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Effect of Surface Hydrophobation for Protection of Early Age Concrete Against Chloride Penetration

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Abstract

For concrete structures in marine environment, chloride-induced corrosion of embedded steel represents a great threat to the durability and safety of the structures. For concrete construction work in marine environment, the concrete may be exposed to splashing and spraying of seawater already during the construction period before the concrete has gained sufficient maturity and density. Experience has shown that a high rate of chloride penetration may take place already at an early age, and this may be a special problem if the concrete construction work is carried out under rough and cold weather conditions. In the present paper, some results of an experimental program are reported, where the objective was to investigate the efficiency of a hydrophobic surface treatment for protection of concrete structures against an early age chloride penetration.

1 Introduction

Along the Norwegian coastline there are a large number of concrete structures, which are showing chloride-induced corrosion within a relatively short period of service [1]. For some of these structures, experience has shown that a high rate of chloride penetration takes place already during the construction period before the concrete has gained sufficient maturity and density [1]. In order to provide more information about the early age resistance of concrete against chloride penetration, an experimental program was carried out, some results of which have already been reported [2]. In the present paper, some results of a further experimental program are reported, where the objective was to investigate the efficiency of a hydrophobic surface treatment for protection of concrete structures against an early age chloride penetration.

2 Experimental

2.1 General

In order to provide a basis for the test program, age of concrete, curing temperature and relative humidity were selected as the main variables. In addition, type of concrete substrate (mould, cut and top cast surface) and time of absorption for the hydrophobic agent were also varied before exposure to the saltwater spraying.

2.2 Materials

2.2.1 Concrete

All the concrete specimens were based on a standardized concrete mixture for laboratory testing [3] (Table 1). An ordinary Portland cement with a w/c-ratio of 0.45 in combination with a naphthalene-based superplasticizer having a solid content of 42 %, were used. The aggregate was mostly of siliceous origin with a maximum particle size of 16 mm.

As a preliminary part of the test program, a number of concrete cylinders (Ø100 x 200 mm) were cast in steel moulds with a piece of plywood disk (Ø100 x 15 mm) in the bottom. This plywood disk was used in order to simulate the casting against a formwork surface. By cutting the concrete cylinders into three 50 mm thick slices, three different types of concrete substrate were obtained, of which one was a plywood mould surface, a cut surface and a top cast surface, respectively. After demoulding the next day, all test specimens were stored for 3 or 7 days in a climate chamber with 20 °C and

Table 1: Concrete mixture (kg/m^3)

Cement (CEM I 42.5R)	420
Water	189
Sand 0 - 8 mm	1053
Aggregate 8 - 11 mm	231
Aggregate 11 - 16 mm	487
SP	1 % weight of cement
w/c	0.45
Slump (mm)	160

50 % RH before surface treatment. The cutting of the specimens was carried out one day before surface treatment.

Based on the results from the preliminary part of the test program, the rest of test program was based on concrete cylinders (Ø100 x 200 mm) with three pieces of plywood disk (Ø100 x 15 mm) inserted in the steel moulds during casting of the cylinders (Figure 1). Thus, from each concrete cylinder, three test specimens with a plywood type of mould surface were obtained. For each test variable, three concrete specimens (Ø100 x 50 mm) were used, of which two for surface treatment and one for reference.

For the main test program, all test specimens were cured for 7 days in climate chambers before surface treatment. The following four climatic conditions were selected:

- Low humidity: Temperature and moisture of 20 °C and 50 % RH, respectively.
- High humidity: Temperature and moisture of 20 °C and 100 % RH, respectively.
- Low temperature: Temperature and moisture of 5 °C and 95 % RH, respectively.
- Low temperature: Temperature and moisture of 5 °C and 100 % RH, respectively

2.2.2 Hydrophobic agent

Only one type of hydrophobic agent was used throughout the test program, and this was a silane-based gel. The gel consisted of a few percent of a thickener, while the rest was a silane of a small molecular size, e.g. isobutyl triethoxy-silane. The gel was applied by use of a 50 mm brush to a thickness of 0.8 mm as recommended by the producer of the product. After application

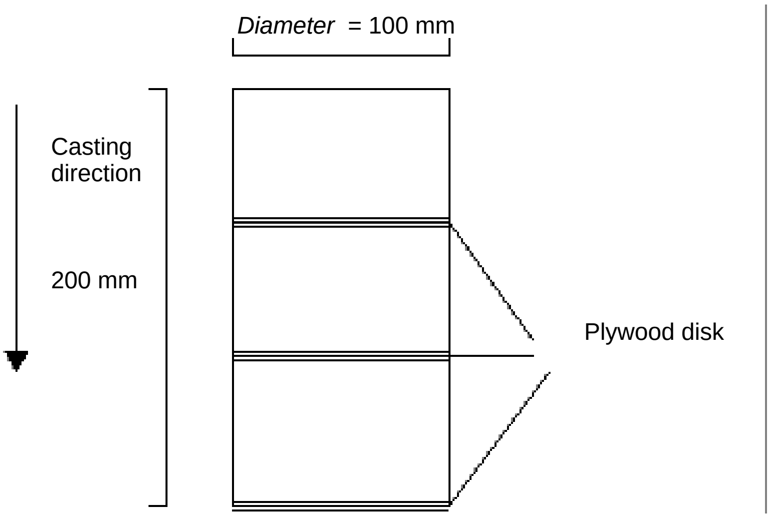

Figure 1: Concrete cylinder with inserted plywood disks

of the surface treatment which was carried out at room conditions (20 °C and 50 % RH), all test specimens were immediately put back into the various climate chambers until time of exposure. For the preliminary part of the test program, absorption times of 3, 14 and 28 days for the hydrophobic agent to act before exposure were used. For the main part of the test program, all surface treatments were allowed to act for 28 days before exposure to the salt solution.

2.3 Testing procedures

For the preliminary part of the test program, only splitting of test specimens and spraying with fresh water was used as a basis for evaluating the hydrophobic efficiency [4]. For the main part of the test program, however, the test specimens were also subjected to an established procedure for intermittent wetting and drying to a 3 % NaCl solution [5]. Each cycle in this exposure consisted of 4 hours of spraying and 4 hours of drying at room temperature, and the exposure took place over a period of six weeks. Then, the depth of chloride penetration was observed by splitting the test specimens and spraying with a standard 0.1 M silver nitrate solution [6]. For some specimens, a more complete chloride penetration profile was also obtained. Before and after exposure, the weight of the test specimens was recorded, and the electrical resistivity of the exposed surfaces by use of a four-probe electrode (Wenner) was also observed.

For each test series in the main test program, nine test surfaces were subjected to testing, of which three were kept untreated as a reference. Among the six treated surfaces, two were used for observing the penetration depth of the hydrophobic agent, two for chloride penetration depth and the last two for observing the more complete profiles of chloride penetration, respectively. All chloride contents were analyzed by use of a spectrophotometric method [7]. For each measurement of electrical resistivity, the average of three measurements was recorded.

3 Results and discussion

3.1 Effect of concrete age, type of substrate and absorption time

As can be seen from Table 2, a much deeper penetration of the hydrophobic agent into the more porous top surface of the concrete specimens was observed compared to that of the denser concrete surfaces of both the cut and the plywood mould surface. The age of the concrete was not so important, but the time of absorption or time for the hydrophobic agent to act during a period from 3 to 14 and 28 days was very important for the observed penetration depth. This effect of action time for the hydrophobic agent is in agreement with previous observations [8, 9].

Table 2: Effect of concrete age, type of substrate and absorption time for the observed depth of hydrophobic agent (mm)

Age of concrete (days)	Concrete substrate	Absorption time under 20 °C and 50 % RH (days)		
		3	14	28
3	Mould	< 0.1	2.9 ± 0.2	3.5 ± 0.8
	Cut	< 0.1	3.1 ± 0.1	4.1 ± 0.7
	Top	11.5 ± 0.8	8.7 ± 0.2	10.7 ± 1.1
7	Mould	< 0.1	7.8 ± 0.8	6.9 ± 0.7
	Cut	< 0.1	7.0 ± 1.2	7.1 ± 0.2
	Top	9.5 ± 0.8	10.6 ± 0.5	10.8 ± 0.4

Table 3: Effect of temperature and moisture conditions on penetration depth of hydrophobic agent

Code	Penetration depth (mm)
T-20-50	9.6 ± 1.2
T-20-100	2.0 ± 2.8
T-05-95	2.8 ± 0.3
T-05-100	< 0.1

Based on the above observations, the rest of the test program was carried out on the basis of a mould surface of 7 days old concrete, which is the most likely type of concrete substrate to be treated at an early age in the field. Also, all further testing was based on a 28 days period for the hydrophobic agent to act before any exposure to the salt solution.

3.2 Effect of temperature and moisture condition

Before exposure to the salt solution, the observed penetration depth of the hydrophobic agent can be seen in Table 3, where the results are the average of readings from two specimens. In the code for the table, (T) or (U) means treated or untreated specimens, while 20 or 5 means temperature (°C), and 50, 95 or 100 means relative humidity (%).

The results in Table 3 clearly demonstrate the importance of the moisture conditions for the observed depth of the hydrophobic agent. When the relative humidity increased from 50 to 100 % at 20 °C, it can be seen that the penetration depth was reduced to approximately one fifth, and at 100 % RH and 5 °C, the penetration depth of the hydrophobic agent was hardly observable. These test results which are also in accordance with previous experience [8,9], clearly demonstrate the importance of the moisture conditions in the concrete substrate for the penetration depth of the hydrophobic agent. The temperature did not appear to be so important.

The observed weight change of test specimens before and after exposure to the salt solution also confirms the importance of the moisture conditions for the efficiency of the surface treatment (Table 4). For the observations of electrical resistivity, however, it was not so easy to find a similar correlation due to the high scatter of the readings.

Table 4: Effect of temperature and moisture condition on changed electrical resistivity and weight of specimens before and after exposure to the salt solution

Code	Electrical resistivity (%)	Weight (%)
U-20-50	- 5.8 ± 16.6	1.53 ± 0.13
T-20-50	-14.9 ± 15.8	0.81 ± 0.16
U-20-100	43.6 ± 20.0	0.14 ± 0.05
T-20-100	45.1 ± 22.9	- 0.12 ± 0.10
U-05-95	5.7 ± 3.5	0.88 ± 0.18
T-05-95	8.5 ± 22.5	0.51 ± 0.05
U-05-100	34.9 ± 20.0	0.08 ± 0.21
T-05-100	28.3 ± 33.6	- 0.60 ± 0.08

3.3 Effect of surface hydrophobation on the resistance against chloride penetration

After 6 weeks of intermittent spraying and drying to the salt solution, all test results are shown in Table 5 and Figures 2 to 4. As a basis for the evaluation, both depth of chloride penetration (C_x), surface chloride concentration (C_S) and apparent chloride diffusivity (D_{app}) calculated on the basis of Fick´s Second Law of diffusion, were recorded. In addition, the chloride penetration rate (V) was also calculated as the total amount of penetrated chlorides divided by surface area and time of exposure ($g/m^2.s$).

At 20 °C and 50 % RH, Table 5 shows that the surface treatment reduced the depth of chloride penetration, apparent chloride diffusivity and chloride penetration rate from 7.8 to 1.6 mm, from 6.5 to 0.3 x 10^{-12} m^2/s and from 3.0 to 0.9 x 10^{-5} $g/m^2.s$, respectively. For increased relative humidity to 100 %, however, a depth of chloride penetration, apparent chloride diffusivity and chloride penetration rate of 5.1 mm, 4.4 x 10^{-12} m^2/s and 1.7 x 10^{-5} $g/m^2.s$, respectively, were observed. For a combination of increased humidity to 100 % RH and reduced temperature to 5 °C, the corresponding numbers were 7.7 mm, 8.3 x 10^{-12} m^2/s and 1.7 x 10^{-5} $g/m^2.s$, respectively.

As can be seen from Table 5, the surface chloride concentration did not reflect the efficiency of the surface treatment. The observations clearly demonstrate, however, that there was a good correlation between penetration depth of the hydrophobic agent (Table 3) and the efficiency of the surface

Table 5: Chloride penetration in untreated and treated specimens

Code	Penetration depth (C_x) [mm]	Surface concentration (C_s) [% concrete weight]	Apparent chloride diffusion coefficient (D_{app}) [10^{-12} m^2/s]	Chloride penetration rate (V) [10^{-5} g/m^2 s]
U-20-50	7.8 ± 1.0	0.64	6.50	2.96
T-20-50	1.6 ± 0.5	0.41 ± 0.02	0.29 ± 0.03	0.87 ± 0.01
U-20-100	6.9 ± 1.0	0.35	6.10	1.50
T-20-100	5.1 ± 1.1	0.40 ± 0.10	4.42 ± 0.74	1.68 ± 0.30
U-05-95	10.0 ± 0.8	0.62	9.80	3.33
T-05-95	5.4 ± 1.4	0.19 ± 0.02	12.80 ± 2.97	1.16 ± 0.02
U-05-100	9.1 ± 0.5	0.61	6.74	3.06
T-05-100	7.7 ± 0.1	0.34 ± 0.02	8.29 ± 0.05	1.72 ± 0.07

treatment. Both Table 5 and Figures 2 to 4 further clearly demonstrate that the efficiency of the surface treatment was not so good on a very wet concrete substrate. Also, for a very wet concrete, a low temperature was not so important for the efficiency of the surface treatment.

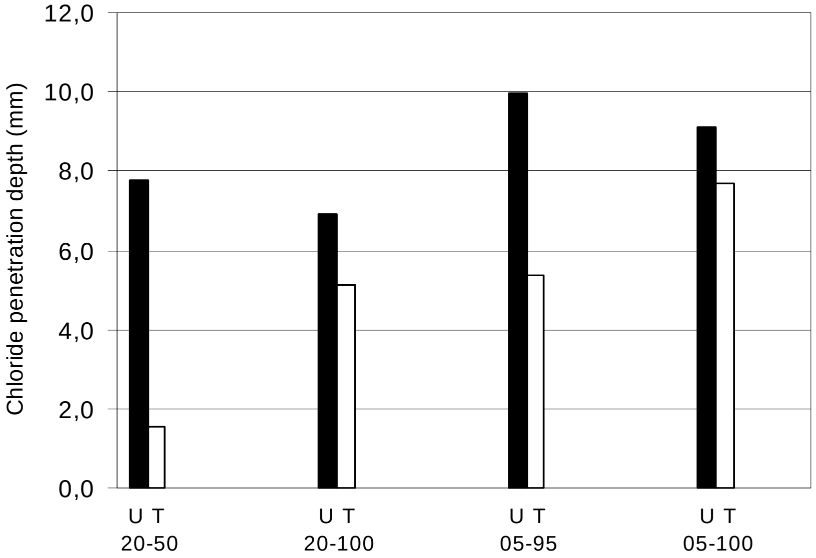

Figure 2: Effect of curing temperature and moisture condition on the efficiency of the surface treatment to reduce the depth of chloride penetration

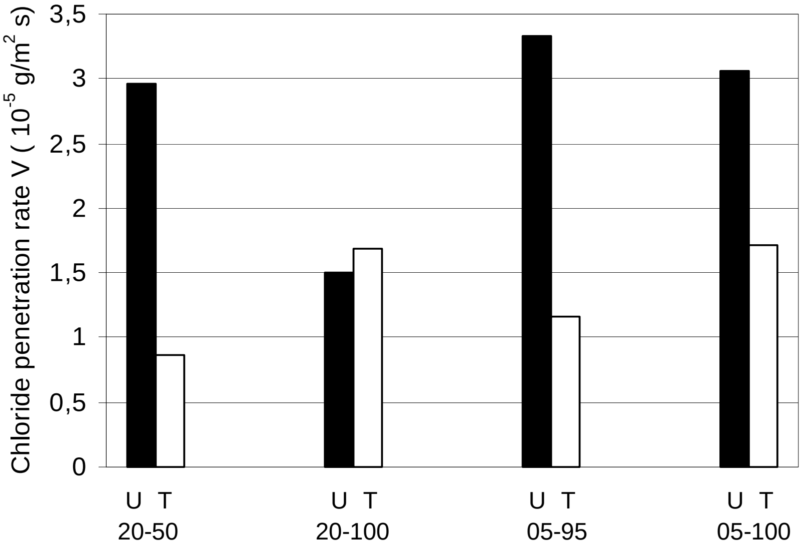

Figure 3: Effect of curing temperature and moisture condition on the efficiency of the surface treatment to reduce the rate of chloride penetration

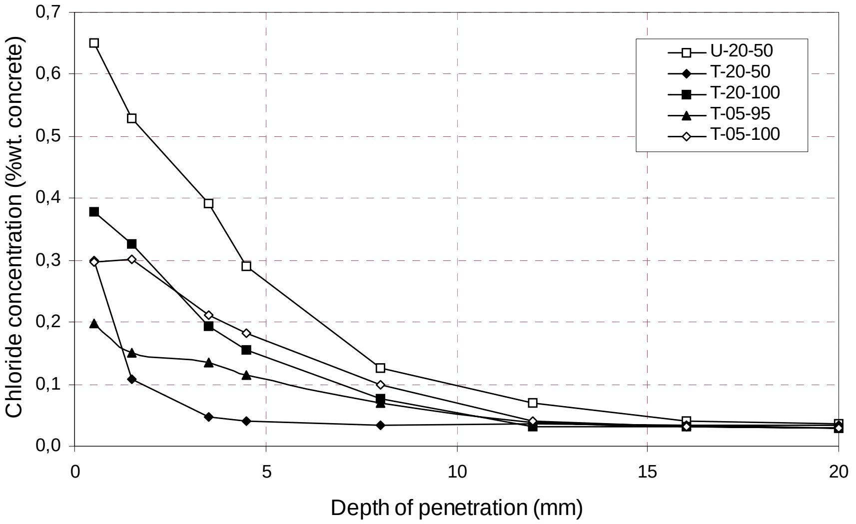

Figure 4: Effect of curing temperature and moisture condition on the efficiency of the surface treatment to reduce the chloride penetration into early age concrete

4 Conclusions

The present experimental investigation was only based on a limited number of variables, and the testing was also only based on accelerated test methods which may not reflect the complete resistance of the concrete against chloride penetration. However, based on the test results obtained, the following conclusions appear to be warranted:

1. For a relatively dry concrete substrate, the hydrophobic surface treatment significantly provided a very efficient protection of the early age concrete against chloride penetration. Thus, at a temperature and relative humidity of 20 °C and 50 %, respectively, the surface treatment reduced the depth of chloride penetration, apparent chloride diffusivity and chloride penetration rate from 7.8 to 1.6 mm, from 6.5 to 0.3 x 10^{-12} m^2/s and from 3.0 to 0.9 x 10^{-5} g/m^2. s, respectively.
2. For a very wet concrete substrate, the ability of the hydrophobic surface treatment to protect the concrete was significantly reduced. Thus, by increasing the relative humidity from 50 to 100 % at 20 °C, the depth of chloride penetration increased from 1.6 to 5.1 mm and

the apparent chloride diffusivity increased from 0.3 to 4.4 x 10^{-12} m^2/s, while the chloride penetration rate increased from 0.9 to 1.7 x 10^{-5} $g/m^2.s$.

3. The test results showed a good correlation between increased depth of hydrophobic agent and reduced depth of chloride penetration.
4. For a very wet concrete substrate, the temperature conditions were not so important for the efficiency of the surface treatment.

5 Acknowledgment

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