4th International Conference on the Durability of Concrete Structures
24–26 July 2014
Purdue University, West Lafayette, IN, USA

Exposure Test on Two Surface Anticorrosion Technologies for Marine Concrete Structure

Haicheng Yang and Jianbo Xiong
CCCC Fourth Harbor Engineering Institute Co., Ltd, Key Laboratory of Harbor & Marine Structure Durability Technology of the Ministry of Communications

Quanke Su and Yu Yan
Hong Kong–Zhuhai–Macao Bridge Authority

ABSTRACT

This paper is to study the effect of surface coating and silane hydrophobic agents for high performance concrete durability in a marine environment of tidal zone and splash zone by exposure test in JiaoZhou Bay. The results indicated that surface coating had good protection and coating quality after a 5-year period and the adhesive strength with concrete surface was more than 2.5 MPa. Surface coating can effectively improve chloride ion penetration resistance of concrete structures. The substrate concrete of specimen treated with silane had some chloride ion penetration, but compared with untreated concrete, chloride content of silane-treated concrete within 10 mm depth from surface was reduced by 43 and 67% in the tidal zone and the splash zone, respectively. Two surface anticorrosion measures technologies were effective in reducing the chloride erosion and improved the service life of marine concrete structure.

1. INTRODUCTION

Chloride-induced corrosion of reinforcement is one of the major causes of the durability deterioration of reinforced concrete structures. Spray anti-corrosion material in surface concrete structures can reduce the chloride ion penetration in severe marine environment and improve the service life of the concrete structures. Surface protection technology mainly refers to the formation of an isolation layer in concrete surfaces that can cut off or delay the corrosive substance, so that concrete structures can achieve the service life of the durability design requirements. Nowadays, surface coating and silane impregnation are usually adopted to improve the durability of marine concrete structures (JTJ 275, 2001). However, surface protection technology measures have a different protection effect on concrete structures serving different seawater corrosion environments. It is necessary to carry out long-term follow-up research through actual environment exposure tests. In this study, scope applicability and long-term durability of surface coating and silane impregnation have been studied for different sea water corrosion environments in JiaoZhou Bay of China. So it can provide certain references for rational selection of anticorrosive measures for concrete structures in similar environments.

2. EXERIMENTAL INVESTIGATION

2.1 Expose specimen making

“ShanShui” PI 52.5 cement was used; the chemical index of cement is shown in Table 1. Ground granulated blast furnace slag (GGBS) was used, which is a product of the Qingdao Liang Football Industry & Trade Co. Ltd., the main index of GGBS is shown in Table 2. Fly ash of Class I was used, which was produced in the Rizhao Hua Neng Power Plant Co. Ltd., the chemical index of fly ash is shown in Table 3. A fine aggregate of natural river sand with apparent density of 2600 kg/m^3, clay content of 1.0%, and fineness modulus of 2.9 were used. Coarse aggregate of crushed limestone with 5–10 and 10–20 mm combined gradation was used. The coarse aggregate had clay content of 0.3%, crushing value of 11.8%, apparent density of 2700 kg/m^3, and packing density of 1480 kg/m^3. “RHEOPLUS 326” superplasticizer and air-entraining agent “MICRO AIR 202”, produced by BASF were used. The mix proportion is show in Table 4.

Table 1. Inspection result of cement chemical index.

Water-soluble Cl^- (%)	SO_3 (%)	Na_2O + 0.658 K_2O (%)	f-CaO (%)	MgO (%)	Ignition loss (%)
0.019	2.05	0.77	2.16	1.92	1.94

Table 2. Main indexes of ground slag.

Particle Density (g/cm^3)	Fineness (m^2/kg)	Activity index (%)		Flow-ability ratio (%)	Cl^- (%)	Ignition loss (%)
		7 Days	28 Days			
2.8	368	77	106	105	0.012	1.19

Table 3. Chemical components of fly ash(%).

Grade	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	f-CaO	SO_3
I	60.81	5.76	24.12	3.03	0.55	0.62	0.63

Table 4. The mixing proportion of concrete.

Place area	Cementitious material consumption (kg)	Material composition(%)			W/B
		Cement (%)	Fly ash (%)	GGBS (%)	
Tidal zone	397	40	15	45	0.36
Splash zone	426	40	14	46	0.34

Preparation and maintenance technology of surface coating specimen was simulated on the bearing platform and pier of Qingdao Bay bridge, that cofferdam dry construction. First, the concrete was cured under standard conditions for 14 days, and second, it was placed outdoor for 4 days for natural curing. Then, surface treatment and coating was done according to the requirements of the Qingdao Bay Bridge Design and the Anticorrosion Coating Construction Guide (Wang, Xiong, & Wang). The coating system performances are shown in Table 5.

Table 5. Coating system performance.

Coating	Designation	Ratio of curing agent	Con-sumption (kg/m²)	Thick-ness (μm)
Bottom layer	Wet curing epoxy sealing primer (one layer)	4:1	0.12	≤50
Intermediate layer	Wet curing epoxy micaceous iron oxide intermediate paint (three layers)	10:1	0.4	300
Top layer	polyurethane finish coat (two layers)	6:1	0.14	90

Materials of silane crème performance index have been shown in Table 6. First, the concrete was cured under standard conditions for 14 days, and second, was placed outdoor for 4 days for natural curing, and then, the concrete substrate was polished and the surface dust was removed. The concrete brush was applied twice, each at a rate of 150 g/m^2 sliane crème with a minimum interval of 6 h.

Table 6. Silane performance indicators.

Major Component	Active substance content	Density below 25°C	pH	Flash point
Iso-octyltreithoxy	80%	0.9 g/cm³	6	74°C

2.2 Exposure test environment

The specimen was placed in field exposure station of the JiaoZhou Bay Bridge (Yang, Gai, & Li, 2012). The average annual temperature of the exposure test location is about 12.3°C, the extreme maximum and minimum temperatures are 38.9 and −16.9°C, respectively. The minimum and maximum average temperatures in January and August are −1.0 and 25.1°C, respectively. The area freezes for about 60 days, from late December to mid-February of the following year, is severely frozen from late January to early February, and has about 47–52 times the annual average of the natural freeze–thaw cycle.

Tides are of the regular semidiurnal type; tidal cycles are about 12 h 25 min; the rising tide time is relatively shorter and Ebb tide is longer. The relative mean high and low tides are +1.39 and −1.40 m, respectively. The specimens were placed in the tidal zone and splash zone at an elevation of −0.40 and +2.00 m, respectively. The specimen placed in the tidal zone is lower than the mean tide level of 0.5 m and the specimen placed in the splash zone can only be immersed in water when a few spring tides occur.

2.3 Test methods

Shellfish, seaweed, and other marine floating biological specimens were removed after the specimens were got back from the exposure stations, and then, dust was collected using a drilling tool, layer by layer according to "Concrete Hardened: Accelerated Chloride Penetration"(NT BUILD 443). The total chloride content was measured by powder samples for chemical titration analysis according to "Testing Code of Concrete for Port and Waterwog Engineering" (JTJ270-98).

3. RESULT AND DISCUSSION

3.1 Surface coating quality

From Figure 1, we can see lots of barnacle, oyster, and other marine creatures growing on the concrete surface of the coating specimen in the tidal zone. But the coating specimen had no obvious marine plankton growth in the splash zone, and the surface was bright and tidy. After removing oysters and other creatures, the coating was seen to retain a good appearance, with no pulverization and layer phenomenon, and had good adhesion between coating and surface concrete, with no visible cracks, scaling, and so on.

JiaoZhou Bay is located in China's frozen regions. Freeze–thaw damage is also one of the main factors influencing the durability of concrete structures. Free water of pore structure concrete is one of the most important reasons that cause cold damage of structures. A continuous sealing film can be formed by using surface coating, blocking sea water transport of

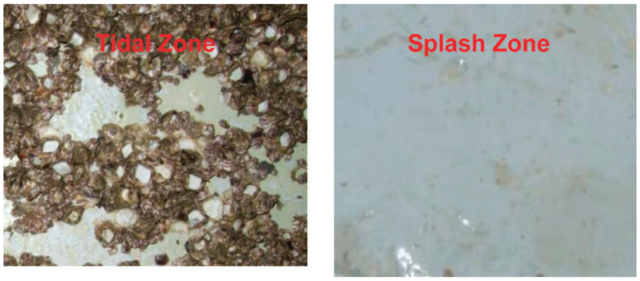
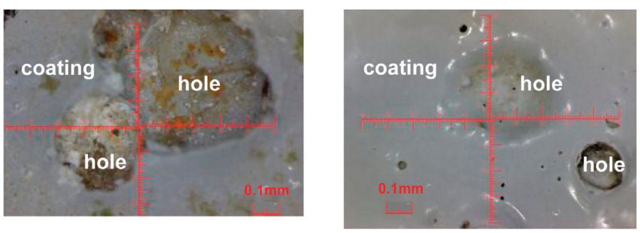


Figure 1. Coating appearance at 5 years exposure age.

concrete, and reducing moisture content of concrete. So frost resistance of concrete can be improved. No closed holes can be observed under the microscope in Figure 2. The unclosed holes surrounding the coating are the weak links that easily cause freeze–thaw damage to occur due to the high moisture content of the concrete for the coating specimen in the tidal zone of below mean tide level. Around unclosed holes of coating specimens under the tidal zone and splash zone have been observed, and the around holes between the coating and the concrete have smooth surfaces and good adhesion. No damage phenomena, such as scaling and cracking occurred. It has been shown that surface coating still had good quality and anti-freeze performance after the 5-year exposure test (about 250 times the natural freeze–thaw cycle).



a. Tidal zone b.Splash zone

Figure 2. Coating morphology under microscope at 5 years exposure age.

The condition due to the contact of the shellfish with the coating area after removing the shellfish and other creatures can be seen in Figure 3. Shells are embedded inside the coating and cut the surface along with the growth of shellfish, and to a certain extent, it damages the integrity and the continuity of the surface coating. So one should consider the influence of marine shellfish on the coating durability for concrete structures in the tidal zone.

Adhesive strength between concrete and coating is an important index of coating quality. The trend of adhesive strength changing with exposure age can be seen from Figure 4. The adhesive strength increased more than the initial strength. The main reason was that most of the surface damage types of coating adhesive strength

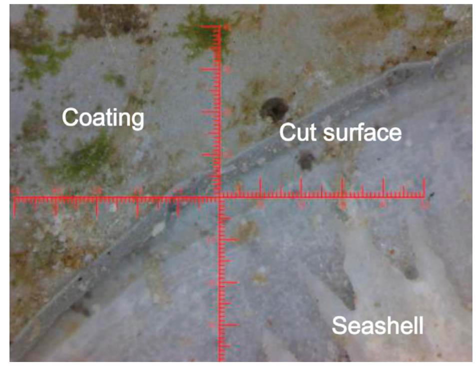


Figure 3. The effect of shellfish growth to coating in tidal zone.

test were concrete surface destruction (Figure 5). With the growth of concrete age, concrete surface strength increased, and so, adhesive strength increased. The adhesive strengths were greater than 2.5 MPa, greater than relevant specifications at home and abroad significantly.

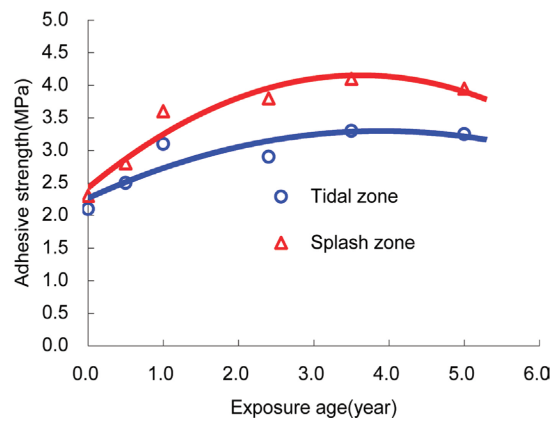


Figure 4. Adhesive strength of coating changing with age.

Figure 5. Typical damage type of concrete coating.

Five years' field exposure tests show that the performance index of coating, such as coating appearance and adhesive strength can meet the requirements of relevant specifications. The coating material itself had good anti-aging performance and frost resistance durability and can improve the frost resistance of concrete structure in the tidal zone.

3.2 Silane quality

Water is the most important carrier of harmful mediums that penetrate concrete structures. For the marine concrete structure under the splash zone, capillary of siphon action can quickly suction water that contains corrosive medium into concrete and cause steel corrosion of concrete and performance degradation. Water absorption can help evaluate concrete absorbency properties and is the most important indicator, and to a certain extent, can characterize concrete permeability, pore characteristics, and so on.

Silane protection, mainly based on silane material can react with gelled material hydration products and make the capillary wall of concrete hydrophobic. So it is difficult for water and other corrosive medium to penetrate. Silane specimens still showed obvious hydrophobia after 5 years' exposure test (shown in Figure 6). Concrete water absorption per unit area at different times had test with reference to Corrosion Prevention Technical Specifications for Concrete Structures of Marine Harbour Engineering (JTJ275-2000). Water absorption of untreated concrete is 2.41 mg/cm^2 at soaking 240 min, but silane concrete of the splash zone is only 1.36 mg/cm^2, a decrease of nearly one time (Figure 7). So it can be illustrated that silane still can significantly reduce concrete water absorption performance after 5 years' exposure test.

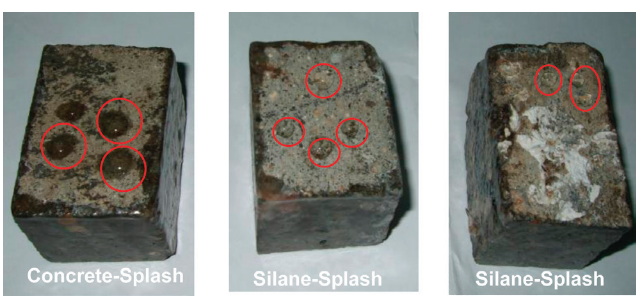


Figure 6. Silane concrete conditions of hydrophobic nature after 5 years' exposure age.

3.3 Analysis protecting effect of anti-corrosion protection measures

Chloride ion concentration at different depths of silane concrete and coating concrete at different exposure age are shown in Figure 8. The amount of penetration of chloride ion content (amount of square meters of chloride ion, kg/m^2) within 10 mm from the surface of concrete is shown in Figure 9.

Chloride ion of seawater did not penetrate inside concrete and the chloride ion content of concrete was

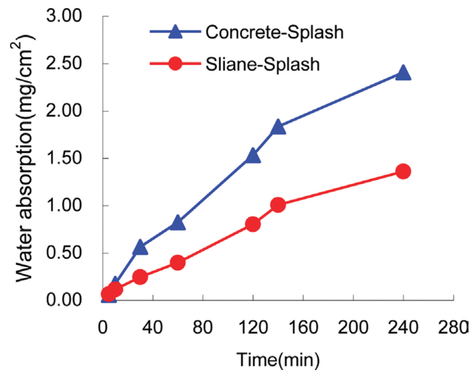


Figure 7. Water absorption performance of silane concrete and untreated concrete after 5 years' exposure age.

substantially the same as the initial concentration of about 0.02–0.03%. However, with the exposure age prolonged, after 5 years' field exposure test, the distance of 1–3 mm from concrete surface had penetrated a small amount of chloride ions (about 0.1%); compared with the same depth of untreated concrete, the chloride ions concentration reduced about four to seven times. Chloride ion concentration deeper from the concrete surface (≥4 mm) was the same as the initial concentration basically. It can be illustrated that chloride ions had only penetrated into concrete surfaces under the protective coating. Although there was a mount of unclosed holes of surface coating, but the coating had better overall protection and can effectively delay chloride ions of seawater erosion into concrete.

The rule of chloride ions penetration of silane impregnation concrete was different from coating concrete. The shallow surface of silane concrete within 5 mm depth from the concrete surface had penetrated a certain amount of chloride ions at 1 year exposure age. Mainly because the silane hydrophobic layer cannot completely close the surface concrete, although the surface treated layer can delay most of the water and harmful ions from entering, but still some water and ion can enter into the concrete substrate through treat layer under high seawater pressure and drying–wetting cycle. However, compared with untreated concrete, the chloride ions content reduced by 48 and 65% at the tidal zone and the splash zone, respectively. So concrete treated with silane showed good seawater anti-erosion performance. As the exposure age extended, the amount of chloride ion content increased continuously. Chloride ion concentration of untreated concrete at the distance of 10 mm from the concrete surface had reached 0.13 and 0.10% (quality of concrete) in the tidal zone and the splash zone, respectively. As the exposure age prolonged, silane material still exhibited excellent seawater corrosion resistance performance, whether silane impregnated concrete in the tidal zone or the

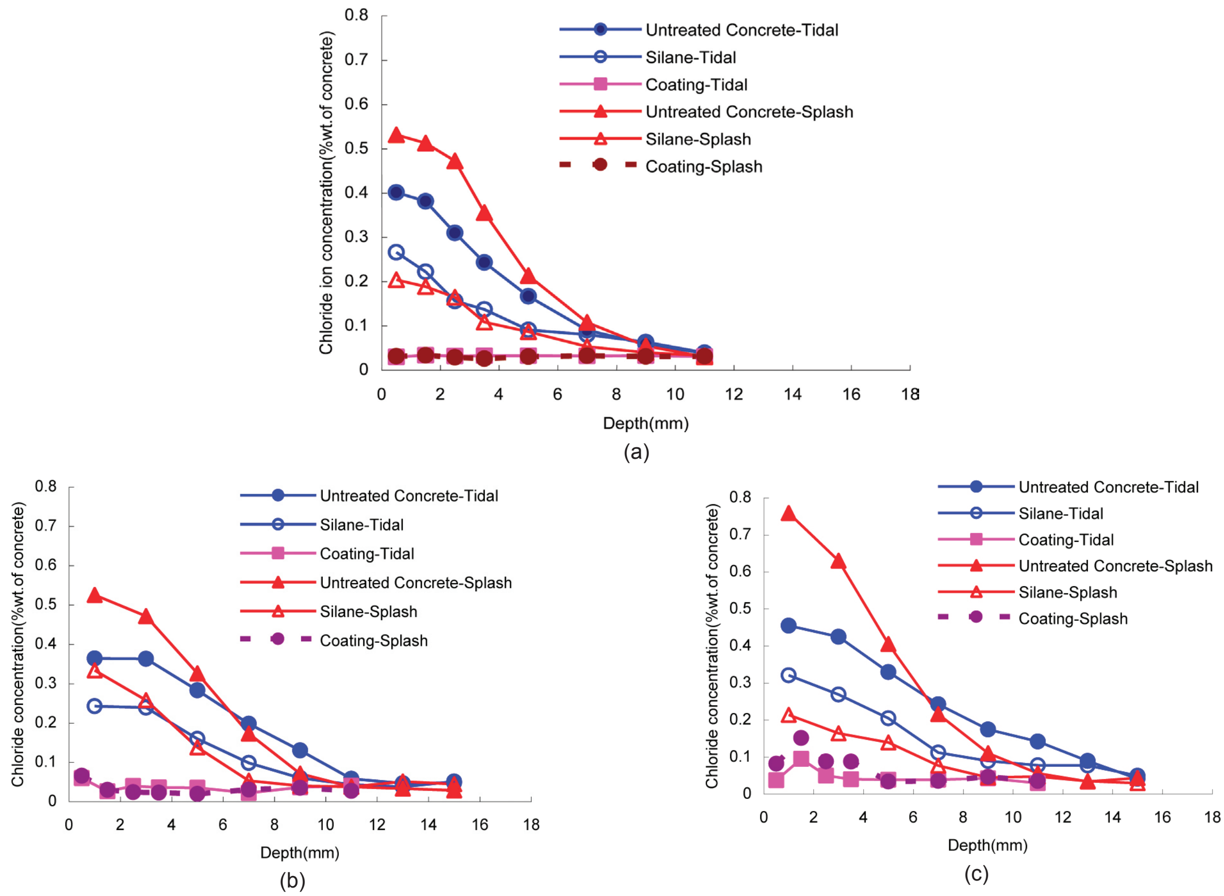


Figure 8. Chloride ion content of surface protection concrete at different exposure age. (a) Exposure age of 1 year. (b) Exposure age of 3 years. (c) Exposure age of 5 years.

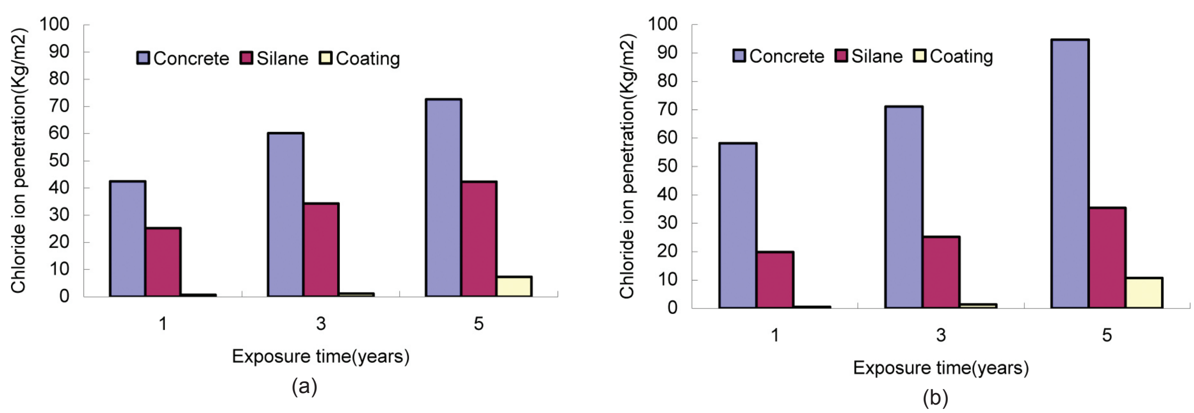


Figure 9. The amount penetration of chloride ion content within 10 mm from the surface of concrete. (a) Tidal zone. (b) Splash zone.

splash zone. Compared to the same depth of untreated concrete, the chloride ions content within 10 mm depth from the concrete surface reduced by 43 and 67% in the tidal zone and the splash zone, respectively (seen from Figure 8). So it can be illustrated that silane materials have different protective effects for concrete structures in different marine environments compared to high degree water saturation of concrete in the tidal zone; silane material had more excellent chloride ion corrosion resistance for concrete in the splash zone.

Under the premise of the above anti-corrosion measures, the initial construction quality and surface coating measures can not only significantly improve chloride ion resistance of concrete structures in the tidal zone but also provide excellent protection in the splash zone. It can be applied to the surface corrosion of marine concrete structures in the tidal zone and the splash zone. Silane anti-corrosion measures can also significantly improve chloride ion resistance of concrete structures in the splash zone, but protection effect for high degree water saturation concrete in the tidal zone (below mean tide level) is not significant; therefore, it is recommended that silane anti-corrosion measures can be applied to corrosion protection of marine concrete structures in the splash zone (above highest astronomical tide) and the atmospheric zone.

4. CONCLUSION

Surface coating has good protection and coating quality after 5 years' field exposure test, and the adhesive strength with the concrete surface was more than 2.5 MPa. The coating can effectively improve chloride ion penetration resistance of concrete structure in the tidal zone and splash zone.

Concrete treated with silane can prevent the penetration of chlorides ion into the concrete substrate effectively. Compared with the same depth of untreated concrete, the chloride ion content within 10 mm depth from the concrete surface reduced by 43 and 67% in the tidal zone and the splash zone, respectively. Silane materials have more excellent chloride ion corrosion resistance for concrete in the splash zone.

Anti-corrosion measures of surface coating and silane can effectively enhance durability of marine concrete structures. The surface coating can be applied to surface corrosion of marine concrete structures in the tidal zone and the splash zone; silane anti-corrosion measures can be applied to corrosion protection of marine concrete structures in the splash zone and the atmospheric zone.

REFERENCES

Yang, H., Gai, G., & Li, C. (2012). Field exposure test on different anticorrosion technology for marine concrete structures. *Journal of Highway and Transportation Research and Development, 29*(4), 79–84.

JTJ 275-2000. (2001). *Corrosion prevention technical specifications for concrete structures of Marine Harbour Engineering (S)*. Beijing: China Communications Press.

Wang, S. N., Xiong, J. B., & Wang, Y. F. *Requirements of Qingdao Bay bridge design and anticorrosion coating construction guide*. QingDao: CCCC Fourth Harbor Engineering Institute Co., Ltd.