 52.5N)	411	308	288	216	206	154	-	-
Extender (FA)	-	-	123	93	-	-	-	-
Extender (GGCS)	-	-	-	-	206	154	-	-
Fine aggregate	852	944	812	914	838	934	826	926
Coarse aggregate	1040	1040	1040	1040	1040	1040	1040	1040
Water	185	185	185	185	185	185	185	185
Total binder (kg/m^3)	411	308	411	308	411	308	411	308
Slump (mm)	70	60	90	65	75	60	70	70

80% Ground granulated Blastfurnace slag (GGBS), was included to make this research internationally relevant. A 19-mm local Greywacke was used as coarse aggregate. The fine aggregate consisted of a 50/50 blend of crusher dust (Greywacke) and dune sand.

Demoulding was performed 24 hours after casting, after which each of the specimens was covered with a plastic wrap. The specimens were then stored in a controlled environment maintained at a temperature of 23 + 2°C and relative humidity (R.H.) of 63 + 2%. The specimens were unwrapped after 7 days before being placed back in the aforementioned environment to cure in air until the age of 56 days.

One of the objectives of this work was to evaluate the effectiveness of hydrophobic (silane) impregnation as a remedial measure for poor quality (high penetrability) cover concrete. Hence, poor quality concrete was produced by exposing the concrete specimens to relatively high temperatures at early age (after demoulding) for 6 hours (Mix 2 - 80°C, Mix 4 - 50°C, Mix 6 - 50°C and Mix 8 - 30°C). Higher (80°C) and lower (30°C) temperatures were used with Mix 2 and Mix 8 respectively as poor quality concrete was not obtained at 50°C. A similar method was described in [15]. After that, the specimens were placed in a controlled environment maintained at 23 + 2°C and R.H. of 63 + 2% until the age of 56 days.

The hydrophobic impregnation product used in this work was Sikagard®-706 Thixo [16]. This is a silane-based cream that was applied to the specimens at 28 days. The product data sheet [17] specifies the application of 1-2 coats at a consumption of 200-300 g/m^2 per coat. Hence, a total consumption of 400 g/m^2 was used, representing the minimum specified amount. The mass of product was varied according to the area of concrete treated so that a constant consumption amount of 400 g/m^2 was used at all times. The treated specimens were placed back in the aforementioned controlled environmental room until the age of 56 days.

2.2. Experimental investigations

To characterise the pore structure and penetrability of the specimens, Oxygen Permeability Index (OPI) and Water Sorptivity Index (WSI) tests were performed [19-23], the results of which were already discussed in [18].

Impregnation depths were measured 28 days after silane treatment following the recommendations given in BS EN 1504-2 (2004) [24]. At a specimen age of 8 weeks, bulk diffusion tests were initiated, conducted in accordance with ASTM C1556 (2004) [25]. Six (3 treated/3 untreated) test specimens (100 mm cubes) were used per mix. An epoxy resin was applied to all the sides of the test specimens, except for the exposure surface, to ensure unidirectional chloride ingress. The samples were then immersed in 165g/L sodium chloride solution at 10 + 5 mm head for 80 days. The exposure was conducted in a controlled environment maintained at 23 + 2°C and 53 + 2% R.H. After the exposure period, the samples were taken out of the sodium chloride solution and sliced into increments of 2 mm and 5 mm for concretes with w/b = 0.4 and w/b = 0.65 respectively. These slices were further processed by pulverizing and milling to obtain powder samples of approximately 10 g. A potentiometric titrator was used to determine the acid soluble chloride ion content, i.e. total chloride content, in accordance with ASTM C1152 (2012) [26]. For each depth increment, the average value obtained from 3 specimens was used in the analysis.

3. 3. RESULTS AND DISCUSSIONS

3.1. Concrete material properties and silane penetration depths

The test results used to characterise the various concrete mixes, i.e. compressive strength and penetrability values, as well as silane penetration depths (as discussed in detail in [18]), are summarised in Table 2. The main mixes (Mix 1-8) achieved OPI values between 9.90 and 10.67, indicating a generally good to excellent concrete quality with regards to penetrability. The poor-quality mixes generally recorded lower OPI values relative to their respective controls, indicating that the treatment of these samples was successful in relation to producing concrete with potentially lower durability.

Silane penetration depths increased with increasing w/b ratios and reduced concrete quality, with "poor quality" mixes typically having noteworthy higher penetration depths, compared to their respective control samples. This was expected from previous studies [28, 29, 30]. Notably, silane penetration depths were found to be very closely related to the OPI values, as discussed in [18].

Silane treated concrete surfaces had significantly lower water absorption relative to untreated concrete, with treated samples hardly permitting any water ingress during the WSI test [18]. The results already discussed in [18] also suggest that the sorptivity of poor-quality concrete can be substantially improved through the application of silane impregnation. However, it must be emphasized that the resistance to capillary absorption is only increased within the impregnated layer; the remainder of the concrete is not affected in its properties.

3.2 Bulk diffusion

The chloride penetration profiles obtained in the bulk diffusion tests are shown in Figures 1 - 8. Three untreated and three treated

Table 2: Concrete properties and silane penetration depths

Mix no		Mix 1	Mix 2	Mix 2 (Poor)	Mix 3	Mix 4	Mix 4 (Poor)	Mix 5	Mix 6	Mix 6 (Poor)	Mix 7	Mix 8	Mix 8 (Poor)
Binder		CEM I	CEM I	CEM I	30% FA	30% FA	30% FA	50% GGCS	50% GGCS	50% GGCS	CEM III/B	CEM III/B	CEM III/B
w/b		0.45	0.60	0.60	0.45	0.60	0.60	0.45	0.60	0.60	0.45	0.60	0.60
f_c (28d) [MPa]		66.7	47.7	31.6	55.3	35.6	24.4	63.1	49.2	26.2	58.5	45.4	27.5
OPI	[log kOPI]	10.54	9.95	9.91	10.06	10.04	9.45	10.34	9.90	9.22	10.67	10.32	9.54
	Class[1]	Excellent	Good	Good	Excellent	Excellent	Poor	Excellent	Good	Poor	Excellent	Excellent	Good
Porosity (%)		9.0	11.9	12.3	9.5	10.9	12.8	7.3	8.8	12.0	7.7	9.8	14.4
Silane penetration [mm]		5.2	7.6	8.0	6.7	7.3	8.7	5.5	6.9	9.9	3.5	5.1	7.8

[1] Concrete durability classification (general quality indicator), according to South African experience and practice (OPI > 10.0: excellent; OPI 9.5 – 10: good; OPI < 9.5: poor) [27]

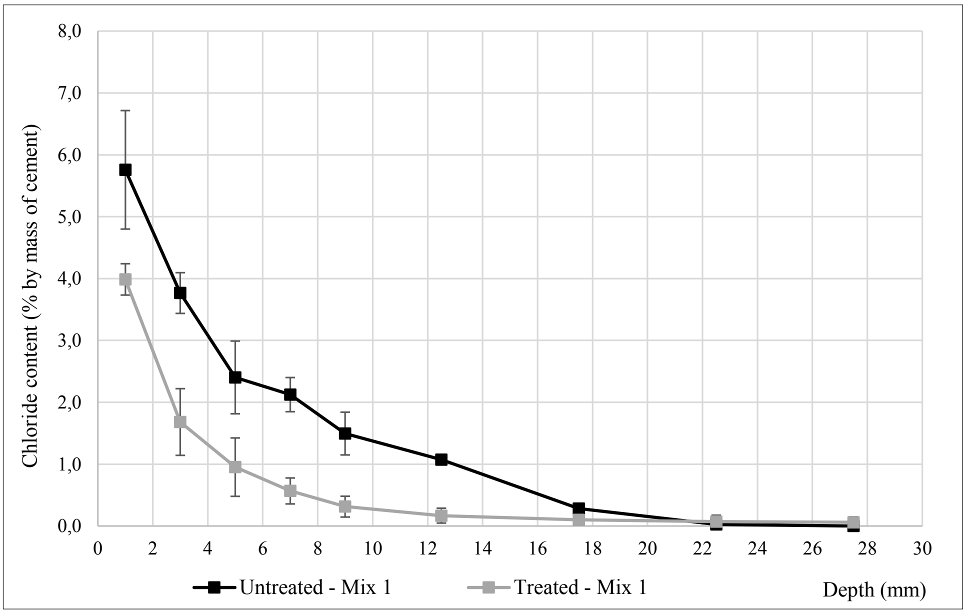

Figure 1: Chloride profiles, bulk diffusion test results, CEM I concrete (Mix 1).

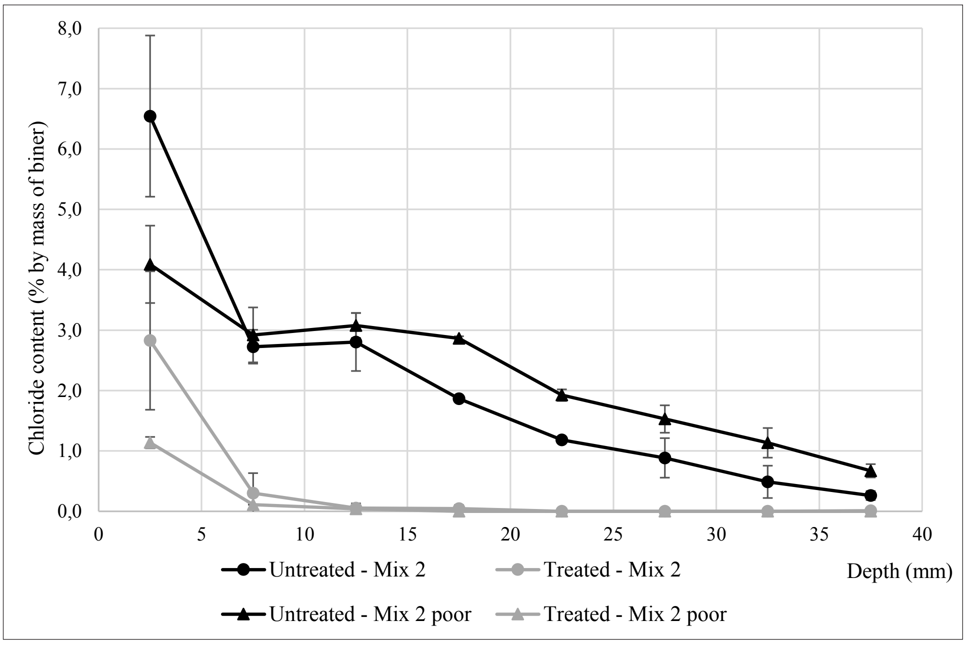

Figure 2: Chloride profiles, bulk diffusion test results, CEM I concretes (Mix 2 and Mix 2 Poor).

100 mm cubes were used per mix. The figures contain error bars indicating the STDV of the three specimens tested per depth increment. Owing to the overlap of the error bars, the influence of w/b ratio and binder type on the near surface concentration in the untreated mixes was not evident. Significantly less chloride ion ingress was noted in the lower w/b slag mixes (Mix 5, Mix 7). This is ascribed to the lower porosity and higher chloride binding capacity of the supplementary cementitious material [31, 32, 33]. Higher chloride penetration was noted in the poor-quality mixes relative to their respective control mixes, as expected [31, 34].

Generally lower near surface chloride concentrations were observed in the silane treated concrete due to lower capillary absorption. Chloride ion penetration in the silane treated samples was lower than in the untreated samples, and the effect was more apparent in the slag mixes. Considering the treated mixes with w/b = 0.45, the chloride penetration depth was approximately 20 mm, 22 mm, 5 mm and 2 mm in Mix 1 (CEM I), Mix 3 (FA), Mix 5 (GGCS) and Mix 7 (CEM III/B) respectively. For the treated mixes with w/b = 0.6 (main and poor quality), no significant chloride penetration was noted beyond 10 mm. As a consequence of the reduced chloride penetration into the concrete cover, the quantity of chloride ions available for diffusion deeper into the concrete would be lessened [8].

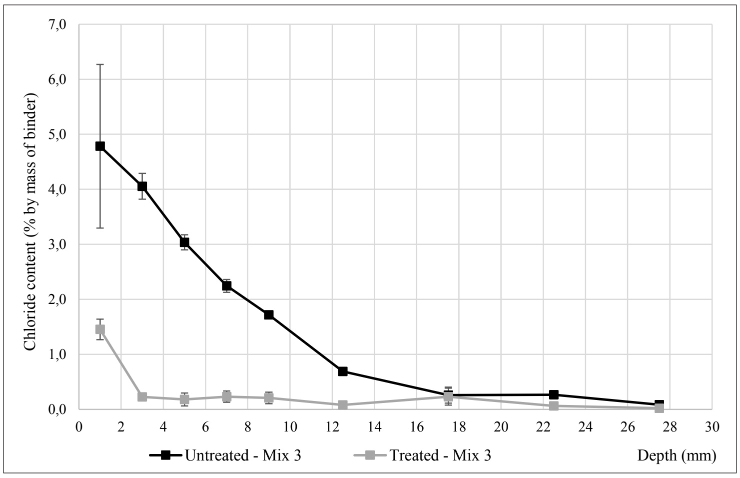

Figure 3: Chloride profiles, bulk diffusion test results, FA concrete, (Mix 3).

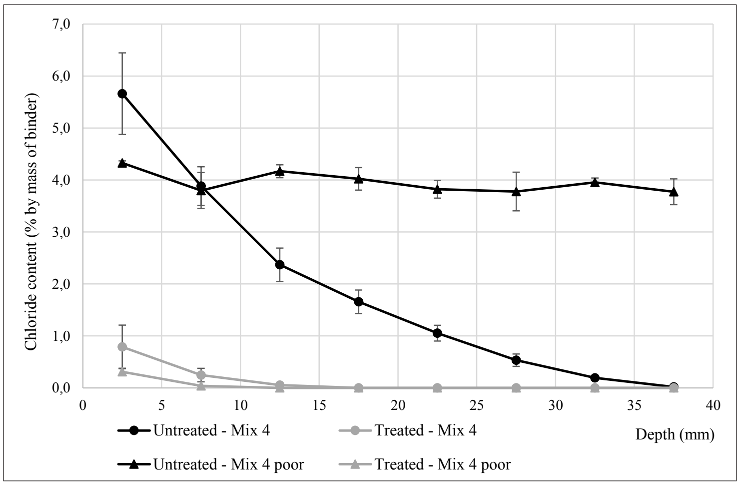

Figure 4: Chloride profiles, bulk diffusion test results, FA concretes (Mix 4 and Mix 4 Poor)

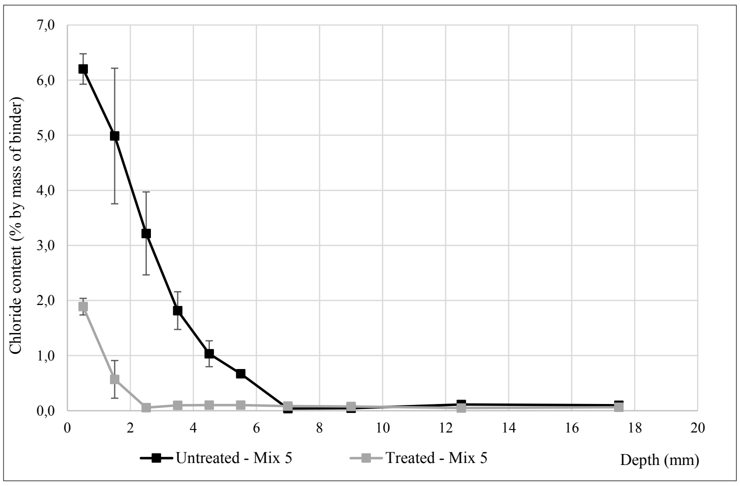

Figure 5: Chloride profiles, bulk diffusion test results, GGCS concrete (Mix 5).

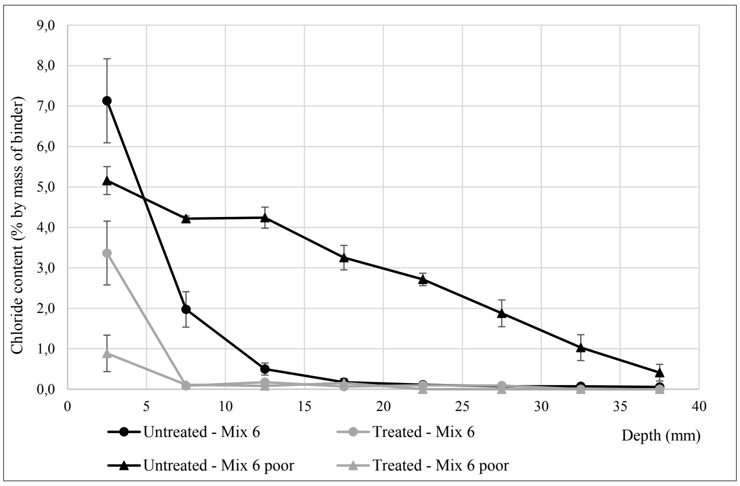

Figure 6: Chloride profiles, bulk diffusion test results, GGCS concretes (Mix 6 and Mix 6 Poor).

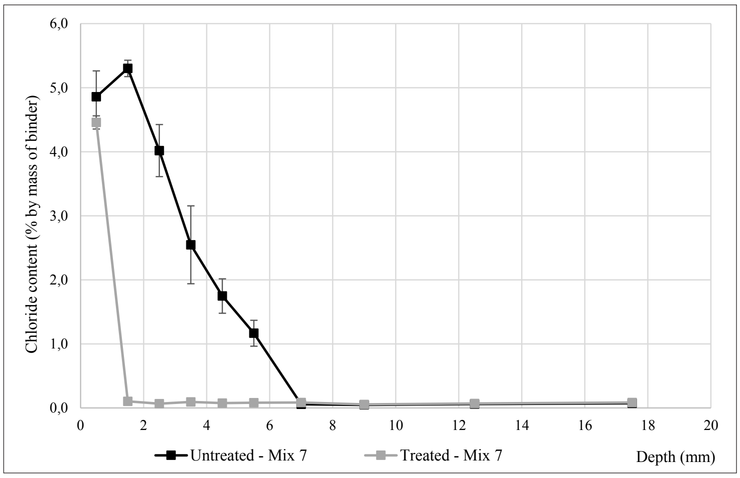

Figure 7: Chloride profiles, bulk diffusion test results, CEM III/B concrete, (Mix 7)

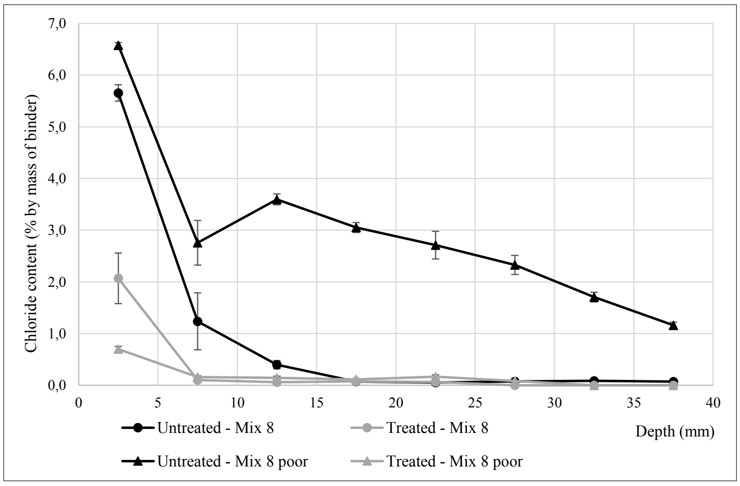

Figure 8: Chloride profiles, bulk diffusion test results, CEM III/B concretes (Mix 8 and Mix 8 Poor).

4. LONG-TERM MODELLING OF CHLORIDE INGRESS

4.1 Curve fitting (non-linear regression) of experimental data to obtain C_S and D_a

The chloride profiling data was curve-fitted (Figure 9) to the error function solution of Fick's second law of diffusion [35] to obtain two regression parameters (surface chloride concentration/C_s) and (apparent chloride diffusion coefficient/D_a) for the untreated and treated concrete mixes.

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4D_a t}}\right) \qquad (1)$$

where,

C (x, t) – chloride content at depth x (m) at time t (s)

C_s – surface chloride content (% by mass of binder)

C_i – initial chloride content (set to 0% by mass of binder)

D_a – apparent chloride diffusion coefficient (m2/s)

t – time (set to 80 days (in [s]), which is the duration of ponding with sodium chloride solution)

x – depth from the surface (m)

The results of the curve fitting are presented in Table 3. The surface chloride concentration was observed to increase with higher w/b ratios, which was mostly apparent in the GGCS and CEM III/B samples. Due to the overlapping results, the influence of the binder type on C_s was unclear. The poor-quality mixes generally recorded lower surface chloride contents relative to their respective control mixes. This is because the significantly higher diffusion coefficient (D_a/m^{2}s-1) of these mixes allowed chloride ions to diffuse deeper inside the concrete, thus reducing the chloride concentration at the surface [36].

Silane treatment generally reduced C_s values by about 50%-80%, compared to the respective untreated mixes, with the exception of Mixes 1, 2, 6 and 7, in which a reduction of 10%-20% was detected. The main reason for the reduction in C_s in treated samples is the reduction in absorptivity, as discussed earlier.

The apparent chloride diffusion coefficients (D_a) decreased with lower w/b ratios and the use of slag, as expected from the pore structure refinement and, in case of the slag mixes, chloride binding [32, 33]. The poor-quality concrete showed higher apparent chloride diffusion coefficients in comparison to their respective control mixes, which was also anticipated. The treated samples had significantly lower apparent chloride diffusion coefficient values than the untreated samples, with reductions ranging from 66% to 99% and only 3 mixes showing a reduction smaller than 80%. As the ingress of chlorides into the concrete cover is reduced, the quantity of chloride ions available for diffusion deeper into the concrete is minimised. Thus, the chloride profiles are steeper in silane treated concrete, which results in smaller diffusion coefficients. A higher percentage reduction in chloride diffusion coefficients was observed in the poor-quality mixes, which can be attributed to the higher penetration depths of the silane in these concretes.

4.2 Modelling of long-term chloride ingress in situ

The short-term chloride ingress characteristics (C_s and D_a) measured in the bulk diffusion test were used to predict long-term chloride ingress in concrete structures in the tidal/splash zone and atmospheric exposure zone, with the aim of quantifying the influence of hydrophobic treatments on the service life of reinforced concrete structures in marine exposure conditions.

The apparent chloride diffusion coefficients used in the predictions were those obtained by curve fitting the chloride profiling data to a solution of Fick's second law of diffusion, as discussed above. The time dependency of the diffusion coefficient D(t), taking into consideration the reduction of chloride diffusivity with time, is described by Equation 2 [29, 37].

$$D(t) = D_0 \left(\frac{t_0}{t}\right)^n \qquad (2)$$

where,

D_0 – diffusion coefficient (m^2/s) at a reference time t0 (set at 136 days (in [s]), which refers to the age at which the concrete specimens were tested for chloride content (profiling))

n – aging coefficient (reduction factor)

t – time (s)

The reduction factor (n) for various binder types and exposure conditions was obtained from literature [37, 38], as shown in Table 4. The reduction factor (n) can theoretically be affected by hydrophobic impregnation of concrete, however, to simplify the chloride ingress predictions, the same n value was used for untreated and treated concrete.

The chloride surface concentrations (C_s/%) used in the prediction of in-situ chloride ingress for the untreated concrete mixes were obtained from literature [39, 40], based on measured data from marine concrete structures and field exposed specimens (Table 4).

The hydrophobic treatment had an effect on the chloride surface concentrations measured in the bulk diffusion test, as discussed earlier. Generally, surface concentrations on treated samples were lower, compared to untreated samples made from the same concrete, as expected. It can therefore be assumed that the hydrophobic treatment also reduces C_s values in in-situ concrete structures. To account for this effect in the modelling of long-term chloride ingress in-situ, the surface concentrations in Table 4 were factored by the ratio (C_{st}/C_{su}) to calculate chloride surface contents for the treated concrete, where C_{st} and C_{su} are the extrapolated surface chloride concentrations (%) for the treated and untreated samples (obtained from curve fitting of experimental data) respectively.

4.3 Predicted time to reinforcement corrosion initiation

The predicted time to reinforcement corrosion initiation depends on the chloride ingress characteristics, quantified by C_s, D_a and the chloride threshold value for corrosion initiation. The latter was assumed to be 0.4% by mass of binder, corresponding to the threshold chloride content commonly used in service life modelling [41, 42, 43].

Table 3: Curve fitting results

			Untreated		Treated		% Reduction	
Mix number	**Binder**	**w/b**	**Cs (% by mass of binder)**	**Da (m^2/s)**	**Cs (% by mass of binder)**	**Da (m^2/s)**	**C_s**	**D_a**
Mix 1	CEM I	0.45	6.0	4.02E-12	5.1	1.09E-12	15	73
Mix 2	CEM I	0.60	6.6	1.77E-11	5.8	9.66E-13	12	95
Mix 2 Poor	CEM I	0.60	4.3	6.62E-11	2.2	1.08E-12	48	98
Mix 3	CEM I/FA	0.45	5.4	6.16E-12	2.4	2.64E-13	55	96
Mix 4	CEM I/FA	0.60	6.4	1.66E-11	1.2	2.81E-12	82	83
Mix 4 Poor	CEM I/FA	0.60	4.2	1.42E-08	0.6	1.28E-12	87	99
Mix 5	CEM I/GGCS	0.45	7.4	7.03E-13	3.2	1.03E-13	57	85
Mix 6	CEM I/GGCS	0.60	11.0	2.63E-12	8.6	6.30E-13	22	76
Mix 6 Poor	CEM I/GGCS	0.60	5.8	5.42E-11	1.6	1.57E-12	72	97
Mix 7	CEM III/B	0.45	4.9	1.35E-12	4.3	4.49E-14	11	97
Mix 8	CEM III/B	0.60	9.3	1.99E-12	4.7	7.86E-13	50	61
Mix 8 Poor	CEM III/B	0.60	5.6	6.51E-11	1.0	2.87E-12	82	96

Table 4: Ageing coefficients (n) for various binders and exposure class [37,38], and chloride surface concentrations (% by mass of binder) – adapted from [39,40]

Concrete type	**Tidal/splash zone (XS3)**		**Atmospheric zone (XS1)**	
	n	**Cs (%)**	**n**	**Cs (%)**
CEM I	0.4	4.0	0.6	2.00
CEM I with 30% FA	0.7	5.0	0.8	2.50
CEM I with 50% GGCS	0.45	6.0	0.65	3.00
CEM III/B (70% GGBS)	0.5	5.0	0.7	2.50

Chloride ingress in untreated and silane treated concrete was modelled using a modified mathematical solution to Fick's second law of diffusion [44, 45]:

$$C(x,t) = C - (C_s - Ci) \cdot erf\left(\frac{x}{\sqrt{4D_a\left(\frac{t_0}{t}\right)^n t}}\right) \qquad (3)$$

where,

C (x,t) – chloride content at depth x (m) at time t (s)

C_s – surface chloride concentration (% by mass of binder)

Ci – initial chloride content (set to 0% by mass of binder)

D_a – apparent chloride diffusion coefficient (m2/s) at reference time (t_0/s)

t_0 – age at testing (136 days/11750400 s)

t – time (s)

x – cover depth (m)

n – ageing coefficient

Hence by fixing the chloride concentration at depth (x/m) and time (t/s) to the critical chloride threshold (Ccr = 0.4% by mass of binder), initial chloride content to 0% by mass of binder, Equation 3 was rearranged to make the cover depth (x/m) the subject ofthe formula:

$$C_{cr} = C_s - C_s \cdot erf\left(\frac{x}{\sqrt{4D_a\left(\frac{t_0}{t}\right)^n t}}\right) \qquad (4)$$

$$x = erf^{-1}\left(\frac{C_s - C_{cr}}{C_s}\right) \cdot \sqrt{4D_a\left(\frac{t_0}{t}\right)^n t} \qquad (5)$$

The identified values for C_s, D_a and ageing coefficient (n) for each mix, as presented above, were incorporated into Equation 5 to obtain the penetration depth of the critical chloride content (0.4% by mass of binder) with time. For typical construction projects in South Africa, concrete mixes with a w/b ratio of around 0.45 would be used in extreme marine exposure conditions (tidal/splash zone /XS3), while more conventional mixes with a higher w/b ratio of around 0.60 are typically used under less severe exposure conditions (atmospheric zone/ XS1). Hence, the results obtained in this research for mixes with w/b ratios of 0.45 and 0.60 were utilized in the prediction of chloride ingress in the tidal/splash (XS3) and atmospheric (XS1) zones respectively.

Figure 9 shows the predicted time to corrosion initiation, in relation to cover depth, for all specimens of w/b ratio = 0.45 (Mixes 1, 3, 5, and 7), which were modelled for tidal/splash zone exposure. Rapid chloride penetration was predicted in the first 20 mm depth of the untreated concrete mixes within the first few years, regardless of the concrete type, as indicated by the initially very steep curves.

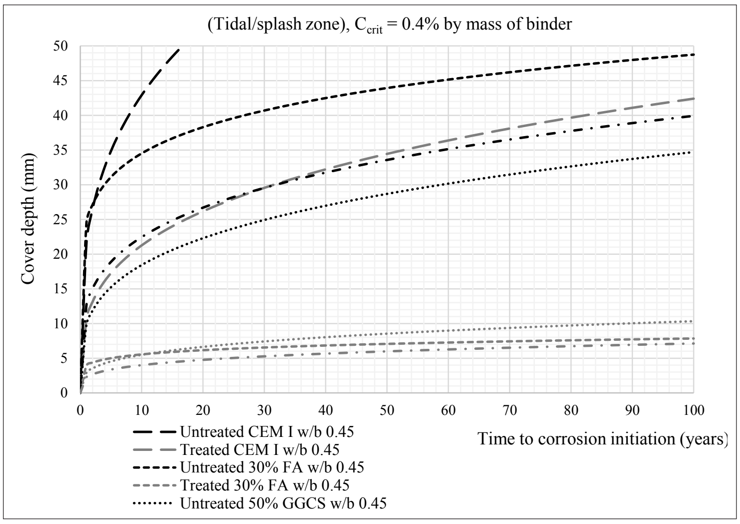

Figure 9: Time evolution of the critical chloride threshold for all mixes with w/b = 0.45, tidal/splash zone.

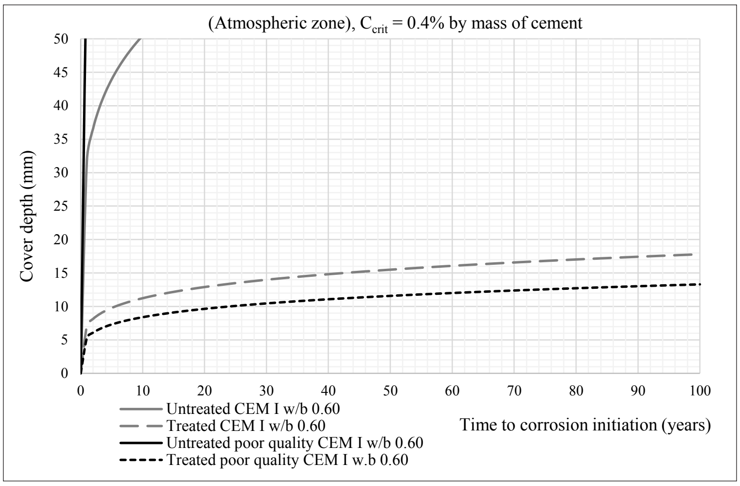

Figure 10: Time evolution of the critical chloride threshold for CEM I mixes, w/b = 0.60, atmospheric exposure zone.

The chloride diffusion coefficient, which is influenced by the continuous cement hydration reactions that decrease capillary porosity decreases with time, yielding a corresponding decrease in the rate of chloride ingress. Figure 10 shows an example (Mix 2) of the predicted time to corrosion initiation, in relation to concrete cover depth, for specimens with a w/b ratio of 0.60, including the poor-quality version, which were modelled for atmospheric exposure. The critical chloride threshold (0.4% by mass of binder) reached 50 mm within only a few years in all untreated poor-quality concrete mixes. These results indicated that relatively large cover depths are necessary to have any useful service life (initiation period), suggesting that the untreated poor-quality concrete mixes were unsuitable from a durability perspective.

Chloride ingress also occurred rapidly in the treated main and poor-quality concrete mixes. However, the predicted depth at which the critical chloride threshold is attained after the first few years is limited to 5-10 mm. For the same time to corrosion initiation, lower cover depths are required using silane-impregnated concrete. Better performance

Table 5: Time to corrosion initiation in relation to different cover depths

Exposure class	Mix no	Time to corrosion initiation (years)							
		cover 20 mm		cover 30 mm		cover 40 mm		cover 50 mm	
		Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
Tidal/splash (XS3)	Mix 1	<1	8	3	30	8	79	17	>100
	Mix 3	<1	>100	4	>100	25	>100	>100	>100
	Mix 5	13	>100	56	>100	>100	>100	>100	>100
	Mix 7	6	>100	30	>100	96	>100	>100	>100
Atmospheric (XS1)	Mix 2	<1	>100	<1	>100	3	>100	10	>100
	Mix 2 Poor	<1	>100	<1	>100	<1	>100	<1	>100
	Mix 4	<1	>100	<1	>100	13	>100	>100	>100
	Mix 4 Poor	<1	>100	<1	>100	<1	>100	<1	>100
	Mix 6	7	>100	70	>100	>100	>100	>100	>100
	Mix 6 Poor	<1	>100	<1	>100	<1	>100	<1	>100
	Mix 8	42	>100	>100	>100	>100	>100	>100	>100
	Mix 8 Poor	<1	>100	<1	>100	<1	>100	<1	>100

was achieved (lower rate of chloride ingress was predicted) in the treated poor-quality mixes compared to their respective treated control mixes, which was a result of the higher silane penetration depth in these mixes.

Table 5 summarises the time to corrosion initiation (years) for different cover depths (20 mm, 30 mm, 40 mm and 50 mm). Hydrophobic (silane) impregnation can effectively increase the time to corrosion initiation regardless of the binder type, water to binder ratio (w/b), and degree of curing. The increase in the initiation period due to silane treatment is more noticeable in the case of low cover depths (20 mm) compared to high cover depths (50 mm).

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5. CONCLUSIONS

The following are the main conclusions that were drawn from the results of this work:

- Silane penetration was observed to be deeper in the concrete mixes of higher w/b ratios and poor quality and therefore showed a strong dependency on the porosity and relative humidity of the near surface zone. The penetration depth of the silane product in the various concretes was noted to correlate to the respective oxygen permeability index values.
- Silane impregnation substantially reduced water absorption, which explains the lower chloride surface concentrations measured in treated concrete.
- The apparent chloride diffusion coefficients (Da), obtained from chloride profiling, were significantly lower for all treated concrete mixes, relative to the control mixes.
- The hydrophobic treatment considerably reduced chloride ingress in all concrete mixes tested. The improvement in chloride ingress resistance was most pronounced in concretes of lower quality, i.e. concrete with higher w/b ratios and poorly cured concrete.
- With regards to chloride ingress, silane-treated concrete samples with higher w/b ratios of 0.60 significantly outperformed untreated concretes made from the same binder type but with lower w/b ratios of 0.45.
- In practice, the results indicate that the time to corrosion initiation in reinforced concrete structures with insufficient cover quantity and quality, of any binder type, can be effectively extended by silane impregnation, providing that proper surface preparation and application methods (regular maintenance and reapplication of the water repellent product after every 10-15 years) are employed. This study can help the various stakeholders to make informed decisions on the use of hydrophobic impregnation as a measure to reinstate the durability of newly constructed structures in the marine environment that failed to achieve necessary cover depth or cover quality. **CB**

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