Characteristics of Concrete Using Ground Granulated Blast-furnace Slag

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ABSTRACT

This report describes the experimental results on the strength development and chloride permeability, etc. of concrete containing ground granulated blast-furnace slag (GBFS) for the prestressed concrete members. Water-binder ratio of the concrete was a range of 30-55%. The binders were blended with high-early-strength Portland cement and GBFS whose specific surface area by blaine was 6000cm^2/g. The concrete specimen was produced under various curing periods for maintaining wet condition. Chloride permeability was evaluated by the salt-water ponding test, the accelerated test and the exposure test.

As a result of the tests, GBFS reduced the apparent diffusion coefficient of chloride ion of concrete. The apparent diffusion coefficient became smaller with increasing the content of GBFS. Wet curing was essential to improve chloride permeability and ensure design strength of concrete containing GBFS.

Keywords. Ground Granulated Blast-furnace Slag, Compressive Strength, Chloride Permeability, Curing, Prestressed Concrete

1 INTRODUCTION

Ground granulated blast-furnace slag (GBFS) is the most general admixture for concrete in Japan. In recent years the construction of concrete structures has been strongly demanded for enhanced durability and reduced environmental impact. GBFS is an industrial by-product, but its use as an admixture is beneficial in this context because of its ability to suppress the concrete's ASR and to contribute to resisting the penetration of chloride ions. Despite those advantages, there are very few examples of GBFS being used for prestressed concrete (PC) highway bridges in Japan. One likely reason for that situation is that the influence of curing conditions on the quality of hardened concrete has not been studied well. Another likely reason is that relatively slow strength development in early age is not convenient to conventional construction approaches, which prioritize work efficiency.

This paper describes experiment results to confirm the strength, the carbonation and the chloride ion permeability of concrete used for PC members, utilizing high-early-strength Portland cement and GBFS. In this study, the influence of curing method was examined in detail. The chloride permeability was discussed the effect of dosage of GBFS and curing methods from the results of salt-water ponding test, accelerated test and exposure test.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mix proportions of concrete

The mix proportions of concrete used in this study are shown in Table 1. Considering the need to ensure early strength of concrete demanded in being applied to PC members, the binder consists of high-early-strength Portland cement and GBFS whose specific surface area by blaine was 6000cm^2/g. In Table 1, "H" indicates concrete using cement only, whereas "BF" indicates concrete containing GBFS. The water-binder ratio (W/B) was set to 30%, 40%, and 55%. The percentage of replacement ratio of the GBFS to cement (GBFS/B) was set to 0%, 30%, and 70%. Water content and superplasticizer content per unit volume of concrete were held constant for concretes with the same W/B. Sand percentage (s/a) was 40% for all concrete. Slump has been adjusted to 12±2.5cm in W/B of 40% and 55%, and 18±2.5cm in W/B of 30%. Target air content was 4.0±0.5%.

Table 1. Mix proportions

	W/B (%)	s/a (%)	GBFS/B (%)	Content(kg/m^3)					
				W	B		S	G	SP
					C	GBFS			
H1	30	40	0	150	500	0	678	1036	7.50
BF1			50		250	250	671	1023	
H2	40		0	173	433	0	678	1036	5.63
BF2-30			30		303	130	674	1028	
BF2			50		217	216	671	1023	
BF2-70			70		130	303	668	1020	
H3	55		0	196	356	0	678	1036	0
BF3			50		178	178	674	1026	

Constituent materials of concrete shown by the symbols in table are is as follows. W: service water, C: high-early-strength Portland cement, GBFS: ground granulated blast-furnace slag 6000, S: mixed sand of river sand and crushed sand, G: crushed stone (max.size:20 mm), SP: superplasticizer(polycarboxylic acid type)

2.2 Testing methods

Compressive strength test. Cylindrical specimens of 100 mm in diameter and 200 mm in height were used to measure compressive strength. The tests were performed at ages from 1 to 365 days, using curing methods as shown in Table 2. The compressive strength of core specimen and the internal temperature were also measured by the thermally-insulated specimens covered with foamed polystyrene on curing I. The steam curing on curing S was started after the time of the start of setting.

Table 2. Curing methods

Symbols	Specific methods of curing
N	standard curing, water curing at 20℃ after de-molding
A	drying after wet curing duration of 3 days
B	drying after wet curing duration of 5 days
C	drying without wet curing
S	drying after steam curing for factory products(max. temperature=60℃）
I	curing using the thermally-insulated specimens of 500×500×400 mm in size covered with foamed polystyrene of 200 mm in thickness

dry condition: temperature is 20℃ and relative humidity is 60% in the lab.

Chloride permeability test in the lab. Salt-water ponding test and accelerated test using electrical migration technique were conducted in the laboratory. In the ponding test, after sealing the sides of cylindrical specimens with epoxy resin, the specimens were immersed in brine (5% NaCl) up to half the height of the specimen as shown in Figure 1. The specimens were cured by the each method in Table 2 to 28 days. The chloride profiles of the specimens were measured with each 10 mm slices from the surface to 50 mm in depth at the immersed periods of 28 days, 91 days, and 365 days.

In the accelerated test, the test specimens are 100mm diameter and 50mm thickness, disc shaped. As shown in Figure 2, the test method is similar to ASTM C1202 “Standard Method of Test for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration”. The testing cells were filled with 0.3N-NaOH solution in anode and 3% NaCl solution in cathode. The constant direct current was applied to keep 60 V of potential difference for the duration of 6 hours. The disk-shaped concrete specimens were used at an age of approximately 2 months. After the current applied, the specimen was split and measured depth of chloride penetration by 0.1 N spraying $AgNO_3$ solution on the split surface.

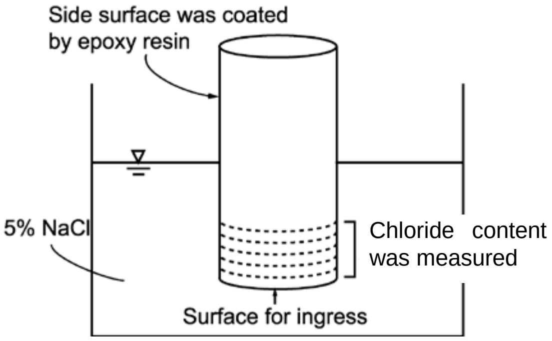


Figure 1. Setup of ponding test

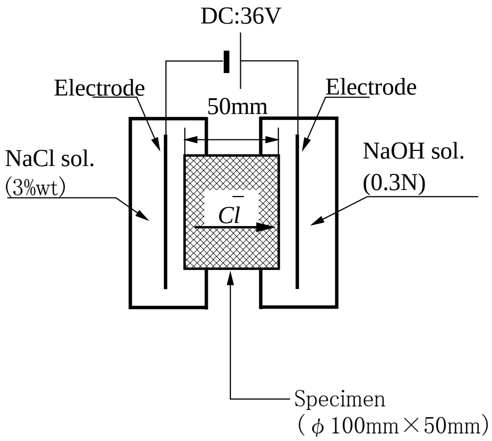


Figure 2. Test setup of the accelerated test

Exposure test. The location of the exposure test site is approximately 20 m from cost line of Japan Sea. Strong sea wind blows at the test site in winter, bringing substantial amounts of airborne salt. Measured at the test site, especially large amount of airborne salt was supplied in December and January because of strong monsoon from north direction. Prismatic specimens with the shorter length at 100mm and the longer length at 400mm were used. The square section of the specimens were exposed to the environment, whereas the four lateral sides were sealed with anti-corrosive coating to allow one-directional diffusion of chlorides. The specimens were settled so that the exposed surface might face to the sea ("sea side"). The wall of the storage building located behind the other test surface of the specimens, and the distance of the surface and the hut was about 500mm ("storage side"). Carbonation depth and chloride content were measured at exposure periods of 2 years, 5 years (actually 5.3 years) and 10 years (actually 10.7 years).

3 COMPRESSIVE STRENGTH

Compressive strength of the concrete cured by standard curing. Figure 3 shows the relationship between GBFS/B and compressive strength of concrete cured by standard curing (curing N). In Figure 3, strength ratio refers to the value into which the compressive strength the concrete of specific GBFS/B is divided by the compressive strength of the concrete of GBFS/B of 0%. Greater values for GBFS/B tended to be associated with lower early strength and greater long-term strength. The compressive strength of concrete of GBFS/B of 50% or 70% almost becomes the same with the concrete of GBFS/B of 0% at 14 to 28 days. The strength ratio of GBFS/B of 30% is about 0.9 at 3 days.

Compressive strength of the concrete cured by wet curing. Figure 4 shows the relationship between ages and strength ratio of concrete with different duration of wet curing. The strength ratio refers to the value into which the compressive strength obtained with specific curing is divided by the compressive strength obtained with curing N. The specimens cured by curing B had a wet curing duration that was 2 days longer than that of curing A, but no differences in strength ratio were seen between these wet curing durations for H2 and BF2. The strength ratio of H2 was unaffected by drying after wet curing, retaining a value of approximately 1.0 over the long term. However, the strength ratio of BF2 declined with age from 7 days later, and was approximately 0.8 at 28 days. For curing C, the strength ratio showed large variations at an early age for both H2 and BF2, and strength also declined over the long term.

The higher the GBFS/B, the lower the strength ratio (based on standard curing N) tends to be in the long term. However, for GBFS/B of 50% and 70%, strength ratio remained almost the same on 28 days and later. For the concrete containing GBFS, it is necessary to extend the duration of wet curing for 5 days to obtain same long-term strength as standard curing.

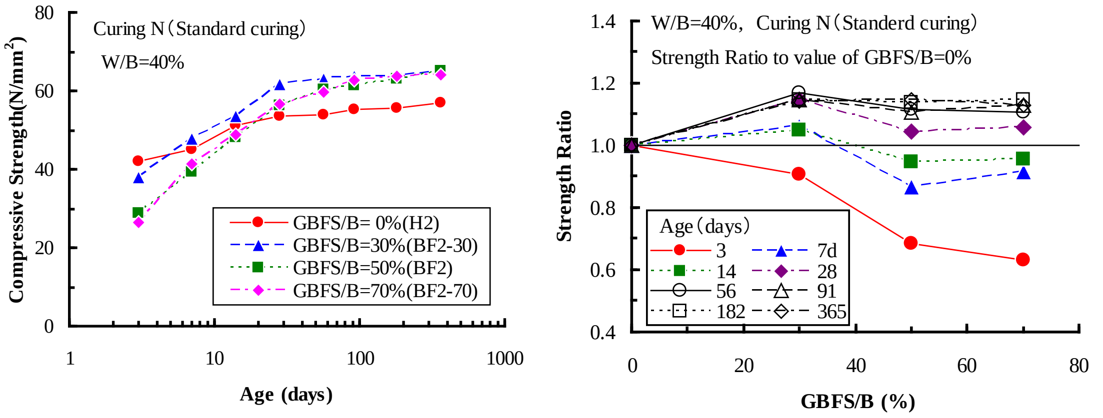


Figure 3. Compressive strength of concrete cured by standard curing

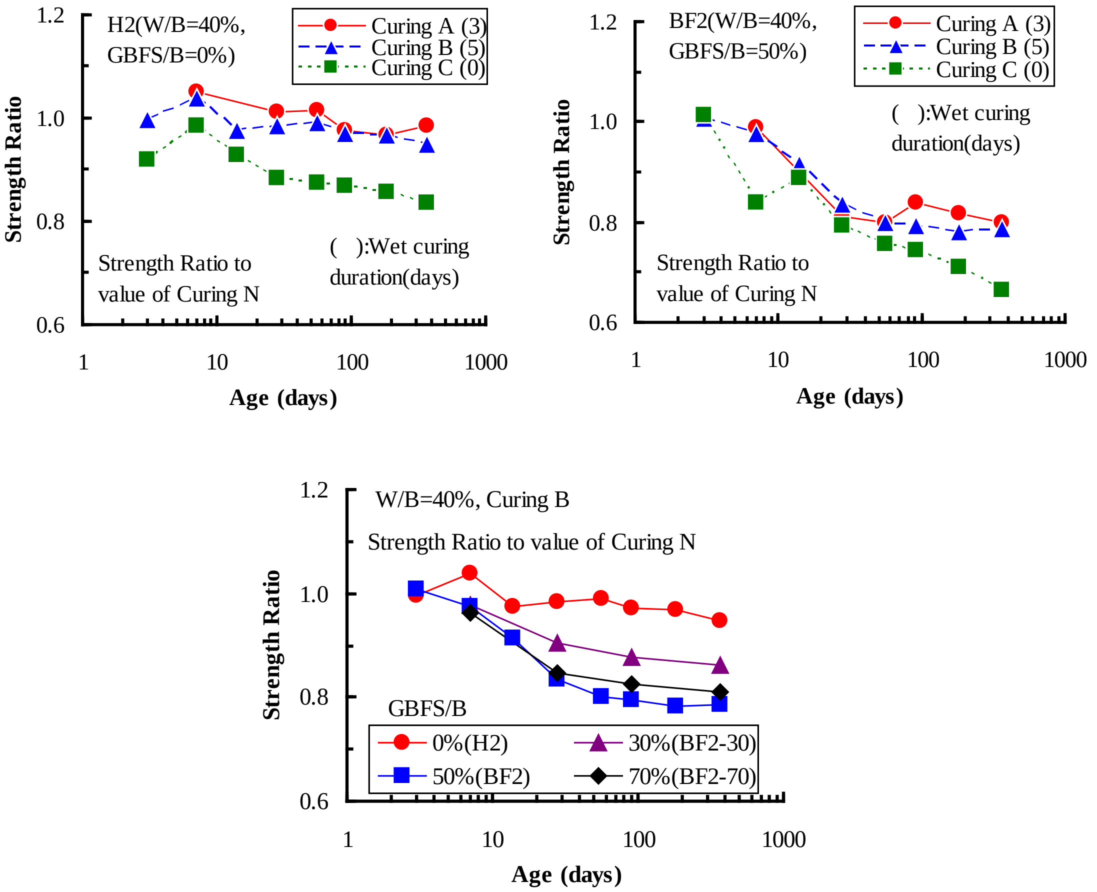


Figure 4. Compressive strength of concrete cured by wet curing

Compressive strength of the concrete cured by steam curing and the core pulled out from thermally-insulated specimen. In Figure 5, concerning strength ratio at 1day, H2 attained a strength ratio of approximately 1.2, but BF2 attained a strength ratio of approximately 1.6. In the long term, strength had a value of less than 1.0 relative to curing N, but a value of about 1.1 relative to curing B. That is to say, steam curing is effective for ensuring the compressive strength of concrete containing GBFS, and enables early strength to be raised with very little adverse affect of long-term strength.

It is difficult to evaluate the strength development of concrete containing GBFS with different curing conditions (curing N, S and I) by maturity as shown in Figure 6. The compressive strength of BF2 at a cumulative temperature of about 100 D° D was largest relative to curing N, with strengths for similar cumulative temperatures diverging by about 20 N/mm^2. This indicates that the hydration of GBFS is strongly dependent on temperature.

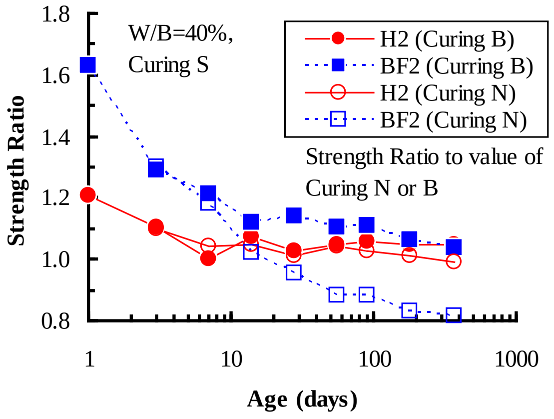


Figure 5. Compressive strength of concrete cured by wet curing

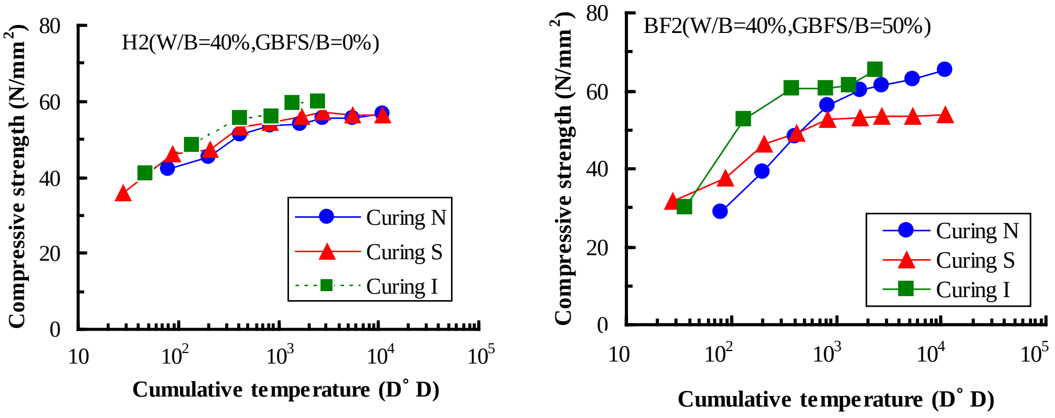


Figure 6. Evaluation of strength development by cumulative temperature

4 CARBONATION

Carbonation depths measured by the exposure test at exposure period of 5 years are as shown in Table 3. The carbonation depth of the concrete GBFS/B of 70% increased when GBFS/B is 50% or less. Even with GBFS/B of 50%, carbonation had advanced with curing C and curing S. Especially, carbonation depths with curing C are large. That is to say, differences in curing method had a substantial influence on carbonation depth. It is important to keep wet concrete to prevent early progress of carbonation when GBFS is used.

Table 3. Carbonation depths measured by exposure test

concrete	curing	Sea side		Storage side	
		Average	Max.	Average	Max.
H2	A	0.0	0.0	0.0	0.0
	C	0.0	0.0	0.0	0.0
	S	0.0	0.0	0.0	0.0
BF2	B	0.0	0.0	0.0	0.0
	C	2.4	5.4	1.8	4.6
	S	0.8	1.7	0.4	1.7
BF2-30	B	0.0	0.0	0.0	0.0
BF2-70	B	1.1	3.4	1.3	2.9

(unit: mm)

5 CHLORIDE PERMEABILITY

Influence of W/B and GBFS/B of 50% to chloride permeability. Profiles of chloride ion ingress into concretes with different mix proportions were obtained from the 10-year exposure test, as shown in Figure 7. The lower the water-binder ratio, the smaller the cover thickness attaining marginal chloride ion concentration(1.2kg/m^3) for causing corrosion in accordance with JSCE Standard Specification. Regardless of water-binder ratio, the concrete with GBFS/B of 50% was highly effective in suppressing the penetration of chlorides into the concrete. That is to say, the use of GBFS in PC members for concrete in the high strength zone is advantageous in terms of resisting chloride penetration.

Apparent diffusion coefficient of chloride ion of concrete (D_c) was estimated with the chloride profiles obtained by the ponding test at the immersed period of 365 days and the exposure test at the exposure period of 10 years. The estimation was carried out with fitting the observed profile to theoretical solution of diffusion equation with fixed boundary condition, that is constant chloride content at the surface of concrete (C_0). Assuming the theoretical solution of chloride profile as eq. (1), C_0 and D_c were determined so as to minimize the difference between observed profile and theoretical profile.

$$C(x;t) = C_0\left(1 - erf\left(\frac{x}{2\sqrt{D_c t}}\right)\right) \tag{1}$$

where, *x*: distance from surface, *t*: time, *erf( )*: Error function

Figure 8 shows the relationship between W/B and D_c. For GBFS concrete, the value of D_c obtained by ponding test was similar to or slightly larger than that for blast furnace cement obtained using the as eq.(2) in JSCE Standard Specifications. However, the value of D_c obtained by the exposure test was quite small, fitting between the curves produced by using -2.7 and -3.2 in the third member of eq.(2). D_c of concrete with GBFS/B of 50% was notably smaller than for concrete without GBFS.

$$\log D = -3.0\left(W/B\right)^2 + 5.4\left(W/B\right) - 2.2 \tag{2}$$

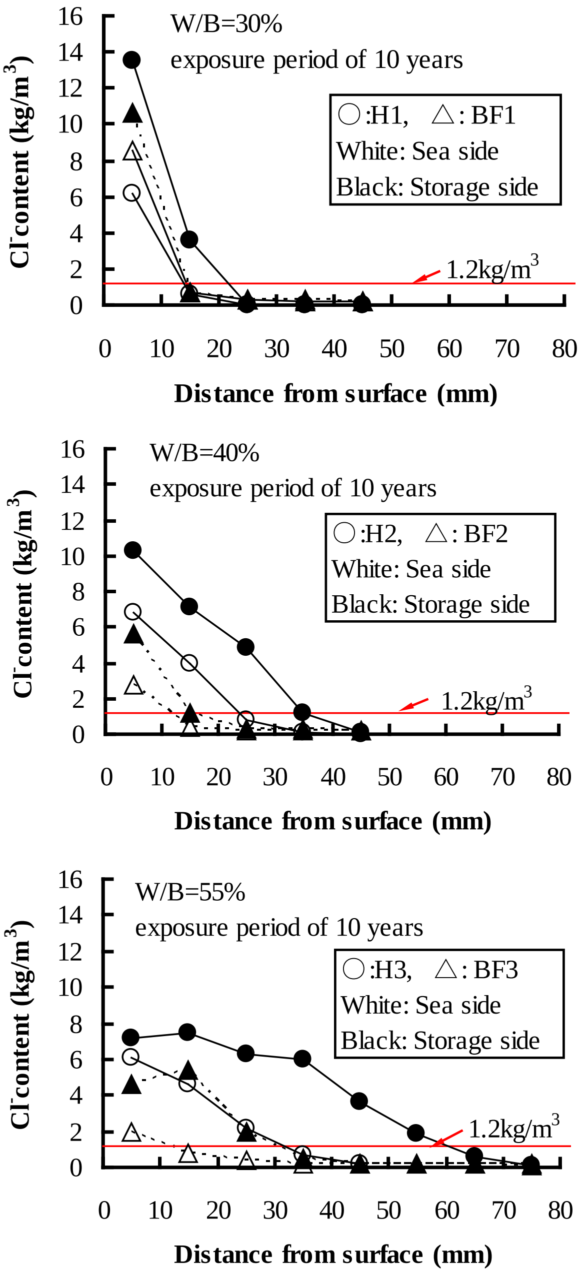


Figure 7. Profiles of chloride ion ingress into concretes

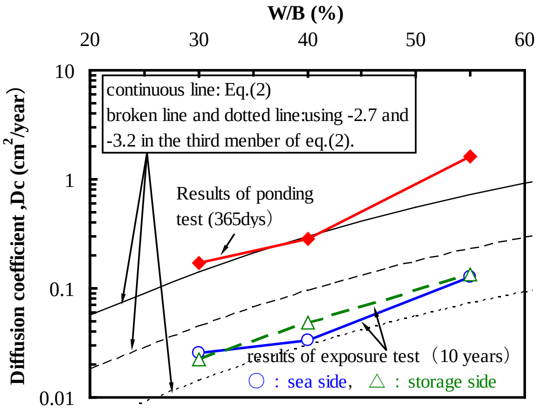


Figure 8. Relationship between W/B and Dc

Influence of GBFS/B and curing methods on chloride permeability. The apparent diffusion coefficient of chloride ion (D_c) obtained by the ponding test and the exposure test, and the chloride penetration depths obtained by the accelerated test are shown in Figure 9. Those values are influenced by the GBFS/B and the curing method of concrete though the degree of the influence is different depending on the kind of the test. Compared with H2 (GBFS/B of 0%), The D_c of BF2 (GBFS/B of 50%) is influenced easily by curing method, and, for instance, is small in the order of curing C, B, and S in the ponding test. Moreover, the D_c decreases by the GBFS/B large, but the chloride penetration depths obtained by the accelerated test of concrete of GBFS/B of 70% grows under the curing condition that wetting to concrete is insufficient.

6 CONCLUSIONS

Concluding remarks are as follows:

1) The use of Ground granulated blast-furnace slag (GBFS) lowers early strength. Nevertheless, with the percentage of replacement ratio of the GBFS to cement (GBFS/B) of 30%, compressive strength at 3 days is approximately 90% of that obtained with GBFS/B of 0%.

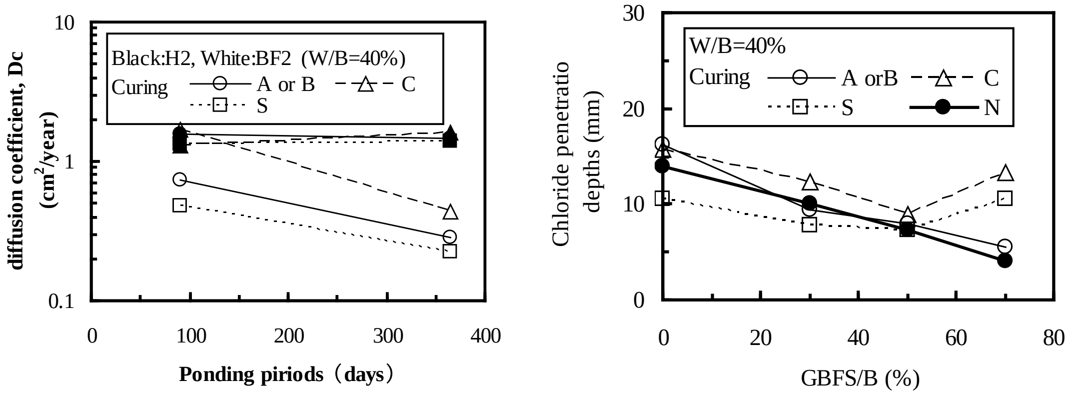
2) Regardless of whether GBFS is used, wet curing is important for proper compressive strength development. However, it is necessary for the concrete using GBFS to extend the duration of wet curing for 5 days to obtain same long-term strength as standard curing.

3) Since the hydration of GBFS is strongly dependent on curing temperature, initial strength of concrete used GBFS rises considerably than that of the concrete not used under high temperature conditions in an early age. Steam curing is effective to obtain initial strength of PC members.

4) Initial wet curing exerts the influence on the carbonation depth of concrete using GBFS. Even if the duration of wet curing is assumed to be 5 days when GBFS/B is 70%, the carbonation depth grows.

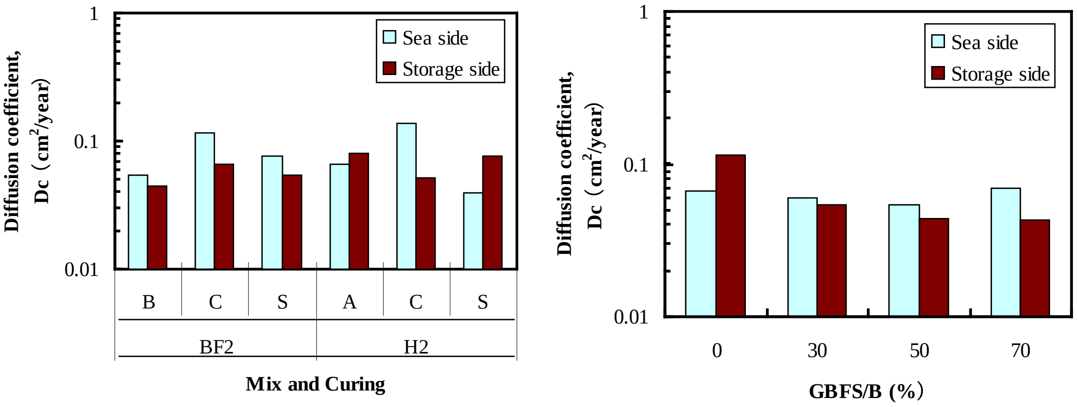
5) With larger GBFS/B, the apparent diffusion coefficient of chloride ion of concrete (Dc) tends to be smaller. However, the duration of wet curing greatly exerts the influence in the

effect. When GBFS/B was 70% and wet curing was insufficient, the chloride penetration depth has grown by the accelerated test.



(a) Results of the ponding test

(b) Results of the accelerated test



(c) Results of the exposure test

Figure 9. Influence of Curing Methods and GBFS/B to chloride permeability

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