ENHANCEMENT OF CHLORIDE RESISTANCE OF PRE-STRESSED CONCRETE SHEET PILE BY BLAST FURNACE SLAG

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1. Introduction

Chloride-induced corrosion is one of the main mechanisms of deterioration affecting the long-term performance of concrete structures. In Japan, a large majority of structures are built either near the costal or indirect contact with seawater. The durability of reinforced or pre-stressed concrete structure depends on the resistance of concrete to chloride penetration. Naturally concrete provides physical and chemical protection to the reinforcing steel from chloride penetrating. The chloride resistance depends on the permeability of concrete and the cover thickness of the reinforcement. High strength concrete (HSC) is seemed to be one of solutions to achieve low permeability and high durability. In addition, partial replacement of cement by blast furnace slag (BFS) in producing HSC has been established. This paper discusses the various factors affecting chloride resistance of concrete after long term exposure under marine tidal environment.

2. Outline of Experiment

2.1 Materials and Mix Proportion

Pre-stressed concrete (PC) sheet piles with dimensions of 1,700 mm x 300 mm x 50 mm and the target of compressive strength about 70 MPa were fabricated. In the center line of specimen, three PC strands (SWPR7B) were embedded with distance of 100 mm from the edges. In order to fix the position of strands, 16 straps were placed at intervals of 100 mm. High Early Strength of Portland Cement (HSPC) and Ground Granulated Blast Furnace Slag (GGBFS) are used. The physical properties of material and mix proportion of concrete are shown in **Table 1** and **Table 2**. Both air-entraining admixture; and air-entraining and water-reducing admixture were used based on the cement mass.

Table 1. Physical properties of material

Material	Description
Cement	High early strength of Portland cement Density = 3.14 g/cm^3, SSA = 4550 cm^2/g
GGBFS	Ground granulated blast furnace slag Density = 2.92 g/cm^3, SSA = 6020 cm^2/g
Gravel	Crushed river gravel Density = 2.62 g/cm^3, MSA = 20 mm
Sand	River sand Density = 2.62 g/cm^3

Table 2. Mix proportion

Name	W/B %	s/a %	Unit content (kg/m3)				
			Water	Cement	GGBFS	Sand	Gravel
BS	32	44.9	150	234	234	770	949
PN	32	45.3	150	469	-	784	950
PS	32	45.3	150	469	-	784	950

Note: B = GGBFS, P = HSPC, S = steam curing, N = water curing

2.2 Curing condition

After casting concrete, formwork was removed after 24 hours and followed by curing. Two types of curing, that was steam curing (1 day steam, 2 days wet and covered sheet) and water curing (3 days wet and covered sheet). After 2 months, exposure test was started. An accelerated test was conducted 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). Following the accelerated test, specimens were placed in an open space near marine and were subjected to two cycles of wetting and drying a day. One cycle was seawater splashing for 4 hours and dried for 8 hours; during 12 years.

2.3 Method of evaluation

After 12 years of continuous exposure, the specimens were transferred from the exposure site to the laboratory and cleaned. The specimens were investigated for the chloride resistance. Measurements were conducted by taking the core samples of 50 mm in diameter for compressive strength, chloride ion concentration and porosity test. Compressive strength was measured according to JIS A 1108. Then chloride ion concentration was measured at certain depths based on JCI-SC5. Porosity of the mortar samples was measured at depth of 30 to 40 mm and pore size distribution was evaluated by MIP (Mercury Intrusion Porosimetry).

3. Results and Discussion

3.1 Relationship between compressive strength and porosity

Table 3 shows the reduction in compressive strength after 12 years exposure about 1.9%, 3.8% and 4.5% for BS, PS and PN, respectively. The number of strength reduction correlated significantly with increasing porosity, where the porosity increased in both PS and PN of 10%, 17% respectively, and vice versa decreased by 4% in BS. It indicates that the higher increasing in porosity, the higher reducing in strength will be. In view point of pore distribution, both PS and PN showed slightly lower porosity in the range of capillary pore than BS at the same depth as shown in **Fig. 1**. It

Keywords: chloride resistance, GGBFS, porosity
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Table 3. Properties of fresh and hardened concrete

Name	Slump (cm)	Air (%)	Temp (°C)	Before Exposure			After Exposure		
				Comp. strength (MPa)	Elastic modulus (MPa)	Porosity (mL/g)	Comp. strength (MPa)	Elastic modulus (MPa)	Porosity (mL/g)
BS	22	4.0	31	65.45	33077	0.0497	64.18	39261	0.0459
PN	18	4.5	31	85.45	37692	0.0371	81.61	43548	0.0447
PS	18	4.5	31	90.00	40769	0.0394	86.56	41704	0.0434

suggests that the higher compressive strength reflects the low porosity.

3.2 Relationship between cement type and chloride diffusion

Fig. 2 shows the total amount of chloride ion penetrated in percent mass of cement at various depths from the surface. Concrete with low porosity usually has high strength and high resistance to the penetration of chloride ion. However, this phenomenon was not shown on both PN and PS. On the contrary, both PN and PS showed a higher chloride ion content than BS. It provides an indication of densified tissue contamination with an appropriate amount of GGBFS after exposure test on BS. Low content of chloride ions in BS may be due to the unconnected of capillary pore in the concrete.

Chloride diffusion coefficient is a measure of the resistance of concrete to chloride diffusion, and can be determined from a non-steady state chloride test using Fick's second law. Then apparent diffusion coefficient (D_a) derived from the total or acid-soluble chloride profile and provided a value about 0.144 cm^2/year for BS and 0.229 cm^2/year for PN (see **Fig. 3**). This indicates that 50% replacement of cement by GGBFS provided higher resistance to chloride ingress than high early strength cement.

3.3 Effect of curing conditions

Generally, curing at early life of concrete greatly affects the porosity of concrete. For evaluation, both PN and PS, which has the same mix proportion but different curing condition, were compared. It can be seen from **Table 3** that porosity of PS increased 10% after exposure, this value lower than PN which the porosity rose 17%. An increasing in porosity can affect the chloride penetration into concrete. In addition, **Fig. 2** also showed the difference of chloride ion concentration between PN and PS. It has found that the steam curing may slightly improve the chloride resistance of concrete. In fact, both PN and PS data are not enough to justify that the steam curing at early life can improve the chloride resistance of concrete. It takes more data to prove it.

4. Conclusion

From the above description, it can be concluded that porosity and connectivity of capillary pores in the concrete, partial replacement of cement by GGBFS, and steam curing at early life of concrete are factors that affected chloride resistance of concrete after 12 years exposure in the marine environment.

Acknowledgement

The authors would like to thank The Port and Airport Research Institute Japan, who has prepared the specimens.

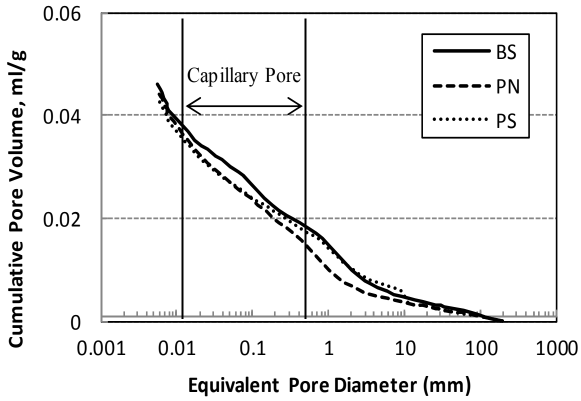

Fig. 1 Porosity at depth of 30-40 mm after exposure

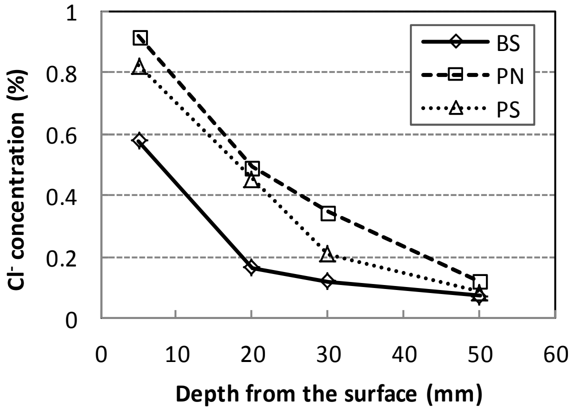

Fig. 2 Chloride ion profile

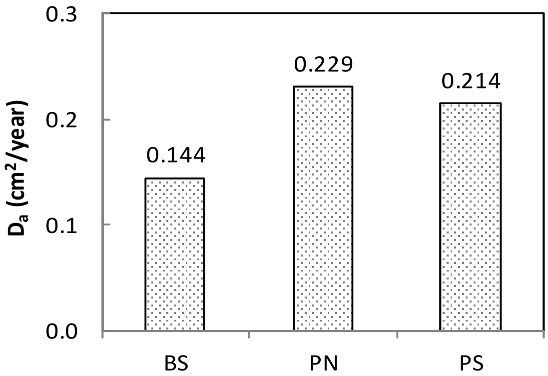

Fig. 3 Apparent diffusion coefficient (D_a)

References

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