Assessing the long-term durability of silanes on reinforced concrete structures

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ASSESSING THE LONG-TERM DURABILITY OF SILANES ON REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Concrete is a porous material. The size and distribution of pores in concrete varies, depending upon the quality of compaction, the materials, the water-to-cement ratio and the degree of hydration. Many of these pores are inter-connected creating larger and more complex pore systems. Water can penetrate this network and cause deterioration of the concrete structure.

Silanes have been generally used in the past to help protect reinforced concrete exposed to an aggressive environment. The treatment works as a pore liner, thus making the concrete hydrophobic. This action helps prevent water ingress and can significantly reduce chloride penetration - a major cause of corrosion of the steel reinforcement in concrete.

This study was initiated after it was identified that long-term performance data of silanes is scarce and lacking in-depth analysis. Most of the research work previously undertaken aimed to illustrate their viability using different proprietary products and in a variety of exposure conditions. Maintenance Agencies have yet to reliably establish the protective period provided by silanes, and as such the whole life cycle costs are relatively unknown, resulting in a general lack of enthusiasm to their use in the last decade.

Twelve structures were selected for investigation, which were treated with silane more than 10 years ago. Cores were extracted and their capillary suction measured in the laboratory in order to assess their permeability when compared to control cores from similar un-treated structures, all constructed during the same time period.

The study is ongoing and this paper presents the findings with regard to the long-term performance of the silanes. These show that silanes have a residual protective effect even after 20 years of service. The results improve our understanding of the effective duration of the hydrophobic protective effect, and thus contribute to future whole life cycle costing of such treatments. In turn this can improve the overall corrosion management strategy available for reinforced concrete structures.

Key-words: Silanes, concrete, capillary suction, bridges, life-cycle

INTRODUCTION
Hydrophobic treatments are used in various forms in the construction industry to prevent water ingress into concrete structures. Chlorides are transported into the concrete pore system by being dissolved into the water and can subsequently cause corrosion of the reinforcement and ultimately spalling of the surrounding concrete. A structure protected from chloride ingress will attain a longer life with a reduced maintenance regime.

Evidence from numerous studies and field applications illustrate that the application of a hydrophobic treatment significantly reduces chloride ingress and therefore corrosion risk of the reinforcement [1-13]. However, there is little or no knowledge regarding the long term performance of these hydrophobic treatments. The research undertaken by Schuermans et al. [14] is one of the few studies which investigated the long-term effects on a quay-wall in a port. They showed that the silane was still present after 12 years of exposure in a marine environment and had a residual protective effect on the concrete.

The objective of our study presented was to improve the understanding of the efficacy and long-term service life of hydrophobic treatments on full-scale motorway bridge structures. The results will help the planning of future protection strategies and aid the whole life cost-benefit decision of whether hydrophobic treatments are good value. In addition, the results can provide guidance on the maintenance of structures with an existing hydrophobic treatment.

**TECHNICAL BACKGROUND**

Concrete is a porous material. The size and distribution of pores in concrete varies and depends on the quality of compaction, the materials, the water-to-cement ratio and the degree of hydration. In general, the pores in hardened cement paste are interconnected and form a network of pore space. This network can be filled by capillary suction if the surface of the concrete is in direct contact with water.

Chloride induced corrosion poses a major durability problem for concrete structures. Chlorides mainly originating from the application of de-icing salts for atmospherically exposed concrete structures are soluble in water. Over time, chlorides will diffuse through this network of pores and reach the steel reinforcement. Chloride induced corrosion, once initiated, can propagate and quickly reach very high intensities.

There are three distinct transport mechanisms for the ingress of water, gases and ions into concrete. These are diffusion of free molecules or ions due to a concentration difference, permeation of gases or liquids through water saturated specimens due to hydraulic pressure difference and capillary suction of liquids due to surface tension acting in capillaries. Whilst, these distinct mechanisms act together under natural environmental exposure conditions for atmospherically exposed concrete, capillary suction tends to be the dominant mechanism [15]. Absorption is sometimes referred to as permeability. This is erroneous as the latter is a steady-state mechanism driven by constant pressure head and requires a fully saturated specimen [15]. Capillary suction under these conditions will be negligible.

A remediation technique to improve concrete durability is to prevent chloride ingress by surface protection of the concrete structure. Several studies have investigated the beneficial effects into the reduction of chloride diffusion in concrete by employing surface treatments [1, 2, 6, 8, 11-12]. Such surface protection systems can be divided into three categories—coatings, pore blockers and pore liners (Figure 1) – that are discussed below.
Coatings

Coatings form a continuous film over the surface of the concrete structure. They usually have crack bridging capabilities and are widely used in the construction industry to protect concrete structures. They can take various forms such as epoxy resins, polyurethane resins, acrylic resins and cement-based polymer-modified coatings. The results of Al-Zahrani et al. [13], Al–Dulaijan et al. [17] and Swamy et al. [18] illustrate that all types of coatings have been successful in reducing the overall level of chloride and the associated overall corrosion risk.

A point of concern has been the bond strength (adhesion) to the substrate. Al-Zahrani et al.[13] demonstrate that cement-based polymer-modified coating systems were capable of achieving higher bond strength as opposed to alternative coating systems. However, water absorption of polyurethane and epoxy based coatings was superior to the cement based and it was suggested that water absorption should be the criterion used to assess the protection performance of a coating.

Pore blockers

Pore blockers such as sodium silicates will react with certain soluble constituents in order to form insoluble products that will block the pores. These insoluble products due to their molecular size will not penetrate the full depth of the pores and not necessarily the full pore network. The performance of pore blockers as an effective method for corrosion protection is still debatable. The study by Jian-Guo Dai et al. [19] illustrated that the water absorption of specimens treated with sodium silicate based pore blockers was similar to that of untreated specimens.

Pore liners

Pore liners due to their small molecular size penetrate the pore system and react with certain concrete constituents to form a hydrophobic lining. An important advantage is their ability to allow moisture to evaporate out of the structure, unlike surface coatings or pore blockers where moisture builds up under this layer that cannot freely evaporate. This action can cause water pressure to build up under
the surface coating or the pore blockers with subsequent damage to the concrete due to expansion of water under freezing conditions.

Silanes belong to the group of silicones and they contain one silicon atom. Alkoxy and alkyl silanes are routinely used for hydrophobic surface treatments. A typical example of an alkyl alkoxy silane is demonstrated by Figure 2. The alkoxy groups (CH$_3$O) linked to the silicate atom contain silicon-oxygen bonds bond to the silicates present in the concrete. The organic alkyllic (CH$_3$O) group remaining will protrude from the pore structure and due to its fatty character lines up the pore and make the area hydrophobic [1, 12].

![Figure 2: Typical alkyl alkoxy silane molecular structure](image)

Penetration of silanes has been found to be a function of the pore system (i.e. percentage of interfacial voids), the alkali resistance of the applied compounds, the water-to-cement ratio and the amount of water currently present in the concrete structure [20]. Some studies have also investigated the optimum dosage required to achieve the greatest protection [11] and the penetration depth relationship with the viscosity of the applied material [10]. Previous work by the Transport Research Laboratory resulted in the publication of reports PPR-136 [21] and PPR-362 [22] which reviewed principal inspection reports, various Managing Area Contractors, laboratory testing and testing of cores taken from full-scale structures. The findings of the above two reports indicated that silanes were effective and reduced chloride ingress into the concrete structures. However, the above studies had a very limited amount of control samples to compare against, no suggestions were made about an effective service life of silanes and the oldest silane application was only four years old at the time of testing.

**METHODOLOGY**

This section describes the structures selected and the testing regime. In particular it discusses the methods employed in order to select the structures, the properties of concrete investigated and the reasons for choosing this testing regime.
Structures

Figure 3 illustrates a typical sub-structure arrangement for bridge motorway structures. Silanes were applied to protect the reinforced concrete crossbeams of a large number of the sub-structures.

A visual inspection was undertaken in July 2010 to obtain a better understanding of their current condition and also to identify control structures that had not been repaired and in an as-built condition.

The structures selected for this study were located in the same viaduct to ensure that exposure conditions amongst them were similar and therefore variability between the samples was kept to a minimum. The structures were constructed during the same time period and have identical concrete mixes. In addition, all the structures tested had received the same proprietary product of silane, Bimasil 100, an isobutyl trimethoxy silane, further reducing variability. However, there are no historical records detailing exact surface preparation procedures, application rates and weather conditions at the time of the application. These are some important factors that can affect performance.

In total 12 structures were selected, of which 8 had previously received a silane treatment, whereas the remaining 4 were in an as-built condition (Table 1). Four cores were taken from the top of the crossbeam. The cores had a specified diameter and length of 80mm. However, length of the cores varied due to difficulties in controlling the process on site. Figure 5 illustrates the coring action from the top of the cross beam; each core hole was carefully filled with shrink resistant mortar.
Figure 4: As found condition of a silane treated structure

Figure 5: Coring action on top of silane treated crossbeam
Table 1: Details of the test structures

<table>
<thead>
<tr>
<th>Structure Reference</th>
<th>Year of silane application</th>
<th>Age of structure at the time of silane application</th>
<th>Current age of structure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1991</td>
<td>20 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B1</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B2</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B3</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B4</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B5</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>B6</td>
<td>1993</td>
<td>22 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>C1</td>
<td>1999</td>
<td>28 years</td>
<td>40 years</td>
<td>Silane treated</td>
</tr>
<tr>
<td>D1</td>
<td>-</td>
<td>-</td>
<td>40 years</td>
<td>Control</td>
</tr>
<tr>
<td>D2</td>
<td>-</td>
<td>-</td>
<td>40 years</td>
<td>Control</td>
</tr>
<tr>
<td>D3</td>
<td>-</td>
<td>-</td>
<td>40 years</td>
<td>Control</td>
</tr>
<tr>
<td>D4</td>
<td>-</td>
<td>-</td>
<td>40 years</td>
<td>Control</td>
</tr>
</tbody>
</table>

Testing

After extraction all the cores were oven dried at 35°C until their weight loss became very low – less than 0.05% weight loss over a period of 3 days. This temperature was selected as a representative site temperature that can be encountered during a hot summer day. In addition, it significantly reduces potential damage to the chemical structure of the old silane treatment as opposed to using considerably higher drying temperatures (i.e. 100°C).

The durability of the silanes was assessed by capillary rise and capillary infiltration. As there is little or no outflow during the testing period then the methods can be designated as absorption measurements. In the first test capillary suction opposes the gravitational effects whereas for the second test, gravity assists to drive the liquid through the unfilled pores. Kropp and Hilsdorf [15] reported that gravitational effects may be neglected. However, capillary infiltration testing was undertaken as part of this work in order to assess whether there will be any effects on specimens obtained from full-scale concrete bridge structures which have been in service for at least 40 years.

Hall [23] proposed an arrangement where the specimen sits on rods and no more than 5mm below the water line. For more accurate work he proposed that specimens are sealed on their sides in order to prevent side absorption. This technique was followed by the authors for the work presented here.
as a proprietary polyurethane sealant was readily available and there was a requirement to measure uni-axial absorption.

For the capillary rise testing the specimens were placed with their silane treated surface facing down in a layer of water no deeper than 5 mm. Figure 6 illustrates the sealed specimens placed in a perforated tray with a small layer of water for the capillary rise testing. Their weights were recorded at 0, 5, 15, 30 minutes and thereafter every 30 minutes over a total period of 4 hours. Their net water absorption was recorded by measurement of weight change.

![Figure 6: Sealed cores inside the water tank for the capillary rise testing](image)

The results of the test provide a comparison between the dry and wet weights of the silane and control specimens. In addition, water absorption and sorptivity can be calculated. The rate of water absorption is expressed by equation (1). Sorptivity is the uni-axial one-dimensional capillary absorption and is expressed by equation (2).

\[
\text{Rate of water absorption} = \frac{W_w}{A_c t} \quad (1)
\]

\[
\text{Sorptivity} = \frac{V_w}{A_c \sqrt{t}} \quad (2)
\]

Where \(W_w\) is the weight gained by the specimen, \(A_c\) the surface area of the specimen, \(t\) the time of exposure and \(V_w\) the volume of water absorbed.

For the capillary infiltration testing the specimens were immersed in a shallow head and allowed to absorb water under submersion. The water was approximately 200mm and at such shallow depths there are no permeability effects due to hydraulic pressures. The net weight gain of the specimens was recorded every hour for the first 6 hours and thereafter every 12 hours up to a total period of 12 days.
DATA ANALYSIS

This section describes the data obtained from the two tests and summarises the observations.

Capillary Absorption

Figure 7 illustrates the average net weight gain of all the specimens tested and the average net weight gain for every structure after 4 hours of capillary rise testing. It can be observed that the average net weight gain of control structures was, in general, higher than that of the silane treated structures. The best performing control structure (D1) had an average net weight gain of 0.12% which matched the average net weight gain of the worst performing silane treated structure (B6). The best performing silane treated structure (B5) exhibited an average net weight gain as low as 0.04%.

It appears that even the oldest silane application (structure A1), which dates back to 1991, still has a residual protective effect on the structure. In addition, the youngest silane application (structure C1) tested from 1999 reduced considerably the net weight gain of the specimens, by 42% relative to the best performing control. Table 2 illustrates the mean results for each structure from the capillary rise testing.

![Figure 7: Average net weight gain for each core and average net weight gain per structure after 4 hours](image-url)
Table 2: Tabulated mean results for absorption testing

<table>
<thead>
<tr>
<th>Structure Reference</th>
<th>Year of Installation</th>
<th>Net Weight Gain (%)</th>
<th>Standard Deviation</th>
<th>Absorption Rate (g/m²/h)</th>
<th>Sorptivity (mm/√h)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1991</td>
<td>0.10</td>
<td>0.0183</td>
<td>35.1</td>
<td>0.070</td>
<td>Silane</td>
</tr>
<tr>
<td>B1</td>
<td>1993</td>
<td>0.12</td>
<td>0.0466</td>
<td>39.5</td>
<td>0.079</td>
<td>Silane</td>
</tr>
<tr>
<td>B2</td>
<td>1993</td>
<td>0.10</td>
<td>0.0290</td>
<td>40.5</td>
<td>0.081</td>
<td>Silane</td>
</tr>
<tr>
<td>B3</td>
<td>1993</td>
<td>0.11</td>
<td>0.0240</td>
<td>45.3</td>
<td>0.091</td>
<td>Silane</td>
</tr>
<tr>
<td>B4</td>
<td>1993</td>
<td>0.11</td>
<td>0.0153</td>
<td>38.1</td>
<td>0.076</td>
<td>Silane</td>
</tr>
<tr>
<td>B5</td>
<td>1993</td>
<td>0.04</td>
<td>0.0213</td>
<td>14.4</td>
<td>0.029</td>
<td>Silane</td>
</tr>
<tr>
<td>B6</td>
<td>1993</td>
<td>0.12</td>
<td>0.0450</td>
<td>43.8</td>
<td>0.088</td>
<td>Silane</td>
</tr>
<tr>
<td>C1</td>
<td>1999</td>
<td>0.07</td>
<td>0.0595</td>
<td>22.4</td>
<td>0.045</td>
<td>Silane</td>
</tr>
<tr>
<td>D1</td>
<td>-</td>
<td>0.12</td>
<td>0.0214</td>
<td>41.7</td>
<td>0.083</td>
<td>Control</td>
</tr>
<tr>
<td>D2</td>
<td>-</td>
<td>0.15</td>
<td>0.0004</td>
<td>55.6</td>
<td>0.111</td>
<td>Control</td>
</tr>
<tr>
<td>D3</td>
<td>-</td>
<td>0.16</td>
<td>0.0002</td>
<td>58</td>
<td>0.116</td>
<td>Control</td>
</tr>
<tr>
<td>D4</td>
<td>-</td>
<td>0.15</td>
<td>0.0005</td>
<td>48.4</td>
<td>0.097</td>
<td>Control</td>
</tr>
</tbody>
</table>

Capillary Infiltration

Figure 8 illustrates the average net weight gain for the structures tested together with the standard deviation. It can be observed that in general the results are in line with the capillary absorption testing. Structures A1 and B5 appear to be amongst the best performing. However, structure C1 did not illustrate very low capillary infiltration results as opposed to its capillary absorption results. Furthermore, difference in the performance was observed for the control specimens with structures D3 and D4 performing better than D1 and D2.

With regards to the standard deviation, it can be observed that the control specimens returned very small values. This is very encouraging as it illustrates that the control structures exhibit similar properties and removes reduces another factor that can cause variability in the results.
Figure 8: Average net weight gain and standard deviation for water penetration testing

**Statistical Analysis**

A statistical analysis was undertaken to assess the significance of the data obtained. The variance of the two samples with regards to their sorptivity was found to be 0.00022 mm$^2$h$^{-1}$ for the silane treated samples and 0.00057 mm$^2$h$^{-1}$ for the control. As there was a significant factor between these values the test for unequal variances was used.

A one tail t-test comparing the control sample to the sample of silane treated specimens yielded a probability (P value) of 0.008. This is the probability of the observed level of difference between these samples occurring due to random effects, such as the choice of sample, in the absence of an overall difference in the pattern of sorptivity in the population. Since P is sufficiently small (i.e. less than 1%) then it is highly unlikely that there is no difference between the populations and therefore that the silane treatment has an effect.

The results obtained for structure B5 appear to be an outlier. Conservatively the analysis was repeated omitting this data. To avoid bias, pair wise elimination was used and the highest value from structure B3 was also removed. The corresponding P value with these results removed is 0.011.

In the analysis including all the data the P value is less than 1% and therefore there is 99% confidence that the silane treatment had an effect. When the outlying high and low results are removed confidence is again approximately 99% that the silane treatment had an effect. In both cases the statistical analysis provides a high level of confidence.

The above statistical analysis tests were repeated using only pre-1993 silane treated structures. This test examined whether there is a significant difference between treated and control specimens 17
years after treatment. Including structures B5 and B6 the P value is 0.024 (98% confidence) and excluding these outliers the P value is 0.031 (97% confidence). These values show that there can be a high level of confidence that there is still an effect from the treatment after 13 years.

**DISCUSSION**

The results of the capillary absorption and water penetration testing suggest that silane treated structures exhibit a protective residual effect even after 20 years of service life. Structures B1 and B6 exhibited the lowest levels of residual protection from their silane application when compared to control structures. However these structures still exhibited lower water absorption rates when compared with the average of the control structures. The control structure D1 appears to be in a very good condition with high quality concrete which exhibits low absorption rates of water. It had the lowest absorption rate of all the controls and the results obtained for it are similar to the poorest performing silane treated structures.

The results are in line with the findings of the field research by Schueremans et al. [14] where a hydrophobic agent was applied to a reinforced concrete structure exposed to a marine environment. They also evaluated the long-term performance of the silane treatment and identified that even after 12 years of service the treatment offered a protective effect and the treated areas exhibited considerably reduced concentrations of chlorides as opposed to untreated areas. The work presented here did not examine chloride penetration profiles between silane and control treated specimens but it covered a longer service life of 10 years.

Structures B5 and C1 exhibited the lowest amounts of net weight gain by capillary absorption. In particular, structure C1 which has the youngest application outperformed all but structure B5. The 8 years age difference between the oldest and youngest silane applications may in part explain the observed differences in their performance. Some possible reasons for the difference in performance between structures B5 and C1 include surface preparation, application rates and environmental conditions at the time of application. Unfortunately, there are no historical records which provided details on the above.

**CONCLUSIONS**

Twelve concrete bridge motorway structures from the UK were investigated to assess the long-term performance of hydrophobic treatments. All had been treated with Bimasil 100 whose active chemical content was isobutyl trimethoxy silane. Four of these structures were used as controls and were in an as-built condition. The structures were selected from the same viaduct and the age of the silane treatments at testing, ranged between 12 and 20 years.

The four as-built control structures in general returned similar results in the capillary infiltration testing. All the silane treated samples demonstrated that the silane provided a protective effect, even with the oldest application dating from 1991. The statistical analysis indicated that there is at least 97% confidence that the variance observed between the silane treated and control specimens was due to a residual protective effect.

The difference in age between the silane treatments appeared to affect the results. In particular, structure C1 with the newest silane application outperformed all other structures but B5. The
enhanced performance of an older silane application of exactly the same proprietary product may be attributed to other factors such as quality control, surface preparation, rate of dosage and weather conditions. Unfortunately, no historical records were available to identify the reasons for a difference in performance.

The findings indicate that the long-term residual effect of a silane treatment should be taken under consideration when determining the corrosion management strategy of a reinforced concrete 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 for capillary absorption and water penetration.

REFERENCES

9. Pfeifer D.W. and Scali J. 1981, Concrete Sealers for Protection of Bridge Structures, Department of Transportation, NCHRP 244, Washington DC.


