Steel making slag concrete as sustainable construction materials

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ABSTRACT: Steel making slag concrete is made of ground granulated blast furnace slag and steel making slag that are by-products at ironworks. This type of construction materials is called environmental conscious material in Japan. This study shows that the strength of steel making slag concrete depends on pH of steel making slag concrete after mixing. It is also shown that the resistance to carbonation and steel rod corrosion of steel making slag concrete is high for a long time due to calcium hydroxide leaching from steel making slag. However, resistance to freezing and thawing of steel making slag concrete is quite low. In this paper, the method to improve the resistance to freezing and thawing is shown.

1 INTRODUCTION

In ironworks, about 36 million tons of steel making slag has been produced every year in Japan [Nippon Slag Association 2003]. Steel making slag concrete consists of by-products at ironworks. Ground granulated blast furnace slag is a binder. Steel making slag like hot metal pretreatment slag is an aggregate. Natural aggregate is not used [Matsunaga 2003]. Steel making slag in this concrete is 60 % in volume. Unless steel making slag is adequately aged, it expands in steel making slag concrete and is eventually broken in pieces [Coastal Development Institute of Technology 2003]. There are two methods in aging. One is natural aging. Steel making slag is exposed to rain or dew for a fixed period. The other is steam aging. Steel making slag is exposed to high temperature steam. The steel making slag is not easy to treat. However, steel making slag concrete can consume much by-products and contributes to solve one of environmental problems.

Main binder of steel making slag concrete is not portland cement but ground granulated blast furnace slag. Slaked lime or a kind of cement is used for alkali activator. The by-products containing the calcium hydroxide or calcium oxide can also be used for alkali activator [Matsunaga 2003]. The strength of steel making slag concrete depends on water to binder ratio as well as that of cement concrete [Coastal Development Institute of Technology 2003]. In general, the variation of properties of steel making slag concrete is bigger than cement concrete. Because, the quality variation of the steel making slag is big.

The purpose of this study is to clarify the influence of pH on strength and durability of steel making slag concrete. As for the durability, carbonation, drying shrinkage, resistance to steel rod corrosion, resistance to sulfate attack and resistance to freezing and thawing were examined.

2 OUTLINES AND EXPERIMENTS

2.1 *Materials and mixture proportions*

Table 1 shows the mixture proportions of steel making slag concrete used in this experiment. Ground granulated blast furnace slag was used as binder. The density was 2.89 g/cm^3 and the specific surface area by blain was 4,000 cm^2/gr. Lime dust powder was used for alkali activator. The density was 3.14 g/cm^3 and the maximum size of particle is 500 μm. Lime dust powder was replaced with ground granulated blast furnace slag in volume. Unit content of water is 150 kg/m^3. Polycarbonate high range water reducing admixture was used. The dosage of high range water reducing admixture was decided so that a slump flow was set to 550 - 650 mm. Hot metal pretreatment slag, which is a type of steel making slag, was used for aggregate. The size of steel making slag aggregate was 0 - 5 mm (density: 3.06 g/cm^3, water absorption: 7.41 %), 5-13 mm (density: 3.22 g/cm^3, water absorption: 4.84 %) and 13 - 20 mm (density: 3.21 g/cm^3, water absorption: 4.20 %). The unit content of steel making slag was 1,915 kg/m^3. As control concrete, the hydrated matrix with ground granulated blast furnace slag and natural aggregate was made. Fine aggregate was river sand (density: 2.58 g/cm^3, water

Table 1. Mixture proportions of steel making slag concrete

G_{max} (mm)	W/B (%)	Air (%)	Unit content (kg/m^3)						H.R.W.R.A (kg/m^3).
			Water	Binder		Steel making slag aggregate			
				BF	LD	0-5mm	5-13mm	13-20mm	
20	23.7	2.0	150	634	0	958	574	383	9.58
	23.5			598	39				
	23.4			562	78				
	23.3			536	107				
	23.3			526	117				

BF: Ground granulated blast furnace slag
LD: Lime dust powder
H.R.W.R.A.: High range water reduce admixture

Table 2. Mixture proportions of hydrated matrix with ground granulated blast furnace slag and natural aggregate

G_{max} (mm)	W/B (%)	Air (%)	Unit content (kg/m^3)						H.R.W.R.A. (kg/m^3)
			Water	Binder		River sand	Crushed stone		
				BF	LD		5-13mm	13-20mm	
20	23.7	2.0	150	634	0	808	485	324	9.58
	23.6			625	9.7				
	23.6			620	15				
	23.6			616	20				
	23.6			607	30				
	23.5			598	39				
	23.4			562	78				
	23.3			536	107				

BF: Ground granulated blast furnace slag
LD: Lime dust powder
H.R.W.R.A.: High range water reduce admixture

absorption: 1.95 %). Coarse aggregate of the size of 5 - 13 mm was crushed stone (density: 2.72 g/cm^3, water absorption: 1.02 %). Coarse aggregate of the size of 13 - 20 mm was also crushed stone (density: 2.72 g/cm^3, water absorption: 0.83 %). Table 2 shows the mixture proportions of the hydrated matrix with natural aggregate.

Furthermore, cement concrete was also used for comparison. The water to cement ratio was 60 %. The sand - total aggregate ratio was 47.7 %. Unit water content was 175 kg/m^3. Fine aggregate was river sand. Coarse aggregate was crushed stone. The same kinds of aggregates were used for the hydrated matrix with ground granulated blast furnace slag and natural aggregate.

2.2 *Durability tests*

The specimens for carbonation test were cured in water for 4 days and in air for 3 days before the start of test. The specimens were kept in the chamber (CO_2 concentration: 20 ± 3 %, temperature: 30 ± 1 °C, relative humidity: 60 ± 3 %).

The size of the prism specimen for measuring drying shrinkage strain was 100 by 100 by 400 mm. The age at the start of drying is 1 day. The specimens were kept in the constant temperature and constant relative humidity room (temperature: 20 ± 1 °C, relative humidity: 60 ± 3 %).

Figure 1 shows the cylinder specimen for steel rod corrosion test. The diameter of steel rod is 13 mm. The covers of steel rod were 10 mm and 20 mm. The specimens for steel rod corrosion test were cured in water for 4 days and in air for 3 days before the start of test. The both ends of specimen were coated with epoxy resin. The specimens were cyclically exposed to 3 % chloride solution for 4 days and in air for 3 days, alternately.

Sulfate resistance was measured in cylinder specimen (diameter: 100 mm, height: 200 mm). The specimens were soaked into 10 % Na_2SO_4 solution. Sulfate resistance was judged by relative dynamic Young's modulus, which is the ratio of dynamic Young's modulus at the arbitrary age to that of the initial stage.

Resistance to freezing and thawing was measured in 100 by 100 by 400 mm prism specimen. It was cured in water for two weeks after 4 hours steam curing in 65 °C. The specimens were cyclically exposed to -18 °C and 5 °C, every 5 hours in water. Resistance to freezing and thawing was also judged by relative dynamic Young's modulus.

2.3 *Measuring pH of hydrated matrix*

The fresh steel making slag concrete was diluted with refined water. 20 g paste of steel making slag concrete was mixed with 200 ml of refined water. pH of the hydrated matrix was measured by using the filter solution. pH of steel making slag was measure by the same procedure. 50 g of steel making slag aggregate was soaked into 500 ml of refined water. After it was filtered, pH of the solution was measured.

3 DISCUSSION OF TEST RESULTS

3.1 *Strength of concrete*

Figure 2 shows the relationship between 28 days compressive strength of each type of hydrated matrix and the dosage of lime dust powder. The circles represent the results of steel making slag concrete, and the squares represent those of hydrated matrix with ground granulated blast furnace slag and natural aggregate. When natural aggregate was used, the required dosage of lime dust powder is equal to 10 % of ground granulated blast furnace slag in order to get the same strength of steel making slag concrete.

Figure 3 shows the relationship between 28 days compressive strength of each type of hydrated matrix and pH after mixing. The compressive strength of steel making slag concrete and hydrated matrix with natural aggregate can be plotted on the same line. That is, the strength of hydrated matrix with ground granulated blast furnace slag strongly depends on pH of the hydrated matrix after mixing.

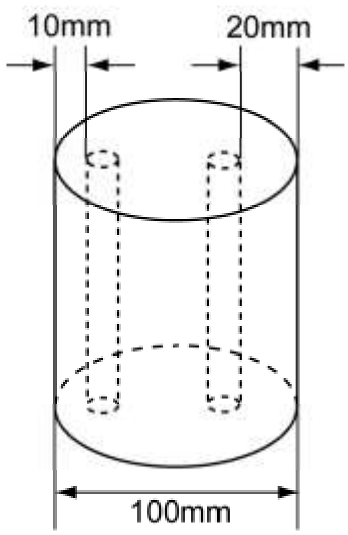

Figure 1. Specimen for steel rod corrosion test

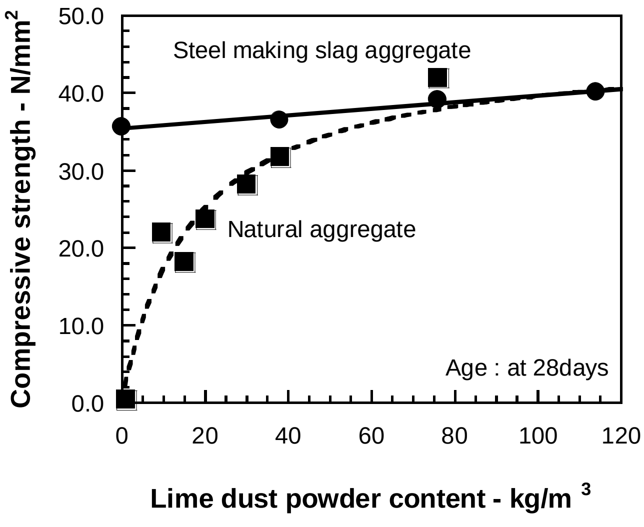

Figure 2. Relationship between compressive strength and lime dust powder content

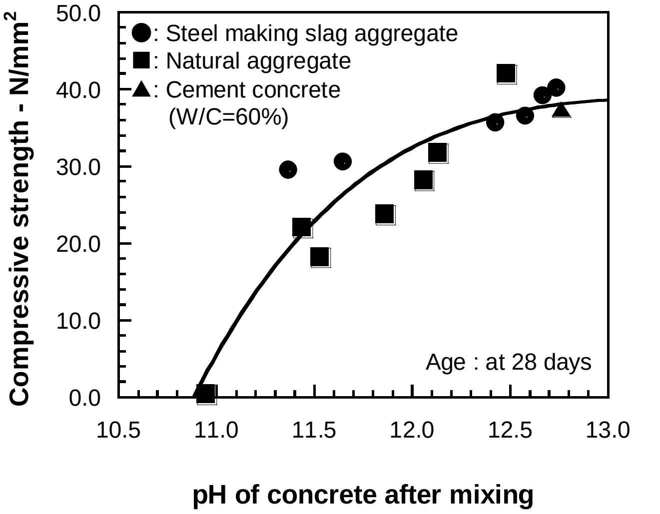

Figure 3. Relationship between compressive strength and pH after mixing

3.2 *Carbonation test results*

Figure 4 shows the result of carbonation test of the hydrated matrix with natural aggregate. The lateral axis in this figure is the root of test period. It is clear that the carbonation speed depends on the dosage of lime dust powder when natural aggregate was used. Figure 5 shows the result of carbonation test of steel making slag concrete. The influence of lime dust powder content on carbonation of steel making slag concrete is small.

Figure 6 shows the relationship between carbonation speed modulus and pH of concrete after mixing. Carbonation speed is the slope of line shown in Figure 4 and Figure 5. The circles represent the results of steel making slag concrete. The squares represent the results of hydrated matrix with natural aggregate. The triangle represents the result of cement concrete whose water to cement ratio is 60 %. The carbonation of each types of hydrated matrix depends on pH. The carbonation of hydrated matrix with natural aggregate is influenced by pH much more than that with steel making slag.

3.3 *Steel rod corrosion*

Figure 7 shows the relationship between corrosion area ratio of steel rod in each hydrated matrix and pH of hydrated matrix after mixing. Corrosion area ratio was obtained from the steel rod which was placed at 10 mm from the concrete surface. The soaking period of the specimen was 4 weeks. The circles represent the results of steel making slagconcrete. The squares represent the results of hydrated matrix with natural aggregate. In this

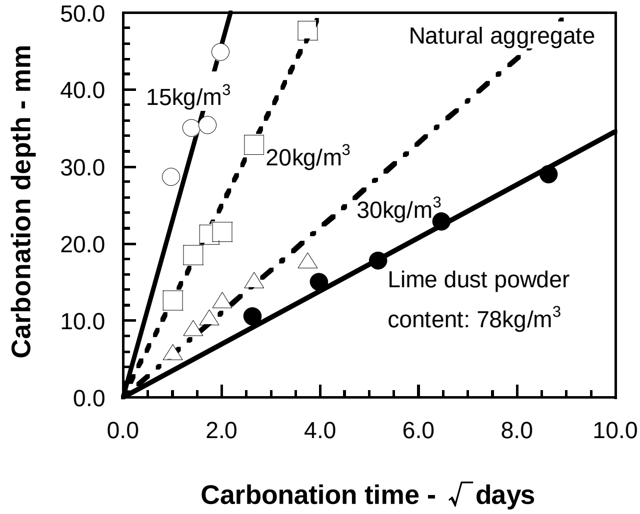

Figure 4. Result of carbonation test

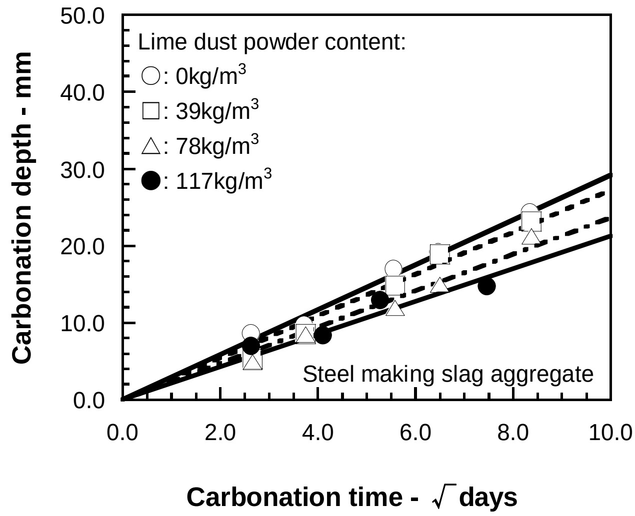

Figure 5. Result of carbonation test

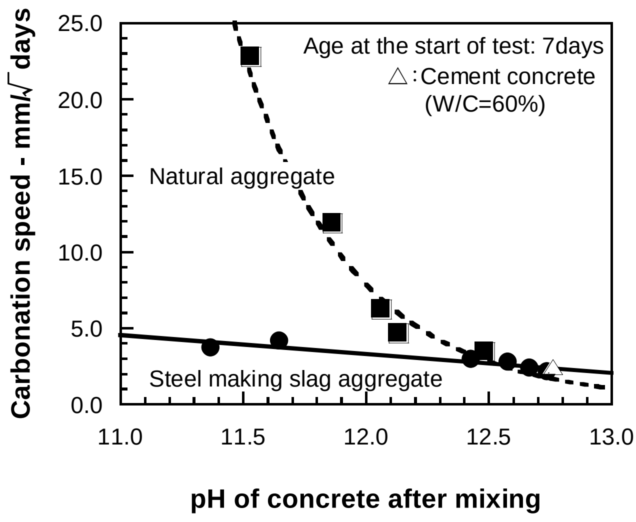

Figure 6. Relationship between carbonation speed and pH after mixing

experiment, pH of hydrated matrix influences on the test results, too. When pH of hydrated matrix after mixing is low, the resistance to steel rod corrosion of steel making slag concrete is higher than that of hydrated matrix with natural aggregate.

Photographs 1 and 2 show the steel rods placed in cement concrete and steel making slag concrete at 15 weeks after the start of test. The dosage of lime dust powder in steel making slag concrete was 78 kg/m^3. The cover of steel rod is 10 mm and 20 mm, respectively. Steel rods in cement concrete were rusty. However, any rust of steel rod placed at 20 mm from the surface in steel making slag concrete was not found.

3.4 *Drying shrinkage strain*

Figure 10 shows the development of drying shrinkage strain of steel-making slag concrete. The more the making slag concrete dosage of lime dust powder, the bigger the drying shrinkage strain.

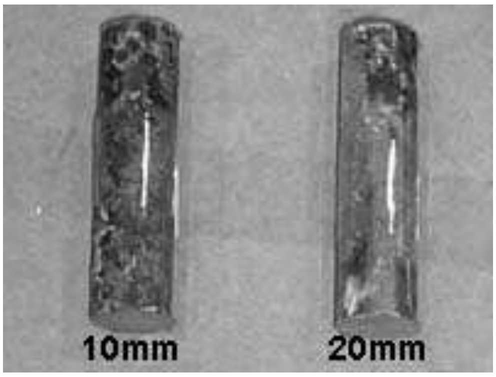

Figure 8. Steel rod in cement concrete

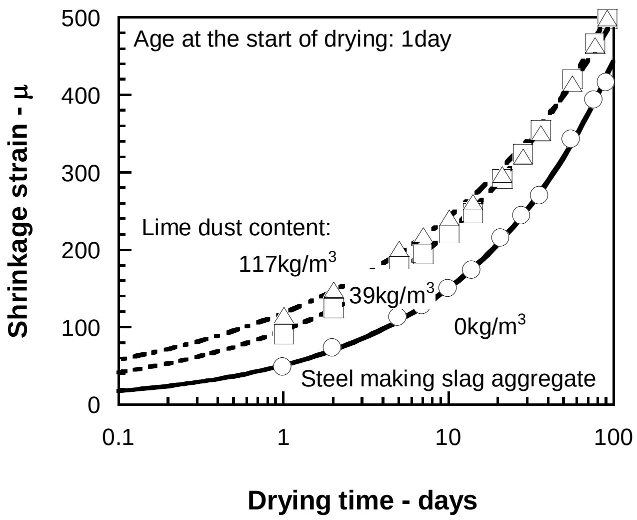

Figure 10 Result of drying shrinkage test of steel

Figure 11 shows the development of drying shrinkage strain of hydrated matrix with natural aggregate. As compared with both results, the drying

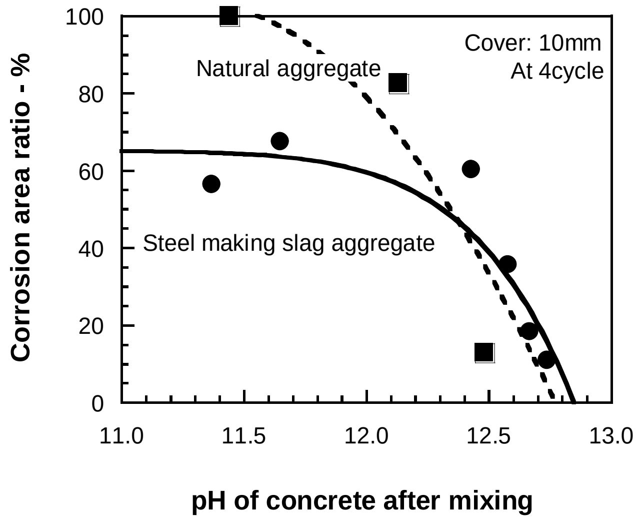

Figure 7 Relationship between corrosion areas ratio of steel rod in hydrated matrix and pH after mixing

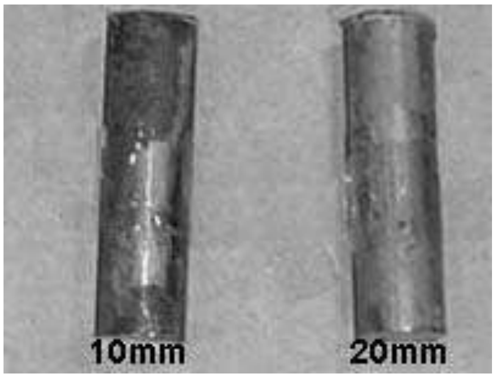

Figure 9. Steel rod in slag concrete

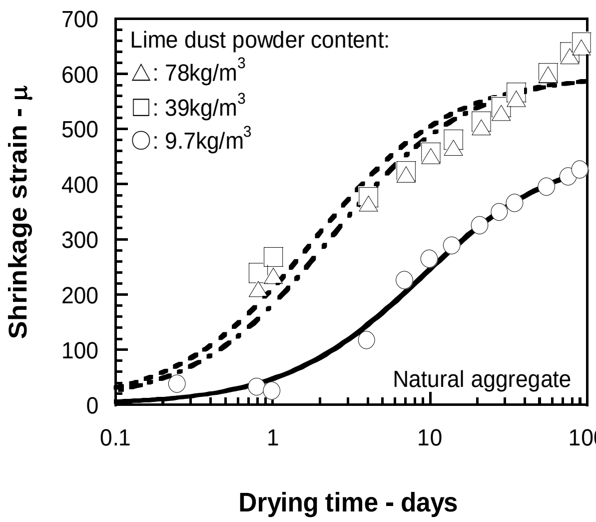

Figure 11. Result of drying shrinkage of hydrated than that of matrix with natural aggregate

shrinkage of steel making slag concrete is smaller hydrated matrix with natural aggregate. It may be due to the effect of high rigidity of steel making slag.

3.5 *Leaching of alkali ingredients from steel making slag*

Figure 12 shows the change of pH of the solution in which the steel making slag was soaked. In this test, two types of steel making slag were used. One was washed before it was soaked in the refined water.The other was used without any treatment. The circles represent the results of non-washed steel making slag. The squares represent the results of the washed steel making slag. It is clear that pH of the steel making solution increases with the lapse of time. The color of phenolphthalein did not turn to red on the steel making slag just after washing. However, it turned to red at 6 hours after washing. It seems that the alkali ingredient leaches from the steel making slag.

Figure 13 shows the development of compressive strength of steel making slag concrete, hydrated matrix with natural aggregate and cement concrete. The circles represent the results of steel making slag concrete. The squares represent those of hydrated matrix with natural aggregate. The triangles show those of cement concrete. Unit content of lime dust powder of steel making slag concrete and hydrated matrix with natural aggregate was 107 kg/m^3. It is clear that the compressive strength of steel making slag concrete develops for longer.

From these figures, it is clear that the ground granulated blast furnace slag paste is supplied with the alkali ingredient leached from steel making slag. Therefore, the compressive strength develops longer. The durability of steel making slag concrete is superior to that of hydrated matrix with natural aggregate even if pH of each hydrated matrix after mixing is the same.

3.6 *Resistance to sulfate attack*

Figure 14 shows the resistance to sulfate attack of cement concrete and steel making slag concrete. The destruction of concrete with the normal portland cement is 7 months after the start of test. Fly ash improves the resistance to sulfate attack of cement concrete. However, it is also broken within one year. The steel making slag concrete has not been broken after one and half years after the start of test. It is very clear that the ground granulated blast furnace slag enhances the durability in resistance to sulfate attack.

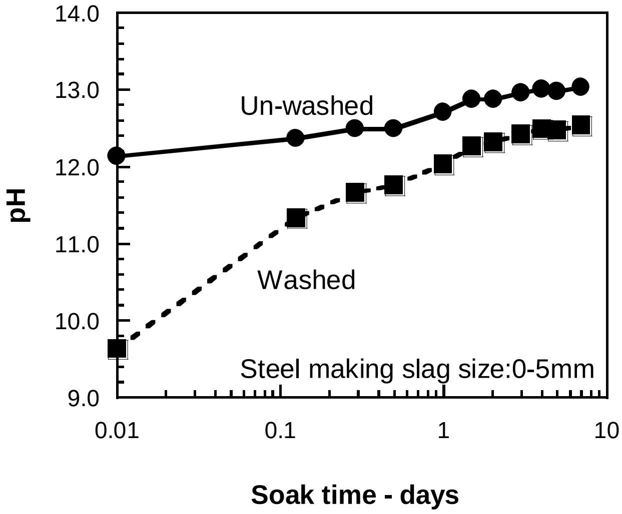

Figure 12. pH change of solution soaked steel making slag in refined water

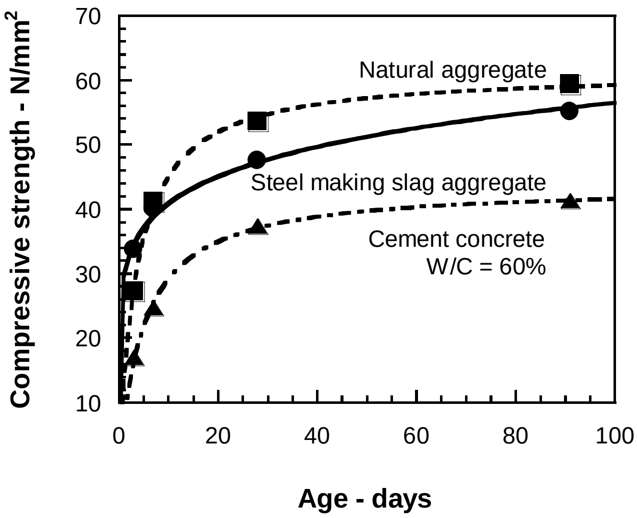

Figure 13. Compressive strength

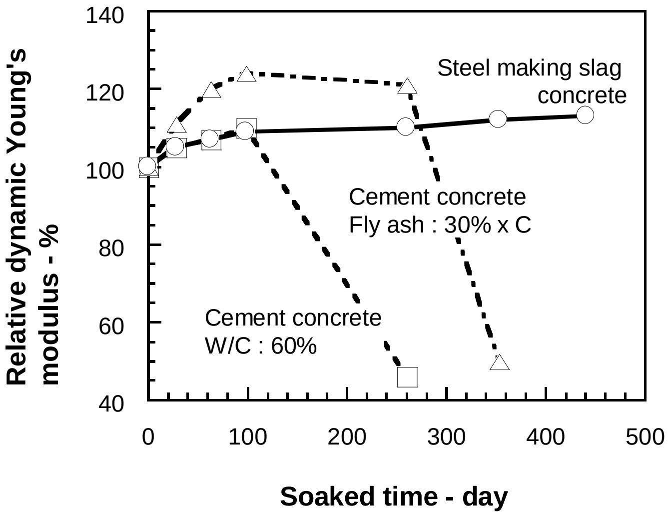

Figure 14. Resistance to sulfate attack

3.7 *Resistance to Freezing and thawing*

Figure 15 shows the resistance to freezing and thawing of steel making slag concrete. Specimen is judged to be broken when relative dynamic Young's modulus falls below 60%. The concrete which is not broken until 300 cycles is judged to be durable. The test results by two methods are shown in Fig.13. In one method, specimens were freezed and thawed out in water. In the other method, specimens were freezed in air and thawed out in water. Normally, the specimen is broken faster when it is freezed and thawed out in water than when specimen is freezed in air and thawed out in water. Steel making slag concrete was broken within 15 cycles by either method. Figure 16 shows the broken specimen attacked by freezing and thawing action.

Figure 17 shows the resistance to freezing and thawing of steel making slag concrete and the hydrated matrix with natural aggregate. Specimens were freezed and thawed out in water. The hydrated matrix with natural aggregate has the highest resistance to freezing and thawing among these concretes. However, it was broken in 250 cycles.
The steel making slag concrete with ordinary steel making slag aggregate was broken in 15 cycles. The resistance to freezing and thawing of steel making slag concrete is quite low. When the water absorption of steel making slag aggregate was improved, the resistance to freezing and thawing was somewhat enhanced. But it was not as durable as the hydrated matrix with natural aggregate.

Figure 18 shows the relationship between air content of steel making slag concrete and the dosage of AE agent. When ordinary steel making slag aggregate is used, the air content increases with the dosage of AE agent. When steel making slag aggregate with low water absorption is used, the air content does not increase so much with the dosage of AE agent. It seems that the effect of AE agent on the air content is different in type of slags.

Figure 19 shows the effect of air content on the resistance to freezaing and thawing of steel making slag concrete with steel making slag aggregate of low absorption. Notation "1A" in this figure means that the standard dosage of AE agent is put. That is, 80 A means that the concrete contains as much AE agent as 80 times of standard dosage. The resistance to freezing and thawing is much improved when AE agent is used 80A, although the compressive strength becomes 20 %smaller. When ordinary steel making slag aggregate was used with air content of 7.7 %, the resistance to freezing and thawing was

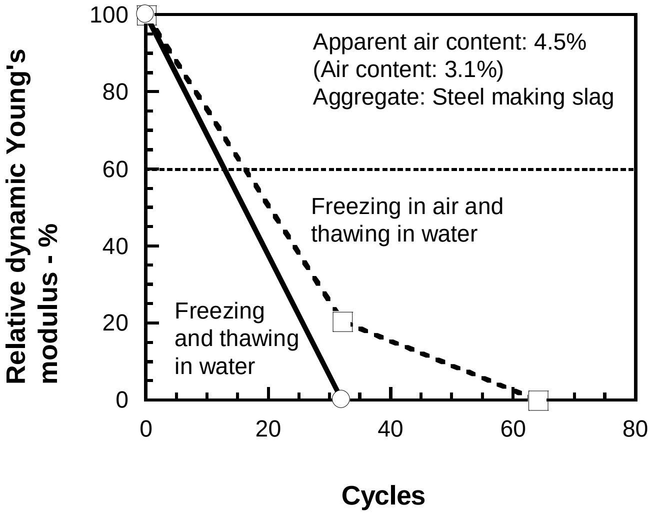

Figure 15. Resistance to freezing and thawing

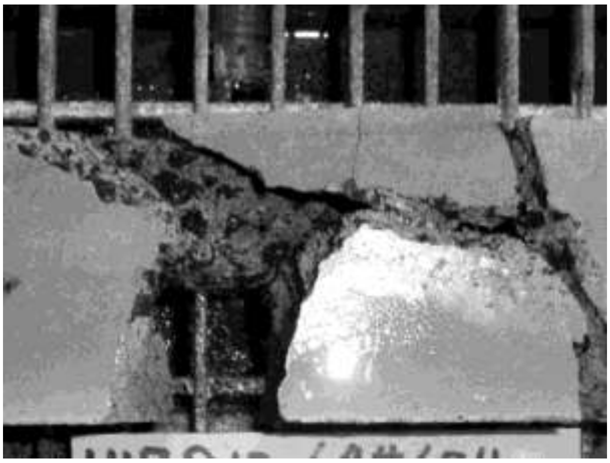

Figure 16. Broken specimen by freezing and thawing

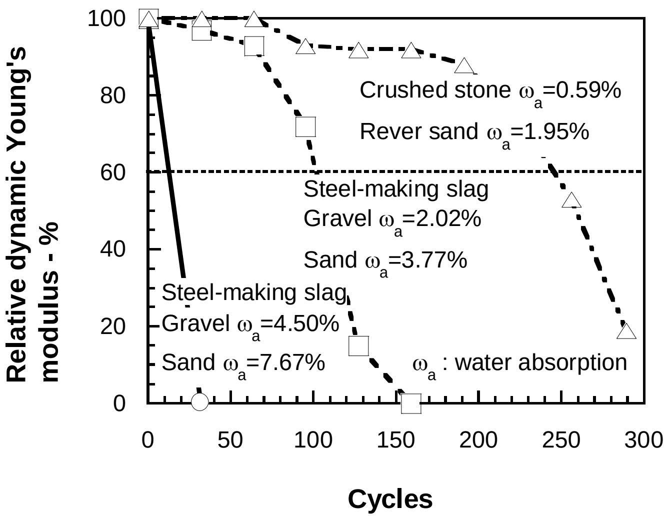

Figure 17. Resistance to freezing and thawing on water absorption of steel-making slag aggregate

very bad as shown in Figure 15. It can be said from these results that the air contained in the steel-making slag concrete with ordinary steel making slag aggregate does not seem to be the entrained air to improve the resistance to freezing and thawing.

Figure 20 shows the effect of cement content on air content. Sand is river sand. Gravel is crushed stone. When river sand and crushed stone is used, concrete without cement can not contain entrained air. However, the more the cement content, the bigger the effect of AE agent on air content.

Figure 21 shows the cement content on resistance to freezing and thawing of steel making slag concrete. Aggregate is ordinary steel making slag. It is clear that the use of cement content improve the resistance to freezing and thawing of steel making slag concrete.

Figure 22 shows the effect of total water content in the steel making slag agregate on the durability factor. Total water content in the steel making slag is calculated from water absorption. Steel making slag was scoured off the weak part by Los Angeles machine in order that water absorption of steel making slag aggregate is reduced. Steel making slag aggregate with several water absorption was made by changing the number of rotations of Los Angeles machine. Durability factor is calculated according to the following equation.

$$Durability\ factor = \frac{P \times N}{300} \qquad (1)$$

Where, P is relative dynamic Young's modulus. N is the number of cycles when relative dynamic Young's modulus reaches P. That is, durability factor

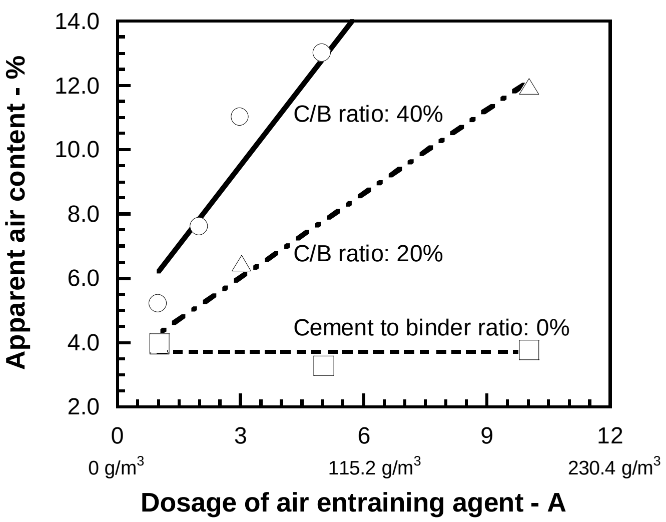

Figure 20. Effect of dosage of AE agent on air content

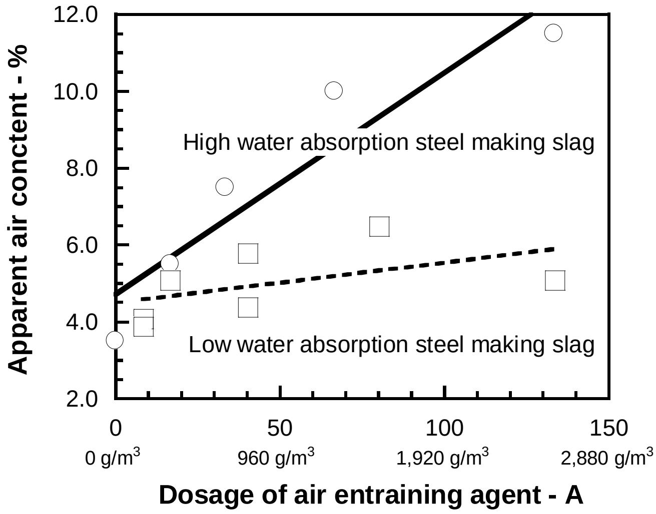

Figure 18. Effect of AE agent on air content

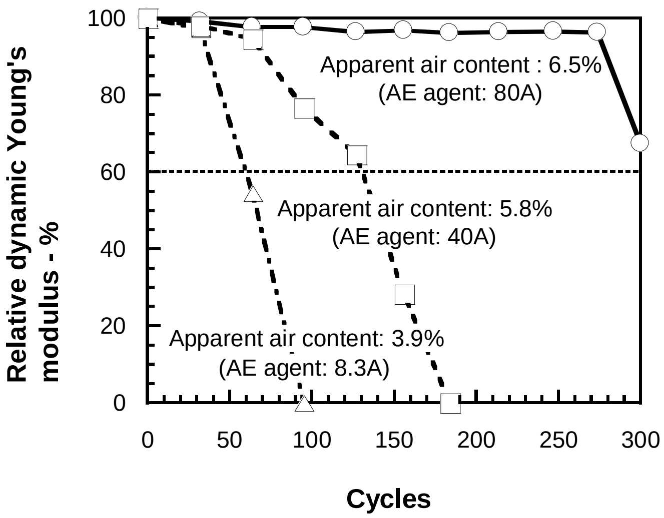

Figure 19. Effect of dosage of AE agent on resistance to freezing and thawing

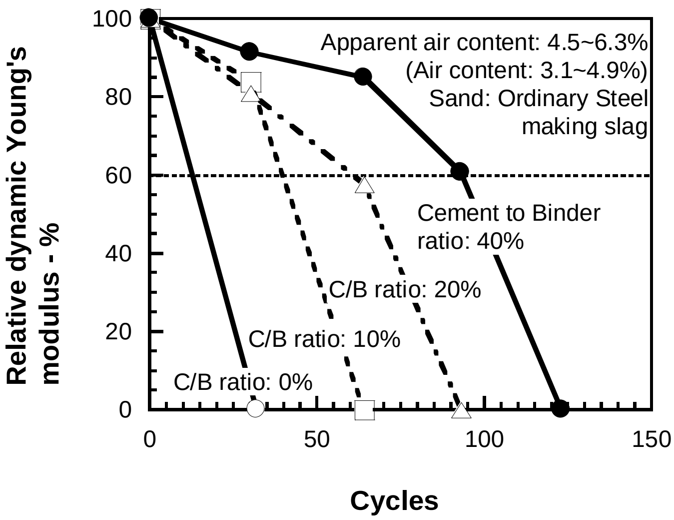

Figure 21. Effect of cement content on resistance to freezing and thawing

is 100 % when relative dynamic Young's modulus is 100 % at 300 cycles. As clear from this figure, the less the total water content in steel making slag aggregate, the higher the durability factor. That is, resistance to freezing and thawing can be improved by the use of steel making slag aggregate with low water absorption. On the other hands, Figure 23 shows the effect of cement content on durability factor. When cement is used the half of binder content, durability factor is 25 %. When the energy to score off the steel making slag is taken into consideration, the cement is useful to improve the resistance to freezing and thawing.

In Figure 24, a part of steel making slag sand (SM slag in this figure) in steel making slag concrete is replaced with blast furnace slag sand (BF slag in this figure). The cement content to binder ratio of every content is 40 %. At 50 % to 50 % in the ratio of steel making slag aggregate and to blust furnace slag sand, the effect of use of blust furnace slag does not appear. However, when only blust furnace slag is used as sand, resistance to freezing and thawing is drastically improved.

Figure 25 shows the multiplier effect of cement content and blast furnace slag sand. Sand of all concrete shown in this figure is blast furnace slag sand. When the cement to binder ratio is 20 %, resistance to freezing and thawing is not good. When the cement to binder ratio is 40 %, the effect of use of blast furnace slag sand appears.

Figure 26 shows the improvement of the resistance to freezing and thawing of steel making slag concrete. In this test, cement to binder ratio is 40%. Fine aggregate is blast furnace slag aggregate and coarse aggregate is steel making slag. A part of

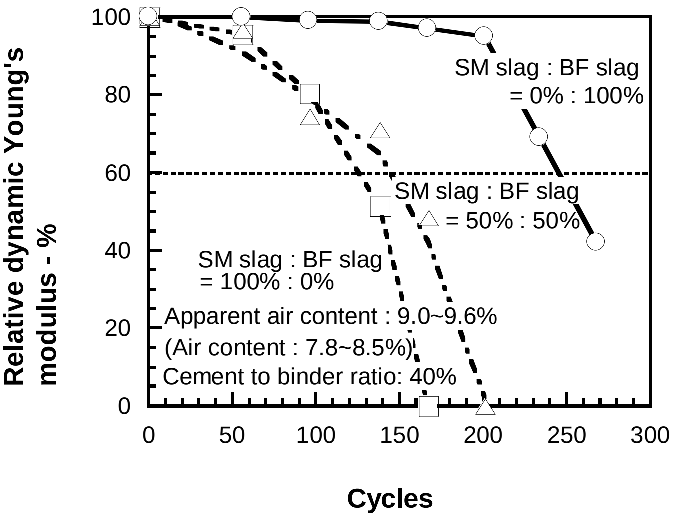

Figure 24. Effect of type of sand on resistance to freezing and thawing

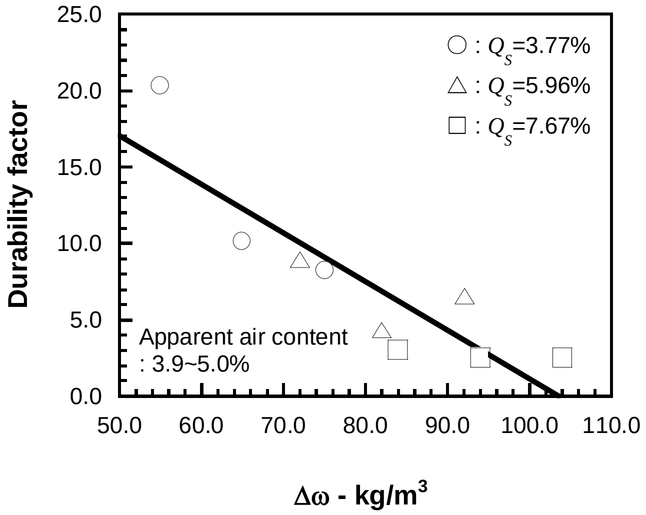

Figure 22. Effect of water absorption on durability factor

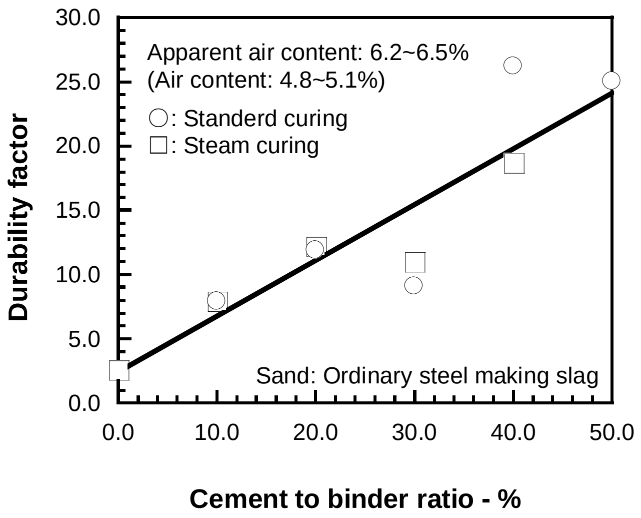

Figure 23. Effect of cement content on durability factor

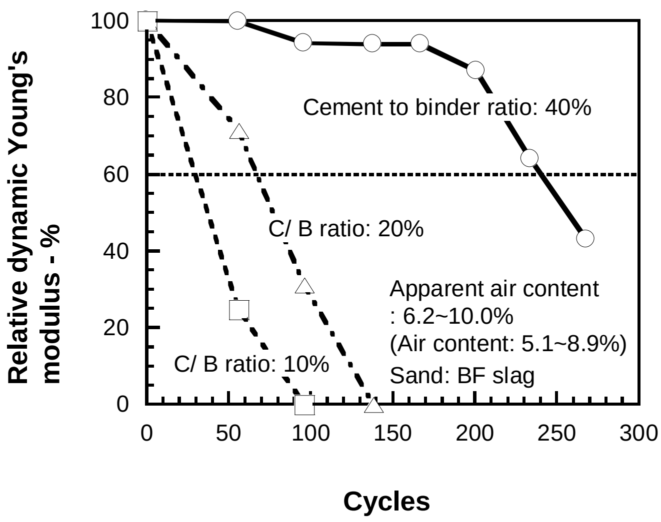

Figure 25. Effect of cement content and type of slag on resistance to freezing and thawing

ground granulated blast furnace slag as binder is replaced with fly ash. As shown in Figure 26, when fly ash binder ratio is 30%, namely cement 40%, fly ash 30% and ground granulated blast furnace slag 30% (Specimen [A]), the resistance to freezing and thawing was improved. However, when fly ash to binder ratio is 60% (Specimen [B]), the resistance to freezing and thawing was not improved.

Figure 27 and 28 show the distribution of air in Specimen [A] and Specimen [B], respectively.

Table 3 is the mixture proportion of the steel making slag concrete improved of resistance to freezing and thawing (Specimen [A]).

4 CONCLUSIONS

The influence of pH of steel making slag concrete just after mix on the compressive is remarkable. The strength of steel making slag concrete develops

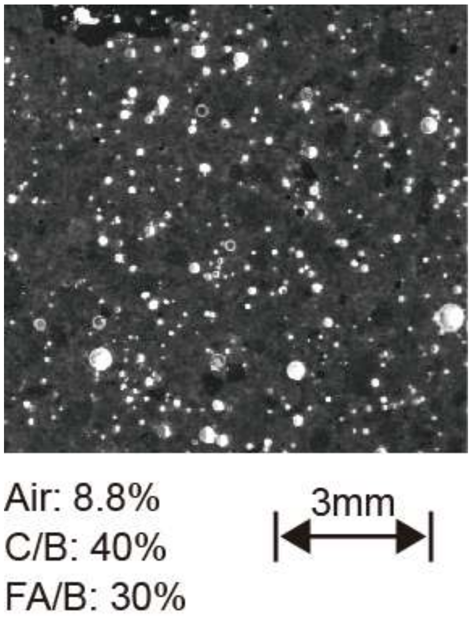

Figure 27. Distribution of air in Specimen [A]

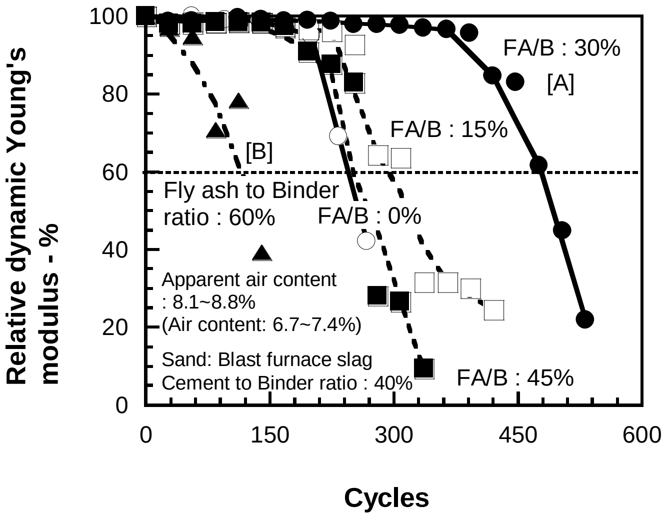

Figure 26. Improvement of resistance to freezing and thawing of hydrated matrix with cement, ground granulated blast furnace slag and fly ash

Table 3. Mixture proportion of durable steel making slag concrete to freezing and thawing action

G_{max} (mm)	W/B (%)	s/a (%)	Air (%)	Unit content (kg/m^3)						Admixture		
				W	Binder			BFS*3	Steel making slag 5-20mm	HRWRA*4 (kg/m^3)	AE*5 (g/m^3)	DF*6 (g/m^3)
					BF*1	C	FA*2					
20	24.9	50.0	6.0±1.5	150	179	240	179	773	836	10.75	345.6	12.8

*1 BF: Ground granulate blast furnace slag *2 FA: Fly ash *3 BFS: Blast furnace slag sand

*4 HRWRA: High range water reduce agent *5 AE: Air entraining agent *6 DF: Deforming agent

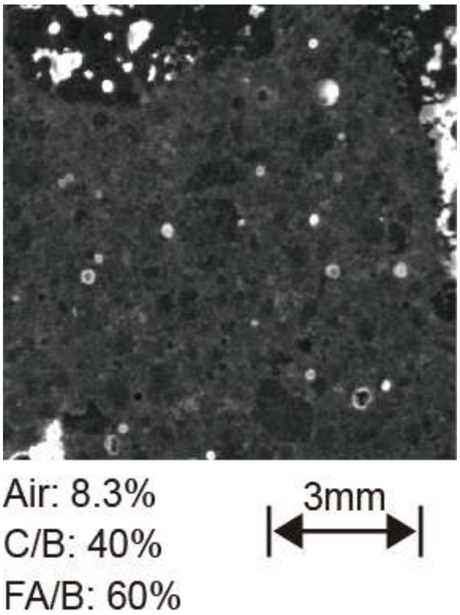

Figure 28. Distribution of air in Specimen [B]

stably when unit alkali activator content is controlled as pH of hydrated matrix after mixing is 12.5 or over. The carbonation rate of steel making slag concrete is lower than that of hydrated matrix with natural aggregate. Furthermore, the rust of steel in steel making slag concrete is also small.

The drying shrinkage of steel making slag concrete is smaller than that of hydrated matrix with natural agregate due to the effect of high rigidity of steel making slag.

The calcium hydroxide leached from steel making slag enhances the performance of steel making slag concrete. The compressive strength of steel making slag concrete develops for longer than the development of compressive strength of hydrated matrix with natural aggregate and cement concrete.

The most serious problem of steel making slagconcrete is low resistance to freezing ang thawing. In this paper, it was shown that use of cement and blust furnace slag sand can improve the resistance to freezing and thawing. It is possible to make the durable steel making slag concrete. In other words, this kind of concrete, steel making slag concrete cannot be used in cold districts.

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