# A-1-5 Long-term performance of silanes applied on reinforced concrete bridges

**C. Christodoulou**
*AECOM, Colmore Plaza, 20 Colmore Circus Queensway, Birmingham B4 6AT.*

**C.I. Goodier**
*Loughborough University, School of Civil and Building Engineering, Leicestershire LE11 3TU, UK.*

**S.A. Austin**
*Loughborough University, School of Civil and Building Engineering, Leicestershire LE11 3TU, UK.*

**J.R. Webb**
*AECOM, Colmore Plaza, 20 Colmore Circus Queensway, Birmingham B4 6AT, UK.*

**G.K. Glass**
*Concrete Preservation Technologies, University of Nottingham Innovation Lab, Nottingham NG7 2TU, UK.*

*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.*

*KEY-WORDS: Silane, concrete, impregnation.*

## 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 Schueremans 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 this study was to improve the understanding of the efficacy and long-term service life of hydrophobic treatments on full-scale motorway bridge structures. The results help the planning of future protection strategies and aid the whole life cost-benefit decision on whether hydrophobic treatments are good value. In addition, the results 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 [15]. This network can be filled by capillary suction if the surface of the concrete is in direct contact with water.

The relevant transport mechanisms for the ingress of water, gases and ions are [16]:

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 [15-17]. 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 impregnation shave therefore been used in various forms in the construction industry to help prevent water and chloride ingress and their benefits are well documented [18, 19]. They can be divided into three categories: a) coatings, b) pore blockers and c) pore liners (Fig. 1).

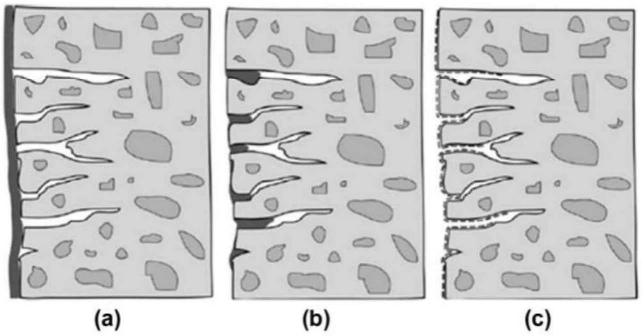


Fig.1. Categories of surface impregnations: (a) coatings, (b) pore blockers and (c) pore liners [20].

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 alkoxysilane is demonstrated by Fig. 2. The alkoxy groups ($CH_3O$) linked to the silicate atom contain silicon-oxygen bonds bond to the silicates present in the concrete. The organic alkylic ($CH_3O$) 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].

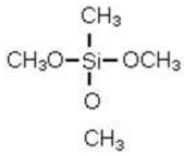

Fig.2. Typical alkyl alkoxysilane molecular structure

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 [21]. 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].

**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.

**Site specimens**

Fig. 3 illustrates a typical sub-structure arrangement of the motorway bridge supporting crossbeams that were examined during this study. Silanes have been applied to a total of 135 similar crossbeams 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.

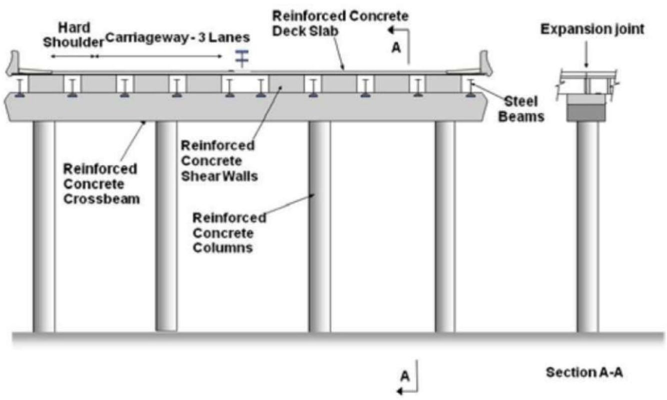


Fig.3. Typical sub-structure arrangement of the UK's Midland Links Motorway Viaducts (MLMV) [22].

The cross-beams were constructed between 1968 and 1970, although the exact date is not known. 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. 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 1). 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.

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

Table 1. Age of cross-beams based on an average construction date of 1969 and age of silane treatment at testing

| Cross-beam Refer-ence | 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 | | | | |

**Laboratory specimens**

Fig. 3 illustrates a typical sub-structure arrangement of the motorway bridge supporting crossbeams that were examined during this study. Silanes have been applied to a total of 135 similar crossbeams 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.

Laboratory specimens were cast to investigate the influence of different surface finishes, water-to cement ratios (w/c) and cement replacements on the performance of silane impregnations. A CIIIA mix design was used with a

50% total content of ground granulated blast furnace slag (GGBS) and w/c ratios of 0.3, 0.35 and 0.4. Furthermore, plywood, steel and hand trowel finishes were also investigated. Four beams were therefore cast for each mix design with plywood panels inserted between the 1075 x 100 x 100mm moulds in order to create the different surface finishes. This work only reports the results for a water-to-cement ration of 0.4; the others are reported elsewhere [23].

From each beam, 12 cores (60mm diameter and 50mm length) were extracted for each type of surface finish examined. The silane impregnation was brush applied at different time intervals in order to also investigate the effect between their performance and age of concrete. In total, 3 different ages were examined, 7 days (single application), 28 days (single application), and 7 & 28 days (double application) (Table 2). The silane impregnation applied was a proprietary water based alkyl alkoxysilane with 20% solid content by weight.

Table 2. Summary of specimens including finish and silane application [23]

| | |
|---|---|
| Tamped Finish: Total of 12 cores. | 3 cores with silane applied at 7 days<br>3 cores with silane applied at 28 days<br>3 cores with silane applied at 7 and 28 days<br>3 control cores |
| Steel Finish: Total of 12 cores. | 3 cores with silane applied at 7 days<br>3 cores with silane applied at 28 days<br>3 cores with silane applied at 7 and 28 days<br>3 control cores |
| Plywood Finish: Total of 12 cores. | 3 cores with silane applied at 7 days<br>3 cores with silane applied at 28 days<br>3 cores with silane applied at 7 and 28 days<br>3 control cores |

**Testing regime**

A very common testing regime to evaluate the performance of silanes is to measure chloride penetration profiles between silane and control treated specimens [14, 24]. One differentiating factor of this work is that this approach was not employed. The site specimens 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.

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 [22, 23]. Thus, measuring the rate of absorption (or sorptivity) can provide useful information on the condition of silane treatments [16, 25].

## RESULTS

The results section is divided in two parts, one for results relating to site specimens and the other for the laboratory specimens.

**Site specimens**

The net weight gain of each specimen and average for each cross-beam's group of specimens after 4 h of testing is shown in Fig. 4. 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.

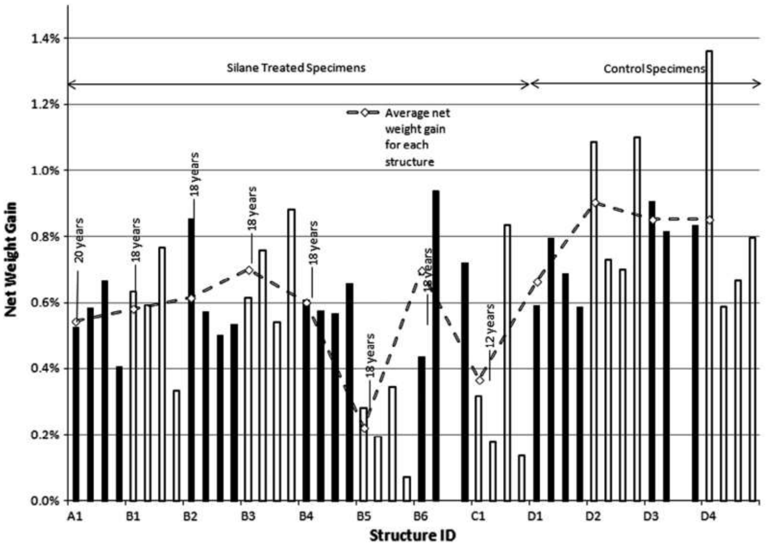


Fig.4. Net weight gain for each specimen and average net weight gain for each cross-beam's group of specimens after 4 h of capillary absorption testing. Note: The change in colour within the vertical bars simply differentiates specimens between different cross-beams [22].

From Fig. 5, it can be observed that specimens from all cross-beams initially had a high rate of water absorption over the first 15 min of testing (0.08 h or 0.29h). 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.

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.

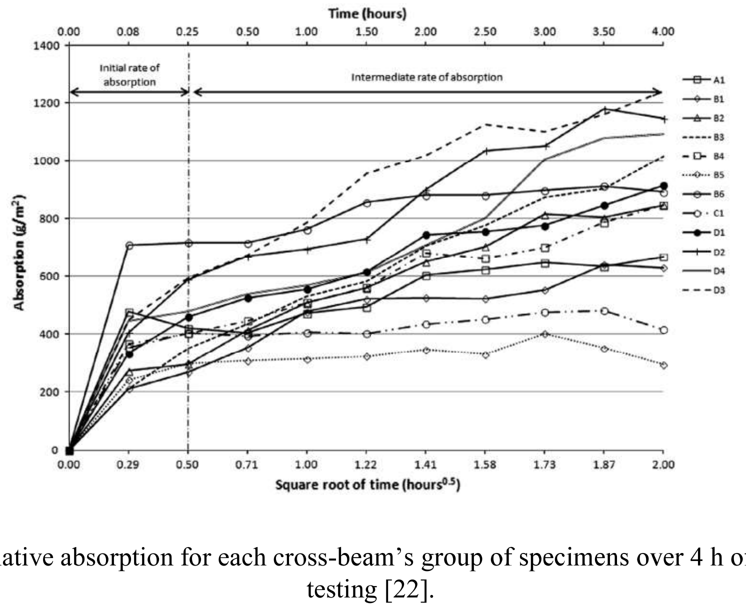


Fig.5. Average cumulative absorption for each cross-beam's group of specimens over 4 h of capillary absorption testing [22].

**Laboratory specimens**

Fig. 6 illustrates the cumulative water absorption of laboratory specimens with w/c 0.4. It can be observed that in all cases, the rate of water absorption of control samples was higher than those of silane treated. This was particularly evident for the specimens with a steel finish. By examining the performance of the control specimens, it can also be observed that the plywood finish resulted in lower rates of water absorption, with the steel finish resulting in the highest.

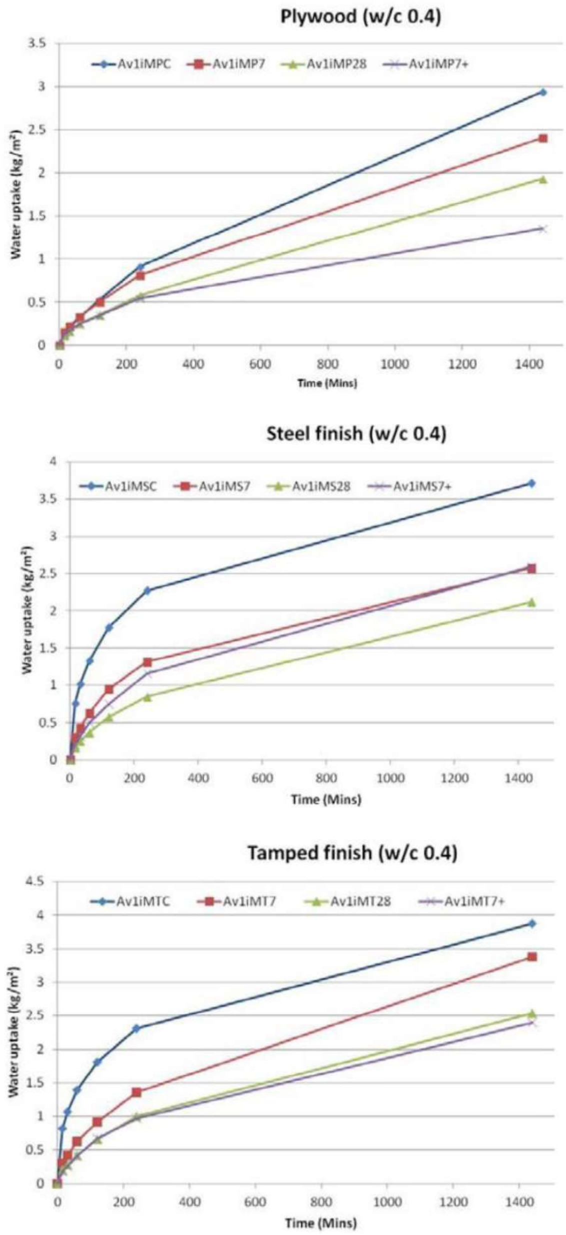


Fig..6. Cumulative absorption for laboratory cured specimens with a w/c 0.4 and different surface finishes (Av1iMTC denotes control specimens, Av1iMT7 denotes silane applied at 7 days, Av1iMT28 denotes silane applied at 28 days and Av1iMT7+ denotes silane applied at 7 and 28 days) [23].

In addition, in all but one cases it was observed that a double application of a silane impregnation offered significantly lower rates of water absorption. This was not the case for the steel finish, where a double silane application had identical performance to a silane impregnation applied at 7 days.

**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 crossbeams include time dependant effects such as weathering, surface preparation, application rates and environmental conditions at the time of application and differences in the quality of the concrete. Unfortunately, no historical records exist providing these details. The variance in their relative performance 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. 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.

For the laboratory-cast specimens, it was observed that plywood finish outperformed all others. This suggests that a plywood finish allows even hydration at the cover zone area. This reinforces the view that the w/c ratio will have a significant effect, particularly for steel and tampered finishes which will require more stringent quality controls. Also, it appears that the application of a silane impregnation at a concrete age of 7 days, provides a lesser reduction in the rate of water absorption than applications at 28 days. The main exception related to specimens with a steel finish where there was hardly any difference between 7 and 28 days. This reinforces the view, that it is generally preferable to allow at least 28 days of concrete hydration before the application of a silane impregnation.

Overall, 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. This is in line with work by Polder and de Vries [24], Schueremans et al [14] and Rodum and Lindland [26]. Their presence and effectiveness over time can be evaluated by extracting cores and testing them in the laboratory by capillary absorption testing.

## CONCLUSIONS

1. 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.

2. In all but one cross-beam, the most recent silane treated specimens outperformed the older silane treated specimens, suggesting a relationship between degradation of the silane impregnation and duration of environmental exposure.

3. Application of silane impregnations after at least 28 days of hardening will result in reduced rates of water absorption as opposed to applications at 7 days only.

4. A double application of silane impregnation is usually beneficial and can further reduce the rate of water absorption.

5. A plywood finish allows for more even hydration and as a result it outperforms other finishes such as steel and tampered. This suggests that a plywood finish may be preferable for fullscale construction as it provides consistency between castings.

## ACKNOWLEDGMENT

The authors would like to thank AECOM, the EPSRC (through the Centre of Innovative and Collaborative Engineering at Loughborough University) and the Highways Agency for their commercial and financial support. This work was funded by the Engineering and Physical Sciences Research Council (Grant No. EP/G037272/1).

## REFERENCES

[1] J. VRIES, R. B. POLDER, *Hydrophobic treatment of concrete,* Constr. Build. Mater. 11 (1997) 259 -265.
[2] P.A.M. BASHEER, L. BASHEER, D.J. CLELAND, A.E. LONG, S*urface treatments for concrete: assessment methods and reported performance,* Constr. Build. Mater. 11 (1997): 413 – 429.
[3] J.L. THOMPSON, M.R. SILSBEE, P.M. GILL, B.E. SCHEETZ, *Characterization of silicate sealers on concrete,* Cem. Concre. Res. 27 (1997): 1561 – 1567.

[4] M. DELUCCHI, A. BARBUCCI, G. CERISOLA, S*tudy of the physico-chemical properties of organic coatings for concrete degradation control*, Constr. Build. Mater. 11 (1997): 365 – 371.
[5] A.M.G. SENEVIRATNE, G. SERGI, C.L. PAGE, *Performance characteristics of surface coatings applied to concrete for control of reinforcement corrosion,* Constr. Build. Mater. 14 (2000): 55 – 59.
[6] A.A. ALMUSALLAM, F.M. KHAN, S.U. DULAIJAN, O.S.B. AL-AMOUDI, E*ffectiveness of surface coatings in improving concrete durability,* Cem. Concr. Comp. 25 (2003): 473 – 481.
[7] H. Y. MOON, D. G. SHIN, D. S.CHOI, *Evaluation of the durability of mortar and concrete applied with inorganic coating material and surface treatment system,* Constr. Build. Mater. 21 (2007): 362 – 369.
[8] M. H. F. MEDEIROS, P. HELENE, *Efficacy of surface hydrophobic agents in reducing water and chloride ion penetration in concrete,* Mat. Struct. (2008): 59 – 71.
[9] D. W. PFEIFER, J. SCALI, 1981, *Concrete Sealers for Protection of Bridge Structures*, Department of Transportation, NCHRP 244, Washington DC.
[10] R. S. C. WOO, H. ZHU , M. M. K.CHOW, C. K. Y. LEUNG, K. JANG-KYO, B*arrier performance of silane-clay nanocomposite coatings on concrete structure*, Comp. Sci. Tech. 68 (2008): 2828 – 2836.
[11] C. C. YANG , L. C. WANG, T. L.WENG, *Using charge passed and total chloride content to assess the effect of penetrating silane sealer on the transport properties of concrete*, Mater.Chem. Phys. 85 (2004): 238 – 244.
[12] M. IBRAHIM, S. AL-GAHTANI, M. MASLEHUDDIN, A. A. ALMUSALLAM, *Effectiveness of concrete surface treatment materials in reducing chloride-induced reinforcement corrosion*, Constr. Build. Mater. 11 (1997): 443 – 451.
[13] M. M. AL-ZAHRANI, S. U. AL-DULAIJAN, M. IBRAHIM, H. SARICIMEN, F. M. SHARIF, *Effect of waterproofing coatings on steel reinforcement corrosion and physical properties of concrete,* Cem. Concr. Comp. 24 (2002): 127 – 137.
[14] L. SCHUEREMANS,D. V. GEMERT, S. GIESSLER, *Chloride penetration in RC-structures in marine environment-Long term assessment of a preventative hydrophobic treatment*, Constr. Build. Mater. 21 (2007): 1238 – 1249.
[15] Concrete Society. Technical Report 31. Permeability testing of site concrete. Surrey (UK), 2008.
[16] J.KROPP, HILSDORF HK. RILEM Report 12. *Performance criteria for concrete durability*. 1995. Oxford (UK): Taylor and Francis.
[17] UNGRICHT H. WASSERHAUSHALT UND *Chlorideintrag in Beton – Einfulls der Exposition und der Betonzusammensetzung.* In: Ph. D. thesis. Universities of Zurich and Basel; 2004. [In German].
[18] P. A. M. BASHEER, L. BASHEER, D. J. CLELAND, A. E. LONG. *Surface treatments for concrete: assessment methods and reported performance.* Constr. Build. Mater. 11 (1997): 413–29.
[19] J. VRIES, R. B. POLDER. *Hydrophobic treatment of concrete*. Constr. Build. Mater. 11 (1997): 259–65.
[20] M. H. F. MEDEIROS, P. HELENE, *Surface treatment of reinforced concrete in marine environment: Influence on chloride diffusion coefficient and capillary water absorption.* Constr. Build. Mater. 23 (2009): 1476–84.
[21] L. BASHEER, D. J. CLELAND, A. E. LONG, *Protection provided by surface treatments against chloride induced corrosion,* Mater. Struct. 31 (1998): 459 – 464.
[22] C. CHRISTODOULOU, C. GOODIER, S. AUSTIN, J. WEBB, G. GLASS, *Long-term performance of surface impregnation of reinforced concrete structures with silane,* Constr. Build. Mater. 48 (2013): 708 – 716.
[23] C. CHRISTODOULOU, H. TIPLADY, C. GOODIER, S. AUSTIN, *Performance of silane impregnants for the protection of reinforced concrete,* Grantham, M., Basheer, M., Magee B. and Soutsos, M. (eds). Concrete Solutions 2014: Proceedings of the International Conference on Concrete Solutions 2014. London: CRC Press, ISBN 978-1-138-02708-4.
[24] R. B. POLDER, H. DE VRIES, *Prevention of reinforcement corrosion by hydrophobic treatment of concrete.* Heron 46 (2001) 227–38.
[25] British Standards Institution, BS EN 13057:2002, *Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance of capillary absorption,* London: BSI; (2002).
[26] E. RODUM, J. LINDL, *Effect of different surface treatment products after 10 years of field exposure,* IN: Proceedings of the 1st International Congress on Durability of Concrete,2012. Trondheim, Norway.