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Water repellent surface impregnation for extension of service life of reinforced concrete structures in marine environments: The role of cracks

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ABSTRACT

The enhancement of long-term durability of marine structures is a matter of interest to many researchers. The study presented in this paper examines the effectiveness of a water reducer and chloride barrier surface impregnation of the concrete cover of reinforced concrete (RC) structures, exposed to a marine environment. Specific focuses is on how surface cracks created (1) before impregnation and (2) after impregnation, affect the effectiveness of the surface treatment. The experiments are conducted in an environment which is as close as possible to the real humid subtropical marine environment.

A series of reinforced concrete (RC) prisms and concrete cylinders, each treated with various commercial surface impregnation agents, were exposed to cyclic sea water shower under an outdoor environment to accelerate the dry/wet cycles for 1 year. Six types of surface impregnation agents, including four types of silane-based water repellent agents and two types of sodium silicate-based pore blockers (water–glass) were applied. Three types of RC prisms were prepared to simulate the different cracking possibilities, which may occur in surface impregnated concrete structures, during their service life. No cracks were introduced in the first prism group, while cracks were introduced before and after surface impregnation, in the second and third groups, respectively. The time-dependent water absorption of all specimens was monitored during exposure to the dry/wet cycles. Finally the specimens were split open to measure the penetration depths of the surface impregnation agents and the chloride penetration profiles. The areas with corrosion evident in the steel reinforcement in the RC prisms were also measured.

Sodium silicate-based pore blockers were found to be inefficient in preventing chloride penetration of concrete under simulated marine exposures. The long-term efficiency of water repellent agents used for surface impregnation was found to be highly dependent on the type of agent and whether impregnation was carried out before or after crack formation.

1. Introduction

Chloride-induced corrosion of steel reinforcement is a major concern regarding the durability of reinforced concrete (RC) structures exposed to marine environments. In practice, the time taken for steel corrosion to occur in marine RC structures is short, in comparison with their designed service life. Thus, there is often a need for supplementary measures to protect such concrete or/and steel reinforcement in such an aggressive environment. Surface treatment is commonly used to improve the resistance of such concrete cover against the penetration of aggressive substances, both in new structures and existing structures, whenever the need for further protection becomes obvious. For instance, the surface of repaired structures is sometimes treated in order to extend the service life of repair measures [1,2].

In general, protective surface treatment can be classified into three categories: (a) surface coating, whereby in most cases a thin or thick polymer film is applied, (b) sealing, whereby the surface near the pores is blocked, and (c) surface impregnation, whereby the surface near zone is impregnated with a water repellent agent, leaving the pores open. Recently there has been an increasing acceptance of surface impregnation materials for buildings and highway bridges.

The protective surface treatment wins favor in that it does not interrupt construction work, and is hence cost-effective [3,4]. In recent years, two types of surface treatments are frequently used in the construction industry. One is a silane-based water repellent agent and the other is a sodium silicate-based pore blocker, which is a Sealant. Both can penetrate concrete pores and react with hydrated cement particles. In the former case, the reaction product, i.e. a silicon resin, can form a hydrophobic lining on the pore walls. The achievable penetration depth in concrete mainly depends on four factors: the type of hydrophobic agent applied, the water to

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cement ratio of the concrete substrate, the initial moisture content and the surface preparation of the concrete substrate [5–12]. In the latter case, the reaction product can block the pores, leading to a modest strengthening, but the penetration depth is usually minimal, apart from when the concrete is extremely porous [2].

Up to now test results on the performance of sodium silicate impregnated concrete is limited, and therefore little is known about its influence on the carbon-dioxide or chloride penetration resistance. In contrast, since 1980s, much research has been conducted on the durability of concrete, impregnated with silane-based water repellent agents. An early review of the assessment methods and reported performance of such hydrophobic impregnation and the corresponding mechanisms are found in Refs. [13,14]. Extensive laboratory tests [15–18] have verified that hydrophobic impregnation can establish an efficient barrier for concrete and postpone the corrosion initiation and reduce the corrosion rate of internal steel reinforcement. Some encouraging results from long-term field exposure tests have also been recently reported [19–21]. Although some of the recent studies indicated that hydrophobic impregnation may only have a minor influence on the diffusion mechanisms of chloride ions in concrete [22,23], its validity in decreasing the internal humidity and significantly suppressing the capillary water absorption has been well recognized [23–25]. The above properties, most certainly can be considered to improve the durability of marine RC structures, since the supply of water and chloride is a key factor influencing the corrosion of internal steel reinforcement.

In a structural design, the existence of cracks is usually allowed in flexural RC members. These cracks, however, may serve as easy paths for water penetration and the chloride ions dissolved in water. It is of utmost importance to know exactly when surface impregnation treatment is most effective: that is whether the water repellant agents or sealants are effective in concrete with cracks, which exist at the time of impregnation or which are formed after impregnation.

However, despite the above-reviewed extensive research work, to date little is known of the extent to which the presence of cracks in concrete structural elements, occurring in surfaces (1) before application of sealants or other surface treatments (2) after application of sealants or other surface treatments, influence the long-term efficiency of these measures and the subsequent durability of structures in a marine environment. Recently, Tittarelli and Moriconi [26] applied one type of silane-based hydrophobic admixture to concrete and studied its influence on the corrosion of reinforcing steel. They found that the addition of silane substantially reduced the rate of corrosion of steel reinforcement in un-cracked specimens. However, it was also found that the corrosion of steel reinforcement in cracked concrete hydrophobic specimens was unexpectedly more severe. The reason suggested was that oxygen diffused faster through the open concrete porosity in the hydrophobic concrete, as compared to the slow diffusion through the water filled pores of the saturated concrete. Concerning this situation, it must be mentioned that the crack width in their study was 1 mm, which is unrealistic in RC structures under service conditions. It is also important to note that Tittarelli and Moriconi added aqueous silane emulsion of an alkyl-triethoxy-silane to the fresh concrete mix; meaning that they had prepared an integral water repellent material. Hence their findings cannot be compared directly with observations found on surface impregnated water repellent concrete in the real case.

In order to avoid misapplications, further studies, under realistic service conditions, are needed to understand how the chloride penetration of surface impregnated concrete and the subsequent corrosion of internal steel reinforcement and durability of structures in a marine environment are influenced by the presence of cracks. Therefore, this project aims to study the long-term effectiveness of different surface impregnation materials after treatment of cracked and un-cracked concrete specimens during a well-controlled outdoor exposure program and to determine which surface treatment material provides the most significant improvement in the durability of marine RC structures with and without cracks.

2. Experiment

2.1. Materials

For the experiment, concrete was made with a cement content of 248 kg/m^3, a water–cement ratio (*W/C*) of 0.68, and a fine-to-coarse aggregate ratio of 0.49. The compressive strength of concrete at 28 days curing was 34.0 MPa. A relatively high *W/C* ratio was chosen for several reasons. Firstly, the penetration depth of silane-based water repellent agents increases with the *W/C* ratio [7,10]. A relatively high *W/C* ratio results in a deeper penetration and therefore provides a better comparison with the performance of different surface impregnation materials. Secondly, in practice, concrete, which needs protection or repair usually has poor quality owing to such as an error in *W/C* at the construction site. Thirdly, a high *W/C* ratio is better suited to show how different surface impregnation materials influence the corrosion of internal steel reinforcement, within a relatively short exposure period (1 year in this study) because chloride ions can penetrate easily. In total, six types of surface impregnation materials are applied in this study (see Table 1). They are listed as A, B, C, D, E and F and form two surface treatment sets, namely silane-based water repellent agents (A, B, C and D), and sodium silicate-based pore blockers (E and F). Their properties and dosage are further described in Table 1. The moisture content of the side surfaces of RC prisms was about 4.0% when the surface impregnations were applied.

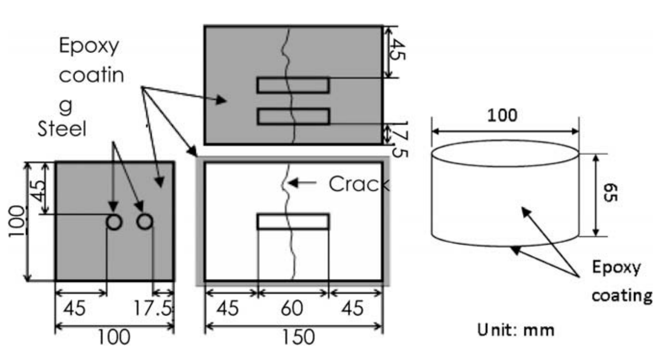
2.2. Details of specimens

Two types of specimens were prepared including forty RC prisms (150 × 100 × 100) mm and 14 concrete cylinders (ϕ 100 × 65 mm) as shown in Fig. 1. The concrete cylinders were prepared, mainly to investigate the chloride penetration profiles in un-cracked concrete when different surface impregnation materials were applied. The RC prisms were prepared to enable an investigation into how surface impregnation influences the chloride penetration of cracked concrete and the subsequent corrosion of internal steel reinforcement. The RC prisms had two layers of steel bars (ϕ10) at a depth of 17.5 mm and 45 mm, respectively (see Fig. 1), to monitor the status of steel bars at different cover depths, after exposure. Two side surfaces of each RC prism were treated with surface impregnation agents while the remaining four sides were sealed by an epoxy resin (see Fig. 1). As seen in Table 2, which provides a compilation of all specimens, there were three types of RC prisms. The first type of prism had no cracks, the surface of the second type was impregnated after the cracks were introduced, and the surface of the third type was impregnated before the cracks were introduced. The test specimens corresponding to the three types, mentioned above, are identified by the symbols "NC", "AC" and "BC", respectively (see Table 2). The presence of steel bars in the prisms contributed to the ease with which cracks were introduced into concrete through splitting tests.

During the splitting tests, the crack widths were controlled using two displacement transducers to bridge the cracks (see Fig. 2a). After the splitting tests, crack widths at the two side surfaces of each RC prism were measured under a microscope (see Fig. 2b). The crack width was measured at five locations of each side surface and their mean value was then taken as the crack

Table 1
Six types of surface impregnation materials used for tests.

Code	Type	Components		Amount per application (g/m^2/time)	Number of applications	Note
A	Silane liquid	Silane Isopropyl alcohol Methanol	35–45% 45–50% 5–10%	115	3	Hydrophobic agent
B	Silane-based cream	Alkylalkoxysilane Ethanol	98.7% 1.3%	510	1	
C	Silane-based gel	Trietoxysilane Ethanol Mineral thickening agent	90% 5% 5%	904	1	
D	Silane/siloxane liquid	Silane/siloxane-based distilled liquid	60–100%	51	2	
E	Sodium silicate	Super silicate particle catalyst	30–60% 1–5%	140	2	
F	Acrylic sodium silicate	Silicate + resin type water repellent coating	Not provided	140	2	Concrete pore blocker



(a) RC prism (b) concrete cylinder

Fig. 1. Dimension of specimens.

width index of that surface. Fig. 3 provides a summary of the measured crack widths, for all the RC prisms, in terms of their mean values and standard deviation. The crack width was aimed at an average value of 0.15 mm in order to approximately represent the real case in RC structures during their service life. It is seen in Fig. 3 that the aimed value was approximately achieved, but the variation of the introduced crack widths was considerable because it was difficult, if not impossible, to produce exactly the same artificial crack widths at two opposite sides of a RC prism during the splitting tests, due to such as the non-homogeneity of the concrete material and the loading eccentricity. The crack widths in RC prisms, and presented in Fig. 3, have been stabilized by epoxy coating after the splitting tests. Some changes may also have occurred in the crack widths during this process, in spite of careful operation.

Table 2
Summary of test specimens.

Specimen types	Conditions of cracks in concrete	Surface impregnation materials						
		N.T	A	B	C	D	E	F
RC prism	NC	2[a]	2	2	2	2	2	2
	AC	2	2	2	2	2	2	2
	BC		2	2	2	2	2	2
Cylinder	NC	2	2	2	2	2	2	2

[a] Number of prepared specimens; NC = non-cracked; AC = surface impregnation after the presence of cracks; BC = surface impregnation before the presence of cracks; NT = non-treated and there is no difference between AC and BC for non-treated RC prisms.

(a) Splitting tests to introduce cracks (b) Measurement of crack widths

Fig. 2. Introducing cracks into RC prisms.

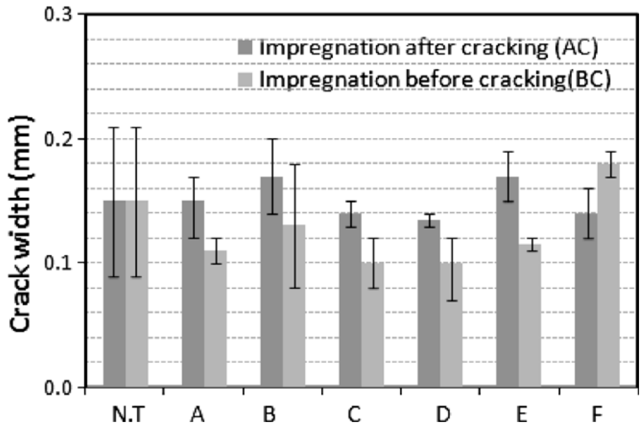


Fig. 3. Crack widths in RC prisms.

2.3. Exposure and test methods

All concrete cylinders and RC prisms were exposed to cyclic sea-water showers under an outdoor environment as shown in Fig. 4. The exposed surfaces of the concrete cylinders and RC prisms were horizontal and vertical, respectively. The exposure site was set up in the Port and Airport Research Institute, which is located near Tokyo Bay, Japan. Two wet/dry cycles took place per day to accelerate the penetration of chloride ions. Each cycle consists of a wet period of 4-h and a dry period of 8-h. The exposure lasted for 770 dry/wet cycles (over about 1 year). Water absorption by all specimens was measured during the exposure period. After exposure, all specimens were washed, dried and split open. The penetration depth of each applied surface impregnation material was determined based on the average value of five single measurements. To obtain the chloride penetration profiles, slices were taken from the concrete cylinders, by cutting at depths of 5, 10, 20, 30, 45, and 50 mm from the exposed surface. The total chloride ion content in each slice was determined, based on an automated ion-selective electrode method [27]. The corroded surface areas of the internal steel reinforcement in the RC prisms, were measured after the prisms were split open. To see clearly how the presence of cracks influences the chloride penetration, five RC prisms including two un-impregnated ones (with and without cracks) and three impregnated ones (NC, AC and BC) were selected. An electron probe microscopy analysis (EPMA) was performed on these prisms, to determine the accurate chloride penetration profiles along the cracks. For un-cracked RC prisms, the analyzed part corresponded to about 40 × 40 mm, while for cracked RC prisms corresponded to about 80 × 80 mm, suggesting that chloride ions might penetrate deeper into cracked concrete. The locations, from which the parts were removed, are shown in Fig. 5.

Fig. 4. Exposure of specimens subject to cyclic sea-water shower.

3. Results and discussion

3.1. Penetration depth of surface impregnation agents

After 1 year of exposure, all specimens were split open and the penetration depths of the surface impregnation agents were then measured. Water was sprayed over the split surface (see Fig. 6). It is seen that sodium silicate has no water repellent properties as silicate gels are formed after chemical reaction with the concrete with the involvement of CO_2. These gels are hydrophilic (see E and F in Fig. 6), and in general the impregnation of sodium silicate is superficial. A clear difference was found in the penetration depth achieved by different hydrophobic agents (see Fig. 7). The sequence of the penetration depth of water repellent agents is as follows: silane-based gel (C) > silane-based cream (B) > liquid silane (A, D). Deeper penetration could be achieved wth silane gel and cream because each has more active silane content than the liquid silane. Additionally, they can remain on the surface, after application and hence increase the penetration over time, until, the point of full absorption. In this way evaporation, which is a problem with low viscosity silanes during application, can be minimized. Because of this characteristic, the RC prisms impregnated with the silane-based gel (C) were chosen for the EPMA to see directly whether the surface impregnation agent with the deepest penetration could even in the presence of cracks effectively prevent reinforcement corrosion. The corroded areas of the internal steel reinforcement in the cracked RC prisms, on which other surface impregnation materials had been applied, were measured for comparison.

3.2. Water absorption

In Fig. 8 the time-dependent water absorption of concrete cylinders and non-cracked RC prisms are shown, respectively. The presented water absorption data is the average of two specimens. In general, concrete cylinders show larger water absorption than RC prisms, because their exposure surfaces were set, respectively, hor-

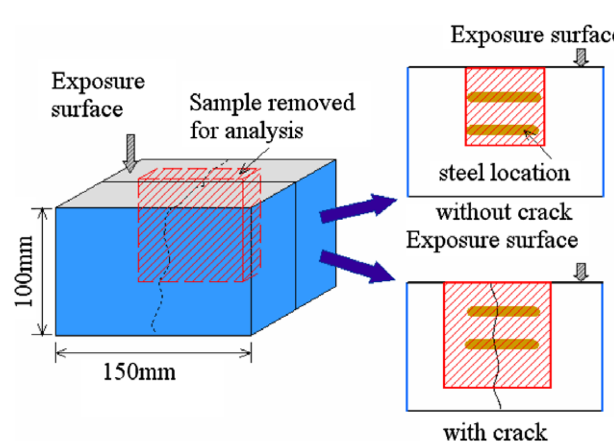


Fig. 5. Part removed for EPMA.

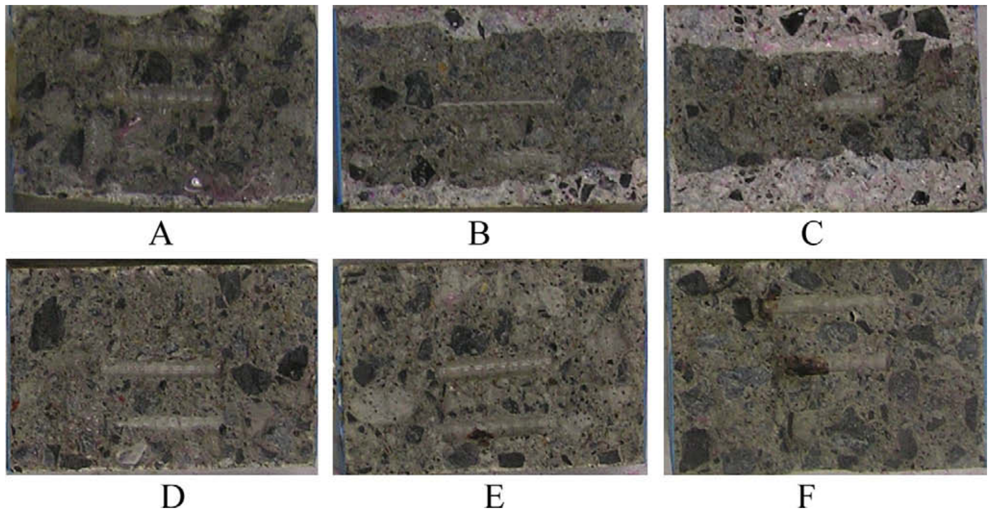


Fig. 6. Split concrete sections after water spraying.

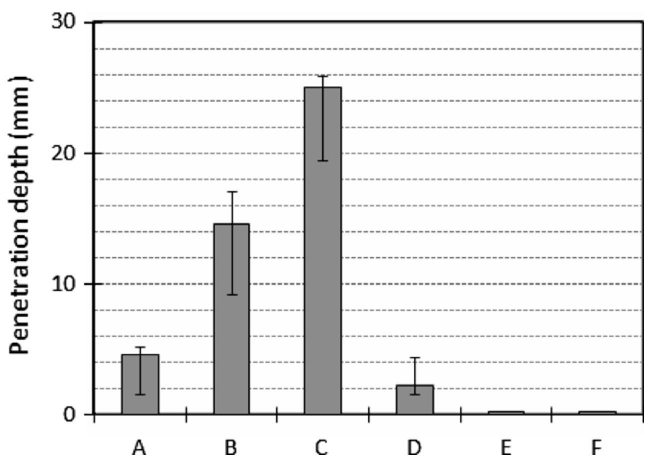


Fig. 7. Penetration depth of different water repellent agents into concrete.

izontally and vertically. From Fig. 8a and b it can be seen that the untreated specimen (NT) absorbs water rapidly at the beginning of exposure. After about 30 dry/wet cycle exposure, the water absorption reaches a maximum, beyond which there is no further water absorption. The specimens, E and F, coated with sodium silicate pore blockers have a similar tendency, but the maximum water absorption decreases by about 30% compared with the untreated specimens. However, the specimens, impregnated with the hydrophobic agents, A, B, C, and D show a much more significant reduction in water absorption, compared with the non-treated specimen (NT). Specimens impregnated with the liquid silane, A and silane-based cream, B exhibited hardly any water absorption during the whole exposure period. Some specimens: A in Fig. 8a and C in Fig. 8b even exhibited weight loss at the beginning of exposure. That is because hydrophobic impregnation prevents the penetration of additional external water. However the internal water can still evaporate during the drying periods. These two competing effects could, effectively, keep the internal environment of concrete dry. It appears that the concrete cylinders and un-cracked RC prisms impregnated with hydrophobic agent D had a sudden increase of water absorption after about, respective 100 and 200 cycles of exposure. This indicates a partial loss of hydrophobic property at that moment, owing to the comparatively small penetration depth (about 2 mm) achieved in concrete (see Fig. 7). The decreased effectiveness of the hydrophobic treatment during the exposure may possibly be attributed at least, partly to such as the ultraviolet deterioration, physical abrasion. But it is also known that a thin water repellent layer, at the surface, can be penetrated by water threads in the surface near pores once these continuous water bridges are established and capillary suction through the water repellent layer begins. For this reason it is recommended that a deep impregnation of silane is ensured if a reliable chloride barrier is to be built. Experiments have shown that a minimum penetration depth of the water repellent agent to 6 mm is usually required [28]. In this study, as shown in Fig. 7, a penetration depth greater than 5 mm has proven to be durable during accelerated exposure.

The time-dependent water absorption of cracked RC prisms in which the surface impregnation was applied after the (AC set) and before the (BC set) cracks were introduced, is shown in Fig. 8c and d. The cracked RC prism without surface impregnation was already saturated after 16 dry/wet cycles. This is significantly less than the above-mentioned 30 cycles in the case of the un-cracked specimens. The water absorption rate of the RC prisms, impregnated with the sodium silicate-based pore blockers, E, F, is almost the same as that of un-impregnated specimens (see NT in Fig. 8c and d). RC prisms of both AC and BC sets (see Fig. 8c and d) show more significant water absorption than the water uptake of impregnated un-cracked RC prisms (see Fig. 8b). The water absorption in the case of crack formation after surface impregnation is most significant (see Fig. 8d). From these results it can be concluded that it is impossible to reach full efficiency of surface impregnation when there is a crack with a width of about 0.15 mm in concrete, regardless of the fact that the crack may have been formed before or after impregnation. Thus, in all cases when cracks in concrete are inevitable under a service condition, application of surface impregnation should be applied when the cracks have stabilized. If this is not possible, repetitive surface impregnation should be applied as soon as the cracks appear.

Comparing the performance of different surface impregnation materials, silane-based cream (B) and gel (C) perform best in both AC and BC sets (see Fig. 8c and d). It should be noted, at this point, that RC prisms impregnated with hydrophobic agents were shown to have a clear decrease of water absorption, regardless of the types of cracks and the type of hydrophobic agents applied, when compared to the condition of un-impregnated specimens. Hence it could be true to say that: service life of reinforced concrete structures can be significantly extended by the application of water repellent treatment.

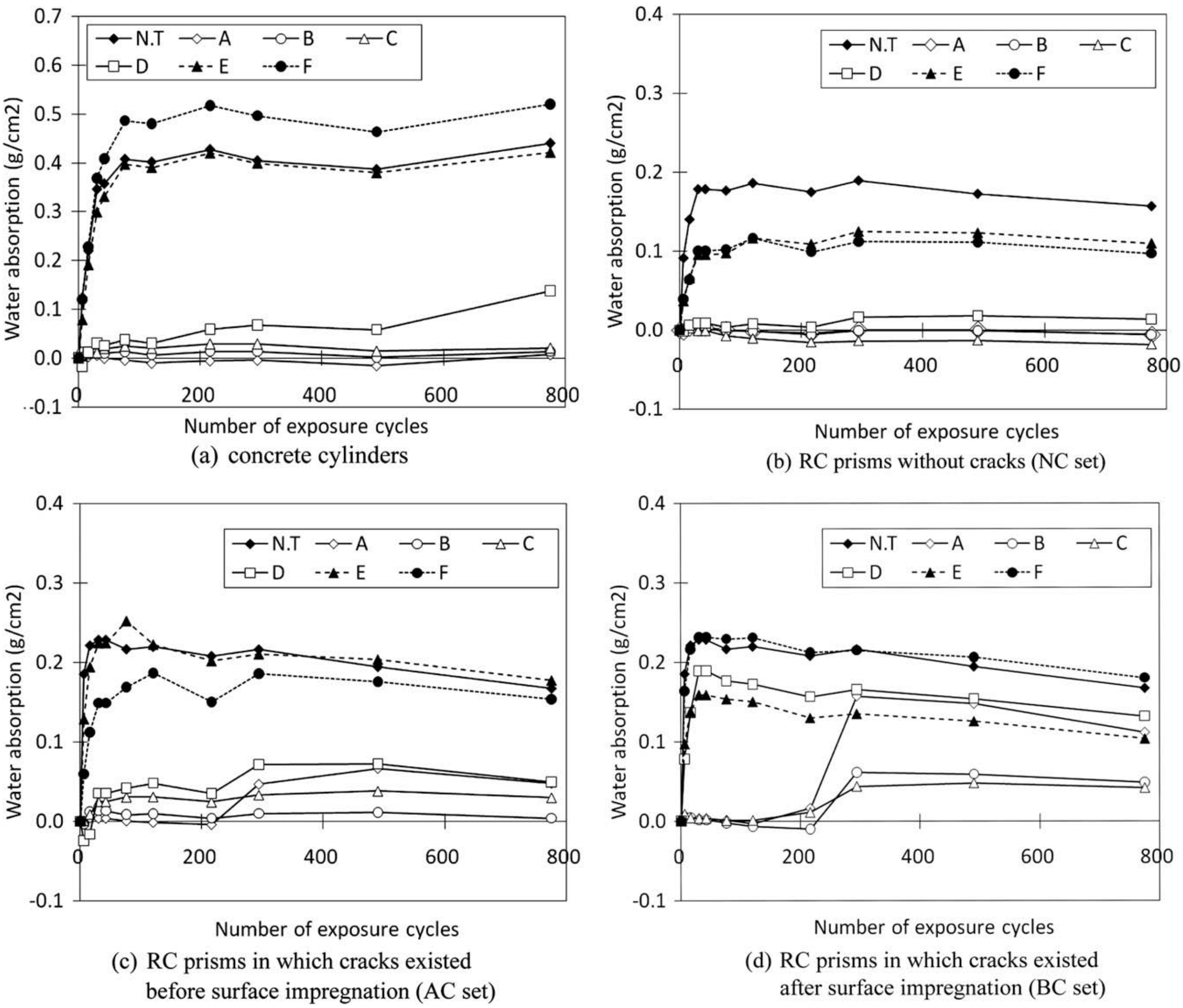


Fig. 8. Water absorption of RC prisms impregnated with different materials.

3.3. Chloride penetration profiles

Fig. 9 shows the profiles of the total chloride content in impregnated and un-impregnated concrete cylinders. Both the penetration depths and the amount of chloride ions decrease significantly, when the specimens are impregnated with hydrophobic agents A, B, and C. Chloride ions are essentially found in the first concrete slice (0–5 mm) only. This is due, to the extent to which the chloride is absorbed on the surface, as well as some chloride penetration into big pores in the hydrophobic layer. It appears that the use of sodium silicate-based pore blockers cannot protect the concrete from chloride penetration (see E and F in Fig. 9). The hydrophobic agent D did not efficiently prevent the penetration of the chloride ion because of its small penetration depth (see Fig. 7).

Fig. 10 presents a mapping of chloride ions, obtained from EPMA for the un-cracked RC prisms. The reference specimen (NT) and the specimen impregnated with silane-based gel (C) were analyzed, exclusively. It was clearly seen that the penetration of chloride ions was successfully suppressed. The penetration depths of chloride ions in the un-impregnated and the impregnated specimens are approximately 33 mm and 10 mm, respectively. The chloride content of the outer thin layer (about 2 mm thick) is

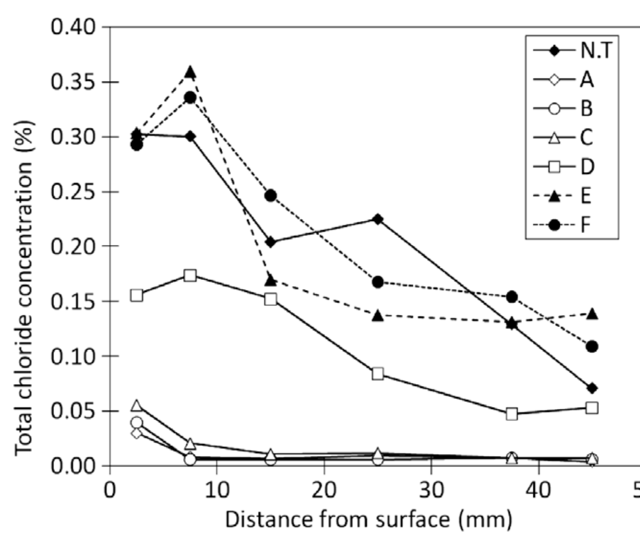


Fig. 9. Chloride penetration profiles in concrete cylinders.

low; this observation can partly be explained by carbonation. It can also be seen from Fig. 10 that chloride ions could penetrate

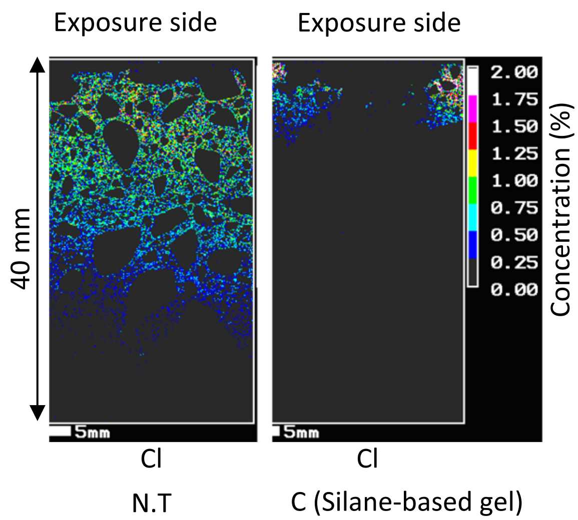


Fig. 10. Comparison of EPMA results on un-cracked RC prisms.

the hydrophobic parts below the carbonated layer, the depth of which was larger than 20 mm in the example using silane-based gel (see Fig. 7). Chloride penetration was completely blocked at some locations whereas at others it was not. This phenomenon indicates that the micro-structure of concrete impregnated with hydrophobic agents may have significant differences at different locations. This could also explain why, in order to avoid any local weakness or chloride breakthrough, a relatively large penetration depth is necessary. In fact this problem has to be considered on the basis of a stochastic approach.

Fig. 11 presents the EPMA results of the RC prisms impregnated with the silane-based gel C in the presence of cracks. It can be seen that in the cracked but untreated specimen (see NT in Fig. 11) chloride ions penetrated the whole specimen. This penetration was a very quick process as the cracks were almost immediately filled with salt solution [29]. It is seen that the chloride ion content decreases gradually to the centre of the specimen (50 mm deep from the exposure surface). The chloride ion penetration depth in the impregnated RC prism with an average crack width of 0.13 mm (see Fig. 4) before the impregnation is about 8 mm only (see AC in Fig. 11), the indication being that the use of a silane-based gel is still quite effective in the suppression of chloride ion penetration if a width of less than 0.13 mm exists in concrete before surface impregnation. However, for the specimen in which the cracks were formed after surface impregnation (see BC in Fig. 11), it is seen that the chloride ions penetrate the concrete up to a depth of about 17 mm from one exposure side (see the top side of BC in Fig. 11). This is smaller than the penetration depth (>20 mm) of the silane-based gel (see Fig. 4). The chloride ions show a penetration bias towards cracked concrete rather than the un-cracked parts. However, the chloride ions penetration depth in another exposure surface is about 70 mm (see the bottom surface of BC in Fig. 11). The crack widths corresponding to the top and bottom surfaces were about 0.08 mm and 0.12 mm, respectively, and the average crack width was taken as 0.1 mm as seen in Fig. 4. Therefore, in case of a crack occurring after hydrophobic impregnation, an increase in its width from 0.08 mm to 0.12 mm may cause a significant increase in chloride penetration even if a large penetration depth has been achieved.

A crack width larger than 0.1 mm is common in engineering practice. Hence, the application of hydrophobic impregnation before crack stabilization in concrete is not recommended, even if the chosen hydrophobic agent can achieve a large penetration depth. According to the findings of the current study, surface impregnation by silane-based gel (C) appears to be able to maintain good efficiency in preventing chloride penetration, if the width of existing cracks in concrete before surface impregnation is less than 0.13 mm. However, if a possibility exists that a crack may further propagate and widen after surface impregnation, the effectiveness of the application will significantly decrease, unless that crack width can be controlled to remain below 0.08 mm. Therefore, a careful assessment on the status and time dependent crack development is deemed necessary before application of surface impregnation for marine RC structures. After impregnation, regular inspections of crack development in the structures are recommended. Based on the result of these inspections, local repetitive surface impregnation may be required.

3.4. Corrosion areas of internal steel reinforcement

Fig. 12a and b shows the influence of different surface impregnation materials on the rate of corrosion of the steel reinforcement embedded in the RC prisms. The degree of steel reinforcement corrosion was evaluated using the ratio of corroded surface area related to the whole surface area of the embedded steel. The former was calculated based on the surface mapping of the steel bars removed from the RC prisms at the end of the exposure time.

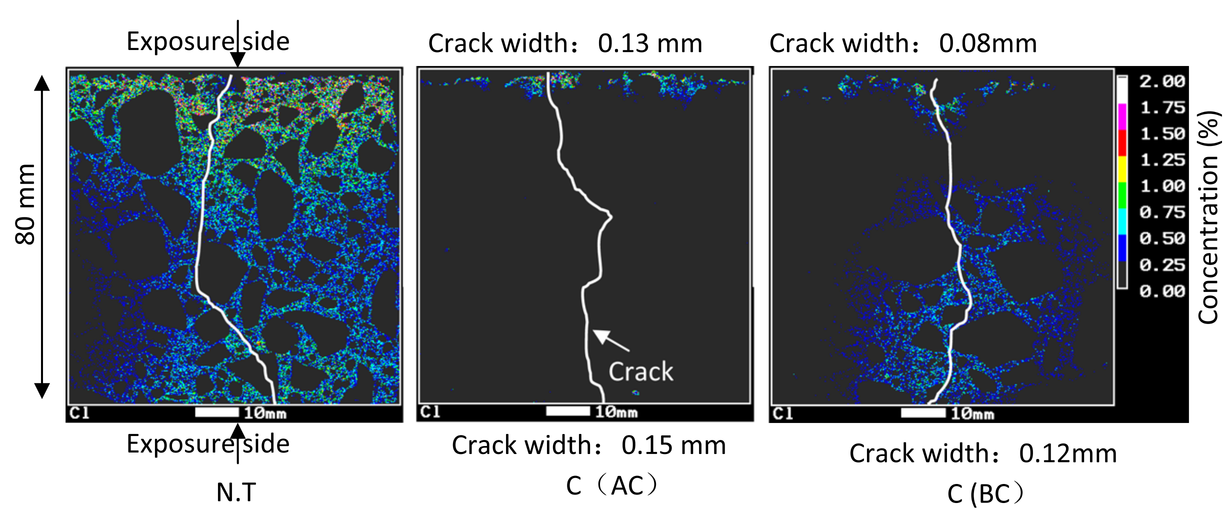


Fig. 11. Comparison of EPMA results on cracked RC prisms.

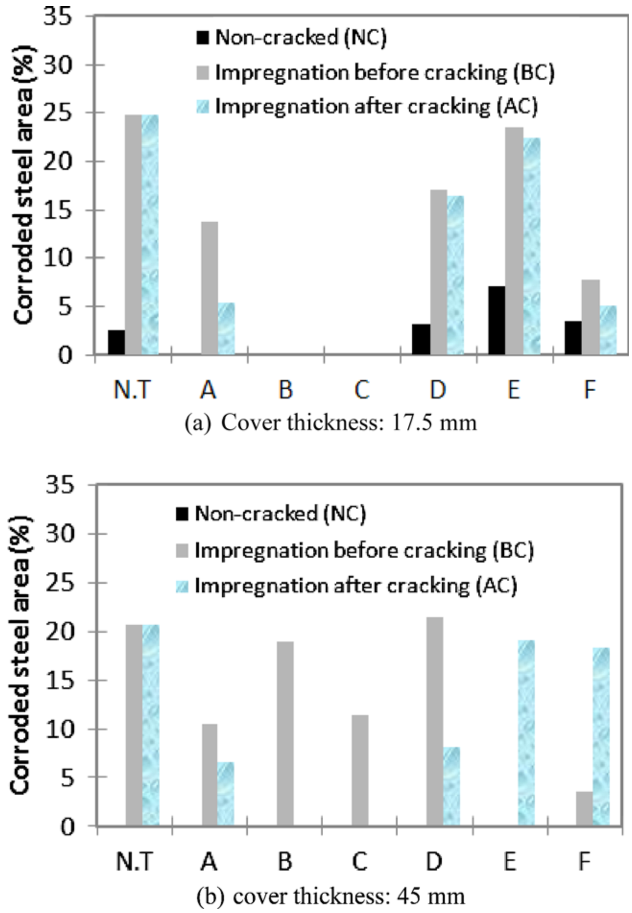


Fig. 12. Influence of surface impregnation on the corrosion of internal steel reinforcement.

In the un-cracked RC prisms, the steel bars with a cover depth of 17.5 mm in the untreated reference specimens (NT) showed significant corrosion. So did the steel bars in the specimens impregnated with the liquid silane, D and sodium silicate, E, F (see NC set in Fig. 12a). This is consistent with results of water absorption and chloride penetration as shown in Figs. 8 and 9. All steel reinforcement under a cover depth of 45 mm, however, showed no corrosion within the testing period (see series NC in Fig. 12b).

It is obvious that the existence of cracks significantly increase the rate of corrosion of internal steel reinforcement in non-impregnated RC prisms, compared to corrosion extent observed in series NC (see Fig. 12a and b). When surface impregnation was applied on RC prisms after crack formation (see series AC in Fig. 12a and b), the internal steel bar corrosion in the two RC prisms impregnated with the silane-based cream, B and gel, C was not initiated within the test period, although the maximum crack width was found to be 0.20 mm and 0.15 mm (refer to Fig. 4), respectively. Thus, even if concrete has cracks before surface impregnation, the internal steel bar corrosion can still be efficiently suppressed, if only deep enough penetration can be achieved. The two types of liquid silane: A and D and sodium silicate: E and F, could not prevent corrosion of internal steel reinforcement but they were able to minimize the rate of corrosion in the impregnated RC prisms (see Fig. 12a and b). Hence corrosion was not been prevented under these conditions, but the service life was extended.

When surface impregnation is carried out before the formation of cracks (see series BC in Fig. 12 a and b), the internal steel bars, under a cover, with a depth of 17.5 mm in the RC prisms and impregnated with the silane-based cream (B) and gel (C) showed no corrosion at all (see Fig. 12a). By contrast, it was surprising to find that corrosion was observed on steel bars covered with 45 mm of concrete and treated in the same way (see Fig. 12b). One reason may be that concrete around the steel bars at a depth of 17.5 mm is water repellent because silane-based cream and gel reached a mean depth of between 15 and 25 mm. As a consequence, the concrete around the steel bars in these prisms has no or little capillary condensed water. This comparatively dry concrete also has a very low electric conductivity. Under these conditions the rate of corrosion is known to be small. This hypothesis presents strong support for the contention that, in a marine environment, deep impregnation water repellent treatment is of vital importance, for a reliable and durable protection of reinforced concrete structures. It is then and only then, that the service life of reinforced concrete structures can be significantly extended by water repellent surface treatment.

4. Conclusions

Based on the results of a 1 year accelerated outdoor exposure test program on sets of concrete and RC specimens, which were surface impregnated, the following conclusions can be drawn:

1. Surface impregnation of un-cracked concrete and RC structures with silane, has proved to be a highly efficient measure to reduce water absorption. During the process, a chloride barrier is built up, which prevents chloride penetration into the pore structure of the concrete during accelerated dry/wet exposure to salt water. The initiation of corrosion of steel reinforcement in concrete as a result can be successfully suppressed. The long-term effectiveness of surface impregnation for un-cracked concrete, however, depends largely on the achieved penetration depth, which, according to the present study, should be larger than 5 mm.
2. For an RC structure with cracks existing before hydrophobic impregnation, the efficiency of a hydrophobic agent relies essentially on that agent's penetration depth. Reinforcing steel in cracked RC prisms, impregnated with silane-based cream and gel did not show any corrosion after 1 year of accelerated dry/wet exposure to salt water, even though the maximum crack width in concrete before the surface impregnation was as large as 0.2 mm. This result indicates that the service life of actual reinforced concrete in an aggressive environment can be significantly extended by surface impregnation with silane.
3. If cracks form in reinforced concrete after surface impregnation with silane, chloride penetration cannot be totally prevented, unless the cracks are fine, such as only ($w < 0.08$ mm). A second surface impregnation then appears to be unavoidable. The rate of corrosion is, however, significantly reduced if the concrete around the steel reinforcement is water repellent. Owing to the reduction of the corrosion rate, the service life of reinforced concrete structures can also be expected to be extended.
4. Independent of the presence of cracks and the sequence of crack formation and surface impregnation, the treatment of the concrete surface with sodium silicate-based pore blockers, does not prevent water absorption and chloride penetration into concrete and consequently this treatment cannot prevent the initiation of corrosion of steel reinforcement.

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