

Chloride Penetration in Surface-Treated Concrete in Natural and Accelerated Environments

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ABSTRACT

This study investigated the chloride penetration of surface-treated concrete in natural and accelerated environments. A part of a real concrete port, including the beams and the columns, was investigated. Concrete specimens cast together with the concrete port were transported to the lab and subjected to wetting and drying cycles for accelerating the ingress of chloride ion. Chloride concentration of the specimens in the lab and the components *in situ* was tested. The results show that the surface treatments obviously slow down the chloride penetration into the concrete in both lab and *in situ*. The chloride penetration *in situ* is more severe than that in specimens under wetting and drying cycles. For the components of the real concrete port, the chloride concentration tested in summer is found higher than that in winter and the chloride concentration in the tensile region of bending beam is higher than that in the column.

1. INTRODUCTION

Chloride-induced corrosion is one of the most dominant causes of the deterioration of reinforced concrete structures (Hartt, 2012; Hobbs, 2001). Once the chloride concentration exceeds a threshold value, the passive film on the surface of reinforcement dissolves and the corrosion occurs in the presence of oxygen and moisture (Arya & Xu, 1995), eventually causing the cracking and spalling of reinforced structures. To predict and improve the serviceability and durability of reinforced concrete structures, the investigation of chloride penetration mechanism and the corresponding protective measures for structures are very important.

The mechanism of the chloride penetration into concrete is widely thought as the diffusion due to the concentration gradient and the convection under pressure (including the capillary suction caused by the surface tension) (Kwon, Na, Park, & Jung, 2009; Marchand & Samson, 2009; Muigai, Moyo, & Alexander, 2012). In fact, the chloride penetration into concrete is always the combination of diffusion and convection and is a complex process. Based on Fick's second law of diffusion, a lot of models have been proposed by Yu, Sun, and Ma (2002), Suryavanshi, Swamy, and Cardew (2002), Yang and Wang (2004), and Arya, Vassie, and Bioubakhsh (2014) to describe the diffusion of chloride considering the chloride ion binding capacity of concrete, time dependence of chloride diffusivity, microdefect of concrete structures, the concrete quality, etc. However, the results of these

studies are based on the specimens without loading into the lab.

Chloride penetration under the uniaxial compressive loads, tensile loads, and the cyclic flexural loads has been studied by Jiang, Wang, Zhao, and Liu (2012), Wu, Li, Wang, and Liu (2016), and Xin (2010) under wetting and drying cycles, and the results show that the compressive loads could promote the chloride penetration resistance, while the tensile loads is on the contrary. Based on Fick's second law, a model of chloride penetration considering the compressive loads has been proposed by Wu et al. (2016). As for the chloride penetration of structures *in situ*, Zhao, Gao, Xu, and Jin (2009) and Jin, Jin, Yan, and Yao (2009) have studied the concrete surface chloride ion concentration varying with seasons or the elevation. However, the comparison of the chloride penetration in the lab and *in situ* is rarely found.

As for the protective measures, concrete surface coatings are widely applied in structures. Different coatings correspond to different protective mechanisms and protective efficacies, and these coatings, including organic coatings and inorganic polymers (geopolymer), have been widely studied and compared. These surface coatings were proved effective in varying degrees in improving concrete durability by artificial wetting and drying cycles (Almusallam, Khan, Dulaijan, & Al-Amoudi, 2003; Brenna, Bolzoni, Beretta, & Ormellese, 2013; Li, Yang, Guo, Du, & Wu, 2015; Moon, Shin, & Choi, 2007) or naturally exposed to marine environment

(Medeiros & Helene, 2009; Moradillo, Shekarchi, & Hoseini, 2012; Rodrigues, Costa, Mendes, & Marques, 2000; Zhang, Yao, & Wang, 2012). However, few reports focus on the durability of structures under loadings *in situ* with surface coatings.

This study was conducted to investigate and compare the chloride penetration of surface-treated concrete *in situ* and in the lab. To achieve this objective, the chloride contents in a surface-treated concrete port and concrete specimens, which have the same mixture and subject to wetting and drying cycles in the lab, were measured and compared. This study can help to understand the chloride ingress behavior in the different components of a real concrete port and also give the comparison between the chloride ingress behavior in the natural and accelerated artificial environments.

2. EXPERIMENTAL PROGRAM

2.1 Materials and concrete mixture

The concrete mixtures applied in part of the concrete port (as shown in Figure 1) are listed in Table 1. The 28-day compressive strength of the concrete, f_c , was 40.42 MPa. The cement shown in Table 1 was ordinary Portland cement of grade 42.5 produced by Jiaxing Dongjin Cement Limited Company. The fly ash was produced by Dinghai power plant, and the slag was produced by Jiangsu Shagang Limited Company. The fine aggregate was medium natural river sand with a fineness modulus of 2.5. Coarse aggregate was normal gravel in the size ranging from 5 to 25 mm.

Six concrete specimens with the size of 150 mm × 150 mm × 300 mm (as illustrated in Figure 2) were cast *in situ* together with the concrete port, using the same bench of concrete. The specimens were cured on the shore near the port and wetted once a day for 28 days.



Figure 1. The port in Zhejiang Province, China.

Table 1. Compositions of concrete mixtures (kg/m³).

Water	139
Cement	180
Fly ash	180
Slag	90
Fine aggregate	779
Coarse aggregate	1032
Superplasticizer	5.4
Corrosion inhibitor	9.0

2.2 Surface treatment

After 2 months of the casting of the port, the surfaces of both the concrete port and the specimens were treated with a protective layer named E-26, which is produced by Ningbo Dada Chemistry Company, Ningbo, China. The E-26 surface treatments contained three layers, and the information is shown in Table 2.

All the surfaces of the port were treated by E-26. To evaluate the effectiveness of the surface treatment, the side and bottom surfaces of three specimens were painted with E-26 protective layer, while the surfaces of the left three specimens were all painted, as shown in Figure 2. They were labeled as LN (in the Lab and No treatment on the top surface) and LT (in the Lab and with Treatment on the top surface), respectively.

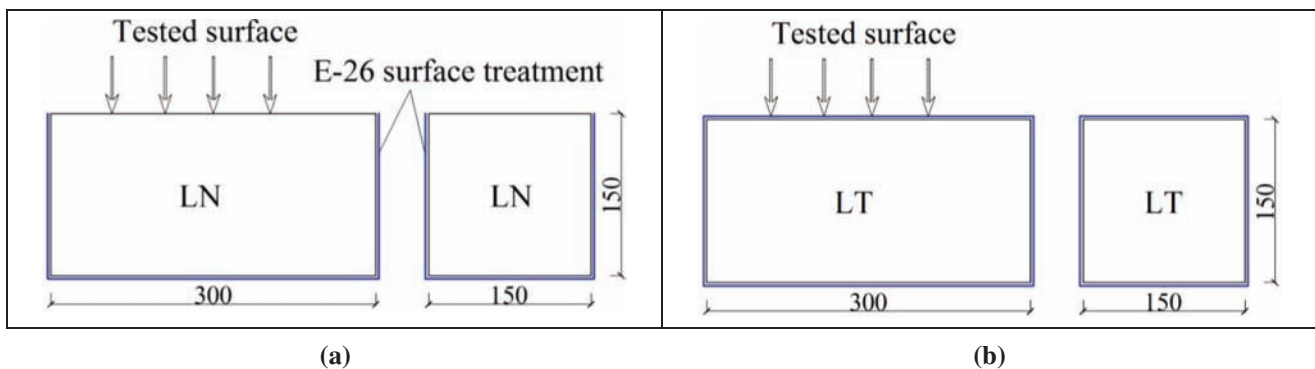


Figure 2. Layout details of concrete specimens (in millimeter). (a) Specimens LN treated except the top surface and (b) specimens LT treated on all the surfaces.

Table 2. Information about E-26 surface treatment.

E-26 surface treatment	Main components	Amount (g/m ²)	Dry film thickness (×m)
Primer	Low-molecular-weight epoxy resin, polyamide curing agent, and additive	100	40
Intermediate coat	Epoxy resin, pigments, fillers, and polyamide	333.3	300
Finish coat	Acrylate polyurethane	208.3	90

2.3 Chloride concentration in the lab

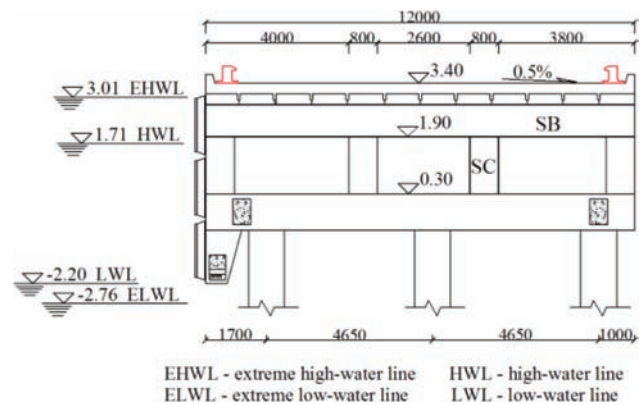
After the drying of the surface treatment, the six specimens were transported to the lab in the Zhejiang University and subjected to alternate wetting and drying cycles for accelerating the ingress of chloride ion. Each cycle lasted 7 days and consisted of a 3-day wetting period followed by a 4-day drying period. During the wetting periods, the specimens were submerged in a 6.15% NaCl solution, and during the drying periods, the specimens were taken out and exposed to the air in the lab. After 2, 4, and 6 months, the specimens were taken out to measure the chloride concentration as follows.

All the specimens were drilled from the top surface to take the powder for every 5 mm. For each specimen, three holes were drilled and the depth of each drilled hole was 50 mm. To avoid the influence of the chloride penetrated from the side surfaces, these holes were on the middle position of the top surface. The powder at the same depth from the three specimens of the same group was mixed, 10 teams of powder for each group were obtained, and the corresponding depths are 0–5 mm and 5–10 mm, until 45–50 mm. The powder was dried in the oven for 24 h at 50°C. Then, 4-g powder from the same depth and 40-mL deionized water were mixed to obtain the solution. The chloride concentration of the solution, as well as the chloride concentration in the concrete, could be calculated using a calibrated Chloride Meter (DY 2501-B). After the tests, the holes were filled with epoxy resin to avoid the ingress of chloride.

2.4 Chloride concentration tests *in situ*

After the concrete part was surface treated for 11, 14, and 18 months, the chloride concentration in some components was measured *in situ*. Since the parts of structures in the spray splash zone always suffered the most severe deterioration, a column (SC) and a beam (SB) located in this zone were chosen for the chloride concentration tests in each shelf, as shown in Figure 3. The column tested was a cylinder with a diameter of 800 mm and a height of 1600 mm, and the elevation level ranged from 0.30

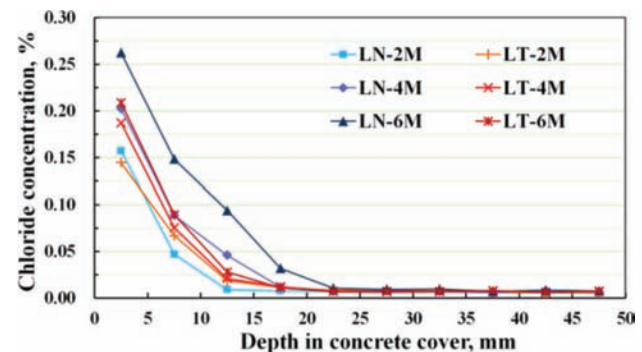
to 1.90 m. The elevation level of tested point was 1.10 m, i.e., the middle of the column. The size of the beam tested was 1200 mm × 900 mm × 12,000 mm, and the elevation level ranged from 1.90 to 2.80 m. The elevation level of the tested point was 2.05 m, i.e., 0.15 m higher than the bottom of the beam, which is located in the tensile region. All the columns and beams were drilled from the surface to take the powder for every 5 mm. Three holes were drilled for each column or beam; the powder for every 5 mm was taken out as a team; and the depth of each drilled hole was 50 mm, which is the same as the specimens. The tests of chloride concentration in the SC and SB were the same, as stated in Section 2.3. The holes were also filled with epoxy resin to avoid the ingress of chloride.

**Figure 3.** Schematic diagrams of the location of the tested SC and SB.

3. RESULTS AND DISCUSSION

3.1 Chloride concentration in the specimens in the lab

The chloride concentrations (concrete weight, %) in the specimens at different depths are shown in Figure 4; LN and LT stand for the specimens without and with the treatment on the top surface, respectively; and 2, 4, and 6M stand for 2, 4, and 6 months, respectively, representing the period of specimens subjected to the alternate wetting and drying cycles.

**Figure 4.** Chloride concentration (concrete weight, %) of the specimens.

The chloride concentration decreases with the increasing of the depth at the first 15 mm (25 mm for LN-6M) according to Figure 4. At the depth more than 20 mm, the chloride concentration maintains a low level, <0.015%, which might be from the materials of the concrete, such as the water or aggregate, rather than the ingress of outside chloride. Therefore, the depth of chloride penetration is about 15 mm at the first 4 months, and it reaches about 20 mm for the concrete without the surface treatment at the sixth month.

At the same depth, the chloride concentration increases with the increasing of the period subjected to alternate wetting and drying cycles, as shown in Figure 4; however, the increasing in LT is smaller than that in LN. For example, the chloride concentrations of LN at the depth 0–5 mm are 0.157, 0.202, and 0.262% after 2, 4, and 6 months of alternate wetting and drying cycles, respectively, and it increases by 29.7% from the fourth month to the sixth month. As for LC, the chloride concentrations at the depth 0–5 mm are 0.187 and 0.209% at 4 and 6 months, respectively, and increases by 11.8%. Besides, the chloride concentration in LT is smaller than that in LN. After 6 months of alternate wetting and drying cycles, the chloride concentration at the depth 0–5 mm in LT is 0.79% of that in LN. Therefore, the E-26 could slow down the ingress of chloride ion into the concrete.

3.2 Chloride concentration *in situ*

The chloride concentrations (concrete weight, %) *in situ* at different depths are shown in Figure 5; SC and SB stand for the column and beam, respectively; and 11, 14, and 18M stand for 11, 14, and 18 months, respectively, representing the service life of the port. Besides, because of the protection of E-26, the chloride concentration does not change significantly.

According to Figure 5, the chloride concentration at the depth 0–10 mm tested at the 14th month is higher than that at the 11th month and 18th month. In fact, the corresponding months of the tests *in situ* are May, August, and December. In summer, the stronger wind and waves result in the severe splashing of waves on the port and the rising temperature accelerates the evaporation of water, which results in a higher chloride concentration in the near-surface concrete, according to Zhao et al. (2009). In autumn, the port receives much more rain than summer, which would wash away part of chloride in the near-surface concrete. In winter, the lower temperature slows down the evaporation of water and induces the smaller concentration of chloride in the near-surface concrete. Therefore, the chloride concentration in near-concrete surface at the 14th month, or in August, is higher than that at the 11th month and 18th month.

E-26 could slow down the transport of chloride ion from outside into the concrete. In the concrete cover, the concentration gradient in the concrete cover will result in the diffusion of chloride ion from the near-surface concrete into the deeper concrete cover, which also results in the decreasing of chloride concentration in the near-surface concrete, as well as the increasing of chloride concentration in the deeper concrete. This is also the reason that at the depth of 15–25 mm, the chloride concentration at the 18th month is higher than that at the 11th month and the 14th month, as shown in Figure 5.

Comparing Figures 5(a) and 5(b), it can be found that the chloride concentration in the near-surface concrete in the beam (SB) is a little higher than that in the column, even though the soakage time of the column is longer than that of the beam, as the tested point in the column is in the design tide level while the beam is higher than the high-water line. Therefore, the major reason is the loading. The seepage flow of liquid in concrete is in direct proportion to the first power of

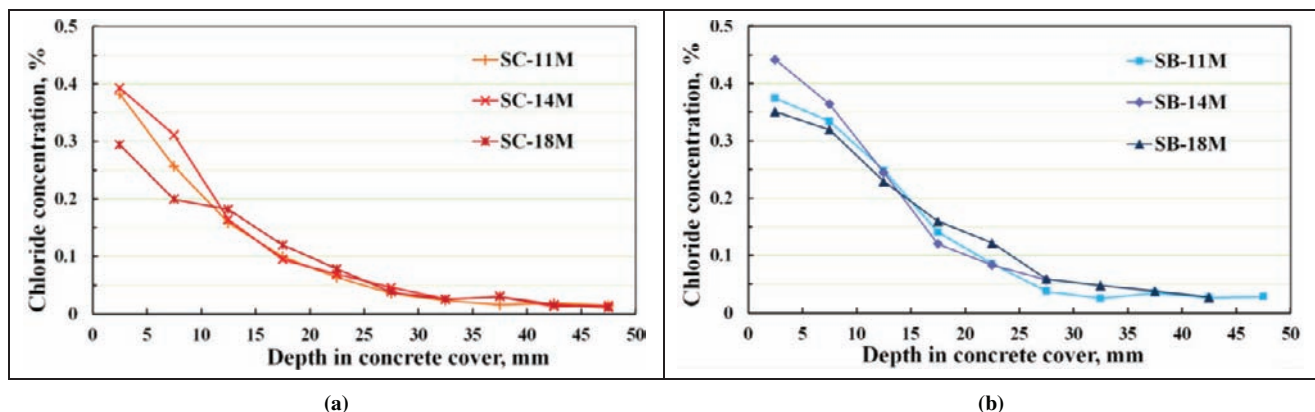


Figure 5. Chloride concentration (concrete weight, %) *in situ*. (a) Results of the column and (b) results of the beam.

porosity and the fourth power of the pore diameter for a given pore size (Jiang et al., 2012). The column is under compressive loads, which could reduce the amount of pores, change the distribution of concrete pore diameter, and reduce microporous average diameter, which result in the reducing of the water transport capacity and chloride transport capacity of concrete (Wu et al., 2016). The beam is under bending load, the point tested is in the tensile region, and the situation is on the contrary. The tensile loads will increase the microporous, and some pores become connected and accelerate the ingress of chloride ion (Xin, 2010).

3.3 Comparison of chloride penetration in lab and *in situ*

Comparing Figures 4 and 5, it can be found that the chloride concentration *in situ* is higher than that of LC, and also, the chloride penetration depth is higher *in situ*. This is mainly caused by the ingress of chloride before the painting of E-26. During 2 months between the casting of the port and the painting of E-26, the hydration reactions of cementitious materials are insufficient and the larger porosity and the pore diameter make it easy for the ingress of chloride ion. As for the specimens, they were cured 2 months before the painting and subjected to alternate wetting and drying cycles. Besides, the stronger wind and waves and the longer exposure time may also result in the higher chloride concentration *in situ*.

4. CONCLUSIONS

The chloride profile of concrete under the surface treatment E-26 of a port and the concrete specimens with the same mixtures were tested and compared. The following conclusions can be drawn from the results of this study:

- (1) The surface treatment could slow down the ingress of chloride ion into the concrete both in concrete specimens and *in situ*.
- (2) In near-surface concrete, the chloride concentration is higher in summer and lower in winter, and in deeper concrete, the chloride concentration increases slowly with service life under the diffusion of chloride from the near-surface concrete.
- (3) In near-surface concrete, the chloride concentration in the tensile region of the bending beam is a little higher than that in the column under compressive loads.
- (4) The chloride penetration *in situ* is more severe than that in specimens for the ingress of chloride *in situ* before the adequate hydration of cementitious materials.

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