Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Strength and Durability of Concrete with Blast Furnace Slag

Paweena JARIYATHITIPONG[1*], Kazuyoshi HOSOTANI[1], Takashi FUJII[2]
and Toshiki AYANO[2]

[1]*Landes Co., Ltd, Japan*
[2]*Okayama University, Japan*
[*]*630-1 Kaide, Maniwa, Okayama 719-3192 Japan*
paweena-j@landes.co.jp, k-hosotani@landes.co.jp, t-fujii@okayama-u.ac.jp,
toshiki@okayama-u.ac.jp

ABSTRACT

The properties of concrete using blast furnace as binder and fine aggregate have been investigated in this study. The experiments focus on the properties of concrete such as compressive strength and young's modulus, carbonation, diffusion of chloride ions, resistance to sulfate attack and resistance to freeze and thaw. The experimental results show that when blast furnace slag is used in concrete, it improves the durability properties of concrete. However, the combination of using both blast furnace slag as binder and fine aggregate shows a greater improvement of those properties of concrete.

Keywords. Ground granulated blast furnace slag, Blast furnace slag sand, Carbonation, Drying shrinkage strain

INTRODUCTION

Blast furnace slag is a by-product generated during the production of iron. It has been classified as an amorphous material when used as a binder material and called granulated blast furnace slag and classified as a crystalline material when used as a material for road paving, called gradually-cooled blast furnace slag. In Japan, the volume of granulated blast furnace slag produced is over 20 million tons per year and 90% of it is used as a material for cement and concrete production (Japan Society of Civil Engineers, 2008). Concrete containing blast furnace slag is well known for improving some properties of concrete such as the watertightness, chemical resistance and chloride ion permeation resistance (Nippon Slag Association, 2011). In addition, it has been know that the sulfuric acid resistance can be improved when Portland cement is combined with ground granulated blast furnace slag, since the deterioration of concrete by chloride ion diffusion and sulfate attack is a serious problem for concrete structures. Currently there are many methods for protecting concrete from this effect, such as oxygen injection, which prevents the production of hydrogen sulfate, or the application of a product to the surface of the concrete which prevents direct contact with the sulfuric acid (Japan Society of Civil Engineers, 1996). Proving that the use of blast

Table 1. Mixture proportions of concrete

G_{max} (mm)	W/B (%)	C/B (%)	Air (%)	s/a (%)	Unit content (kg/m^3)						HRWRA*4 (B×%)
					W	OPC	GGBS*1	RS*2	BFS*3	G	
20	25.0	40.0	2.0	45.0	175	280	420	0	701	860	1.0
	45.0					156	233		829	1,017	0.4
	60.0					117	175		869	1,066	
								831	0		
	25.0	100.0				700	0	684	0	878	1.0
	45.0					389		800		1,027	0.4
	60.0					292		807		1,073	
								0	875		

*1 GGBS: Ground granulated blast furnace slag, *2 RS: River sand, *3 BFS: Blast furnace slag sand,
*4 HRWRA: High-range water reducing admixture

Table 2. Mixture proportions of concrete for drying shrinkage test

Type of sand	Type of gravel	G_{max} (mm)	W/B (%)	Air (%)	s/a (%)	Unit content (kg/m^3)					HRWRA*2 (B×%)
						W	C	GGBS*1	S	G	
Sandstone	Sandstone	20	60	4.5	48.0	175	292	0	848	976	0.6
Limestone	Limestone								858	954	
Andesite	Andesite								858	946	
Slate	Slate								868	965	
BFS	Sandstone			2.0	50.0		117	175	965	969	0.4

furnace slag in concrete will improve the durability properties of concrete will help the designer choosing a suitable material for construction. In this paper, the properties of concrete such as compressive strength and young's modulus, carbonation, diffusion of chloride ion, resistance to sulfate attack and resistance to freeze and thaw of concrete containing blast furnace slag as a binder and as a fine aggregate are experimentally investigated.

OUTLINE OF EXPERIMENTS

Materials and mixture proportions. Table 1 shows mixture proportions of concrete for test of compressive strength, Young's modulus, carbonation, diffusion of chloride ions and sulfate attack resistance. Ordinary Portland cement (Density: $3.15g/cm^3$, Blaine fineness: $3{,}300cm^2/g$) and ground granulated blast furnace slag (Density: $2.89g/cm^3$, Blaine fineness: $4{,}150cm^2/g$) are used for binder. As a fine aggregate, river sand (Density in saturated surface dry condition: $2.60g/cm^3$, Water absorption: 1.98%) and granulated blast furnace slag sand (Density in saturated surface dry condition: $2.73g/cm^3$, Water absorption: 0.40%) are used. As a coarse aggregate, crushed sandstone (Maximum size: 20mm, Density in saturated surface dry condition: $2.74g/cm^3$, Water absorption: 0.36%) is used. The polycarboxylate type of high range water reducing admixture is used as an additional admixture. Unit water content of concrete is 175 kg/m^3. Water to binder ratio of concrete is 25%, 45% and 60%.

Table 2 shows mixture proportions of concrete for a drying shrinkage test. Ordinary Portland cement (Density: $3.15g/cm^3$, Blaine fineness: $3{,}300cm^2/g$) and ground granulated blast furnace slag (Density: $2.89g/cm^3$, Blaine fineness: $4{,}150cm^2/g$) are used as binder. As an aggregate, crushed sandstone, crushed limestone, crushed andesite, crushed slate and granulated blast furnace slag sand are used. The properties of the aggregates are shown in Table 3.

Table 3. Properties of aggregate for drying shrinkage test

Type of rock	Fine aggregate		Coarse aggregate	
	Density* (g/cm^3)	Water absorption (%)	Density* (g/cm^3)	Water absorption (%)
Sandstone	2.57	3.16	2.76	0.51
Limestone	2.60	2.61	2.67	0.86
Andesite	2.60	2.14	2.65	1.07
Slate	2.63	2.39	2.70	0.71
Blast furnace slag	2.74	0.44		

* Density in saturated surface-dry condition

Table 4. Mixture proportions of concrete for freeze and thaw test

W/B (%)	C/B (%)	Air (%)	s/a (%)	Unit content (kg/m^3)					HRWRA*3 (B×%)
				W	OPC	GGBS*1	BFS*2	G	
40.0	40.0	2.0	50.0	178	178	267	865	882	0.5

*1 GGBS: Ground granulated blast furnace slag, *2 BFS: Blast furnace slag sand, *3 HRWRA: High-range water reducing admixture

Table 4 shows mixture proportions of concrete for freeze and thaw testing. Ordinary Portland cement (Density: 3.15g/cm^3, Blaine fineness: 3,300cm^2/g) and ground granulated blast furnace slag (Density: 2.89g/cm^3, Blaine fineness: 4,150cm^2/g) are used as binder. As a fine aggregate, crushed sand (Density in saturated surface dry condition: 2.65g/cm^3, Water absorption: 1.98%) and granulated blast furnace slag sand (Density in saturated surface dry condition: 2.69g/cm^3, Water absorption: 0.40%) are used. As a coarse aggregate, crushed sandstone (Maximum size: 20mm, Density in saturated surface dry condition: 2.74g/cm^3, Water absorption: 0.49%) is used. The polycarboxylate type of high range water reducing admixture is used as an additional admixture.

Test Method. Compressive strength and Young's modulus were measured following JIS A 1108: 2006 (Method of test for compressive strength of concrete) and JIS A 1149: 2010 (Method of test for static modulus of elasticity of concrete), respectively. Cylinder specimens (ϕ100×200mm) were used. Compressometer (Base length: 100mm) was used for measuring strain of concrete.

Cylinder specimens (ϕ100×50mm) were used for the carbonation test. Specimens were cured in water up to 28 days. The specimens were kept in the chamber (CO_2 concentration: 5.0 ± 0.2 %, temperature: 20.0 ± 1 °C, relative humidity: 60 ± 5 %). At a predetermined date, the specimens were cut and sprayed with the 1% phenolphthalein solution at the cutting face and were measured for the diameter of the coloration area.

A diffusion chloride ion test followed a method described in JSCE-G 572-2007 (Test method for apparent diffusion coefficient of chloride ion in concrete by submergence in salt water). Cylinder specimens (ϕ100×150mm) were used. As chloride ions penetrated from the top surface, the side and bottom surfaces were sealed with epoxy resin. Specimens were cured in water for 28 days. After curing, specimens were soaked in NaCl solution of 10% concentration to the solution by mass for 91days. After soaking, the epoxy resin on the surface of specimen was removed, and specimens were cut to a thickness of 7mm by dry-type cutter (blade thickness: 3mm). Chloride ion content in each specimen was measured by the potentiometric titration method shown in JIS A 1154: 2003 (Methods of test for chloride ion content in hardened concrete).

Sulfate resistance was measured in a cylinder specimen (ϕ100×200mm). After casting the mortar, specimens were cured in water for 7 days after 4 hours of steam curing at 65 °C. Steam curing followed a method described in the Standard Specifications for Concrete Structures - 1996 (Materials and Construction) (JSCE, 1996). After curing, specimens were soaked in Na_2SO_4 solution of 10% concentration to the solution by mass. Sulfate resistance was judged by mass change.

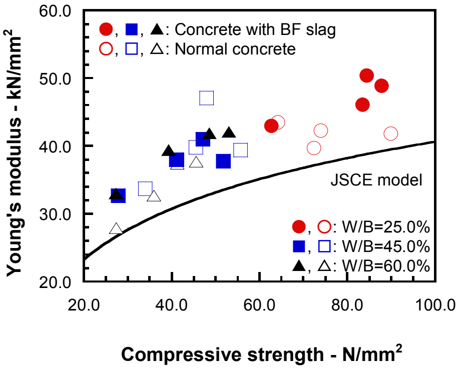


Figure 1. Relationship between compressive strength and Young's modulus

The size of the prism specimen for measuring drying shrinkage strain is 100×100×400 mm. Specimens were cured in water for 7 days. Two pairs of gauge points are put on each surface, except the casting surface and its opposite side. The drying shrinkage strain is measured by a Whittemore strain meter (Gauge length: 250mm, Minimum reading: 1/1,000 mm). The specimens are kept in the constant temperature and constant relative humidity room (temperature: 20.0 ± 1.0°C, relative humidity: 60 ± 5%).

100×100×400 mm prism specimens were used for the freezing and thawing test. They were cured in water for two weeks after 4 hours of steam curing at 65 °C. Steam curing obeyed a method followed a method described in Standard Specifications for Concrete Structures - 1996 (Materials and Construction) (JSCE, 1996). The specimens were cyclically exposed to -18 °C and 5 °C in salt water of 10% concentration to the solution by mass every 5 hours. Resistance to freezing and thawing was assessed through the relative dynamic Young's modulus.

EXPERIMENTAL RESULT AND DISCUSSION

Compressive strength and Young's modulus. Figure 1 shows the relationship between compressive strength and Young's modulus of concrete. ●, ■ and ▲ shows results of concrete with ground granulated blast furnace slag and blast furnace slag sand whose water to binder ratio is 25%, 45% and 60%, respectively. ○, □ and △ shows results of concrete with ordinary Portland cement and river sand whose water to cement ratio is 25%, 45% and 60%, respectively. They are results of age at 7days, 28days, 91days and 182days. The curve line shown in the figure is the relationship between compressive strength and Young's modulus of normal concrete shown in Standard Specifications for Concrete Structures -2007 (Design) (JSCE, 1996). From this figure, the relationship between compressive strength and Young's modulus of concrete with blast furnace slag is the same as that of normal concrete.

Carbonation. Figure 2 shows the result of the carbonation test of normal concrete, and Figure 3 shows that of concrete with concrete with blast furnace slag. ○ and △ in Figure 2 represent the result of concrete whose water to cement ratio is 25% and 60%, respectively.● and ▲ in Figure 3 represent the result of concrete whose water to binder ratio is 25% and 60%. From these figures we determined that a bigger water to binder ratio produces a faster carbonation speed.

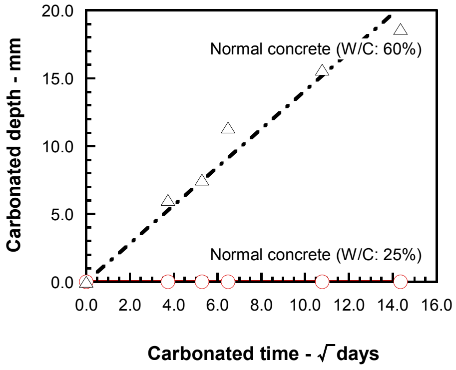


Figure 2. Result of carbonation test of normal concrete

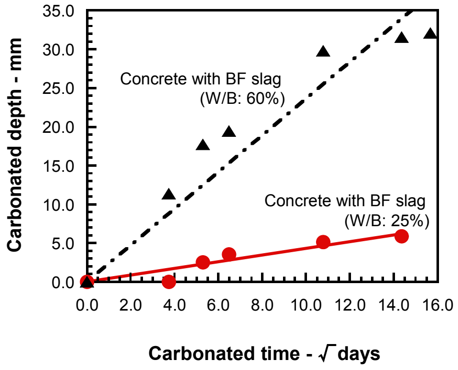


Figure 3. Result of carbonation test of concrete with blast furnace slag

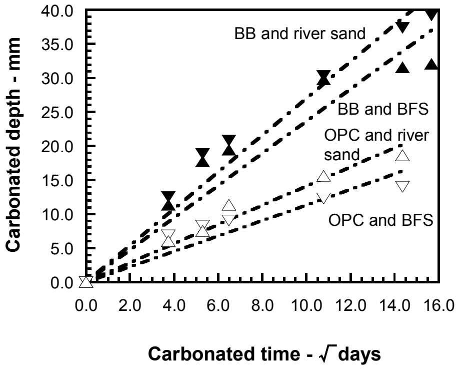
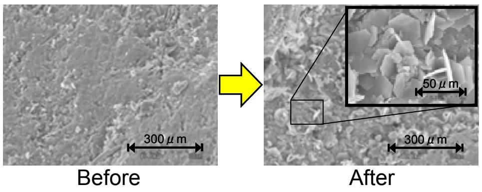


Figure 4. Effect of binder and aggregate on carbonation of concrete

Figure 4 shows the effect of binder and aggregate on the carbonation property of concrete. The drawing △ represents the experimental result of concrete using only ordinary Portland cement as a binder and river sand as a fine aggregate. The results of the use of ground granulated blast furnace slag used in a proportion of 4:6 by mass ratio of ordinary Portland cement in concrete are presented as the drawing ▼ when ground granulated blast furnace slag sand is used as a fine aggregate, and the drawing ▲ when river sand is used. The change of type of binder in concrete shows a greater effect to the carbonation than the change of the type of fine aggregate. The progress of carbonation of concrete using only ordinary Portland cement is faster when compared the results of concrete using the same type of fine aggregate. On the other hand, when concrete containing the same type of binder but a difference type of fine aggregate is produced, the concrete containing blast furnace slag sand shows slower progression of carbonation.

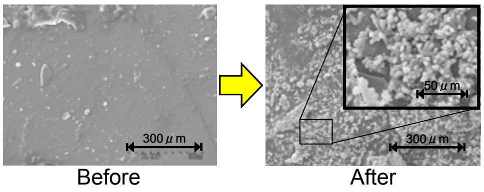
Photo 1 and photo 2 show respectively electron microscope pictures of the surface of river sand and the blast furnace slag sand before and after immersing them in a saturated aqueous calcium hydroxide solution. The hexagonal plate of calcium hydroxide crystal has been found on the surface of river sand, while the C-S-H crystal has been found on the blast furnace slag after an immersion. Since the river sand has a low reactivity, the calcium hydroxide is precipitated on the surface which is a vulnerable part. On the other hand, the high reactivity blast furnace reacts with calcium hydroxide at the interface of the particle of sand and solution, producing a stronger product of reaction which might cause a slower progression of carbonation in concrete.

Diffusion of chloride ions. Figure 5 shows the chloride ions distribution in concrete when normal concrete is immersed after 91 days in an aqueous sodium chloride solution with concentration 10% by mass. Drawing as ○, □and △ in a figure respectively represent the



Before After

Photo. 1. Surface of river sand soaked in calcium hydroxide aqueous solution



Before After

Photo. 2. Surface of blast furnace slag sand soaked in calcium hydroxide aqueous solution

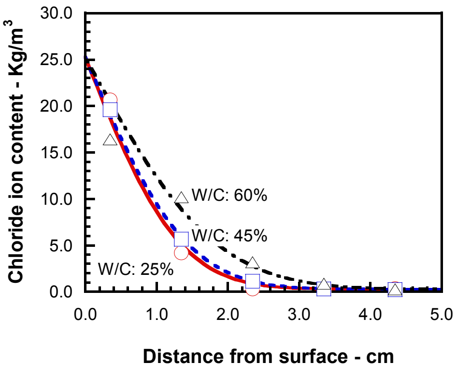


Figure 5. Chloride ion distribution of normal concrete

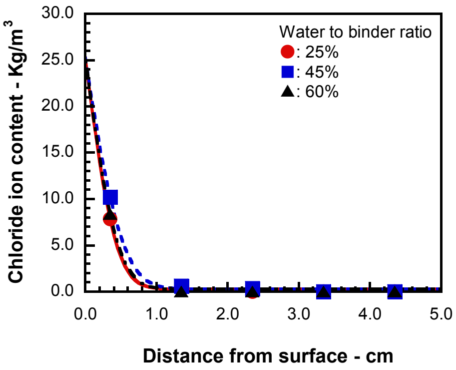


Figure 6. Chloride ion distribution of concrete with blast furnace slag

result of 25%, 45% and 60% water to cement ratio of concrete. The larger water to cement ratio, the deeper penetration of chloride ions have been found.

Figure 6 shows the chloride ions distribution in concrete when concrete containing cement and the blast furnace slag is used at a ratio 6:4 as a binder is immersed after 91 days in an aqueous sodium chloride solution with concentration 10% by mass. Drawing as ●, ■ and▲ in a figure respectively represent the result of 25%, 45% and 60% water to binder ratio of concrete. The effect of water to binder ratio on a penetration of chloride ion is very small. The penetration of the chloride ion into concrete is suppressed even in a larger water to binder ratio concrete. A comparison of figure 5 and figure 6 shows that concrete with the blast furnace slag has a significant smaller penetration of chloride ions into concrete than normal concrete.

Sulfate attack resistance. Figure 7 shows the mass change of concrete when it is immersed in an aqueous sodium chloride solution with concentration 10% by mass. The experimental concrete specimen is a normal concrete using ordinary Portland cement as a binder and river sand as a fine aggregate. Drawing as ○ and △ in a figure respectively represent the result of 25% and 60% water to cement ratio of concrete. The concrete with water to cement ratio 60% lost mass ratio up to 88% at 660 days of immersion. Furthermore, it is completely collapsed at 700 days of immersion. The larger water to cement ratio of concrete, the larger mass loss is found. It also shows the lower resistance to sulfate.

On the other hand, Figure 8 shows the mass change of concrete when it is immersed in an aqueous sodium chloride solution with concentration 10% by mass. The concrete specimen contains blast furnace slag and cement at a ratio of 6:4 as a binder and the blast furnace slag

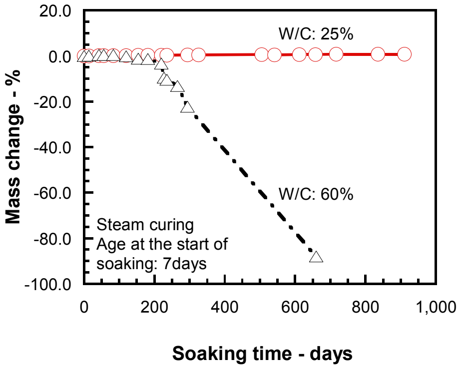


Figure 7. Resistance to sulfate attack of normal concrete

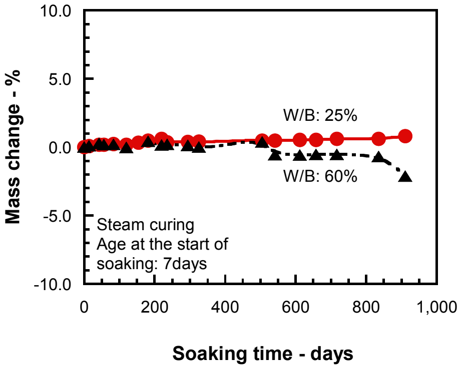


Figure 8. Resistance to sulfate attack of concrete with blast furnace slag

sand is used as a fine aggregate. Drawing as ● and ▲ in a figure respectively represent the result of 25% and 60% water to cement ratio of concrete. The tendency shows the same as the normal concrete results. The larger water to binder ratio of concrete, the larger mass loss is found. Hence, the mass change of 60% water to binder ratio concrete is about -2% at 900 days of immersion period. It shows the high resistance to sulfate compare with a normal concrete.

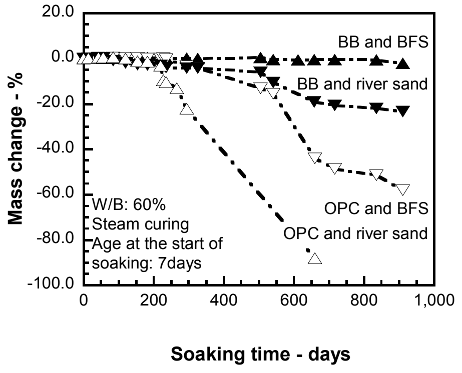


Figure 9. Effect of binder and aggregate on sulfate attack resistance of concrete

The effect of the type of binder and aggregate in concrete on a resistance to sulfate attack are shown in Figure 9. Drawing as △ represents the results of normal concrete and ▼ represents the results of concrete containing the blast furnace slag which is the blast furnace slag to cement ratio of 6:4 and containing 100% blast furnace slag sand as a fine aggregate. The change of the type of binder in concrete shows the greater effect to the resistance to sulfate attack than the change of the type of fine aggregate. The concrete using ordinary Portland cement shows the greater mass change on the immersion experiment compare with concrete using blast furnace slag. On the other hand, when concrete containing a same type of binder but difference type of fine aggregate, concrete containing blast furnace slag sand shows higher resistance to sulfate attack. It could be assumed that the use of blast furnace slag sand prevents an accumulation of calcium hydroxide around the fine aggregate particles and prevents the formation of ettringite. Therefore, these mechanisms improve the resistance of concrete to sulfate attack.

Drying shrinkage. Figure 10 shows the measurement of drying shrinkage of normal concrete with various aggregates. Drawing as ▲, △, □ and ○ represent the dry shrinkage stain of concrete with Slate, Andesite, Sandstone and Limestone respectively. Only ordinary Portland cement is used as a binder. The used fine aggregates are the same type of coarse aggregate for each concrete. Drawin ● represents the drying shrinkage of concrete with a combination of blast furnace slag sand and sandstone gravel. The blast furnace slag and

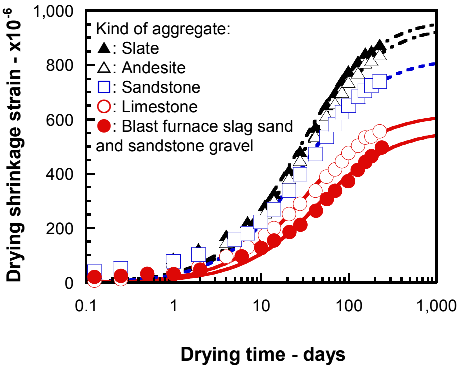


Figure 10. Effect of aggregate on drying shrinkage strain of concrete

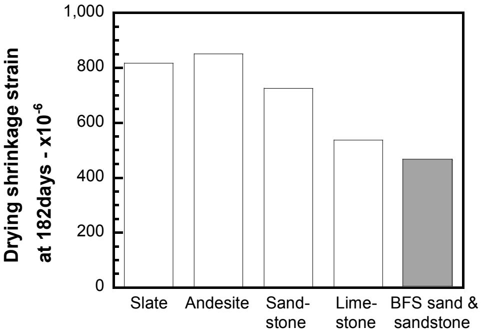


Figure 11. Comparison of drying shrinkage strain at 182days

cement at ratio 6:4 were used as binder material. Figure 11 shows the comparison of drying shrinkage of each concrete at 182 days. Drying shrinkage of concrete with limestone gravel has a smaller stain compared with concrete with other gravel types. It also shows a small drying shrinkage stain when the blast furnace slag is used as fine aggregate in concrete.

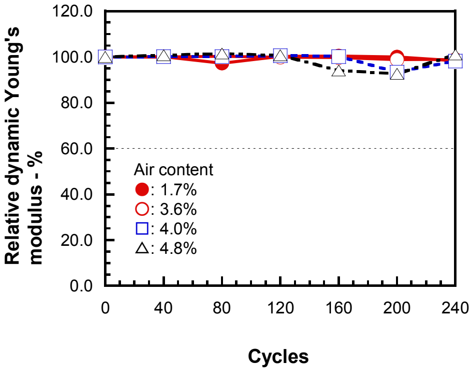


Figure 12. Result of freezing and thawing resistance test

Resistance to freeze and thaw. Figure 15 shows the test result of freeze and thaw test of concrete containing blast furnace slag as binder and fine aggregate. Drawing as ●, ○, □and △ represent the concrete with air content at 1.7%, 3.6%, 4.0% and 4.8% respectively. All the mixture of concrete shows the high resistance to freeze and thaw.

CONCLUSIONS

When blast furnace slag is used partly as a binder in concrete, it improves the resistance of concrete to chloride ions and sulfate attack. But the carbonation speed of concrete is faster compared with concrete with ordinary Portland cement. Therefore, those properties such as carbonation, resistance to chloride ions, resistance to sulfate attack and drying shrinkage and resistance to freeze and thaw are improved when the blast furnace slag sand is used in concrete.

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