# Long-term performance of surface impregnation of reinforced concrete structures with silane

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**ABSTRACT**

Silanes can act as hydrophobic pore liners for reinforced concrete (RC) structures. They can significantly reduce the depth of chloride penetration, a major cause of steel reinforcement corrosion. However, there is little published information on their long-term performance. Thirty two concrete cores were extracted from eight full-scale RC bridge supporting cross-beams that were treated with silane 20 years ago. Their water absorption by capillarity was measured and compared with sixteen control cores extracted from four non-silane treated RC cross-beams constructed at the same time. Results show that silanes may provide a residual protective effect against water even after 20 years of service.

**Keywords**

Reinforced concrete; silane; hydrophobic treatment; impregnation; durability; capillary; absorption

## 1. INTRODUCTION

Concrete is a naturally porous material. The size and distribution of pores in concrete varies and depends on the constituent materials, quality of compaction, the materials used in the mix design, the water-to-cement ratio, the degree of hydration, and curing [1]. Some of these pores will be interconnected to form a network of pore space that can be penetrated by water, gas or ions.

The relevant transport mechanisms for the ingress of water, gases and ions are [2]:

i. diffusion of free molecules or ions due to a concentration difference;
ii. permeation of gases or liquids through water saturated specimens due to hydraulic pressure difference; and
iii. capillary suction of liquids due to surface tension acting in capillaries.

Whilst, these mechanisms act together under natural environmental exposure conditions for atmospherically exposed concrete, capillary suction tends to be the dominant mechanism [1-3]. Ions such as chlorides are transported into the concrete pore system by being dissolved into water, which subsequently cause corrosion of the steel reinforcement and ultimately spalling of the surrounding concrete cover.

Hydrophobic treatments have therefore been used in various forms in the construction industry to help prevent water and chloride ingress and their benefits are well documented [4-9]. They can be divided into three categories: coatings, pore blockers and pore liners (Figure 1).

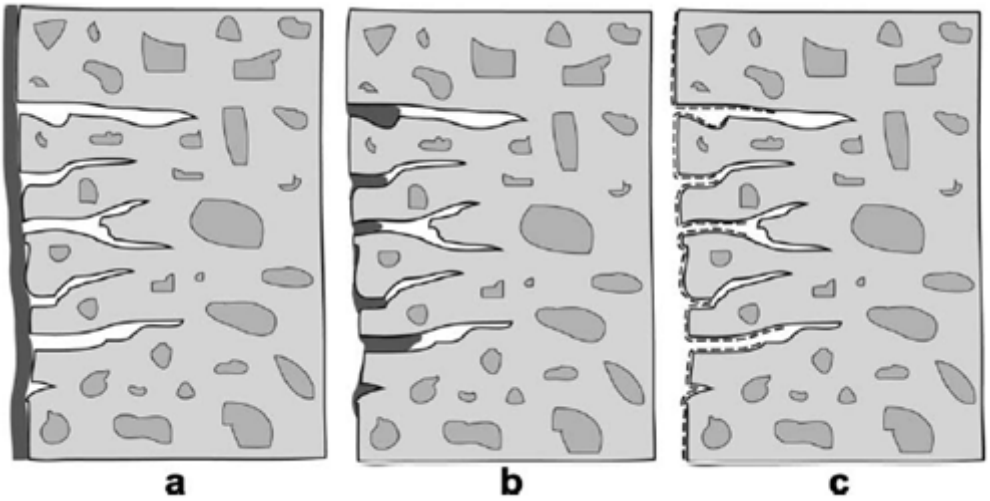


Figure 1: Categories of surface treatments a) coatings, b) pore blockers and c) pore liners [10]

Silanes belong to the pore liner category and are a group of silicones containing one silicon atom [11]. Alkoxy and alkyl silanes are routinely used for hydrophobic surface treatments. The basic composition of an alkyl alkoxy silane is shown by Figure 2. The alkoxy groups ($CH_3O$) linked to the silicate atom ($S_i$) contain silicon-oxygen bonds that will bond to silicates present in the concrete. The organic alkylic ($CH_3$) group remaining will protrude from the pore structure and are responsible for the hydrophobic characteristics [5-6].

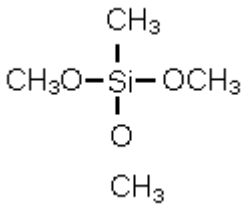


Figure 2: Typical alkyl alkoxy silane molecular structure

Evidence from numerous studies demonstrate that the application of silanes significantly reduces water uptake, which as a result reduces the ingress of chlorides and hence also reduces the corrosion risk to the reinforcement [6, 9, 12-18]. However, their performance is affected by surface imperfections, cyclic wetting and drying, skill of the applicator, surface preparation, application rates and local environmental conditions at the time of application.

Polder and de Vries [19] demonstrated that silane treated specimens still had a residual protective effect even after 5 years of outdoor exposure in the Netherlands, by measuring the water absorption and chloride content. In a similar study, Schueremans et al. [20] demonstrated the protective effects of silanes after 12 years of exposure in an aggressive marine environment on a RC quay-wall in a port in Belgium by measuring their chloride content.

Work by the Transport Research Laboratory [21, 22] in the UK indicated that silanes were reasonably effective in reducing chloride ingress into concrete structures based upon a review of principal inspection reports, various Managing Area Contractors, laboratory testing, and testing of cores extracted from full-scale motorway RC structures. The performance of the silanes was tested primarily by means of water absorption and sorptivity, but the age of silane at time of testing was limited to 5 years.

From all of the above it is apparent that very little is known regarding the durability of silane treatments and their long-term residual protection (i.e. following at least 10 years of service). Very commonly their performance is assessed by measuring chloride contamination at various depths over time. However, this is only an indirect method and does not provide information on the residual hydrophobic effect against water uptake. Extracting cores for laboratory testing from full-scale structures is neither desirable nor always feasible.

The objective of this study was to address this gap in knowledge, improve our understanding of the efficacy and long-term service life of silane treatments by undertaking testing of full-scale RC structures. The findings will help contribute towards the development of new improved corrosion management strategies and assist in a more accurate whole life cost assessment of silane treatments The findings also provide additional information regarding the maintenance requirements of RC structures with an existing silane treatment. Early results of this work have also been reported [23].

## 2. METHODOLOGY

This section presents the basic theory, selection strategy for the cross-beams, the properties of the concrete investigated, and the test methods applied including their selection criteria.

### *2.1 Capillary theory*

The transport of chlorides into concrete is governed by a mixed mode of capillary absorption of water and diffusion. *Capillarity absorption* can be defined as the transport of liquids in porous and non-saturated solids due to surface tension acting in capillaries and without appreciable external pressure [2]. For short-term contact between the liquid and the porous solid surface, a non-steady-state transport mechanism exists. This resembles conditions encountered on site by atmospherically exposed full-scale RC structures. It can be measured as the increase in mass due to capillary water absorption as a function of the square root of time

and it is usually termed as *rate of absorption*. It can be also expressed as the increase in volume as a function of the square root of time which, termed *sorptivity*.

*Diffusion* can be defined as the transfer of mass by random motion of free molecules or ions in a pore solution resulting in a net flow from regions of higher concentration to regions of lower concentration [2, 24].

Concrete in contact with a salt solution will become contaminated with chlorides primarily due to capillary absorption rather than diffusion alone. Absorbed chlorides can continue to penetrate by diffusion but at a significantly lower movement rate. Thus, measuring the rate of absorption (or sorptivity) can provide useful information on the condition of silane treatments.

The rate of water absorption can be expressed by equation (1) [2]. Sorptivity is the uni-axial one-dimensional capillary absorption and can be expressed by equation (2) [2].

$$\text{Rate of water absorption} = \frac{W_w}{\left(A_c \sqrt{t}\right)} \qquad kg/m^2/h^{0.5} \qquad \textit{Equ. (1)}$$

$$\text{Sorptivity} = \frac{V_w}{\left(A_c \sqrt{t}\right)} \qquad m/h^{0.5} \qquad \textit{Equ. (2)}$$

where $W_w$ (grams) is the weight gained by the specimen, $A_c$ ($mm^2$) the surface area of the specimen in contact with the water, t (seconds) the time of exposure and $V_w$ ($mm^3$) the volume of water absorbed.

Measurement of water sorptivity can also be related to the rate of chloride absorption [10, 25].

Table 1 provides a summary of the European Standard BS EN 13057 [26] for measurement of the capillary water absorption of hardened concrete.

| Standard | Output Properties | Testing Time | Specimen Size |
|---|---|---|---|
| BS EN 13057 [26] | Sorption coefficient $kg/m^2h^{0.5}$ or $m/h^{0.5}$ (i.e. equations 1 and 2 respectively) | Intervals of 12 min, 30 min, 1 h, 2 h, 4 h and 24 h are appropriate in most cases. | Diameter (100 $\pm$ 5) mm Length (25 $\pm$ 0.5) mm |

Table 1: Standard test method for the determination of water absorption of concrete

### 2.2. *Cross-Beams*

Figure 3 illustrates a typical sub-structure arrangement of the motorway bridge supporting cross-beams that were examined during this study. Silanes have been applied to a total of 135 similar cross-beams across the UK's Midland Link Motorway Viaducts (MLMV). Of these, 93 cross-beams were located in the viaduct that was chosen for these investigations, whereas the remaining were distributed amongst four other viaducts.

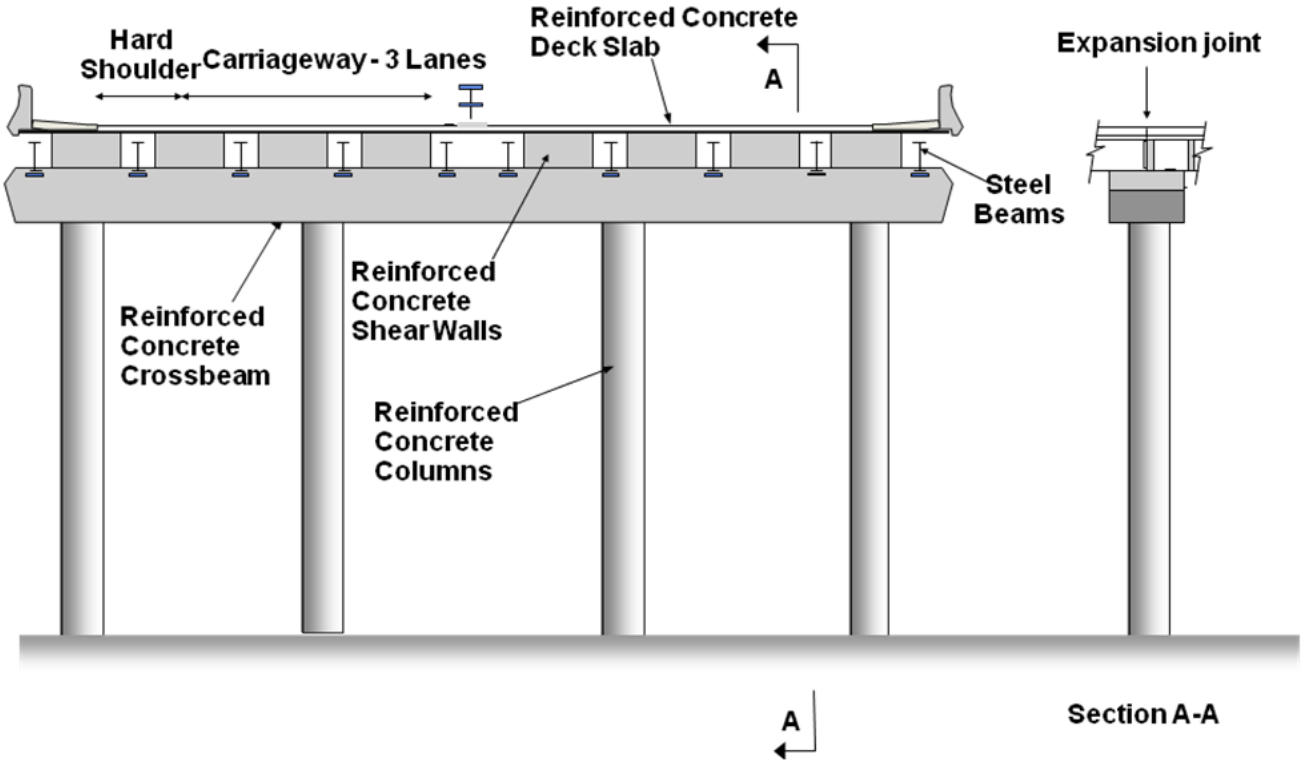


Figure 3: Typical sub-structure arrangement of the UK's Midland Links Motorway Viaducts (MLMV).

The methodological procedure employed is outlined in Figure 4. The cross-beams were constructed between 1968 and 1970, although the exact date is not known. Thus, 1969 is used as the average construction year for calculations of age of silane at time of testing. Although specimens were extracted from cross-beams of the same viaduct, hence suggesting that at least comparable concrete was used, due to the nature of construction, there will be variations in the overall concrete quality. Due to the age of the cross-beams, there were no historical records available providing information on concrete mix design such as maximum aggregate size. Such details could have been approximated by petrographic analysis however this was consider outside the scope of the current study and would have required a large number of additional site cores.

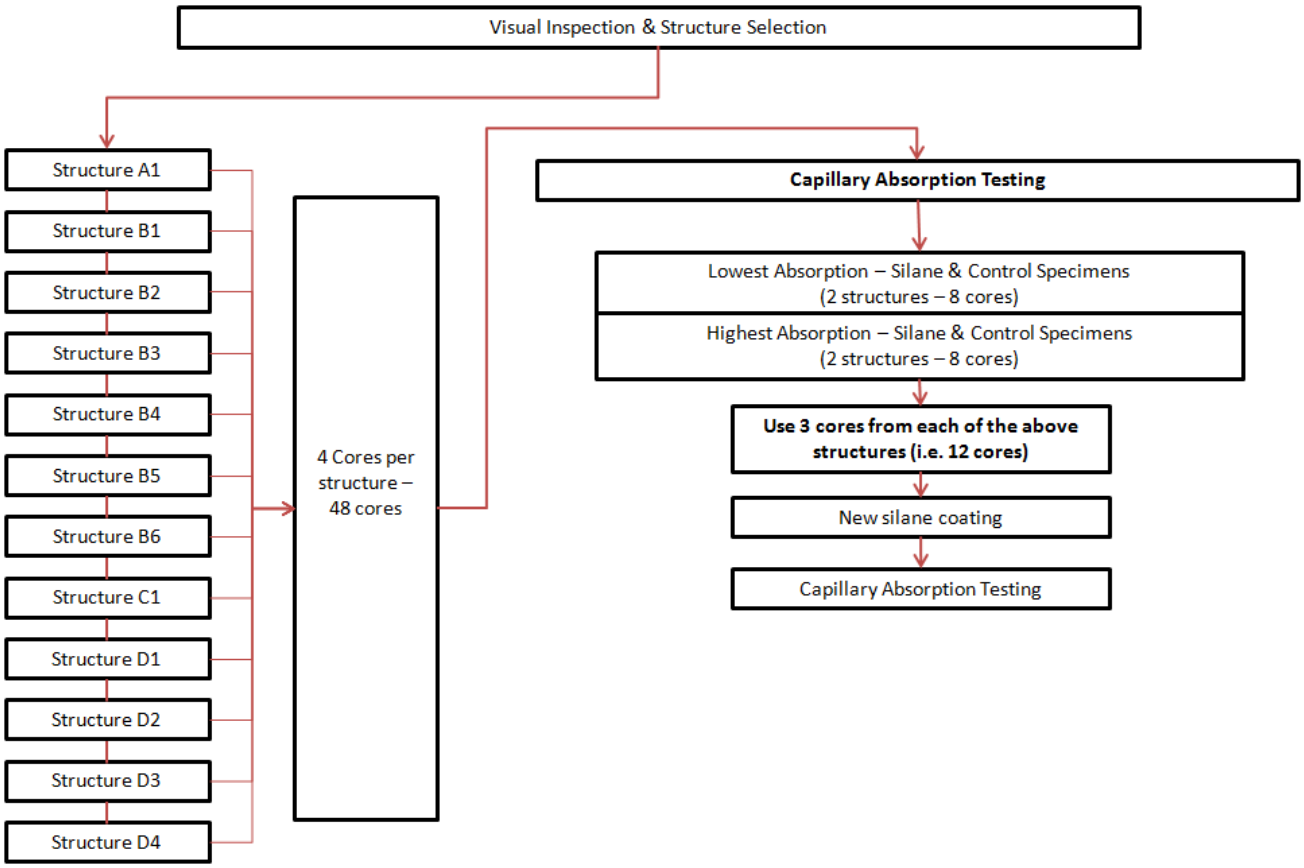

Figure 4: Selection and testing programme for silane treated cross-beams

Twelve cross-beams were selected, of which eight had previously received a silane treatment 20 years following their construction, whereas the remaining four had not, hence were acting as control specimens (Table 2). Variations in the performance of specimens extracted from the control cross-beams could give an insight with regards to site variations in concrete quality. The chemical composition of the silane treatment was isobutyl trimethoxy silane. No historical records exist detailing the exact surface preparation procedures, application rates or weather conditions at the time of the application, important factors that can affect silane performance.

Table 2: Age of cross-beams based on an average construction date of 1969 and age of silane treatment at testing.

| Cross-beam Reference | Year of silane application | Age of cross-beam at silane application (years) | Age of silane at testing (years) | Age of cross-beam at testing (years) |
|---|---|---|---|---|
| A1 | 1991 | 23 | 20 | 43 |
| B1 | 1993 | 25 | 18 | |
| B2 | 1993 | | | |
| B3 | 1993 | | | |
| B4 | 1993 | | | |
| B5 | 1993 | | | |
| B6 | 1993 | | | |
| C1 | 1999 | 31 | 12 | |
| D1 | Control cross-beams (No silane) | - | - | |
| D2 | | | | |
| D3 | | | | |
| D4 | | | | |

Four cores (diameter and length of 80mm) were extracted from each cross-beam, all from the top surface, which represented the most critical area for water ingress (Figure 5). This residual risk can be attributed to the simply supported articulation arrangement of the bridges with carriageway expansion joints above every cross-beam that were known to be susceptible to water leakage. After coring, each core hole was carefully repaired with a shrink-resistance compensating repair mortar.

Figure 5: Coring on top of a silane-treated RC cross-beam

A correction factor in accordance with BS 1881-122 [27] was applied to normalise the cores into an equivalent of 75mm diameter and to eliminate minor differences in length between the cores as a result of the coring process (Equ.3).

$$\text{Correction factor} = \frac{V}{\left(A_c \times 12.5\right)} \qquad \textit{Equ.(3)}$$

where V ($mm^3$) is the volume of the specimen and $A_c$ ($mm^2$) the surface area of the specimen in contact with water.

### *2.3 Testing*

A very common testing regime to evaluate the performance of silanes is to measure chloride penetration profiles between silane and control treated specimens [19, 20, 22]. One differentiating factor of this work is that this approach was not employed. The cross-beams were silane treated after approximately 20 years of service life and there were no historical records of the chloride levels at the time of silane application. As such, there would be no previous information to compare against and it was thus deemed that chloride

concentration testing had limited potential for investigating the efficiency of the silane treatments and it required destructive testing of the valuable core specimens.

Investigation of the effectiveness of the silane treatment as a chloride barrier was therefore conducted by measuring the capillary absorption, a non-destructive technique. Two sets of tests were undertaken: the first on the original silane treated and control cores, the second on a subset of these to which a new silane was applied. This subset created additional background information on what could have been the potential effectiveness of silanes on aged concrete when the silanes are young. As the original silane proprietary product (based on isobutyl trimethoxy silane) was no longer commercially available, a frequently commercially available silane product was used instead. The properties of the new silane are summarised on Table 3. In the study by Calder and McKenzie [22] it is reported as product 2.3.

The procedure outlined by BS EN 13057 [26] was adopted with the following changes:

i. The diameter of the cores was reduced to 80 mm and their length increased also to 80 mm. This change was required in order to be in a position to extract cores from full-scale RC cross-beams which are heavily reinforced.
ii. The cores were oven dried at 35$^{o}$C as opposed to the recommended 40$^{o}$C. The drying temperature was lowered in order to minimise potential damage to the chemical structure of the residual silane impregnations.
iii. The drying period was extended until the weight loss of the specimens (due to moisture loss) became stabilised to less than 0.05% weight loss over a period of 2 days, as opposed to the r not greater than 0.2% in 2 hours. This aimed to minimise any effects on the sorptivity due to initial water content of the specimens as a result of their greater length.
iv. All but the test face (silane treated face) were sealed against sideways ingress of water and evaporation of moisture with a proprietary polysulphide sealant. This approach is in line with the recommendations of Kropp and Hilsdorf [2] in order to measure uniaxial rate of water absorption and sorptivity.
v. The immersion depth was approximately 5mm below the water line as proposed by Hall [28] instead of 2 $\pm$ 1mm. This approach does not alter the results in any way as all of the non-tested surfaces of each core were sealed against water with a proprietary polysulphide sealant.

The specimens were placed with their silane treated surface facing down in a layer of water no deeper than 5 mm (Figure 6). Their weights were recorded at 0, 5, 15, 30 minutes and thereafter every 30 minutes over a total period of 4 hours.

Figure 6: Cores sealed with proprietary polysulphide sealant for capillary absorption testing

The specimens from the best and worst performing control cross-beams were selected to form a new family of 6 specimens for additional testing with a new silane impregnation (Figure 4). The specimens received a light surface preparation to remove the build up of laitance by abrading the surface with sand paper and cleaning with an air lance. The specimens then received the new silane treatment (Table 3) and were air cured indoors for 7 days. Following, they were prepared and tested for capillary water absorption in the same procedure as the previous cores. The aim of this approach was to demonstrate the effect on the rate of water absorption for the control specimens following application of the new silane. In addition, it can provide a comparison in the performance between newly applied and old silanes.

| Type | Chemical Type | Solid Content, by weight | Flash point | Application method | Application rate |
|---|---|---|---|---|---|
| Water based silane | Alkyl alkoxy silane | 20% | >93 $^{o}$C | Brush applied | 3 – 5 l/m$^2$ |

Table 3: Characteristics of applied alkyl alkoxy silane treatment.

The results for all the testing are expressed as a percentage of net weight gain for each core which is used to calculate rate of absorption (i.e. equation 1) and sorptivity (i.e. equation 2).

## 3. DATA ANALYSIS

This section describes the data obtained and discusses the results of the tests on the original and on the newly applied silane treatments, together with their statistical significance.

### *3.1 Original Silane Treatment*

The net weight gain of each specimen and average for each cross-beam's group of specimens after 4 hours of testing is shown in Figure 7. It can be observed that in general the specimens exhibited variability in their performance. This may be associated with micro-structure differences of the specimens, even for the same cross-beam, as a result of lower quality control of the concrete on site possibly producing micro-structure inconsistencies. Silane treated specimens from cross-beams B5 and C1 (18 and 12 years old at time of testing) presented the lowest net weight gains.

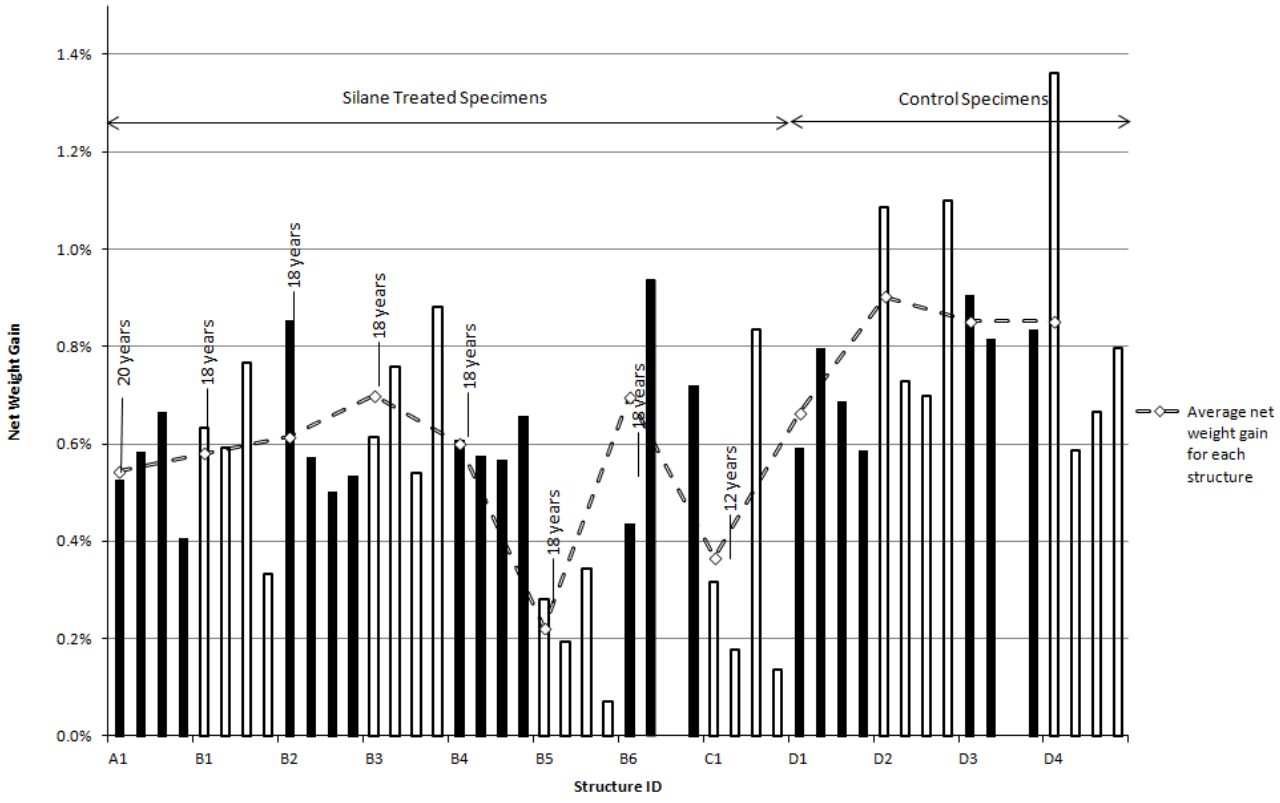


Figure 7: Net weight gain for each specimen and average net weight gain for each cross-beam's group of specimens after 4 hours of capillary absorption testing.

***Note: The change in colour within the vertical bars simply differentiates specimens between different cross-beams. The age of the silane at time of testing is also noted.***

The results were used to calculate average cumulative water uptake for each cross-beam's group of specimens over a period of 4 hours of capillary absorption testing, on which the rate of absorption can

therefore be calculated (Figure 8). In accordance with BS EN 13057 [26], the rate of water absorption may be calculated as the linear portion of the slope or in cases where this does not exist, it may be calculated as the slope from the y-axis intercept to the last reading taken (equation 1).

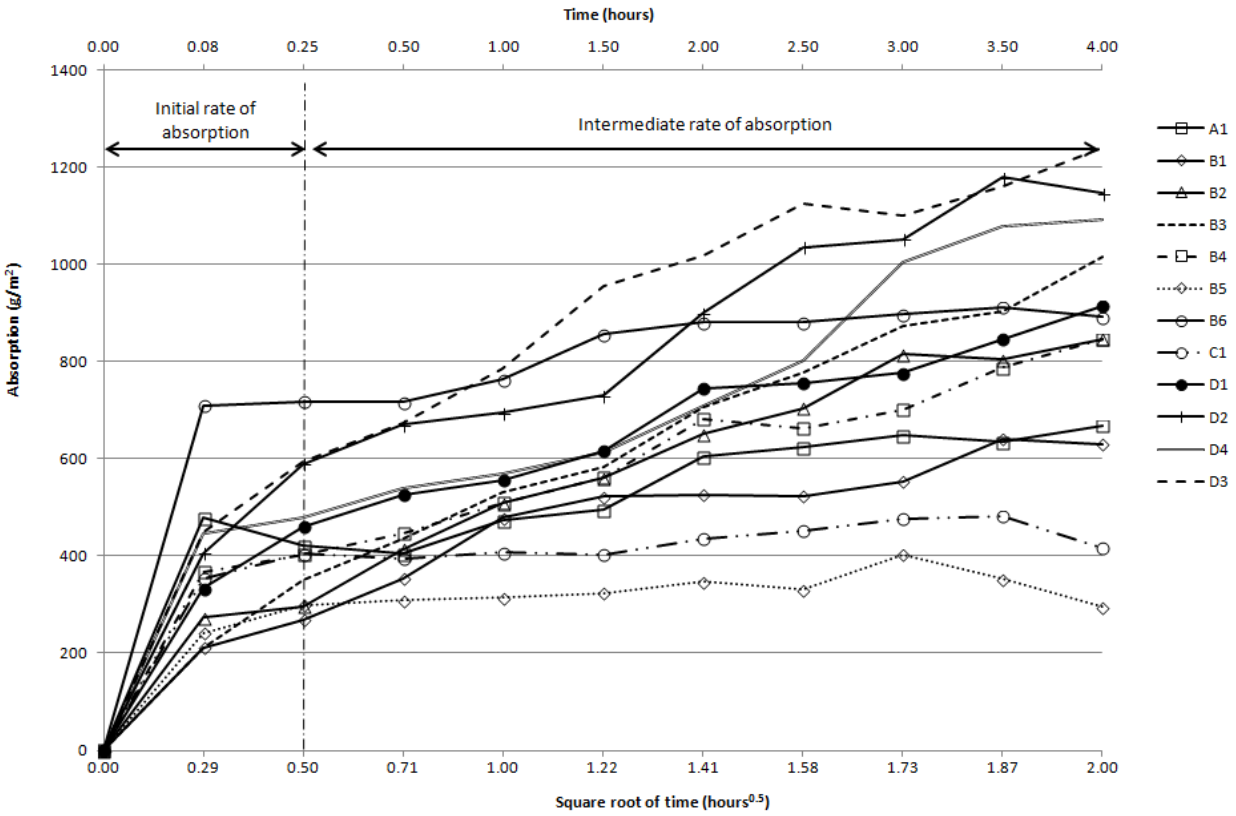


Figure 8: Average cumulative absorption for each cross-beam's group of specimens over 4 hours of capillary absorption testing.

From Figure 8, it can be observed that specimens from all cross-beams initially had a high rate of water absorption over the first 15 minutes of testing (0.08 hours or 0.29 hours$^{0.5}$). After this time, for the silane treated cross-beams, in most cases the rate of water absorption was significantly reduced or almost eliminated, indicating steady state conditions. For the control cross-beams, in most cases, the rate of water absorption was reduced but never eliminated.

As such, three distinct rates of water absorption may be derived (Table 4), i.e. initial between zero and 15 mins (0 to 0.29 hours$^{0.5}$), secondary between 15 mins and 4 h (0.29 to 2.00 hours$^{0.5}$) and overall average (0 to 2.00 hours$^{0.5}$). Each cross-beam is ranked accordingly, to provide a more informed assessment on the relative performance of cross-beams such as B5 and C1 which had a high rate of water absorption over the first 15 minutes of testing but thereafter reached steady state conditions.

| Cross-beam Reference | Initial rate ($g/m^2/h^{0.5}$) 0 - 15 min | Ranking (High to low rate) | Secondary rate ($g/m^2/h^{0.5}$) 15 min – 4 h | Ranking (High to low rate) | Average rate ($g/m^2/h^{0.5}$) | Ranking (High to low rate) | Age of silane at testing |
|---|---|---|---|---|---|---|---|
| A1 | 841 | *6* | 124 | *9* | 335 | *9* | *20 years* |
| B1 | 538 | *12* | 181 | *8* | 315 | *10* | *18 years* |
| B2 | 593 | *11* | 275 | *5* | 423 | *7* | |
| B3 | 703 | *9* | 332 | *1* | 507 | *4* | |
| B4 | 805 | *8* | 221 | *7* | 422 | *8* | |
| B5 | 599 | *10* | 26 | *11* | 148 | *12* | |
| B6 | 1436 | *1* | 87 | *10* | 446 | *6* | |
| C1 | 808 | *7* | 6 | *12* | 208 | *11* | *12 years* |
| D1 | 920 | *5* | 227 | *6* | 456 | *5* | - |
| D2 | 1178 | *3* | 278 | *4* | 573 | *2* | - |
| D3 | 1188 | *2* | 323 | *2* | 620 | *1* | - |
| D4 | 956 | *4* | 307 | *3* | 546 | *3* | - |

Table 4: Initial, secondary and average rate of water absorption in $g/m^2/h^{0.5}$ for each cross-beam's group of specimens based on 4 hours of capillary absorption testing.

The variance in the rate of water absorption observed may be partly explained by changes in the micro-structure of the specimens as water progress from the cover zone (where concrete may be more porous and exhibit surface cracking) towards the core of the specimens. The thickness of this cover zone is affected by quality control on-site and curing conditions. In addition, as all the specimens were extracted from the top of the cross-beams, this effect may be exaggerated as concrete in this area will be more prone to bleeding.

It can be observed that control cross-beams D2, D3 and D4 exhibited high rates of water absorption, being in the top four worse performing cross-beams for the initial, secondary and average rates of water absorption. Although all control structures (D1, D2, D3 and D4) initially performed better than silane treated cross-beam B6, the later quickly reached near steady state conditions (refer to its secondary rate, Table 4) whereas control cross-beams continued their water absorption..

Silane treated cross-beam B3 had a very low initial rate of water absorption when compared to all other cross-beams. However, its intermediate rate of water absorption was the highest and it did not approach near steady state conditions within the 4 hours of the test. Its average rate of water absorption is comparable to that of specimens from control cross-beams and may be associated with a diminished residual hydrophobic effect.

Cross-beam C1, with the youngest silane treatment at 12 years at time of testing, was ranked average for its initial rate of water absorption but thereafter reached steady state conditions and was the best performer based on the intermediate rate of water absorption. Cross-beam B5, with the silane treatment at 18 years at time of testing, was one of the best performing based on initial, secondary and average rates of water absorption and reached near steady state conditions after 15 minutes of testing. Cross-beam A1, with the

oldest silane treatment at 20 years at time of testing, was one of the best performing silane treated cross-beams.

The testing data for each cross-beam (average net weight gain, rate of absorption, sorptivity and standard deviation) following 4 hours of capillary absorption are shown in Table 5.

| Cross-beam Reference | Age of silane at testing | Net Weight Gain (%) | Coefficient of Variation | Average Rate of Absorption ($g/m^2\ h^{0.5}$) | Average Sorptivity ($mm/\sqrt{h}$) | Standard Deviation |
|---|---|---|---|---|---|---|
| **A1** | 20 | 0.55 | 0.198 | 335 | 0.335 | 0.1014 |
| **B1** | 18 | 0.58 | 0.312 | 315 | 0.315 | 0.1113 |
| **B2** | | 0.62 | 0.262 | 423 | 0.423 | 0.1068 |
| **B3** | | 0.70 | 0.218 | 507 | 0.507 | 0.1101 |
| **B4** | | 0.60 | 0.069 | 422 | 0.422 | 0.0737 |
| **B5** | | 0.22 | 0.531 | 148 | 0.148 | 0.0926 |
| **B6** | | 0.70 | 0.360 | 446 | 0.446 | 0.1807 |
| **C1** | 12 | 0.37 | 0.879 | 208 | 0.208 | 0.2109 |
| **D1** | Control cross-beams (No silane) | 0.67 | 0.148 | 456 | 0.456 | 0.1305 |
| **D2** | | 0.90 | 0.244 | 573 | 0.573 | 0.1480 |
| **D3** | | 0.85 | 0.056 | 620 | 0.620 | 0.0662 |
| **D4** | | 0.85 | 0.410 | 546 | 546 | 0.1823 |

Table 5: Average results and coefficient of variation for each cross-beam's group of specimens after 4 hours of capillary absorption testing

*3.2 Statistical Analysis*

From Table 5 it can be observed that in a number of cases there was a large coefficient of variation for specimens extracted from the cross-beam (e.g. B5, C1, D4). To examine the significance of this variance a simple one tail t-test was undertaken for each group of specimens based on the average, standard deviation and standard error values. For cross-beam C1 which exhibited the largest variance, the one tail t-test indicated a probability of less than 0.3% that the observed variance was a result of specimens belonging to a different family.

A statistical analysis was also undertaken to assess whether the samples of silane and control specimens belong to the sample population. For the silane treated samples the variance in sorptivity was found to be

0.0146 $mm^2 h^{-1}$ and for the control samples 0.0075 $mm^2 h^{-1}$. As there was a significant difference between these values the one tail t-test for unequal variances was used. The test yielded a probability of less than 3% that the observed difference between the variance of the two samples occurring due to random effects, such as the choice of sample. As such, it is highly unlikely that there is no difference between the populations and therefore the silane treatment has an effect.

| Cross-beam Reference | Average Sorptivity (mm/√h) | Comment | Average Sorptivity (mm/√h) | Comment |
|---|---|---|---|---|
| **B5** | 0.148 | 18 years old silane | 0.148 | 18 years old silane |
| **C1** | 0.208 | 12 years old silane | 0.208 | 12 years old silane |
| **D1** | 0.456 | Best performing control - No silane | 0.055 | New silane – 1 month old |
| **D2** | 0.573 | Worst performing control - No silane | 0.072 | New silane – 1 month old |

Table 6: Comparison of control and silane treated cross-beams following the application of a new silane treatment.

*3.3 New Silane Treatment*

Cross-beams D1 and D2 were the best and worst performing control. A new silane treatment was applied in order to approximate the effect of a newly applied silane treatment on the sorptivity of aged concrete extracted from full-scale RC cross-beams. Table 6 compares the sorptivity in their original untreated condition and 1 month after the application of a new silane treatment. These are in turn compared with the sorptivity of the best performing and previously treated cross-beams B5 and C1, with the silane at 18 and 12 years old respectively at time of testing.

It can be observed that following the application of a new silane treatment the sorptivity for both D1 and D2 control cross-beams was significantly reduced, as would be expected. Both cross-beams demonstrated similar sorptivities indicating similar levels of hydrophobic effect afforded by the new silane treatment. Based on the originally best performing control cross-beam D1, a reduction of sorptivity of at least 90% was achieved.

When compared to cross-beam C1 with 12 year old silane at time of testing, a reduction on the sorptivity of approximately 78% was achieved. Similarly, comparing the results to the best performing cross-beam B5 with 18 year old silane, a reduction in sorptivity of approximately 70% was achieved.

The results may be associated with a reduction in the hydrophobic effect of silanes over time. In addition, the new silane treatment was applied in a laboratory environment under strict quality control conditions as opposed to site conditions where a greater variability would be expected to exist when applying surface treatments to large areas. Furthermore, the new silane treatment is a different proprietary product than the original, as the latter is no longer available, which, albeit of similar chemical composition, may also produce performance variations.

## 5. DISCUSSION

The results suggest that the silane treated specimens exhibited a residual protective effect even after 20 years of service life. Specimens from cross-beams B5 and C1 (18 and 20 years old respectively at time testing) were overall the best performing silane treated specimens. In particular, specimens from cross-beam C1 - which had had the most recent application - outperformed all specimens except from cross-beam B5. Possible reasons for the difference in performance between specimens of silane treated cross-beams include time dependant effects such as weathering, surface preparation, application rates, environmental conditions at the time of application and differences in the quality of the concrete. Unfortunately, no historical records exist providing these details.

The average water absorption of the specimens (Figure 8) was found to have a fluctuating rate throughout the duration of the test. This is not uncommon, especially when dealing with specimens extracted from full-scale structures [22]. The variability of concrete within site structures will generally be greater than that of laboratory cast specimens. The specimens for this study were extracted from the top of the RC cross-beams an area where concrete is predisposed to bleeding and segregation which can give rise to inconsistencies of the cover zone.

The application of a new silane treatment had a considerable hydrophobic effect on the properties of the specimens tested. Specimens from control cross-beams D1 and D2 demonstrated a reduction in their sorptivity of at least 90% following the application of a new silane impregnation. Comparing the performance of the newly silane treated specimens with that from previously treated cross-beams such as B5 and C1 provides a baseline of the likely hydrophobic effect of this type of silane on the cross-beams when they were first applied.

Figure 9 compares the sorptivity of the silane treated specimens of this study against those of Calder and McKenzie [22]. It can be observed that very similar sorptivities were recorded for the new proprietary silane and their product 2.3 applied on laboratory specimens and artificially weathered. They also evaluated the performance of other proprietary products, referenced as products 3.2 (cream based silane) and 4.1 (crystal growth pore blocker), both being at service for 4 years prior to testing and extracted from a bridge parapet and an abutment respectively. Some similarity can be observed in the sorptivity between product 4.1 after 4 years of service life and the new silane used in our study after 1 month of application. It needs to be noted that apart from differences in proprietary materials, product 3.2 was applied to RC parapets which are directly exposed to spray water as opposed to abutments where product 4.1 was applied.

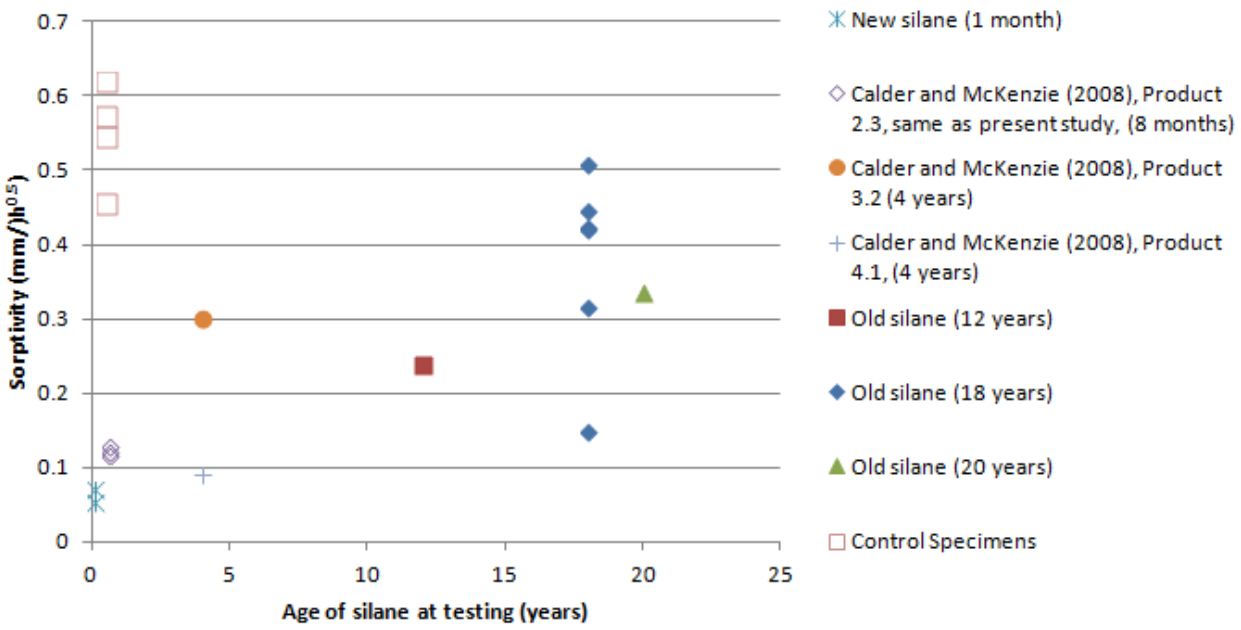


Figure 9: Comparison of the sorptivity of silane treated specimens examined in the study against the sorptivity of specimens from Calder and McKenzie [22].

Polder and de Vries [19] also undertook an assessment on the performance of silane treated specimens following 5 years of exposure to an outdoor environment in the Netherlands. However their results are not directly comparable as they obtained readings at approximately daily intervals with no readings in the first 4 hours as in the present work. Schueremans et al. [20] examined the performance of silanes from samples extracted from a full-scale RC quay wall following 12 years of service based on chloride ion concentration. Rodum and Lindland [29] undertook similar investigations with a number of proprietary products applied to a RC quay wall in Norway, measuring chloride content at various depths over a period of 10 years. Although both of those studies [20, 29] demonstrated the long-term performance of silane impregnations it is not possible to provide a direct comparison with the results of the present work.

The published data on the long-term performance of silane treatments from full-scale RC structures remains scarce. In addition, differences were found on the sampling, testing and reporting methods which hinders comparisons between the studies. Additional research is required in order to develop time dependent relationships on the performance of various proprietary silane products.

## 6. CONCLUSIONS

Overall, there is very little published empirical evidence that provides insight into the durability of silane treatments and their long-term residual protection (i.e. following at least 10 years of service). Such a gap in knowledge is undesirable given the scale of infrastructure treated with hydrophobic treatments such as silanes. From the results the following can be concluded:

- All the treated cross-beams demonstrated that the silane impregnation still provides a residual hydrophobic effect, even with the oldest application from 20 years ago. Statistical analysis indicated with at least 97% confidence that the variance observed between the silane treated and control specimens was due to a residual protective effect.
- In all but one cross-beam, the most recent silane treated specimens outperformed the other older silane treated specimens, suggesting that there is a relationship between degradation of the silane impregnation and duration of environmental exposure..
- Silane impregnations should be considered when determining the corrosion management strategy of a RC structure. Treatments as old as 20 years can still be present and offer a residual protective effect. Their presence and effectiveness can be evaluated by extracting cores and testing them in the laboratory by capillary absorption testing.

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