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Properties of Concrete with GGBS and its Applications for Bridge Superstructures

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ABSTRACT

Chloride diffusion coefficient of the concrete mixed with ground granulated blast-furnace slag (GGBS) was investigated. As the results, GGBS reduced the effective diffusion coefficient of chloride ion by from 1/5 to 1/10. Also, GGBS with specific surface area of 6000 cm^2/g improved the chloride resistance of concrete when water to binder ratio (W/B) was was smaller than 45%. In addition, GGBS with specific surface area of 6000 cm^2/g was applied to prestressed concrete bridge. The effective diffusion coefficient of the concrete used for bridge superstructure showed the lower value. As the results of simple simulation by using Fick's second low, it is expected that steel bars in concrete will not occur corrosion for 100 years.

Keywords. GGBS, Chloride, Diffusion coefficient, Migration test, Prestressed concrete

INTRODUCTION

It has been well known ground granulated blast-furnace slag (GGBS) can increase the abilities to prevent water penetration and chloride penetration, and it can improve the durability of concrete structures (Ramezanianpour, 1995). Also, the use of GGBS for concrete material contributes to the saving the natural resources and energy in cement manufacturing process and to reducing CO_2 emissions and environment impact. In Japan, GGBS has been rarely used for bridge superstructures because the increase of strength at early ages is smaller than that of the concrete without GGBS. While the some applications to pre-tensioned concrete have been reported (Ishida, 2000) (Fukunaga, 2009), the application to post-tensioned concrete has been very few. The more positive use of GGBS has been required.

In this study, the specimens which include normal-strength concrete and high-strength concrete were examined by changing water to binder ratio (W/B). The effectiveness of GGBS on strength and chloride ion diffusion coefficient was measured by migration test. Moreover, the application of GGBS which has the surface area of 6000 cm^2/g for prestressed concrete bridge superstructures was presented.

OUTLINE OF EXPERIMENT

Mixture proportions. Table 1 shows the properties of materials for concrete specimens. Ordinary Portland cement, GGBS with the surface area of 4000 cm^2/g or 6000 cm^2/g specified in Japan Industrial Standard were used for binder. The replacement ratio of GGBS to cement was 50%. There are three series; the concrete without GGBS (normal concrete) (Series N), the concrete GGBS with 4000 cm^2/g surface area (Series B-4), and the concrete GGBS with 6000 cm^2/g surface area (Series B-6). Crushed stone that the maximum size was 20 mm and washed sea sand were used for aggregates. Both water reducing and air entraining agent and air entraining agent were added to get the target slump of 8 cm and the target air content of 4.5%.

Table 1. Material properties

Material	Properties
Cement (C)	Ordinary Portland cement, Density: 3.16g/cm^3, Surface area: 3360cm^2/g
Ground granulated blast-furnace slag (GGBS)	GGBS 4000, Density: 2.91g/cm^3, Surface area: 4070cm^2/g GGBS 6000, Density: 2.91g/cm^3, Surface area: 5990cm^2/g
Fine aggregate (S)	Washed sea sand, Density(SSD): 2.58g/cm^3, Absorption: 1.59%
Coarse aggregate (G)	Crushed stone (maximum size: 20mm), Density(SSD): 2.91g/cm^3, Absorption: 0.81%
Chemical admixure	Water reducing and air entraining agent (Ad_1) (Lignin sulphonic acid based)
	Air entraining agent (Ad_2) (Alkyl ether based)
	Superplasticizer (Ad_3) (poly carboxylic acid based)

Table 2. Mixture proportions and fresh properties of concrete

Mixture	W/B (%)	Unit weight (kg/m^3)					Ad_1 (×C%)	Ad_2 (×C%)	Slump (cm)	Air (%)
		W	B		S	G				
			C	GGBS						
N-35	35	175	500	-	714	997	0.30	0.002	8.5	3.7
N-45	45	175	389	-	771	1042	0.25	0.002	8.5	4.3
N-55	55	175	318	-	832	1038	0.25	0.002	5.5	4.3
N-65	65	175	269	-	851	1061	0.25	0.002	8.0	4.1
B-4-35	35	175	250	250	698	995	0.35	0.002	11.0	4.2
B-4-45	45	175	194	194	765	1033	0.25	0.002	7.0	4.4
B-4-55	55	175	159	159	810	1051	0.25	0.002	11.5	5.6
B-4-65	65	175	135	135	849	1054	0.25	0.002	6.0	3.6
B-6-35	35	175	250	250	680	992	0.50*	0.002	19.0	2.6
B-6-45	45	175	194	194	765	1033	0.25	0.002	9.0	3.1
B-6-55	55	175	159	159	810	1051	0.25	0.002	13.0	2.7
B-6-65	65	175	135	135	847	1056	0.25	0.002	17.0	3.0

* Ad_3 was used.

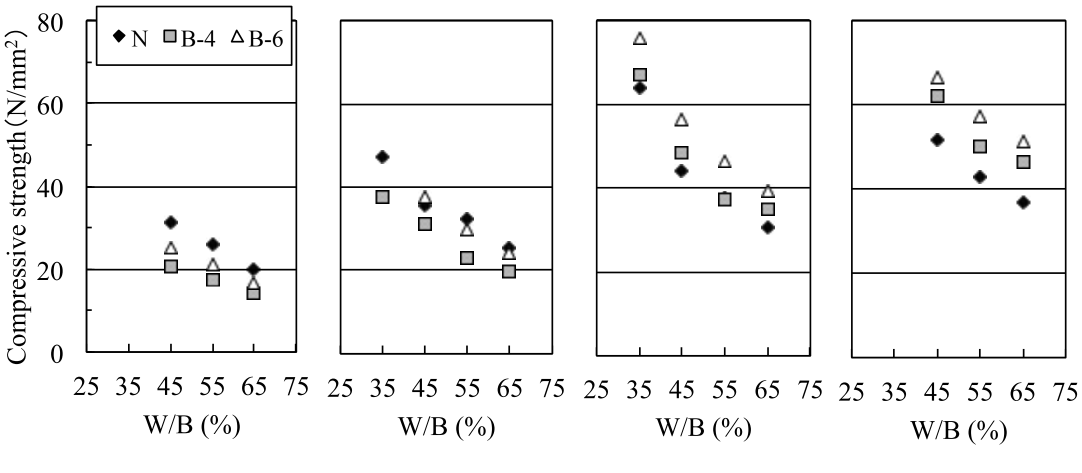
The binder to water ratio (W/B) was changed from 35% to 65%. The water content for all mixtures was 175 kg/m^3. The mixture proportions and the measured slump and air content were shown in Table 2. For only the concrete with W/B of 35% in Series B-6, superplasticizer was used as chemical agent.

The cylindrical specimens which had the diameter of 100 mm and the height of 200 mm were used. At 24 hours after placing, they were demolded, and cured in the 20 ℃ controlled water. At the 3, 7, 28 and 91 days, compressive strength of concrete was measured. For W/B=35%, only 7 days' and 28 days' strengths were measured.

Method of migration test. At 28 days, a sample with the diameter of 100 mm and the height of 50 mm was obtained from the center of cylindrical specimens. The test method followed the JSCE standard "Test method for effective diffusion coefficient of chloride ion in concrete by migration" (JSCE-G571-2003). In order to investigate the chloride penetration speed during the non-steady-state, 9 samples were used for the mixture N-55 and B-4-55. 3 samples of them were used for the calculation of the effective diffusion coefficient of chloride ion (D_e) of concrete. Other 6 samples were used to determine the distribution of chloride in concrete sample during migration test.

EXPERIMENTAL RESULTS AND DISCUSSIONS

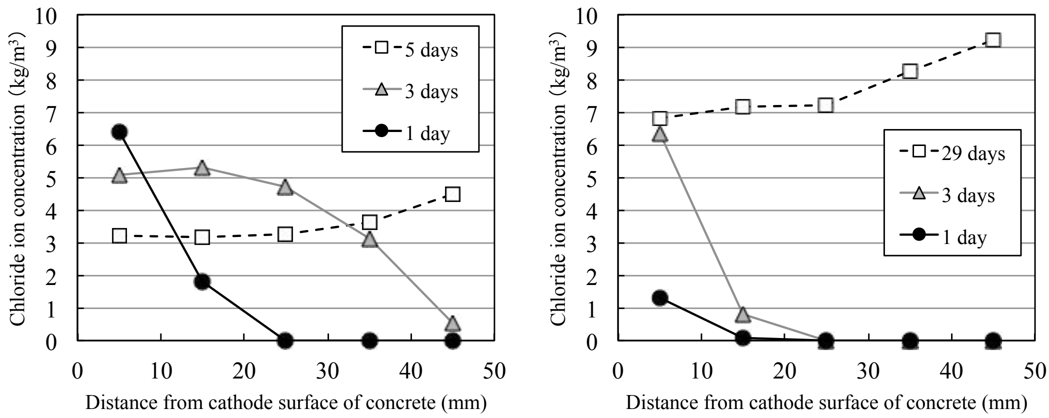
Compressive strength. Figure 1(a) to (d) show the compressive strength of concrete at 3, 7, 28 and 91 days. The strengths of Series B-4 at 3 days and 7 days are smaller than that of normal concrete. While the strength of Series B-6 at 3 days is smaller than that of normal concrete, the strengths at 7 days are almost same. Also, the strength of Series B-6 at 28 days is larger than that of normal concrete. When GGBS with 6000 cm^2/g surface area is used, the strength at 7 days can be increased.



(a) 3 days **(b) 7 days** **(c) 28 days** **(d)91days**

Figure 1. Mixture proportions and fresh properties of concrete

Chloride distribution. After 5 days from the beginning of the migration test of mixture N-55, the chloride ion was detected in the anode cell solution. On the other hand, it took 29 days by detecting chloride ion for B-4-55 specimens. GGBS can reduce the penetration speed of chloride. Figure 2(a) and (b) show the total chloride concentration distribution of N-55 and B-4-55 concrete, respectively. In the case of N-55, the chloride penetrates to 20 mm from the cathode surface at the 1 day, and to 40 mm from the surface at the 3 days. The concentration near the cathode surface decreased after 5 days. The reason is the cathode solution (NaCl solution) was not changed, and the concentration of chloride ion decreased. In the case of B-55-50, it is found that the concentration at 3 days is smaller than that of N-55 at 1 day. In addition, the concentration of B-4-55 is higher than that of N-55 when the chloride has penetrated to the anode surface. Binding chloride ion of the concrete with GGBS is larger than that of normal concrete as the previous research (Luo, 2003) has reported.



(a) N- 55 **(b) B-4-55**

Figure 2. Total chloride concentration distribution during migration test

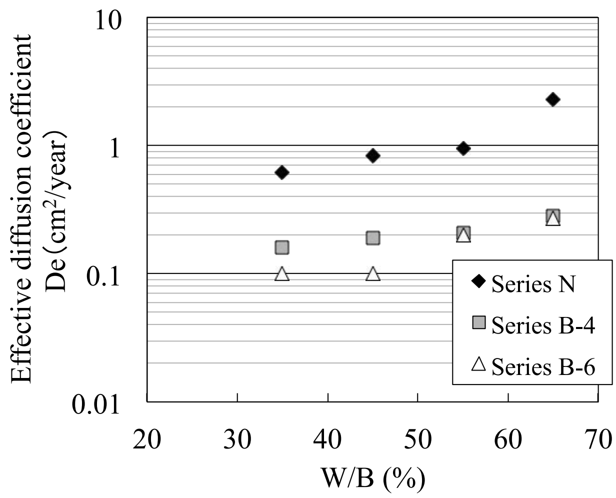


Figure 3. Relationship between W/B and effective diffusion coefficient (D_e)

Effective diffusion coefficient. Figure 3 shows the relationship between W/B and effective diffusion coefficient (D_e) in concrete (1.0 cm^2/year = 3.17×10^{-12} m^2/s) . It is found that the smaller W/B becomes, the smaller D_e is. The value of D_e of the concrete GGBS show from 1/5 to 1/10 rather than normal concrete. Effective diffusion coefficient indicates the penetration speed under the steady state. As the results, the chloride penetration speed in the concrete with GGBS is small under both steady and unsteady condition. In the actual situation, the concrete with GGBS improve durability to the salt damage remarkably.

When the W/C is smaller than 45 %, D_e of Series B-6 shows the smaller value than that of Series B-4. Larger specific surface area of GGBS increased the strength at early stage, and resulted in the smaller coefficient. The concrete mixed GGBS 6000 has the advantages both of high strength and high chloride resitance. Thus, this concrete is suitable to bridge superstructure in the condition in which chloride supplies. Highly-durable concrete can reduce cover depths and self weight of concrete members.

APPLICATION OF GGBS TO POST-TENSIONED TYPE PC BRIDGE

Information about the structure. In order to improve the resistance to chloride penetration, the concrete mixed with GGBS has been proposed, it has been applied to the pre-tensioned concrete. Because GGBS sometimes increases the viscosity of concrete, it is easier to control the fresh properties of concrete in the manufacturing factories rather than in-situ concrete. In this study, the application to situ-cast post-tensioned concrete is reported.

The new bridge which GGBS 6000 was used was constructed because the old bridge constructed 70 years ago had narrow width and presented deterioration due to the salt damage. It is located about 500 m from the mouth of a river in the north area of Kyushu Island, Japan. It has 242 m of the length, and is 5-span bridge consisting of situ-cast post-tensioned concrete box girder. Photo 1 and 2 show the construction of box girder on the column capital and side view of the bridge, respectively.

Table 3 is the typical mixture proportions of used concrete. W/B is 41% for design strength of 40 N/mm^2, and target slump is 15 cm. Ordinary Portland cement was used. Blended sand of washed sea sand and crushed limestone sand for fine aggregate and crushed limestone for coarse aggregate were used.

Photo 1. Construction of box girder

Photo 2. Side view of the bridge

Table 3. Mixture proportions for new bridge superstructure

W/B (%)	s/a (%)	Unit weight (kg/m^3)					Super-plasticizer (kg/m^3)	Target slump (cm)	Target air (%)
		W	B		S	G			
			C	GGBS					
40	46.8	155	189	189	931	973	2.08	15.0	4.5

EFFECTIVE DIFFUSION COEFFICIENT OF USED CONCRETE

Sampling and experimental method. Concrete was sampled at the ready mixed concrete plant. After 24 hours from the mixing, the cylindrical specimens were demolded and cured in the 20 ℃ controlled water. After 28 days, the migration test (JSCE-G571-2003) was conducted and effective diffusion coefficient (D_e) in concrete was calculated.

Results and discussions. It took about 40 days by detecting chloride ion in the anode solution. D_e of the concrete sample was 0.060 cm^2/year. From the laboratory experiments mentioned above (Figure 3), it was expected that D_e was near to 0.1 cm^2/year. As the results, the smaller D_e value was obtained. It is possible that the volume of cement paste of the concrete for a bridge is smaller than that in Table 2. The effect of aggregate content on chloride diffusion coefficient should be clarified.

Simple simulation by using Fick's second low was conducted in order to predict the chloride concentration profiles. Primarily, an apparent diffusion coefficient should be used for prediction, however there is not enough data. Also, the difference of curing condition between laboratory concrete and concrete in actual structural members should be considered. In this study, an effective diffusion coefficient was used just as it was. Surface concentration is 13 kg/m^3 which indicates the most severe condition in JSCE Standard Specifications. It was supposed that both surface chloride content and diffusion coefficient were constant value.

Figure 4 shows the simulation results until 100 years. For this bridge, the minimum cover depth was 70 mm and uncoated steel bar and tendon were used. From the calculation, it seems that the chloride concentration will be smaller than 1.2 kg/m^3, which is threshold value to occur steel corrosion in JSCE Standard Specifications. Therefore, GGBS 6000 can achieve the highly-durable concrete under the severe condition.

Follow-up monitoring. In order to confirm the chloride penetration in the future, concrete specimens for monitoring were produced, and exposure test was started shown in Photo 3. A wall type member and several cylindrical specimens were placed near the bridge. In the wall concrete, steel bars were embedded, electric potential and polarization curve can be measured periodically. Also, chloride concentration in the concrete will be investigated.

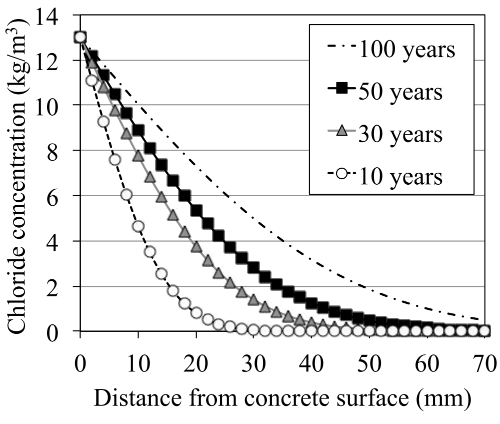


Figure 4. Prediction of chloride diffusion

Photo 3. Exposure test

CONCLUSIONS

In this study, the specimens which include normal-strength concrete and high-strength concrete by changing W/B from 65% to 35% were examined. The effectiveness of GGBS on chloride ion diffusion coefficient was investigated by migration test. Moreover, the application of GGBS which has the surface area of 6000 cm^2/g for bridge superstructures was presented. The conclusions are as follows:

(1) GGBS which has the surface area of 6000 cm^2/g (GGBS 6000)increased the strength at early age compared to the case of 4000 cm^2/g (GGBS 4000). GGBS 6000 is suitable to prestressed concrete which is higher strength at early age for prestressing is required.

(2) It was experimentally proved that GGBS decreased the effective diffusion coefficient of chloride ion by from 1/5 to 1/10. Also, below 45 % of W/B, the diffusion coefficient of the concrete with GGBS 6000 was smaller than the case of GGBS 4000.

(3) The effective diffusion coefficient of the concrete used for bridge superstructure showed the lower value. As the results of simple simulation based on one-dimensional Fick's second low, it is expected that steel bars in concrete will not occur corrosion for 100 years.

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