- Technical Paper -

PERFORMANCES OF PRE-STRESSED CONCRETE SHEET PILE AFTER 12 YEARS EXPOSURE IN THE MARINE TIDAL ENVIRONMENTS

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ABSTRACT

Performances of PC sheet piles were evaluated after 12 years exposure in the marine tidal environment. An evaluation of mechanical properties, carbonation depth, porosity, chloride content and PC steel condition were carried out. Overall, all specimens showed satisfactory performance: only a few concrete corner and edge chips, low chloride content and low rate of corrosion were observed. Investigation results indicated that BS5 (B = GGBFS, S = steam curing, and cover thickness of 5 cm) showed the best performance (more durable) although its strength was lower than the other.

Keywords: chloride diffusion, corrosion rate, PC sheet pile

1. INTRODUCTION

Pre-stressed concrete (PC) sheet piles are commonly used for river revetment or retaining wall and are rarely used in port and harbor structure due to corrosive environmental conditions. Such as reinforced concrete in general, deterioration due to reinforcement corrosion becomes the most important durability issue. Steel corrosion may occur directly through oxidation of metals or by penetration of aggressive substances through pores or cracks of the concrete cover. A chemical protection normally provided to all steel embedded due to the high-alkaline nature of Portland cement concrete. In addition, a physical protection is also provided by the concrete cover with adequate thickness. However, this protection is largely depending on the quality of the concrete.

In this study, compressive strength, pulse velocity, chloride resistance of concrete, carbonation depth, microstructures (porosity data) and corrosion states of PC strands after 12 years exposure in the marine environment are evaluated.

2. EXPERIMENTAL

2.1 Materials

The specimens were made with High-Early-Strength of Portland cement (HSPC) and Ground Granulated Blast Furnace Slag (GGBFS). The physical properties and chemical analysis of cement are shown in Table 1. Further, the properties of aggregates and admixtures are shown in Table 2.

2.2 Mixture Proportion

The mixture proportions of concrete are summarized in Table 3. The water to binder ratio (w/b) was 32% with target slump and air content about 8.0 ± 2.5 cm and 4.0 ± 1.0%, respectively. Both air-entraining admixture; and air-entraining and water-reducing admixture were used based on the cement mass.

Table 1 Physical and chemical compositions of cements [1]

Items	HSPC	GGBSF
Density, g/cm^3	3.14	2.92
Blaine fineness, cm^2/g	4550	6020
MgO, %	1.4	6.2
SO_3, %	2.9	0.1
LOI, %	1.3	0.2
Total alkali, %	0.56	-
Ion chloride, %	0.004	0.005

Table 2 Properties of materials [1]

Material	Specification
Fine aggregate	River sand (density = 2.62 g/cm^3)
Coarse aggregate	Crushed river gravel (density = 2.62 g/cm^3, MSA = 20 mm)
AEWR agent	Polycarboxylate ether based
AE agent	Alkylcarboxylic

Table 3 Mix proportion [1]

Material	Mix-1	Mix-2
Water-binder ratio w/b, %	32	32
Sand-aggregate ratio s/a, %	45.3	44.9
Water, kg/m^3	150	150
Cement, kg/m^3	469	234
GGBFS, kg/m^3	-	234
Sand, kg/m^3	784	770
Gravel, kg/m^3	950	949

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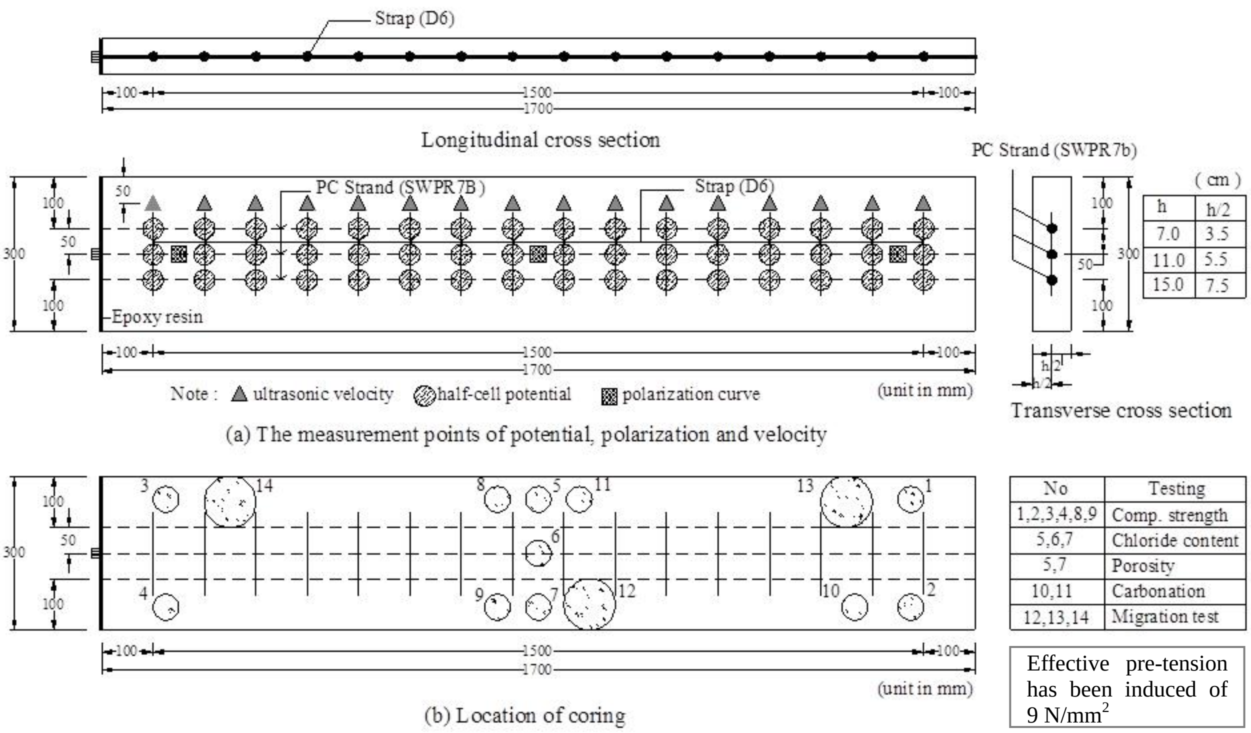

Fig. 1 Sheet pile specimen

2.3 Specimen Designs

There are three sheet pile specimens, namely BS5, PN5 and PS7. The name index means [B = GGBFS, P = HSPC, S = steam curing, N = water curing] and the number indicates the thickness of concrete cover in cm. Details of the specimen are described in Table 4.

Fig. 1 shows sheet pile specimen model geometry and measurement points of potential, polarization, velocity and coring. As shown, PC sheet pile height is 110 mm and 150 mm, and cover thickness is 50, 70 mm respectively, with specimen length of 1700 mm. In center line of specimen, three PC strands (SWPR7B) with distance of 100 mm from the edges were embedded. In order to fix the position of strands, 16 straps were placed at intervals of 100 mm.

After 2 months in a specific curing (see Table 4), the specimens were conducted accelerated test in the laboratory, as repeated wet-dry cycle. One cycle was 3.5 days, consisted of 1 day wet (sprayed warm seawater of 40^{o}C) and 2.5 days dry (air dry), and continued until 220 cycles (770 days all). The number of 220 cycles is almost equal to 3 years in the real-time study [1]. Furthermore, specimens were placed in an open space near marine and were subjected to two cycles of seawater wetting and drying in a day. One cycle was seawater splashed for 4 hours and dried for 8 hours; during 12 years.

2.4 Method of Evaluations

After 220 cycles of accelerated test, several tests were conducted. Details of testing and the results have been published; please refer to reference No. 1, 2 and 3. Furthermore, in this paper we will present condition after 12 years of continuous exposure under marine tidal environments. First, specimens were transferred from the exposure site to the laboratory and cleaned. Then specimens were investigated for corrosion of steel bar by using half-cell potential and anodic polarization curve by contact method. The half-cell potential was measured at interval 100 mm for each strand; whereas polarization curve was only checked at three points (15 cm from both edges and in the middle of specimen). The measurement was conducted with the silver/silver chloride electrode after 1 hour of pre-wetting.

In addition, ultrasonic pulse velocity (UPV) was measured by the direct method with path length of 100 mm. The UPV reading was conducted at 16 points along sheet pile. After that, core samples of 50 mm in diameter, were taken for compressive strength, chloride analysis, porosity and carbonation depth testing.

Table 4 Specimen of sheet pile model

Specimen	Mix condition	Curing condition	Height (cm)
PN3	Mix-1	Condition-2	7
BS5	Mix-2	Condition-1	11
PN5	Mix-1	Condition-2	11
PS7	Mix-1	Condition-1	15

Note: Curing condition-1: 1 day steam → 2 days wet → coated sheet
Curing condition-2: 3 days wet →coated sheet

Compressive strength was measured according to JIS A 1108. Testing was conducted on six core samples for each specimen. At the same time, a static elastic modulus was also conducted.

Chloride ion concentration was measured at certain depths of core samples (50 mm in diameter) based on JCI-SC5. Cores were taken from three points at midspan of the sheet pile. Then cores were cut into 5 pieces (thickness varied from 10 to 20 mm) and crushed into powder.

Porosity of the mortar samples was measured at depth of 30 to 40 mm of core samples. Then pore size distribution of the samples was evaluated by MIP (Mercury Intrusion Porosimetry).

Carbonation depth was evaluated on freshly cut surface of core samples after spraying a 1% phenolphthalein solution.

Effective chloride diffusion was evaluated by electric migration technique according to JSCE-G571-2003, where core samples (100 mm in diameter) were taken, and cut 30 mm from the surface of the sample. Then concrete sample divides the anode (0.5 mol/L of NaCl solution) and cathode (0.3 mol/L of NaOH solution) of a migration cell. The constant DC potential of 9Volts was applied across the cell, and negatively charged chloride ions migrate from the cathode toward the anode through the concrete pore solution.

3. RESULTS AND DISCUSSION

3.1 Visual Observation

Observations were made by washing the exterior surface of the specimens, then carried out checks on all corner, edge and surface of the specimen whether the steel corrosion has occurred. If steel corrode, there are usually signs of deterioration on the concrete surface such as rusting, cracking and spalling. From visual inspection, there were no adequate information on the corrosion risk of steel embedded in concrete, and only a few concrete corner and edge chips were observed. This was caused by the removal of surface mortar and fine aggregate as a result of seawater splashes. Degradation phenomenon such as small cracks or leaching of rebar rust is not identified.

3.2 Mechanical Properties

Compressive strength of concrete specimens after 12 years exposure in the marine tidal environment is shown in Fig. 2. The value is based on average of 6 core samples for each specimen. It is found that strength of concrete decreased slightly. Decrement in strength was observed in all specimens with maximum 4.7% reduction (in case of PN5). There is no significant difference in strength decreasing between steam and water curing.

The pulse velocity varies between 4.50 and 4.63 km/s with coefficient of variation of 0.81 to 1.44% as shown in Fig. 3. A good correlation between compressive strength and pulse velocity value is found, where the higher of strength, the higher value of pulse velocity are observed.

On the contrary, from Fig. 4, it is found that the elastic modulus of concrete increased (maximum 11%) after 12 years exposure, and no significant variation between compressive strength and elastic modulus data was observed. It confirms that the degradation of concrete properties in macroscale is not significantly occured.

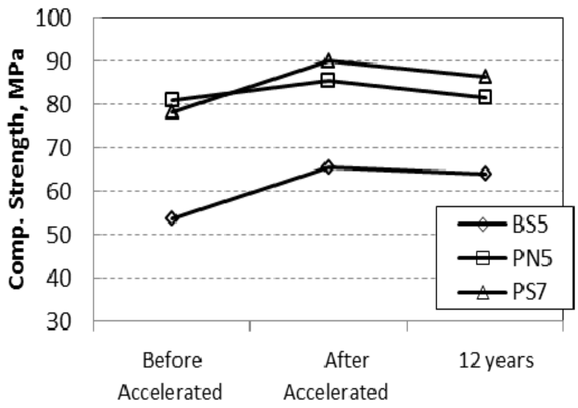

Fig. 2 Compressive strength of concrete

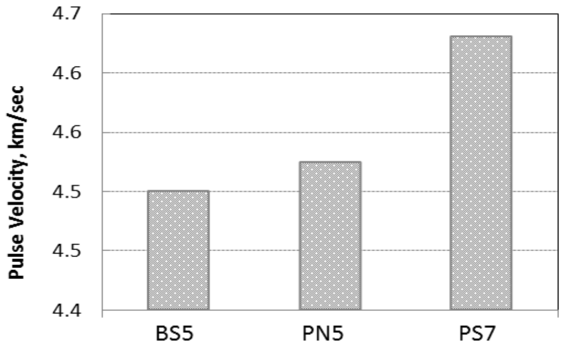

Fig. 3 Pulse velocity after 12 years exposure

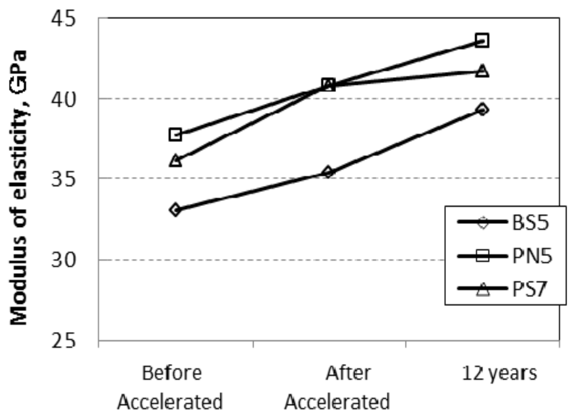

Fig. 4 Elastic modulus of concrete

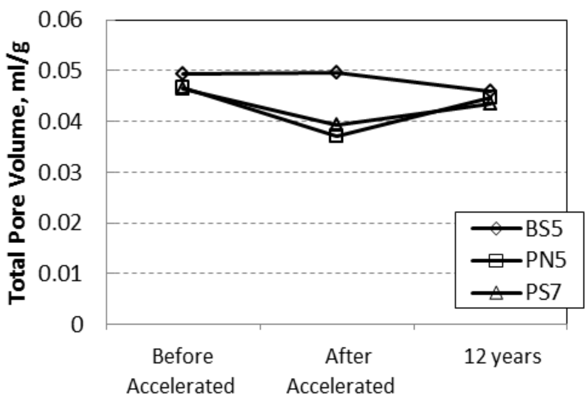

Fig. 5 Pore volume of mortar samples

3.3 Porosity and Depth of Carbonation

Pore volume and pore size distributions of the mortar samples collected at 30-40 mm depth of the specimens are shown in Fig. 5 and Fig. 6, where porosity and pore size distribution in a certain range show almost the same trend for all specimens. It is found that porosity of PN5 and PS7 increase after 12 years exposed to a corrosive environment, and vice versa in BS5 as shown in Fig. 5. It seems that partial replacement of cement by GGBFS causes a reduction in the pore volume, and may also cause a reduction in the connectivity of the capillary pore. The capillary pore defined here is the porosity of pores whose diameter ranging from 0.01 to 5 µm. In addition, the capillary pore distribution was slightly higher for BS5 than the other, but it did not affect significantly.

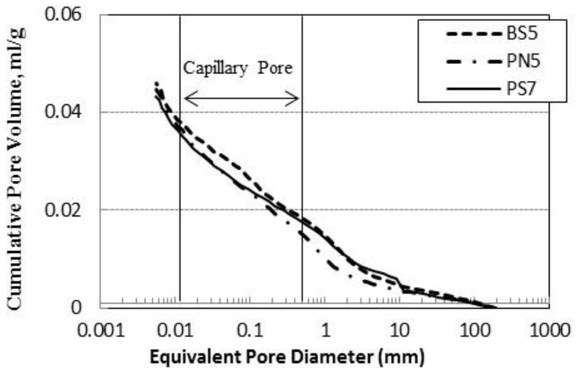

Fig. 6 Porosity of mortar samples

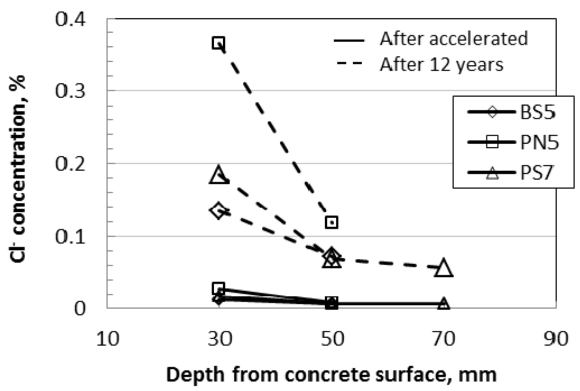

Fig. 7 Average of chloride ion in concrete

Carbonation depths of the core samples were not identified in this investigation. This is caused by the compactness of concrete where the total pore volume was very small (about 10%).

3.4 Chloride Content in Concrete

Total amount of chloride ion as a percentage of cement mass at 30, 50 and 70 mm depth from the surface of specimen is shown in Fig. 7. The amount of chloride content varied between 0.134% and 0.365% at the depth of 30 mm, whereas at 50 mm depth showed a little amount which varies between 0.069% and 0.118%. It is found that sheet pile composed of GGBFS shows the lowest amount of chloride content compared with others at the same depth. It indicates that the microstructure of concrete using GGBFS is significantly improved and can provide a good barrier against chloride-inducement.

Numerous studies have shown that when present in sufficient quantities, chloride ions will promote the corrosion of steel in concrete [6]. If the chloride content of 0.4% (by mass of cement) in the concrete is assumed as a threshold value for the initiate of steel corrosion, nowadays position of 0.4% chloride content in specimens of BS5, PN5, and PS7 are in the depths of 1.12cm, 2.7cm and 2.02 cm respectively from the surface.

3.5 Chloride Diffusion Coefficient

The diffusion coefficient (D) and concrete cover combine to provide a measure of the resistance of concrete to chloride ingress. Both the apparent (Da) and effective (De) diffusion coefficient were measured, and the results could be seen in Table 5. The apparent diffusion coefficient (Da) was measured from non-steady-state of chloride test using Fick`s second law, while De was measured from steady-state of chloride test using Fick`s first law.

From the Table 5, BS5 showed the lowest diffusion coefficient. It means BS5 has good resistance to chloride ingress as compared to the other.

3.6 PC Strand Monitor

(1) Natural electrode potential test

Fig. 8 shows the natural electrode potential after 12 years exposure in the marine tidal environment. Significant change in natural electrode potential of strands occurred in PN3 and showed increasing potential for corrosion. On the other hand, irrespective of cement type, PC sheet pile with height of 11 and 15 cm have potential value in the range of -56 to -101 mV:CSE/25^{o}C. According to ASTM C876-91 (1999), potential less negative than -200 mV:CSE indicates 90% probability of no corrosion.

Table 5 Diffusion coefficient (D) of specimens

Name	Da (cm^2/year)	De (cm^2/year)
BS5	0.1435	0.120
PN5	0.2294	0.379
PS7	0.2136	0.399

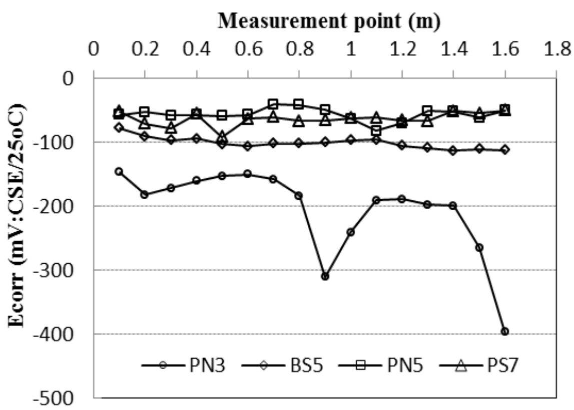

Fig. 8 Natural electrode potential

Table 6 Average polarization resistance of steel [5]

Specimen	Polarization Resistance (kΩ.cm^2)	Corrosion Penetration (μm/year)	Rate of Corrosion
PN3	245	1.46	Low/moderate
BS5	564	0.539	Passive
PN5	228	1.34	Low/moderate
PS7	203	1.6	Low/moderate

As comparison, PN3 with height of 7 cm is used. From the Fig. 8, it can be seen that the potential value decreased sharply in some points. Then potential value in the range of -150 to -400 mV:CSE/25^{o}C, indicates an increasing probability of corrosion. This is caused by the presence of small cracks in some parts of sheet pile as a result of the strand corrosion development on the edge whose no cover concrete. It can be concluded that PC sheet pile with height of 7 cm only has a 20-year service life, and it is recommended to increase the height to 11 cm to improve the durability.

From the view point of polarization resistance of steel (Rct) as described in Table 6, BS5 showed passive corrosion rate with value larger than 250 kΩ.cm^2, whereas PN3, PN5 and PS7 showed a low/moderate corrosion rate. It indicates that BS5 (50% partial replacement of cement by GGBFS) provided higher resistance to chloride ingress than the other.

(2) Polarization curve

Anodic polarization curve of each specimen is shown in Fig. 9. PC strands were embedded in concrete exhibited various polarization curve with potential between 0.2 and 0.6 V, and current density were the range between 1 to 10 μA/cm^2, and 10 to 100 μA/cm^2. Based on the passivation film associated with anodic polarization curve, BS5<PS7<PN5 can be classified into grade 3 and PN3 is grade 1 as a degree of passivity exist [4].

Average of corrosion potential is sequenced as BS5<PS7<PN5<PN3 with values ranging from -125 to -370 mV:CSE. Irrespective of the cement types and curing conditions at the early life of concrete, for the same cover thickness, PN5 exhibited more potential corrosion compared to BS5. It shows that GGBFS is a good barrier against chloride-induced due to compactness of microstructure, hence it can reduce the risk of corrosion.

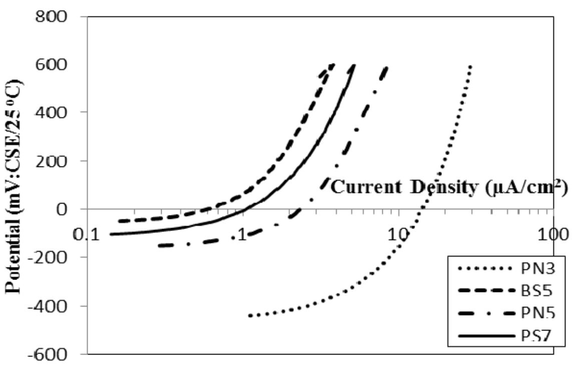

Fig. 9 Anodic polarization curve

(a) (b)

Photo 1 Verification of rebar corrosion by removing cover concrete: (a) BS5; (b) PN5

In addition, results from both anodic polarization curve and natural electrode potential test showed that PN3 has started to corrode after 12 years exposure.

(3) Verification of rebar corrosion

From Photo 1, it can be seen that there was a little corrosion on the ends of strand caused by the absence of cover concrete and was characterized by the presence of leaching of rebar rust in the concrete. However, this little corrosion did not affect the whole strand.

While in PN3 as shown in Photo 2, on the edge of strand whose no cover, strand was corroded along the 5 to 7 cm and the ends of strand have been ruined. Total area of corrosion was observed after removing all concrete is approximately 1.01%.

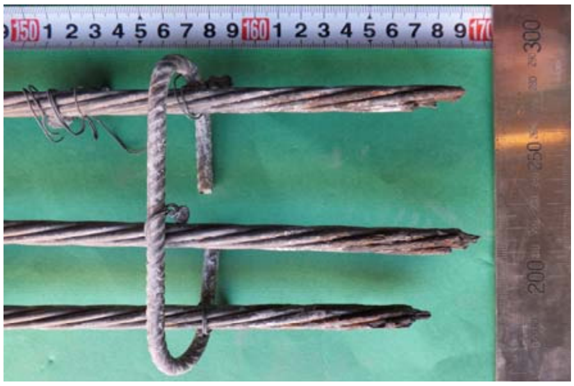

Photo 2 Rebar corrosion in PN3

4. CONCLUSIONS

In order to evaluate the performance of PC sheet pile under marine tidal environment, repeated of wet-dry cycle were conducted. The results obtained may be summarized as follows.

(1) Compressive strength decreased slightly after prolonged exposure to the marine tidal environment while the elastic modulus kept increasing.

(2) The pore volume increased both in PN5 and PS7, but decreased in BS5. Meanwhile, pore size distribution showed a similar trend in the range of capillary pore.

(3) Carbonation were not identified in this investigation.
(4) Chloride content in specimens is less than 0.4% by mass of cement which indicates that corrosion has not yet occurred.
(5) All PC strand embedded in concrete exhibited good passivity and only a little corrosion on the ends of strand caused by the absence of cover concrete, except PN3 that showed increasing potential for corrosion. It is recommended to increase the height of PC sheet pile become 11 cm to improve the durability.
(7) Specimen BS5 showed the best performance, which can provide a good barrier against chloride-induced due to compactness of microstructure, and can reduce the risk of corrosion.

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REFERENCES

[1] H. Hamada, H. Yokota, Y. Kikuchi, "Durability Evaluation of Pre-stressed Concrete Sheet Pile under Marine Corrosive Environments by Acceleration Test", Technical Note of The Port and Airport Research Institute, No. 1097, June 2005 (in Japanese).

[2] H. Hamada, K. Nakahashi, R. Kuroki, "An Acceleration Test for Chloride Ion Permeability and Corrosion of Steel Embedded of High Strength Concrete", Annual Papers of JCI, Vol. 21, No. 2, 1999, pp. 979-984 (in Japanese).

[3] N. Yuasa, H. Hamada, Y. Miyazaki, "An Acceleration Test of PC Sheet Pile for Durability Evaluation Under Marine Environment", Annual Papers of JCI, Vol. 21, No. 2, 1999, pp. 1027-1032 (in Japanese).

[4] N. Otsuki, " A study of Effectiveness of Chloride on Corrosion of Steel Bar in Concrete", Report of Port and Harbor Research Institute:127-134.

[5] P.K.. Mehta and PJM. Monteiro, "Concrete: Microstructure, Properties, and Materials 3rd ed", Mc Graw Hill, 2006, pp. 442.

[6] T. Amino, at al, "The Influence of Chloride Content at the Rebar on Corrosion Progress in Concrete of Dolphins", 34th Conference on Our World in Concrete & Structure, Singapore, 2009.