Materials and Structures (2008) 41:59–71
DOI 10.1617/s11527-006-9218-5

ORIGINAL ARTICLE

Efficacy of surface hydrophobic agents in reducing water and chloride ion penetration in concrete

M. Medeiros · P. Helene

Received: 28 April 2006 / Accepted: 6 December 2006 / Published online: 24 January 2007

Abstract Hydrophobic agents are surface protection materials capable of increasing the angle of contact between the water and the concrete surface. For this reason, hydrophobic agents reduce water (in liquid form) penetration in concrete. Therefore, many European construction regulating agencies recommend this treatment in their maintenance policy. Nonetheless, there continues to be a gap in the understanding about which transport mechanisms of the concrete are modified by the hidrophobic agents. The aim of this study was to fill this gap in regards to reinforced concrete structures inserted in a marine environment. To this end, certain tests were used: Two involving permeability mechanism, one determining capillary absorption, and the last, a migration test used to estimate the chloride diffusion coefficient in saturated condition. Results indicated the efficacy of the hydrophobic agents in cases where capillary suction is the mechanism of water penetration (reduced by 2.12 and 7.0 times, depending of the product). However, when the transport mechanism is permeability this product is not advisable. Moreover, it was demonstrated that the chloride diffusion coefficient (in saturated condition) is reduced by the hydrophobic agents, however, the magnitude of this reduction is minor (reduced by 11% and 17%, depending on the product).

Résumé *Les agents hydrofugents sont des matérieux de protection des surfaces capables d'augmenter l'angle de contact entre les molecules de l'eau et la surface en béton. Grâce à cette propriété, ils réduisent la pénetration de l'eau (en forme liquide) dans le béton. Pour cette raison, plusieurs agences européennes de régulation de la construction civil recommandent ce genre de traitement dans leur politique d'entretien. Cependant, il y a encore une lacune dans la compréhension de quels méchanismes de transport du béton sont modifiés par les agents hydrofugents. L'objetif du présent étude c'est de répondre à cette question, dans ce qui concerne les structures en béton renforcées, inserées dans un environnement maritime. Dans ce but, quelques testes ont étés réalisés : deux dirigés au méchanisme de la perméabilité, un visant déterminer l'absorption capillaire et l'autre, un teste de migration, pour estimer le coefficient de diffusion du chloride, dans des conditions de saturation. Les résultats ont indiqué l'éfficacité des agents hydrofugents dans les cas dont la succion capillaire est le méchanisme de pénétration de l'eau (réduction de 2.12 et de 7.0 fois, selon le produit appliqué). Par contre, quand le méchan-*

M. Medeiros (✉) · P. Helene
Department of Civil Engineering, School of Engineering, University of São Paulo, Av. São Remo, 463, ap. 51-B, Butantã, Sao Paulo, SP, Brazil
e-mail: marcelo.medeiros@poli.usp.br

isme de transport est la perméabilité, ce traitement n'est pas indiqué. En plus, c'est démonstré que le coefficient de diffusion du chloride (dans des conditions de saturation) est réduit par les agents hydrofugents, même si l'importance de cette réduction est inférieur (de 11% et de 17%, selon le produit).

Keywords Concrete · Superficial protection · Durability · Service-life · Water-repellent

Mots-clés Béton · Protection superficielle · Durabilité · Vie utile · Hydrofugent

1 Introduction

The rapid deterioration of concrete structures due to reinforcement corrosion has become a growing problem in recent years. Considerable resources are used to repair and rehabilitate deteriorated structures around the world. Consequently, studies [1–5] have been conducted to evaluate the effectiveness of sealers and other concrete surface treatment materials.

Among the various procedures used to protect concrete surfaces, hydrophobic impregnations are the least harmful to essential concrete appearance, mainly inhibiting capillary water absorption of the concrete. Hydrophobic agents are used on vertical surfaces of concretes exposed to the environment.

Jacob and Hermann [6] showed that hydrophobic agents could be effective for at least 10 years when applied to a 6-month-old concrete facade. The authors also showed that longer-term efficiency is very unlikely on young concrete since the hydration process has not concluded. In such cases, new surfaces not humid from the impregnation products can be constantly formed. Consequently, the concrete of the substrate needs to have a minimum age of 28 days or more. Some conditions must be avoided when applying hydrophobic agents: high or low temperatures, high air humidity and high construction element humidity.

Since 1986, a hydrophobic agent named isobutiltrimetoxisilane (100% pure) has been used on the bridges in the United Kingdom to prevent chloride penetration. Many agencies in the United States and the Department of Transportation in Germany have also been using hydrophobic agents on bridges subjected to chloride penetration. Also, it is a maintenance policy of the Ministry of Transportation in The Netherlands to use hydrophobic agents as treatment against the penetration of aggressive substances in concrete [7]. Nevertheless, it is important to develop studies to further understand the specific conditions in which the hydrophobic agents effectively function to prevent inadequate application of this type of product.

The main objective of this study was to clarify which transport mechanisms of the concrete are modified by the hidrophobic agents. This information is extremely important to help the civil engineer specify products of protection for reinforced concrete structures. Moreover, this work presents information on the influence of the number of coatings in the efficacy of protection of the hydrophobic agents.

2 Functioning mechanism

Hydrophobic agents always result in silicon resins that are chemically bound to the concrete base. Currently, the most commonly used are silanes, siloxanes oligomerics and a mixture of these two components.

Silanes are uncoloured hydrophobic treatments chemically known as alkiltrialkoxisilane. Their small molecular structure (1.0×10^{-6}–1.5×10^{-6} mm diameter) allows it to efficiently penetrate even in a highly dense substrate. They are sold in relatively high concentration (around 20%) and chemically react with silica or alumina based materials. Because of their reduced molecular structure, they are very volatile [8].

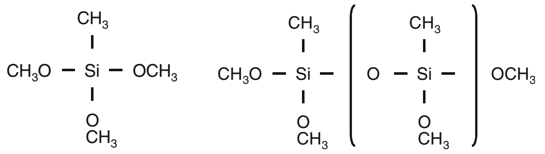
Siloxanes are uncoloured hydrophobic agents chemically known as alkilalkoxisiloxanes. Although their molecular structure is relatively large (1.5×10^{-6}–7.5×10^{-6} mm diameter) compared to silanes, siloxanes also efficiently penetrate the substrate of concrete. The chemical reaction with silica and alumina guarantees the high efficacy and durability of the hydrophobic concrete surface. This hydrophobic agent has a durability of over 10 years and cannot be easily removed. They can be applied on humid surfaces and are less volatile than silanes [8].

In general, the performance of hydrophobic agents is not consistent due to their solid content (varying from 5% to 40%) and the porosity of the substrate to be protected. Basically, higher solid contents are needed for high porosity surfaces [8].

Chemically, silanes are formed of small molecules that have one silicon atom, as shown in Fig. 1a. Siloxanes are short chains of a few silicon atoms in which the molecules have alkoxy groups (organics) connected to the silicon atom (Fig. 1b) that react to the silicate of the concrete, forming a stable bond (Fig. 2) [7].

Silanes, siloxanes and similar substances function by penetrating concrete pores, forming a hydrophobic layer, thus inhibiting penetration by water in liquid form (which may be contaminated with chloride), but allowing water vapour to enter and exit, allowing concrete to ''breathe'' freely [9].

It should be noted that, depending on exposure conditions, porous construction materials (such as concrete) absorb liquids (such as water) by capillary forces. The liquid viscosity, the angle of contact between the liquid and the material, and the porous radius, influences these forces. In a given concrete sample, when the pore structure and water viscosity are constant, then, only the angle of contact (α) can be changed. A small angle of contact (<90°) indicates a molecular attraction between the liquid and the substrate and, in this case, the liquid particles on the concrete surface tend to disperse and are absorbed. If attraction between the solid and the liquid is minor, the angle of contact is larger than 90° and the liquid drops remain as spheres on the concrete surface. In such cases, the material is called hydrophobic. Both cases are shown in Fig. 3. It should be noted that this product is not considered a type of paint, but an impregnation agent [10].



(a) Silane **(b)** Siloxane

Fig. 1 Molecular structure of silane (**a**) and of siloxane (**b**) [7]

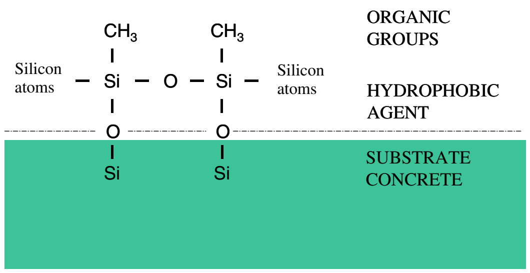


Fig. 2 Chemical bond of the hydrophobic agent with concrete [7]

3 Requirements for hydrophobic agents

It is known that steel corrosion is dependent upon available humidity and oxygen; therefore, any reduction of their penetration in concrete will also reduce the kinetics of the corrosion process if it has already begun. Consequently, one of the most important roles of hydrophobic agents is the reduction of concrete water absorption. It is also critical that this reduction be effective for many years; as a result, it is essential that the hydrophobic agent sufficiently penetrate the concrete [11].

The hydrophobic agent is affected by ultraviolet radiation. However, only the surface is affected since UV rays cannot penetrate con-

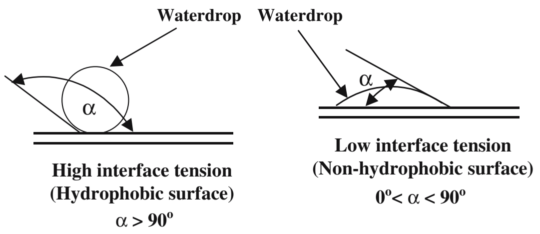


Fig. 3 Interaction between water and hydrophobic and non-hydrophobic concrete surface [7] and [10]

crete. As a result, a minimum penetration depth of the hydrophobic agent on the substrate is essential for obtaining a highly effective water repellent effect. It is easy to achieve a sufficient penetration depth on porous substrates such as ceramic bricks; however, the same does not apply to concrete because of its lower porosity as compared to ceramic bricks [7]. Also, the production of denser and more resistant concretes has required products that can easily penetrate in the reduced pore structure of concrete.

Vries et al. [11] recommend specifications for surface protection materials:

- Less than 20% water absorption for concrete with no protection;
- Minimum penetration depth equal to 2 mm;
- Water evaporation has to be higher than 60% of concrete without the protection.

The NHRP Report 244 of the "National Cooperative Highway Research Program" from the USA recommends the use of surface protection systems that reduce water absorption by 75%, compared to concrete without the protection. The "German Committee for Reinforced Concrete" specifies absorption reduction by 50% [12] and [13].

4 Experimental procedure

4.1 Materials

The concrete of the substrate was produced with a Brazilian Portland cement designated CPII E-32, which is equivalent to ASTM C 595 [14] (Slag-modified Portland cement). This cement has blast furnace slag addition and is one of the most widely used cements in the state of São Paulo, Brazil. Coarse aggregate was a dense, crushed granitic stone. Fine aggregate was natural siliceous sand.

The proportion of the concrete used in this study was of 1.0 (Portland cement): 1.8 (fine aggregate): 2.7 (coarse aggregate) and the water/cement ratio was equal to 0.52. This substrate had compressive strength of 32 MPa after it was cured in water for 28 days. The mortar content (α) was of 51%, and the cement consumption (C) was equal to 358 kg/m^3.

The surface hydrophobic agents used are silane/siloxane-based products. One was dispersed in water and the other in solvent. Information on these materials is shown in Table 1.

Before the application of the protective products, the specimens were dried in a 100°C ventilated oven until constant mass. They were then kept in the laboratory to cool down before the application of the products.

4.2 Test procedure

The specimens used as substrate for the application of the hydrophobic agents were cylindrical (10 cm diameter and 20 cm length) and were cured for 91 days in a wet chamber with relative humidity of 100%. This curing period corresponds to a stabilization level of the graphic compressive strength versus time, as shown in Fig. 4. The curing period was chosen to eliminate the influence of an additional curing that could occur in the specimens exposed to water. This could especially affect the control series.

The wait-time between applications was of 6 h, according to manufacturer guidelines. After applying, tests were executed 7 days afterwards. For all tests, 3 specimens were used in each case studied.

All the relevant information about the tests conducted in this study is mentioned below.

Table 1 Data on products studied

Product	Specific gravity (g/cm^3)	Viscosity (Temp. = 20°C)	Active substance content	Setting time (h)
Silane/siloxane dispersed in water	1.0	10 CPs	22% bymass	2 a 6
Silane/siloxane dispersed in solvent	0.78	8 CPs	Not declared	2 a 6

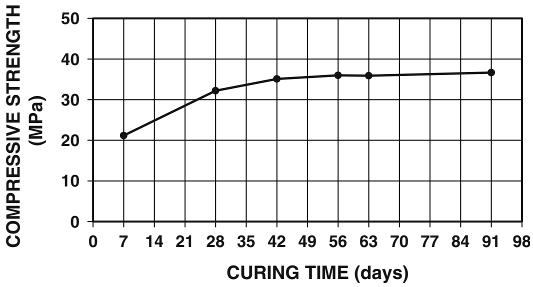


Fig. 4 Increase in the compressive strength of the concrete (1:4.5; α = 51% eC = 358 kg/m^3)

4.2.1 *Immersion absorption*

This test was conducted in accordance to the standard ASTM C642/97 [15]. Two coats of silane/siloxane based hydrophobic agents were applied to the specimens.

The water level in the test recipient was fixed at 25 cm. This assured that the variation of the water pressure on the specimen was between 250 kgf/m^2 (on the base) and 50 kgf/m^2 (at the top), as shown in Fig. 5.

An additional procedure was used after the immersion, consisting of maintaining the specimens in a controlled environment in which the relative humidity was 70 ± 3% and the temperature was 21 ± 2°C. The intention was to investigate whether the product prevents water from leaving the concrete. This situation is not suitable for reinforced concrete structures since water is kept inside the concrete.

4.2.2 *Capillary water absorption*

This test was conducted in accordance to standard DIN 52617/87 [16]. Cylindrical specimens of 20 cm in height and 10 cm in diameter were used. The lateral side of the specimens was sealed with silicon up to 3 cm in height so that only one circular face of the specimen was exposed to water.

The weight of specimens was monitored in a period of time (0–96 h) along the contact with the water.

The number of coatings of protection materials varied from 1 to 4, compared to the control series (without surface treatment).

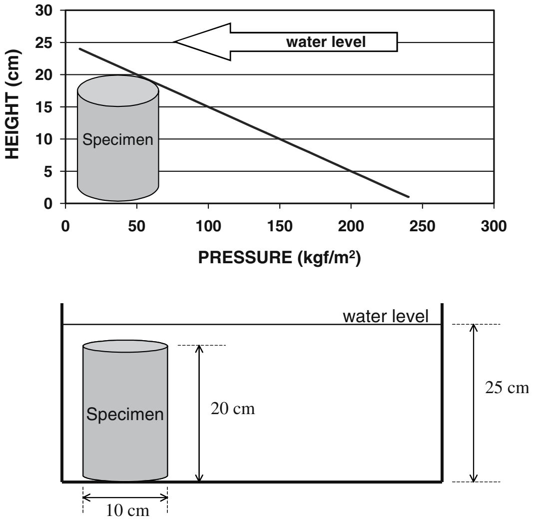


Fig. 5 Variation of pressure in the specimen in immersion absorption test

4.2.3 *Pipette absorption test*

A similar configuration to Karstens' permeability test was adopted [17]. Each cylindrical specimen (10 cm diameter and 20 cm length) was cut into 2 slices with 5 cm in width each from the central nucleus of the original specimen. Therefore, slices of concrete with 10 cm in diameter and 5 cm in length were obtained. The hydrophobic agent was applied on one of the circular faces, and the test was then conducted. The apparatus used has a different shape from the one Karstens initially proposed because it is only appropriate for horizontal surfaces. The apparatus was fixed on the concrete surface using silicon as shown in Fig. 6. The volume of water absorbed was measured as a function of time.

For this test, the pressure varies with time. It is equal to 120 kgf/m^2 in the beginning of the test and, as the water level drops, it can be reduced until it equals zero.

4.2.4 *Estimation of chloride diffusion coefficients*

The method used to estimate the chloride diffusion coefficient was in accordance with the procedure described by Luping; Nilsson [18]. It is based in measuring the depth of colour change of a surface of concrete broken in the direction of

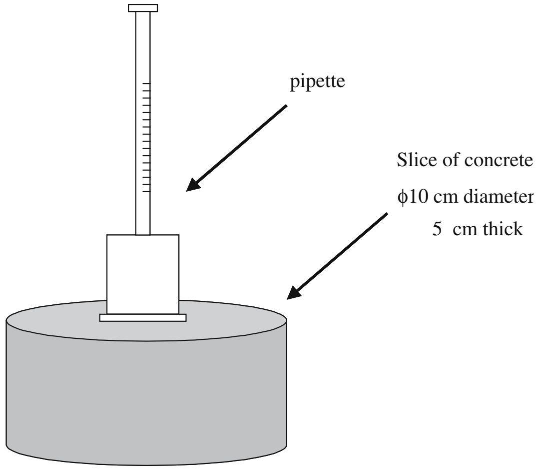


Fig. 6 Apparatus of pipette absorption test attached to concrete slice

the chloride flow using a 0.1 M $AgNO_3$ solution [19] and in the application of the Eq. 1 in a migration test.

$$D = \frac{RT}{zFE}\frac{x_d - a x_d^b}{t} \qquad (1)$$

where, D is diffusion coefficient (cm^2/s), R is gas constant (J/molK), T is temperature (K), z is valency of the ion, F is Faraday constant (J/Vmol), E is field density (V/m), x_d is penetration depth (m), t is test time (s), a and b are test constant.

For chloride ion $z = -1$, when $E = -600$ V/m and $T = 298$ K. Then, $a = 1.061$ and $b = 0.589$.

The model used is based on Fick‘s second law because the test is developed in a non-steady-state condition.

Slices of 50 mm in thickness were obtained by sawing the mid-portion of the cylindrical specimen (10 cm diameter and 20 cm length). Then, the slices were kept in an oven at 100°C until obtaining constant mass. Then, the surface protection materials were applied on one of the circular surfaces of specimens. Seven days after the application of protection, the specimens were saturated using the procedure of ASTM C 1202/97 [20].

The 50 mm thick slice was placed between two acrylic cells. One cell was filled with a 0.3 N NaOH solution and the other with a 3.0% NaCl solution. The cells were connected to a 30 V power source and maintained for 30 h. The schematic presentation of the accelerated chloride migration test cell is illustrated in Fig. 7.

5 Test results and discussion

5.1 Immersion absorption

The results shown in Fig. 8 indicate that the silane/siloxane dispersed in water did not improve the capacity for preventing humidity from entering the concrete. The silane/siloxane dispersed in solvent delayed the penetration of water in the beginning; however, after 96 h, the same saturation degree as in the control was observed.

Therefore, hydrophobic products are not suitable when a certain reinforced concrete structure is subjected to water pressure of 250 kgf/m^2. This is well illustrated in Fig. 8, where it can be seen that the results from the curves in the graphic for the concretes with and without the treatment dispersed in water were statistically identical. The concrete treated with the hydrophobic dispersed in solvent had a result statistically equal to the control concrete after only three days of immersion.

It was observed that the amount of water that penetrated the control specimens and the specimens treated with two applications of silane/siloxane based hydrophobic agents at the end of the immersion absorption test was practically the same (Fig. 7). Consequently, the loss of water to the environment (relative humidity = 70 ± 3%

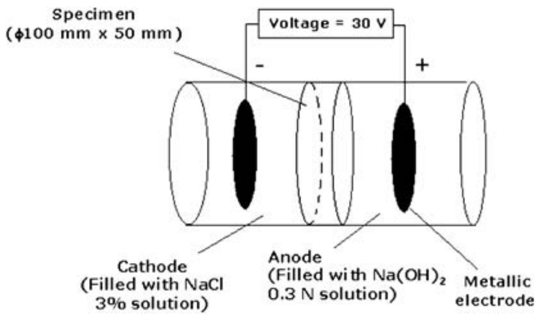


Fig. 7 Experimental arrangement of accelerated chloride migration test cell

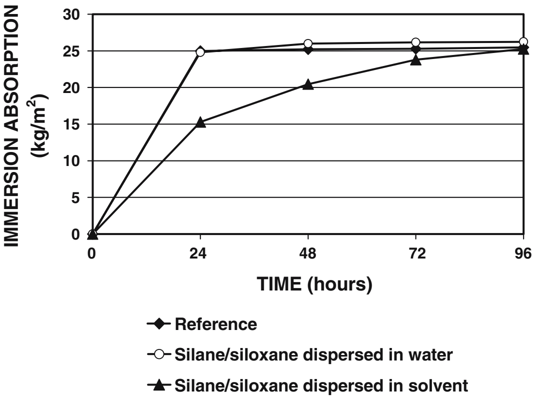


Fig. 8 Immersion absorption of untreated and treated concrete surfaces, applying two coatings of the hydrophobic agents

and temperature = 21 ± 2°C) was also compared, as shown in Fig. 9.

It was verified that the amount of water lost to the environment is practically the same in all cases: the control and the specimens treated with silane/siloxane based hydrophobic agent dispersed in water and in solvent.

This indicates that the silane/siloxane products used in this study are in accordance with the guidelines shown by Vries et al. [11], in which the water evaporation for the concrete treated with the hydrophobic agent has to be ≥60% of the same concrete with no treatment.

This confirms that the hydrophobic agents do not obstruct the pores of the concrete surface, allowing the water in vapour form to enter and exit the treated concrete.

5.2 Capillary water absorption

Figure 10 shows the results of the capillary water absorption test, indicating that the silane/siloxane based hydrophobic surface agents have a significant effect when the water penetrates by capillary suction. Moreover, the treatment with the hydrophobic agent dispersed in solvent was statistically more efficient than the one dispersed in water as shown in Fig. 10. The results were statistically analyzed using the ANOVA-TWO WAY models. The superiority of the silane/siloxane dispersed in solvent is explained by the lower viscosity of this product (Table 1). The liquid with lesser viscosity tends to be absorbed more easily by the pores of the concrete and provides a more efficient protection.

Further evidence of the efficiency of hydrophobic surface agents tested in this work is represented in Table 2. This table presents results of sorptivity, which is the volume of water that penetrates per unit of area and time. In the present work, the time adopted for the calculation of sorptivity was 24-h, the most widely adopted time period in the field. Sorptivity, S, is obtained empirically from the slope of the cumulative absorbed volume of water per unit area of inflow

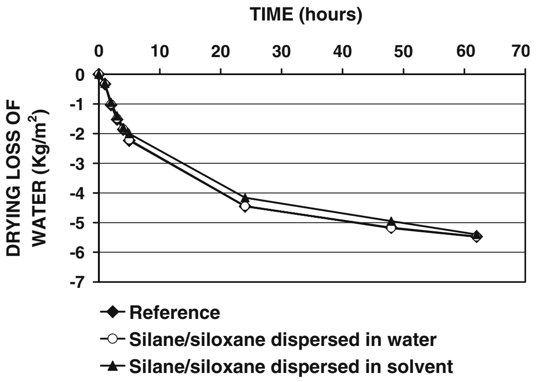


Fig. 9 Drying loss of water X Time (saturated specimens conditioned in relative humidity = 70 ± 3% and temperature = 21 ± 2°C)

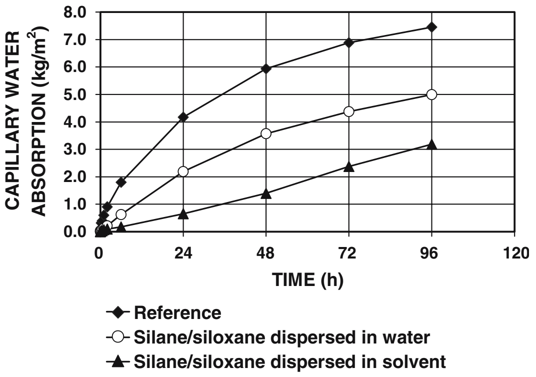


Fig. 10 Capillary water absorption of untreated and treated concrete surfaces, applying two coatings of the hydrophobic agents

Table 2 Sorptivity in treated and untreated concrete specimens (measuments for 24 h)

Hydrophobic agente	Sorptivity (mm/h$^{1/2}$)
None (reference)	0.8045
Silane/siloxane dispersed in water	0.3786
Silane/siloxane dispersed in solvent	0.1149

surface versus square root of time. Then, the data in Fig. 10 were used to calculate the sorptivity of the treated and untreated concrete using Eq. (2).

$$\text{Sorptivity} = \frac{V_w}{A_c\sqrt{t}} \tag{2}$$

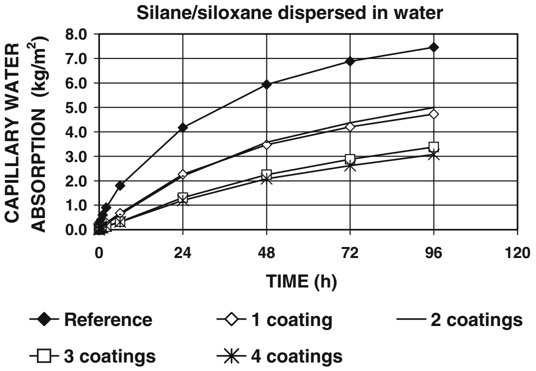
where, V_w is volume of water absorbed by the specimen (mm^3), A_c is the cross-sectional area of each specimen (mm^2) and t is time of exposure (h).

Table 2 indicates that use of surface hydrophobic agents greatly reduces sorptivity. The silane/siloxane dispersed in water reduced the sorptivity by 2.12 times and the silane/siloxane dispersed in solvent reduced the sorptivity by 7.0 times. This result is explained for the rise of the angle of contact between water drops and the treated concrete surface. These results clearly show hydrophobic agents reduce capillary water absorption potential.

This information is critical since water is the main vehicle for the penetration of aggressive ions, originating from exposure to sea and/or an industrial environment.

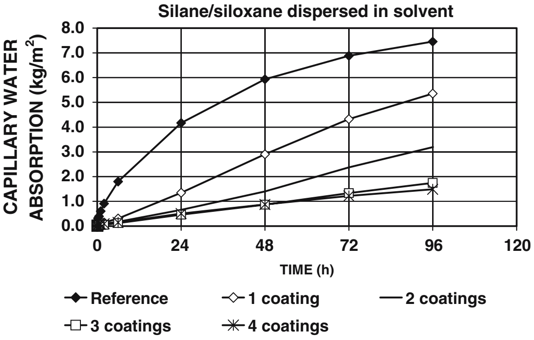
Figure 11 and Fig. 12 show the capillary water absorption curves in a period of time for different number of coatings of the silane/siloxane based hydrophobic agents dispersed in water and in solvent, respectively.

It was verified, with 99% reliability, that water absorption decreased as the number of coatings increased. The respective water absorption reduction rates are also shown in Fig. 11 and Fig. 12.



Absorption reduction	
Number of coatings	Reduction rate (%)
1	37
2	33
3	55
4	59

Fig. 11 Number of coatings X Capillary water absorption (silane/siloxane dispersed in water)



Absorption reduction	
Number of coatings	Reduction rate (%)
1	28
2	57
3	77
4	80

Fig. 12 Number of coatings X Capillary water absorption (silane/siloxane dispersed in solvent)

It is important to emphasize that two coatings of the hydrophobic agent dispersed in water presented no statistically significant advantage compared to one coating of the same agent. Moreover, three and four coatings of this product demonstrated the same results as seen in Fig. 11 and Fig. 12 Therefore, it can be concluded that more than three applications of this hydrophobic agent provides no advantage. Table 3 shows the number of applications required for each hydrophobic agent to be within the water absorption decrease limit guidelines established in the literature.

The silane/siloxane dispersed in water used in this study was in accordance only with the

Table 3 Number of coatings required to follow water absorption limit guidelines established in literature

Limit	Information source	Material	
		Silane/siloxane dispersed in water	Silane/siloxane dispersed in solvent
50%	German Commitee for Reinforced Concrete	3	2
75%	The US NHRP Report 244: "National Cooperative Highway Research Program"	>4	3
80%	Vries et al. [11]	>4	4
		Number of coatings	

"German Committee for Reinforced Concrete" limit, which is the least demanding limit found in the literature. It is possible that an increase in the number of applications could result in improved effectiveness consistent with those found in the literature. However, more than 4 applications were considered impractical and costly.

The silane/siloxane dispersed in solvent is in accordance with all guidelines found in the literature, as can be observed in Table 3.

5.3 Pipette absorption test

Figure 13 shows the results of this test: both silane/siloxane hydrophobic surface agents are highly effective in inhibiting water penetration in concrete; however, the hydrophobic agent dispersed in solvent was more effective than all results presented previously.

Figure 14 and Fig. 15 show the permeability curves in a period of time for different number of coatings of the hydrophobic agents dispersed in water and solvent, respectively.

As shown in the capillary water absorption results, the number of applications increases the material's hydrophobic capacity. Based on the ANOVA TWO-WAY statistic model, this can be stated with an accuracy of 99%. The hydrorepellence effect of the first application could make the penetration of other coatings of repellent agents difficult, but the results show that the hydrophobic agent can still penetrate the substrate after the first application.

For both hydrophobic agents the first coating is the most important since it has the highest surface repellent capacity. The other coatings did not proportionally increase the repellent capacity when compared to the first. Similar results were presented by Nwaubani et al. [21] in a study on the treatment of stone surfaces.

The results show that both hydrophobic agents have the capacity of considerably inhibiting water

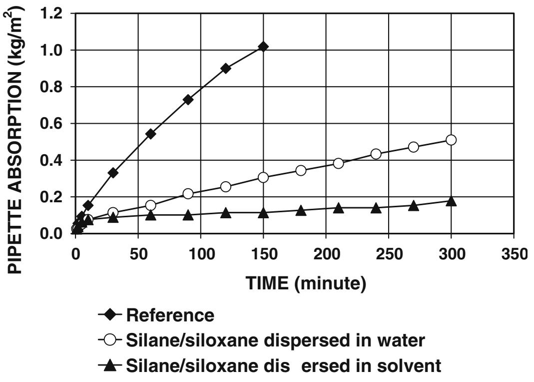


Fig. 13 Pipette absorption of untreated and treated concrete surfaces, applying two coatings of the hydrophobic agents

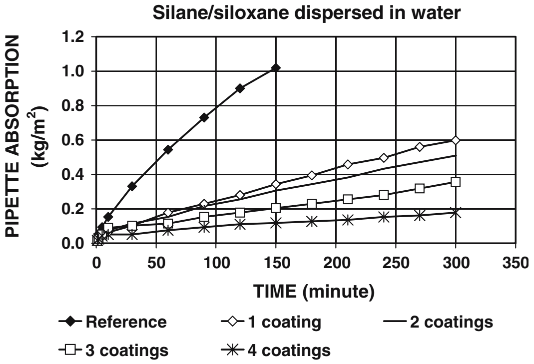


Fig. 14 Number of coatings X Pipette absorption (silane/siloxane dispersed in water)

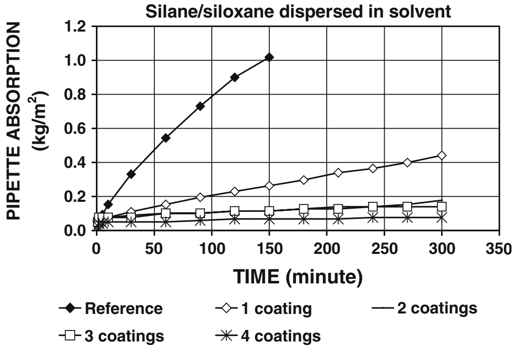


Fig. 15 Number of coatings X Pipette absorption (silane/siloxane dispersed in solvent)

penetration when water pressure is lower than 120 kgf/m^2 (such as in this test procedure), the equivalent of a 3.5 cm water level.

5.4 Chloride diffusion coefficients

Figure 16 presents the results of a chloride diffusion coefficient determined by the method proposed by Luping; Nilsson [18].

The results indicate that the application hydrophobic agents on the concrete surface cause the reduction of the chloride diffusion coefficient. However, the magnitude of this reduction is small (11% and 17% for the silane/siloxane dispersed in water and in solvent, respectively). It should be noted that this type of result is only related to the penetration of chloride ions by diffusion (saturated concrete), excluding chloride penetration by absorption of contaminated water.

Therefore, this type of surface treatment does not primarily inhibit chloride ion penetration. The main effect is to reduce the water penetration, which may be contaminated with chloride ions.

It is important to verify again that the silane/siloxane dispersed in solvent presented efficiency greater than the silane/siloxane dispersed in water. The greatest penetration resulted from the lower viscosity of the silane/siloxane dispersed in solvent (Table 1).

5.5 Comparison of results between test types

Some noteworthy findings were obtained comparing results from various test performed in this study.

Although the humidity penetration mechanism for the immersion test and the pipette absorption test is the same (permeability), the correlation of the results between both tests is not considered very high ($r^2 = 0.64$), as shown in Fig. 17.

As expected, the correlation between the capillary absorption test and the immersion test was not high ($r^2 = 0.52$). This can be explained by the fact that it is the capillary suction that controls the capillary absorption test, whereas for the second test, it is the permeability. Figure 18 was used to illustrate these statements. Therefore, the mechanisms can be considered different.

The pipette absorption test and the capillary absorption test presented the highest correlation between the results, with $r^2 = 0.75$ (Fig. 19). This result is surprising since the pipette absorption test is controlled for the permeability, whereas the capillary water absorption test is controlled for the capillary suction.

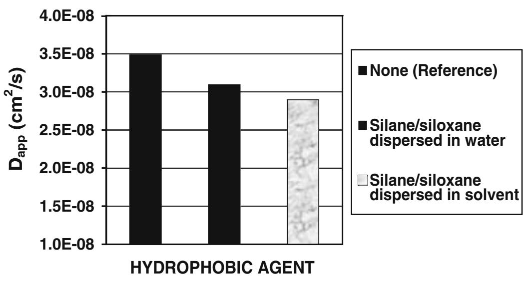


Fig. 16 Apparent chloride diffusion coefficients (Dapp) ofuntreated and treated concrete surfaces

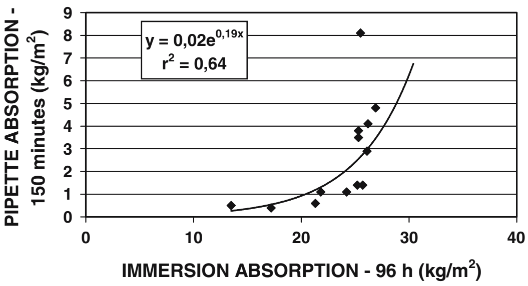


Fig. 17 Relationship between immersion absorption (96h) and pipette absorption (150 min)

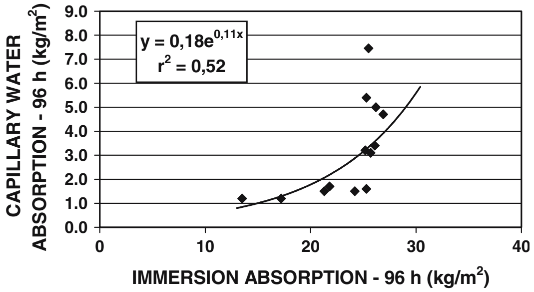


Fig. 18 Relationship between immersion absorption (96h) and capillary water absorption (96 h)

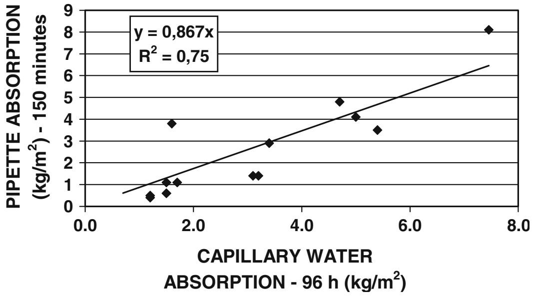


Fig. 19 Relationship between capillary water absorption(96 h) and pipette absorption (150 min)

This leads to the conclusion that the capillary water absorption results are very similar to the permeability test results with pressure of 120 kgf/m^2 (pipette absorption).

6 Conclusions

The results showed that the surface hydrophobic agent is efficient in the cases in which the water penetration mechanism is the capillary suction. Both hydrophobic agents were in accordance with the "German Committee for Reinforced Concrete" guidelines, in which absorption must to be reduced by least 50% in relation to the control concrete.

In relation to the number of applications, the silane/siloxane dispersed in water was not in accordance with the National Cooperative Highway Research Program and Vries et al. [11], which the most rigorous criteria.

When the concrete is exposed to water under pressure, the immersion test showed that the hydrophobic agents are not efficient when pressure is equal to 250 kgf/m^2. However, the pipette absorption test showed that the hydrophobic agents are efficient when concrete is exposed to a water level of 12 cm (120 kgf/m^2). It is noteworthy that this product is permeable. Although it can inhibit water penetration it cannot effectively substitute for a waterproofing product.

Therefore, it was concluded that, in general, the surface hydrophobic agents do not have sufficient capacity for stopping water penetration under pressure. This type of product is recommended for the restriction of the water absorption of parts of concrete with vertical or inclined surfaces that are submitted to rainwater, for example.

It was also verified that the silane/siloxane based hydrophobic agents do not prevent water from evaporating, thus confirming that the hydrophobic treatment allows water vapor to enter and exit concrete.

The results indicate that the use of surface hydrophobic agents should only be used when the water exposure conditions are well known. It needs to be verified whether the structure is being submitted to water permeability or capillary absorption. If there is water pressure, this pressure needs to be considered and, in general, another option is recommended.

It is noteworthy that the efficiency of the treatment increases with the number of applications of a silane/siloxane based hydrophobic agent. This was statistically verified from the ANOVA-TWO WAY statistic models and can be stated with an accuracy of 99%. It was also verified that it is the first coating of the silane/siloxane agent that provides concrete with a high hydrophobic capacity.

The silane/siloxane dispersed in solvent presented higher efficiency in decreasing water penetration in comparison to the silane/siloxane dispersed in water. This result is explained by the greatest penetration capacity in the concrete caused by the lower viscosity of the silane/siloxane dispersed in solvent.

In regards to the influence of the hydrophobic treatment in the chloride diffusion coefficient, it can be said that the hydrophobic agent reduces the diffusion coefficient, however, the magnitude of this reduction is minor (11% and 17% for the silane/siloxane dispersed in water and in solvent, respectively).

Therefore, it can be said that the main effect of a hydrophobic treatment is the reduction of the sorptivity of the concrete (reduced by 2.12 and 7.0 times for the silane/siloxane dispersed in water and in solvent, respectively).

It should be pointed out that although the hydrophobic agent does not markedly influence the chloride diffusion coefficient (in saturated concrete), these materials effectively inhibit water penetration (that it can be contaminated with chloride ions) by capillary suction. It is important to remember that, according to Kropp [22], the capillary suction mechanism is one of the main factors responsible for the chloride contamination of the reinforced concrete in non saturated conditions.

Consequently, it can be concluded that the hydrophobic agents are efficient only in non-saturated conditions where the main transport mechanism is capillary suction. In saturated conditions and in water under pressure conditions, this type of product does not present satisfactory effectiveness.

The results showed that the pipette absorption test and the capillarity water absorption test presented a satisfactory correlation ($r^2 = 0.75$) although the water penetration mechanism in each of the tests is not the same.

Another important factor that needs to be better understood is the efficacy of the durability of the agents used. The authors are studying this aspect and results will be published in the near future.

Acknowledgements The authors would like to thank the Polytechnic School of University of São Paulo (POLI-USP) and FAPESP (Research Support Foundation of the State of São Paulo) for making this study possible by financially supporting it. We also thank Jim Hesson for revising the text.

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