Hydrophobe V
5th International Conference on Water Repellent Treatment of Building Materials
Aedificatio Publishers, 299-310 (2008)

Investigation of Chloride Ingress in Cracked Concrete Treated with Water Repellent Agents

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Abstract

In this paper, results of a test are presented in which reinforced concrete (RC) prisms treated with different water repellent agents have been exposed to cyclic seawater shower for one year. Purpose of the test was to investigate how the water repellent treatment influences the water absorption and chloride ingress into reinforced concrete with and without the existence of cracks. Uncracked RC prisms, some cracked before the water repellent treatment, and some cracked after the water repellent treatment were prepared for comparison. Four types of water repellent agents, i.e., liquid silane, liquid silane/oligomeric siloxane, silane-based cream and silane-based gel were applied to treat the concrete surface. Time-dependent water absorption of all the un-cracked and cracked RC prisms was monitored. After one-year exposure, all the specimens were broken open. The penetration depths of water repellent agents in the treated specimens were measured and corrosion areas of the inner steel reinforcement were quantitatively evaluated. The chloride ingress profiles in the cracked and un-cracked RC prisms were evaluated using electron probe microscopy analysis (EPMA). Based on the test results, effectiveness of water repellent treatment as a water and chloride barrier of cracked concrete under marine environment is discussed.

Keywords: cracks, concrete, water repellent agents, chloride ingress

1 Introduction

Corrosion-induced deterioration is a great concern for reinforced concrete (RC) structures exposed to marine environment. To have structures in good condition during their service period it is required to have enhanced durability design at the initial designing stage and/or to perform strategic maintenance afterwards. Due to the relatively severe construction and service conditions, such as high humidity, salt attack, dry and wet cycling, and the difficulty in setting scaffolds during repair etc., marine RC structures require materials for new construction or repair which are easy to use but long-lasting. Recently, the application of water repellent agents to protect newly-built or to repair existing concrete structures has gained some popularity, particularly for building and highway structures in Japan [1]. This technique can reduce water penetration into concrete and its ease of application makes it attractive for the construction industry.

Laboratory tests have shown that the water repellent treatment can establish a chloride barrier for concrete in saline environment [2, 3]. However, there are still two major concerns with respect to their effectiveness in increasing the durability of actual RC structures under marine environment, e.g. superstructures of port piers. One is the applicability of this technique to concrete with different initial conditions, e.g. relatively high internal humidity, carbonation etc. [4]. The other is the compatibility of the water repellent treatment with cracks, which will be the focus of this study.

2 Experimental

2.1 Materials and specimens

Two types of test specimens were prepared. One is a cylinder-type concrete specimen of 100mm in diameter and 65mm in height (see Fig.1). The other is prism-type (150×100×100mm^3) reinforced concrete (RC) specimen (see Fig.2). The top surfaces of all cylinder-type specimens were treated with different water repellent agents and then cured for two weeks. The remaining surfaces were sealed with an epoxy resin (see Fig.1).

All prism-type RC specimens had layers of deformed steel reinforcement located at 25mm and 50mm, respectively, from the concrete surface (see Fig.2). Three types of RC prisms were prepared. The first type had no cracks. In the second type cracks were introduced through splitting tests (see Fig.3) before the water repellent treatment. The crack widths were controlled using displacement transducer during the tests (see Fig.3). After the splitting tests, crack widths were measured through microscopic observation. For each cracked side surface, the average of five measured values was taken as the crack width index. In the third type cracks were introduced after applying the water repellent agent on two side surfaces. Two side surfaces of the prism-type RC specimens were treated with water repellent agents while the remaining surfaces were sealed with an epoxy resin (see Fig.2). The surface moisture content was about 4.0% for both cylinder and prism-type specimens when the water repellent product was applied.

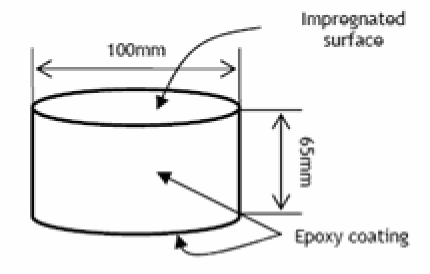


Figure 1: Cylinder-type specimens

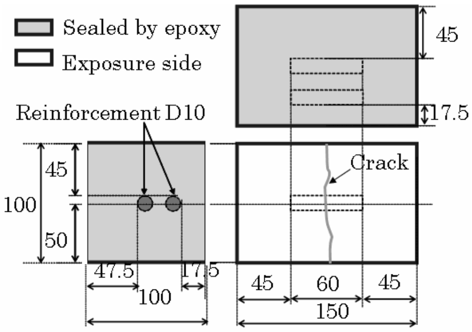


Figure 2: Prism-type specimens

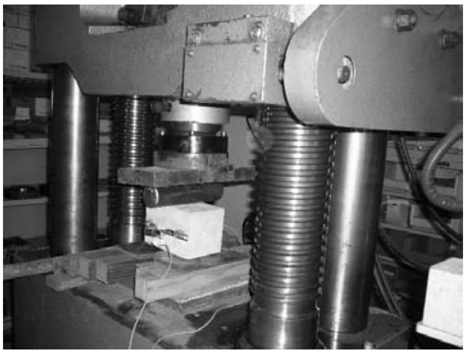


Figure 3: Introducing cracks into RC prisms

Figure 4: Cyclic sea-water shower spray

The concrete specimens were made with a cement content of 248kg/m^3, a water to cement ratio of 0.68, and a fine-to-coarse aggregate ratio of 0.49. The compressive strength of concrete at 28 days curing was 34.0MPa. A rather large water to cement ratio was chosen for this research in order to obtain a good penetration depth and to enable a clear assessment of the performance of the four water repellent agents. Before the water repellent treatment, all the specimens had been exposed in room air (Tokyo climate) for three years. Since a relatively large water to cement ratio was used, all the cylinder-type specimens were found to have carbonated edge parts in an average depth of 7.8mm [4]. The prism-type RC specimens were also carbonated to an average depth of 3.6mm.

Four types of water repellent agents were applied to the specimens. They are: liquid silane (A); silane-based cream (B); silane-based gel (C); and, liquid silane/oligomeric siloxane (D). Further details related to their properties and amount for use can be found [4]. Table 1 summarizes the test series. For each testing variable, two specimens were prepared.

Table 1: Information of specimens

Specimen Code	Crack information			Note
	NC	BC	AC	
0-1(2)	o			Reference cylinder
X(A~D)-1(2)	o			Cylinder
0-NC(BC)-1(2)	o	o		Reference prism
X-NC(BC, AC)-1(2)	o	o	o	Prism

Note: X = A~D, type of water repellent agents; 0 = untreated ; NC = no crack; BC = crack introduced before surface treatment; and AC = crack introduced after surface treatment.

Table 2: Crack width (mm) in the exposed sides of prism-type RC specimens

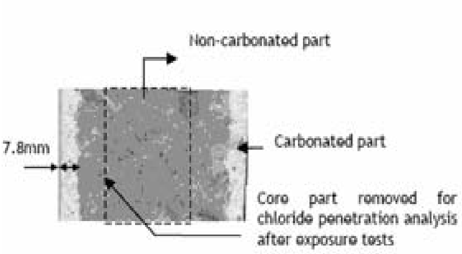
Code	**0-BC-1**	**A-BC-1**	**B-BC-1**	**C-BC-1**	**D-BC-1**	**A-AC-1**	**B-AC-1**	**C-AC-1**	**D-AC-1**
Exposed side 1	0.21	0.12	0.15	0.14	0.20	0.12	0.09	0.12	0.08
Exposed side 2	0.09	0.17	0.13	0.13	0.14	0.10	0.12	0.07	0.18
Average	*0.15*	*0.15*	*0.14*	*0.13*	*0.17*	*0.11*	*0.11*	*0.10*	*0.13*
Code	**0-BC-2**	**A-BC-2**	**B-BC-2**	**C-BC-2**	**D-BC-2**	**A-AC-2**	**B-AC-2**	**C-AC-2**	**D-AC-2**
Exposed side 1	0.35	0.15	0.16	0.14	0.17	0.11	0.07	0.15	0.11
Exposed side 2	0.15	0.18	0.14	0.19	0.25	0.18	0.13	0.14	0.10
Average	*0.25*	*0.16*	*0.15*	*0.17*	*0.21*	*0.14*	*0.10*	*0.14*	*0.10*

2.2 Exposure environment and test methods

Both cylinder-type and prism-type specimens were exposed to cyclic seawater shower as shown in Fig. 4. There were two wet/dry cycles in one day. Each cycle consists of a 4-hour of wet period and an 8-hour of dry period. The water absorption of all specimens was followed up during the exposure. After 770 dry/wet cycles (about one year), the specimens were washed, dried and split open. The penetration depth of the applied water repellent agents was determined based on the average value of five single measurements. For cylinder-type concrete specimens, slices were obtained by cutting at the depths of 5, 10, 20, 30, 45, and 50mm. Only the core part of each specimen (see the area enclosed in the dotted lines in

Fig. 5) was removed for the determination of the chloride penetration profile so as to avoid the interference of carbonation. The total chloride ion concentration in each slice was determined based on an automated ion-selective electrode method.

For the prism-type RC specimens, all the specimens with the code of ×-×-1 (see Table 1) were broken open and the corrosion areas of the internal steel reinforcement were measured. Those with the code of ×-×-2 were left to continue their exposure. To see the effects of cracks on the chloride ingress profiles, five RC prisms from the reference series (0-NC-1, 0-BC-1) and the series with maximum silane penetration depth (C-NC-1, C-BC-1, and C-AC-1) were selected on which electron probe microscopy analysis (EPMA) was performed to determine the accurate chloride penetration profiles. For un-cracked RC prisms, the analysed part corresponds to 40 × 40mm^2 while for cracked RC prisms, 80 × 80mm^2 considering that chloride ions might penetrate deeper into cracked concrete. The locations of the removed parts are indicated in Fig. 6.



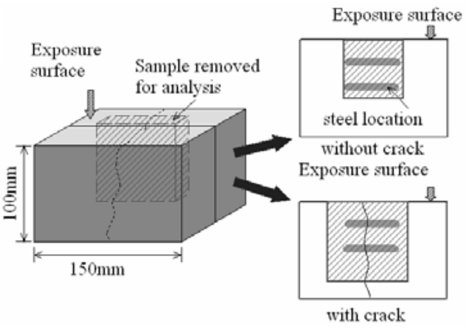
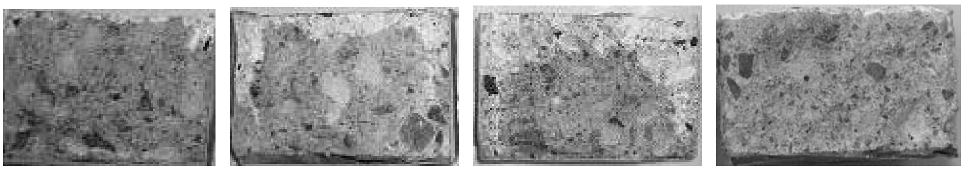


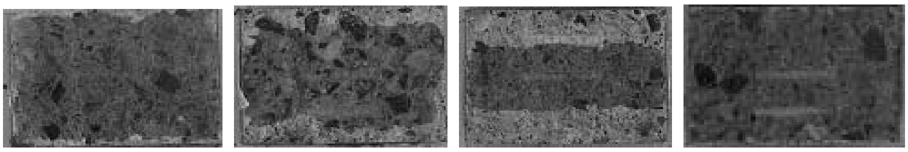
Figure 5: Part for chloride penetration analysis in cylinder-type concrete specimens

Figure 6: Part for chloride penetration analysis in prism-type RC specimens



(A) (B) (C) (D)

Figure 7: Split concrete cylinders after water spray



(A) (B) (C) (D)

Figure 8: Split RC prisms after water spray

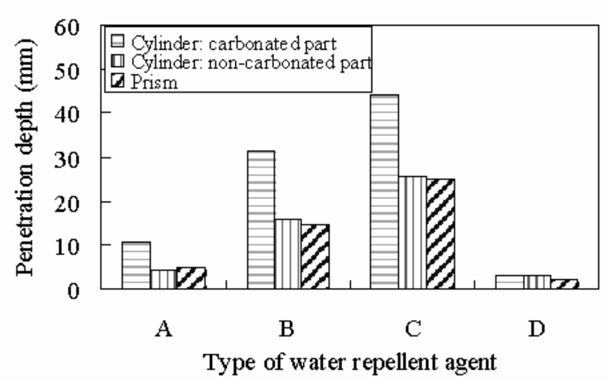


Figure 9: Penetration depth of different water repellent agents into concrete

3 Results and discussion

3.1 Penetration depth

After one year exposure to cyclic seawater shower, all cylinder and prism specimens were split as to measure the penetration depth by spraying water on the split surface (see Figs.7 and 8). It turned out that the penetration of water repellent agents into concrete was influenced by both the type and the carbonation condition of the concrete. Although the authors found in the past studies that a very dry and carbonated concrete condition may reduce silane penetration [4], silanes generally achieved much greater penetration depth in the carbonated concrete part compared to a non-carbonated part (see Figs.7 and 9) because of the coarser pore structure of concrete after carbonation.

3.2 Water absorption

Fig.10 plots the relationship between water absorption of treated and untreated cylinder-type concrete specimens and exposure time. The average water absorption of two specimens is presented. The exposure started in July 2006 and ended one year later. On the whole, it is seen that all the water repellent specimens (A, B, C, and D) show significant decrease of water absorption compared to the reference series (0). The specimens treated with water repellent agents even show some weight loss at the beginning stage. This is because the water repellent treatment can prevent the external water from penetrating but the internal water still can evaporate. The dual effects can keep effectively the internal environment of concrete dry. On the other hand, it is shown that after relatively long-term exposure, the specimens treated with water repellent agents may show some water absorption. In particular for the water repellent agent D, which had the smallest penetration depth (see Fig. 7), the effectiveness of water repellent treatment decreases during the exposure possibly due to ultraviolet deterioration, physical abrasion etc. Therefore, a certain penetration depth has to be achieved in order to obtain a durable water repellent treatment.

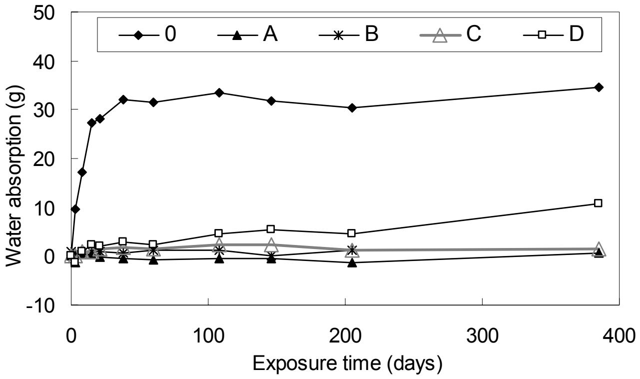


Figure 10: Water absorption during the exposure cylinder-type specimens

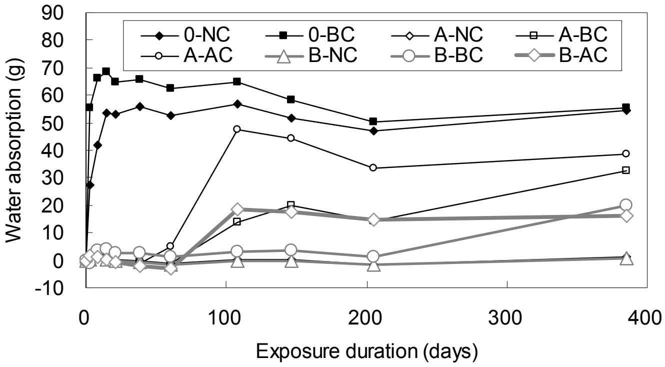


Figure 11: Water absorption during the exposure: prism-type specimens

Figs.11 and 12 present the effects of cracks on the water absorption of RC prisms treated with different water repellent agents. The series 0-NC and 0-BC are presented in both figures as reference. Again, the average water absorption of two RC prisms specimens is presented. For untreated RC prisms, as predicted, the specimens with pre-cracks (0-BC) show more water absorption than the un-cracked ones (0-NC) in terms of both water absorption rate and water absorption amount (see Fig.11). Those RC prisms treated with water repellent agents and cracked afterwards (A(B)-AC in Fig.11 and C(D)-AC in Fig.12) show larger water absorption than those cracked before the water repellent treatment (A(B)-BC in Fig.11 and C(D)-BC in Fig.12). Both specimens of BC and AC series show greater water absorption than the treated ones without cracks (A(B)-NC in Fig.11 and C(D)-NC in Fig.12). Nevertheless, compared to the untreated RC prisms and even the un-cracked ones (0-NC in Fig.11 and Fig.12), all the treated RC prisms still show clear decrease of water absorption. Therefore, the water repellent treatment is still effective in reducing the water absorption even though there are cracks induced before or after treatment. In the meantime, it shall be noticed that the effectiveness of water repellent treatment may be largely reduced particularly when the cracks are formulated after the treatment, e.g. the after-crack having a width of 0.10~0.21mm in the current study (Table 2). In other words, the application of water repellent treatment is more effective on concrete having stable cracks.

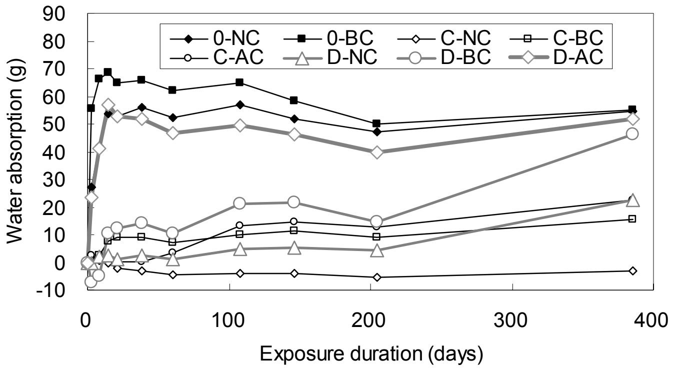


Figure 12: Water absorption during the exposure: prism-type specimens

3.3 Chloride penetration

Fig.13 shows the total chloride content distribution profiles in treated and untreated concrete cylinders. Both the penetration depths and the amount of chloride ions present decreases significantly when the water repellent agents A, B, and C are used. The chloride ions were mainly found in the first concrete slice. This is due to a certain extent of chloride adsorbed on the surface as well as the chloride penetration in the water repellent concrete layer (e.g. see C-NC-1 in Fig.14). The water repellent agent D did not appear to efficiently prevent the chloride ions from penetrating which could mainly be attributed to the loss of water repellency effectiveness during the exposure as discussed earlier for Fig.10.

Fig.14 presents the chloride ion mapping, obtained from EPMA, in the cracked concrete compared to those in un-cracked concrete. Only the reference series 0 and series C were analyzed for comparison purposes. Water repellent agent C was selected because it achieved the maximum penetration depth as mentioned above. The chloride content of the outer

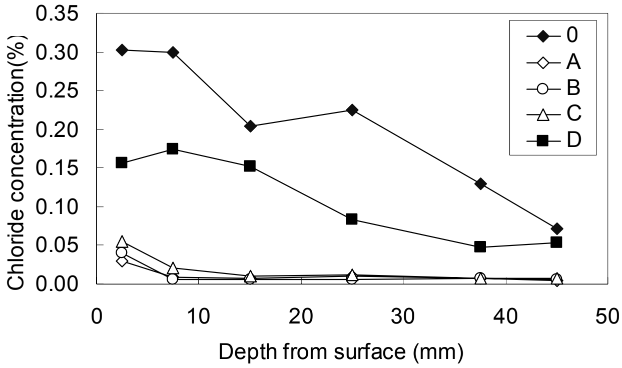
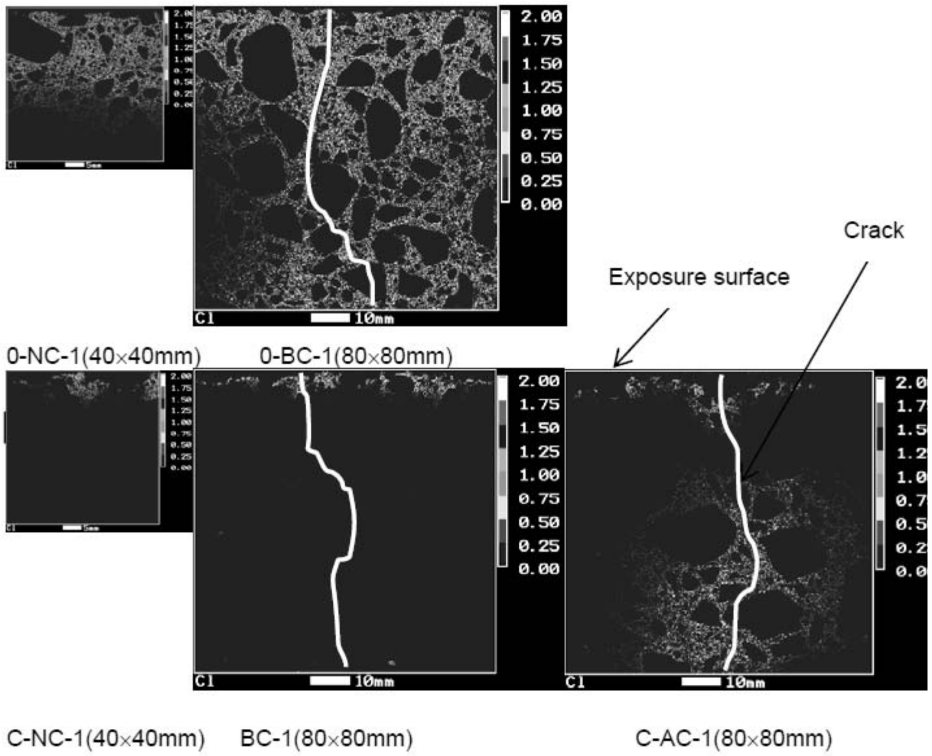


Figure 13: Chloride penetration profile in cylinder-type concrete specimens



0-NC-1(40×40mm) 0-BC-1(80×80mm)

C-NC-1(40×40mm) BC-1(80×80mm) C-AC-1(80×80mm)

Figure 14: Chloride mapping in RC prisms obtained from EPMA

thin layer (about 2mm) is low in all tested specimens, indicative for a complete carbonation. In the case of un-cracked concrete, the penetration depths of chloride ions in the un-treated sample 0-NC and the treated sample C-NC were 33mm and 10mm, respectively. In the cracked and untreated sample 0-BC-1 chloride ions penetrated throughout the whole specimen. The chloride ion content decreases gradually until the center of the specimen (50 mm deep from the exposure surface).

For the treated specimen C-BC-1 with an average initial crack width of 0.13mm (see Table 2) before the water repellent treatment, the penetration depth of chloride ions is only about 8mm. The chloride ion contents near the crack are relatively high. However, the water repellent treatment is still effective in preventing the chloride ions from further penetration.

The specimen C-AC-1 had an average crack width of 0.10mm introduced after the water repellent treatment. The crack width was 0.07mm on one exposure surface and 0,12 mm on the other surface. From Fig.14 one can see that the chloride ions penetrated into the concrete to a depth of 17mm from one exposure side, which is smaller than the penetration depth (25mm) of the water repellent agent C in specimen C-AC-1 (see Fig.9), while the penetration depth of chloride ions from the other exposure surface (with the 0.12 mm crack) is 70mm. Obviously, in case of cracks introduced after water repellent treatment an increase of the crack width from 0.07mm to 0.12mm causes a significant increase of chloride penetration.

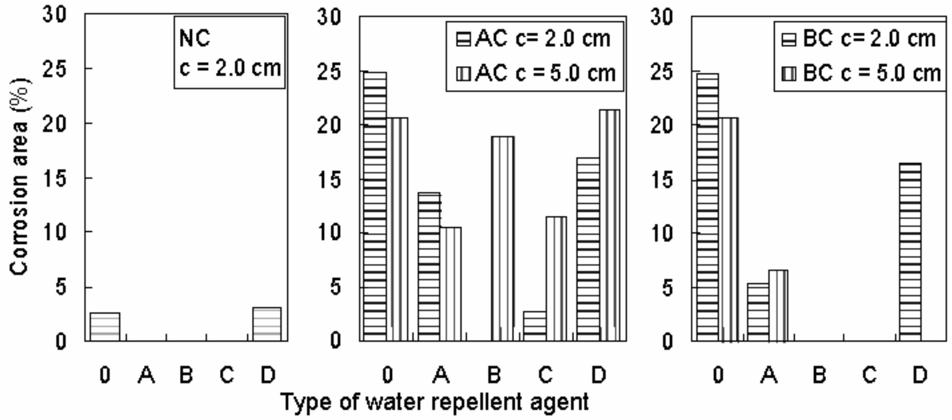
Cracks larger than 0.1mm in width are very common in engineering practice. Hence, it is recommended to apply water repellent treatment for concrete structures with stabilized cracks. If the cracks further propagate after the water repellent treatment, the application effectiveness may be significantly diminished. Of course, even with cracks occurring after the water repellent treatment, the chloride ions mainly concentrate near the crack surface. On zones away from cracks, the water repellent agent is still effective in preventing chloride penetration (see Fig.14).

3.4 Corrosion area of steel reinforcement

Fig. 15 shows the influence of the different water repellent agents on the corrosion of internal steel reinforcement embedded in the RC prisms. The steel reinforcement was taken out after breaking open the RC prisms at the end of the exposure time. Then, the surface of steel reinforcement was mapped. The corrosion of steel reinforcement was evaluated using the ratio of corroded surface area to the whole initial surface area. In un-cracked RC prisms (see NC series in Fig.15), steel reinforcement at the location of 20mm from the exposure surface in the reference specimen and the one treated with water repellent agent D was corroded. This is very consistent with the results of water absorption and chloride penetration as presented in Figs.10 and 13. All steel reinforcement at the location of 50mm from the exposure surface remained uncorroded.

Compared to non-cracked samples (NC), introducing a crack before water repellent treatment (BC) leads to an increase of the corrosion area of steel reinforcement for the untreated one and the one treated with D (see Fig.15**)**. Application of cream-type (B) and gel-type (C) silanes to the prisms having crack width ranging from 0.13 to 0.19 mm prevented the corrosion of the steel reinforcement.

When the crack was introduced after the water repellent treatment, all the RC prisms showed corrosion of internal steel reinforcement although the treated ones showed relatively less corrosion area, in other words, a decreased corrosion speed. The corrosion area of steel reinforcement at the location of 50mm from the exposure surface is not always less than that of steel reinforcement at the location of 20mm (see Fig.15). This is mainly due to the differences of crack widths in the two exposed sides of the specimen. In the AC series, only the steel reinforcement at the 20 mm location from the exposed surface which were treated with B and C, showed no or a rather small corrosion area. This can be attributed to the relatively small crack widths (0.09mm and 0.07mm) in the corresponding exposure surfaces. Hence, there may be a threshold value of crack width of around 0.09mm, beyond which the effectiveness of water repellent treatment will be lost. There is a need to further study how the water repellent treatment influences the corrosion rate of internal steel reinforcement in concrete when cracks are present. However, as a general conclusion, it is suggested not to apply water repellent treatments to RC concrete members with propagating cracks.



c: distance from the centre of steel reinforcement to the exposed surface.

Figure 15: Influence of water repellent treatment on the corrosion of steel reinforcement

4 Conclusions

1. For un-cracked concrete, the water repellent treatment proves its high efficiency both in reducing water absorption and as a chloride barrier under accelerated dry/wet exposure condition. Due to these dual effects, water repellent treatment can prevent corrosion of the internal steel reinforcement in concrete.

2. Considering that the water repellent applied to a concrete surface may be destroyed by UV deterioration, physical abrasion etc., a relatively large penetration depth should be achieved in order to keep the long-term effectiveness of water repellent treatment for the expected service life of the structure.

3. Silane-based cream and gel formulation appear to be superior to silane liquid when treating concrete surfaces with existing cracks. According to the current test results, steel reinforcement in untreated concrete has corroded heavily after 770 accelerated dry/wet cycling exposure. For those specimens with surface crack widths ranging from 0.13mm to 0.17mm before the water repellent treatment, the silane-based cream and gel still seem to be effective in reducing water absorption, chloride penetration, and stopping the internal steel reinforcement from corroding.

4. Water repellent treatments may not be effective in preventing water absorption, chloride penetration, and steel corrosion if cracks are developed in the concrete after the water repellent treatment unless the crack width can be controlled so as to keep it to a minimum width (<0.1 mm).

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