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Utilization of Coal Gasification Slag Collected from IGCC as Fine Aggregate for Concrete

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Abstract

The Integrated coal Gasification Combined Cycle (IGCC) has received a lot of attention in recent years from the viewpoint of reducing CO2 emissions. IGCC is basically different from conventional pulverized coal-fired thermal power generation systems; electricity is generated by a combined cycle using gas turbines and steam turbines. Thus, it is said that IGCC is much more efficient than a conventional coal-fired power plant. In IGCC, the by-product is collected not as coal ash but as coal gasification slag. Coal gasification slag has a tremendous amount of potential for effective use in the field of concrete production because no hazardous material leaches from it and it is simple to handle compared with coal ash.

This paper describes how the aggregate test and concrete test were conducted on coal gasification slag in order to examine whether coal ash slag can be used as a fine aggregate for concrete. The results of these tests showed that concrete made from slag has almost the same compressive strength as concrete in which natural sand is used. In addition, the drying shrinkage rate and freeze-thaw resistance, which are values related to the durability of concrete, of such slag concrete did not show any difference from those of concrete made with natural sand. From these experimental results, it can be concluded that coal gasification slag has a possibility for use in structural concrete.

Keywords: CO_2 emissions, IGCC, effective use, coal gasification slag, fine aggregate

1 Background and objective of research

Current pulverized coal-fired power generation systems emit more CO_2 per unit electric power than systems using other fossil fuels. Thus, improvement in power generation efficiency presents an important challenge. Recently, the Integrated Coal Gasification Combined Cycle (IGCC), which generates electricity by gasifying coal unlike in conventional thermal power generation, has been drawing attention as a high-efficiency coal-fired power generation technology for the 21st century. The introduction and expansion of this system for the medium and long terms are being planned and dedicated efforts have been made to develop the system in Japan [1)].

This system is more efficient than the conventional pulverized coal-fired power generation system and as such, is capable of reducing CO_2 emissions and collects coal after gasification reactions not as coal ash, but as molten slag. Granulation causes molten slag to reduce in volume, changing the granular material into a few millimeters in size. Molten slag elutes no toxic substances unlike coal ash and allows for simplified handling when used. Thus, it is most probable that molten slag will be used effectively in the field of concrete.

This paper investigates the usage possibilities of coal molten slag discharged from the gasifier in the Integrated Coal Gasification Combined Cycle system, as a fine aggregate for concretes by conducting a series of experiments in order to verify such possibilities.

2 Overview of EAGLE and EG slag

2.1 Overview of EAGLE and gasifier

Figure 1 is a display of the overview of the EAGLE (Coal Energy Application for Gas Liquid & Electricity) system that has been newly developed for the efficient use of coal, an example of a coal gasification fuel cell combined cycle system in Japan.

In the coal gasification process, pulverized coal having a diameter of 75 μm or less is used as a fuel and is reacted with oxygen as a gasifying agent under high temperature and pressure to generate gas that is mainly composed of hydrogen and carbon monoxide. The gasified coal is supplied to the gas turbine facility and the fuel cells to generate electricity. The gas after being supplied to the gas turbine facility is recovered by the heat recovery boiler and mixed with steam generated in the gasification facility to generate electricity in the steam turbine.

The EAGLE system features combined cycle generation in which three power generation forms are combined - gas turbine facility, steam turbine, and fuel cells. This advantage allows for an improvement in gross thermal efficiency of about 60% and a reduction in CO_2 emission of about 30%. [2)]

The gasifier (hereinafter referred to as EAGLE furnace), placed in a pressure vessel within the EAGLE system consists of three units including the heat recovery unit, the coal gasification unit and the slag cooling unit.

As shown in Figure 2, upper and lower coal burners are installed in the coal gasification unit that discharges slag directly. Proper allocation of an amount of oxygen among respective burners yields high overall gasification efficiency. The lower part of the gasifier is kept at a high temperature with the lower burner, which allows for the stable gravity flow of molten slag to the slag cooling unit.

2.2 Features of EG slag

The slag that has flowed from the coal gasification unit is water-cooled in the slag cooling unit, passes through the slag crusher and is collected within the slag rock hopper. The slag rock hopper has a mechanism that allows for the discharge of the slag under normal pressure from the under-high-pressure EAGLE furnace.

The EG slag collected within the slag rock hopper is discharged into the slag separation tank as necessary and then reserved in the slag bunker. The Slag discharged from the EAGLE furnace is hereinafter referred to as EG slag.

3 Tests conducted during research

In this paper, basic tests on concrete materials were conducted to ensure the appropriate usage of EG slag as a fine aggregate for concretes as shown below.

(1) Aggregate test:

EG slag was verified for conformance to quality requirements as an aggregate for concretes that are specified in JASS5 (Japanese Architectural Standard Specification defined by the Architectural Institute of Japan) [3)] and JIS (Japanese Industrial Standards). The Alkali-Silica Reaction Test was also conducted.

(2) Concrete test:

As fresh concrete tests, properties such as slump and bleeding were verified using the slag substitution rate, water-cement ratio, and slump as parameters. As hardened concrete tests, a compressive strength test and Young's modulus test were conducted. Durability tests such as the Drying Shrinkage Test and Freeze-Thaw Test were conducted.

4 Aggregate test

4.1 Test overview and EG slag as test object

Various aggregate tests were conducted in order to gain an understanding of the basic physical properties of EG slag as a fine aggregate.

Test items include screening (fineness modulus value), density in oven-dry conditions, water absorption, content of materials finer than 75 μm sieve, bulk density, solid content, solid volume percentage for shape determination, soundness, aggregate crushing value, collapse strength and alkali-silica reaction.

Four types of EG slags manufactured from multiple coking coals (A, B, C, and D) were used for testing.

EG slags that have just been discharged from the EAGLE furnace have an angular shape with poor grain diameter and granular distribution. As such, improvement processing was carried out by grinding and washing.

Grinding treatment was performed on all four types of EG slag. (Numbers in parentheses Table 1 are values after the grinding process.)

Washing treatment was performed only on EG slag A and D after grinding. The slags treated with grinding and washing are EG slag A+ and D+, respectively.

Picture 1 shows unprocessed EG slags that have just been discharged from the EAGLE furnace.

In the pictures, unprocessed slags discharged from the EAGLE furnace have sharply-angulated edges with a glassy and glossy surface. These are typical characteristics of a granulated slag.

Picture 2 shows pictures of EG slag before and after grinding treatment. It is confirmed that grinding treatment removes angled portions from EG slags and provides a smooth shape.

4.2 Aggregate test results and consideration

Overall results of aggregate testing are shown in Table 1.

Grinding treatment was performed on all four types of EG slag. Physical property values after grinding treatment are shown in parenthesis under physical property values in Table 1.

A before-and-after test was conducted on changes in physical properties of EG slags A+ and D+, which were simultaneously treated with grinding and washing.

The slags discharged from the furnace and not treated with grinding showed significant variation in physical properties such as in density in oven-dry conditions and water absorption. As such, they proved not to be within the specifications defined in JIS A 5005(Japanese Industrial Standards for an aggregate for concretes).

Figure 3 shows the granular distributions of EG slag. For granular distribution, unprocessed slags discharged from furnace are out of specs (area shown with dotted line) as shown in Figure 3. Grinding brings slags within specifications indicated by the dotted line in the figure. It has been found that unprocessed slags discharged from the furnace can be used effectively as an aggregate for concretes after being treated with grinding and washing.

For alkali-silica reactivity, any of these slags proved to be harmless in JIS A 1145 (chemical test) and JIS A 1146 (mortar-bar test)

5 Concrete test

5.1 Test overview

(1) Material used

The materials used in tests are listed in Table 2. With regard to EG slags, a slag manufactured in the EAGLE furnace was treated with grinding and washing to improve its grain level and grain shape. The processed slag, which has been improved in grain size and grain shape to as A+ slag, was used as a fine aggregate. Land sand from Oigawa was used as fine aggregates to be mixed with slag.

(2) Test factor, level and proportion

Table 3 shows test factors and levels. The water-cement ratio (hereinafter referred to as W/C) levels were: 60, 50, and 40%. When W/C was 50%, there were five slag substitution rate (volume ratio of EG slag fine aggregates to all fine aggregate amounts) levels of 0, 25, 50, 75, and 100%. When W/C was 40% or 60%, there were three levels of 0, 50, and 100%. Table 4 shows a proportion table.

5.2 Test method

Table 5 shows test items and test methods. Standard curing was applied to test pieces until they were specified of material ages. For compressive strength and drying shrinkage tests, test pieces were tested after they were cured for 1 week, 4 weeks, 13 weeks, 27 weeks, and 1 year. For Young's Modulus, measurement was conducted after they were cured for 4 weeks and one year.

After applying standard curing for 7 days after demolding, test pieces were cured in a steady temperature and humidity room at a temperature of 20±2ºC and humidity of 60±5% until they were test material age, before conducting the Drying Shrinkage Test.

5.3 Test results

(1) Compressive strength test

Figure 4 shows the relationship between the slag substitution rate and the compressive strength of material ages.

An increase in slag substitution rate caused little change in the compressive strength from that of unsubstituted slags until the material is 28 days old. Although strength increased until the material is 182 days old, there was little increase in strength when material age was 182 to 365 days old. One feature was that the strength increased as the slag substitution rate increased when the material was 91 days old or older. This was ascribable to the increased adhesion on slag surface due to the pozzolanic reaction that occurred at the boundary between EG slag and cement paste.

(2) Young's modulus

Figure 5 shows the relationship between compressive strength and Young's Modulus.

The value calculated from the representative Young's modulus formula in Japan (Japanese Architectural Standard Specification: JASS5) is shown with a solid line in the figure. Young's Modulus value of one-year-old material was confirmed to be higher than that of 28-day-old material. Although the values were higher than that of JASS5 on the whole, the correlation between compressive strength and Young's modulus were favorable.

(3) Drying Shrinkage Test

Figure 6 shows the results of the drying shrinkage test.

The rate of length change showed little changes and remained stable after the material was 91 days old. For difference in slag substitution rate, length change was a little smaller than that of concrete using natural fine aggregates (substitution rate is 0). 6-month-old material had a length change rate of 6 to 7×10^{-4}% and satisfied a target length change rate of 8×10^{-4}% or less specified in JASS5.

(4) Freeze-Thaw Test

Figure 7 shows the results of freeze-thaw test.

The results showed a tendency in which the increase in the slag substitution rate caused a decrease in the relative dynamic modulus of elasticity and durability. However, the material had a relative dynamic modulus of elasticity of 89% after 300 cycles even when the slag substitution rate was 100%, indicating sufficient reeve-thaw resistance.

6 Summary

The results overview obtained during research are as follows.

(1) Before using EG slag manufactured from an EAGLE furnace as a fine aggregate for concretes, it is necessary to reform the slag with grinding or washing.

(2) Until the material is 28 days old, an increase in slag substitution rate causes little change in the compressive strength from that of unsubstituted slag. One feature is that strength increases as the slag substitution rate increases when the material is 91 days old or older.

(3) The freeze-thaw resistance of concrete added with EG slags is smaller than that of the natural fine aggregates used in this test but is within the tolerance.

According to the above test results, the EG slag fine aggregate and concrete mixed with it indicate almost the same results as with natural fine aggregates. Thus, it was confirmed that the use as a fine aggregate for concretes is adequate and possible. However, with regard to long term concrete durability and aggregate elution characteristics, further verification is necessary.

References

[1] Yoshitaka Ishibashi, and others: Integrated Gasification Combined Cycle, thermal and nuclear power generation, pp.403-404, 2001.10

[2] Masao Tonooka: Current status and future development of Coal Energy Application for Gas Liquid & Electricity (EAGLE) for fuel cells, lecture documents of annual meeting held by Japan Society Of Mechanical Engineers, pp.117-118, 2004

[3] Architectural Institute of Japan: Japanese Architectural Standard Specification and Explanation -JASS5 - Reinforced Concrete Construction, 2009

Table 1: Aggregate test results

Test item		Test method	EG slag						Standard value (JIS A 5005)
			A	A+	B	C	D	D+	
Screening (fineness modulus)		JIS A 1102:2006	3.64 (2.79)	2.64	3.60 (3.00)	3.98 (3.42)	3.68 (2.35)	2.64	Within standard range
Density in oven-dry conditions	[g/cm^3]	JIS A 1109:2006	2.74 (2.70)	2.78	3.06 (3.04)	2.49 (2.52)	2.75 (2.62)	2.78	2.5 or more
Water absorption	[%]	JIS A 1109:2006	1.32 (0.93)	0.60	0.70 (0.77)	0.46 (0.71)	1.69 (3.69)	1.68	3.0 or less
Content of materials finer than 75 μm sieve	[%]	JIS A 1103:2006	2.44 (9.46)	3.53	1.14 (5.16)	0.40 (4.40)	3.09 (15.65)	4.86	7.0 or less
Bulk density	[kg/ℓ]	JIS A 1104:2006	1.74 (1.89)	1.97	1.89 (2.19)	1.487 (1.81)	1.731 (2.04)	-	-
Solid content	[%]	JIS A 1104:2006	63.4 (69.8)	70.8	61.7 (72.1)	59.8 (71.9)	62.9 (77.7)	-	-
Solid volume percentage for shape determination	[%]	JIS A 5005:2009	56.8 (63.8)	62.2	57.7 (63.5)	55.4 (60.8)	58.3 (67.6)	-	53 or more
Soundness	[%]	JIS A 1122:2005	0.75	-	0.79	2.78	4.04	-	10 or less
Aggregate crushing value	[%]	BS method	24.7 (15.4)	-	23.34 (16.3)	(13.7)	(17.6)		-
Alkali-silica reaction		JIS A 1145:2007	Harm-less		Harm-less	Harm-less	Harm-less		
		JIS A 1146:2007	Harm-less		Harm-less	Harm-less	Harm-less		

Values in lower parentheses are physical properties after grinding. Slag A+ and D+ are ground slag A and D treated with washing.

Table 2: List of materials used

Material	Type	Symbol	Specifications
Cement	Normal Portland cement	C	Density: 3.16 g/cm^3
Fine aggregate	EG slag	Sg	Treated with grinding and washing Density in oven-dry condition: 2.78 g/cm^3, water absorption: 0.60%
	Land sand	S	Oigawa sand Density in oven-dry condition: 2.60 g/cm^3, water absorption: 1.02%
Coarse aggregate	Crushed stone	G	Oume tight sand Density in oven-dry condition: 2.70 g/cm^3, water absorption: 0.44%
Chemical admixture	Air entraining and water reducing agent	Ad1	Lignin sulfonic acid
	AE agent	Ad2	Alkyl ether
Mixing water	Tap wate	W	

Table 3: Factors and levels

Factors and levels						Conditions		
W/C	Slag substitution rate					Slump (cm)	Air content (%)	Ambient temperature (°C)
	0	25	50	75	100			
60	○	—	○	—	○	18±1.5	4.5±1.0	20
50	○	○	○	○	○			
40	○	—	○	—	○			

Table 4: Proportion table of concrete test

Proportion name	Unit quantity [kg/m^3]						
	Water	Cement	Fine aggregate		Coarse aggregate	Admixture	
	W	C	Sg	S	G	Ad1	Ad2
60-N-0	173	288	0	890	954	0.721	0.003
60-N-50	168	280	479	450	965	0.700	0.058
60-N-100	163	272	968	0	975	0.679	0.100
50-N-0	175	350	0	827	961	0.875	0.003
50-N-50	170	340	446	418	972	0.850	0.064
50-N-100	165	330	902	0	984	0.825	0.104
40-N-0	177	443	0	755	950	1.106	0.006
40-N-50	172	430	407	383	964	1.075	0.100
40-N-100	167	418	826	0	977	1.044	0.167

Proportion No. is represented with the water-cement ratio, cement type, and slag substitution rate (%).

Table 5: Test items and test methods

Test item	Test method	Material age	Remarks
Fresh properties	—		See previous report (4).
Compressive strength	JIS A 1108: 1999	Material ages: 7, 28, 91, 182, and 365 days old	
Young's Modulus	JIS A 1149: 2001	Material age: 28 and 365 days old	
Drying shrinkage	In conformity to JIS A 1129: 2001	Measurement material ages: 7, 28, 91, 182, and 365 days ol	
Freeze-thaw	In conformity to JIS A 1148: 2001	300 cycles	

Figure 1: Overview of EAGLE system

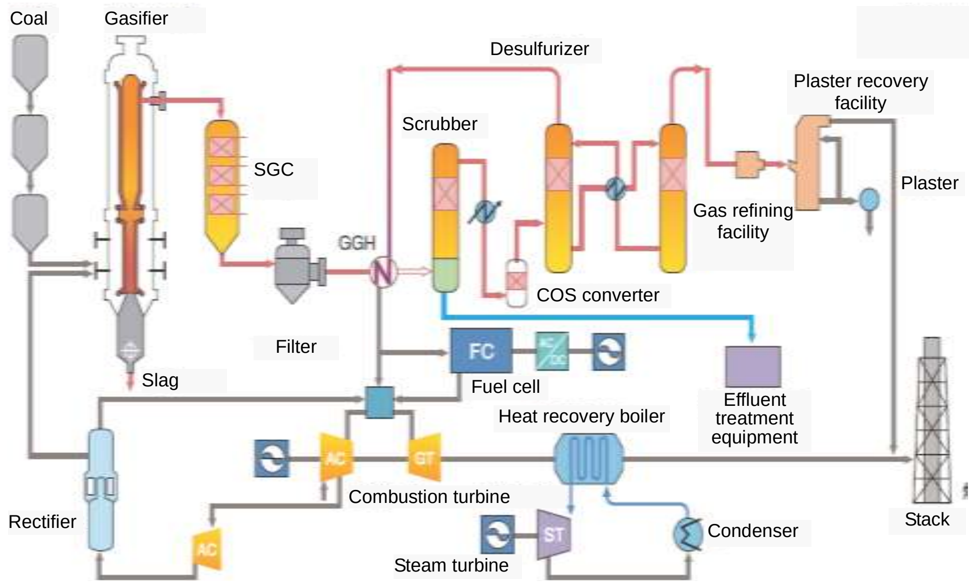


Figure 2: Structure of coal gasification unit

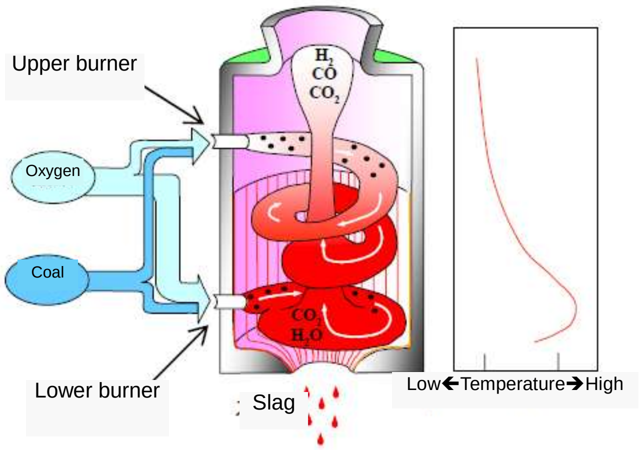


Figure 3: Granular distributions of EG slags (A and A+)

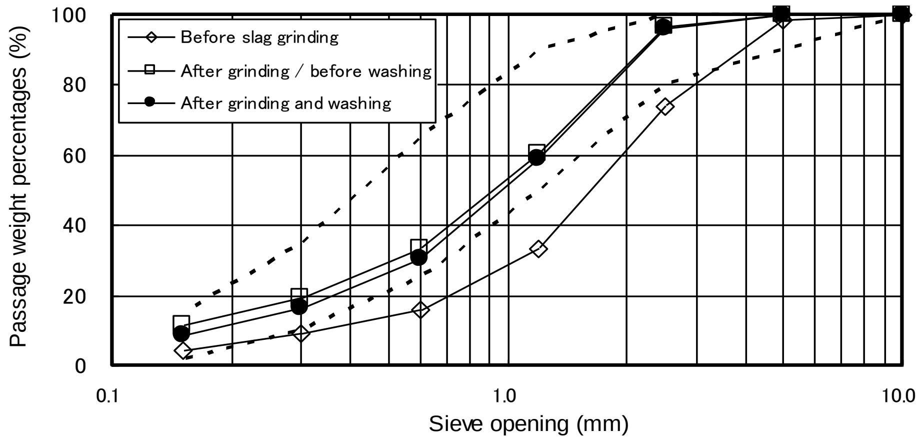


Figure 4: Relationship between slag substitution rate and compressive strength

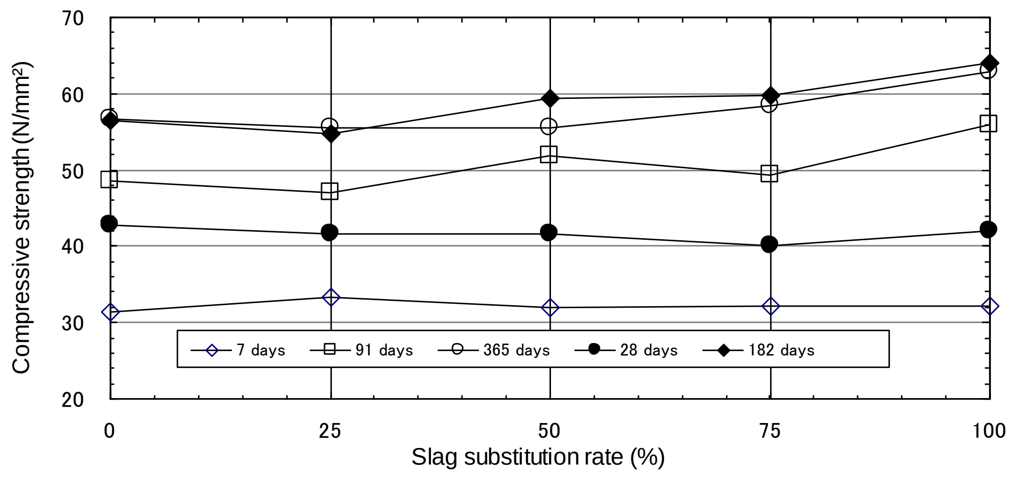


Figure 5: Relationship between compressive strength and Young's modulus

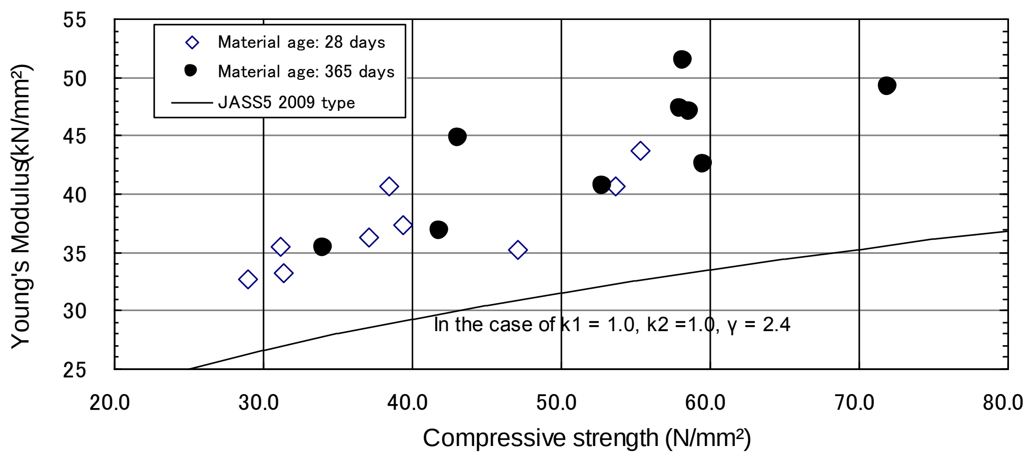


Figure 6: Drying shrinkage test results

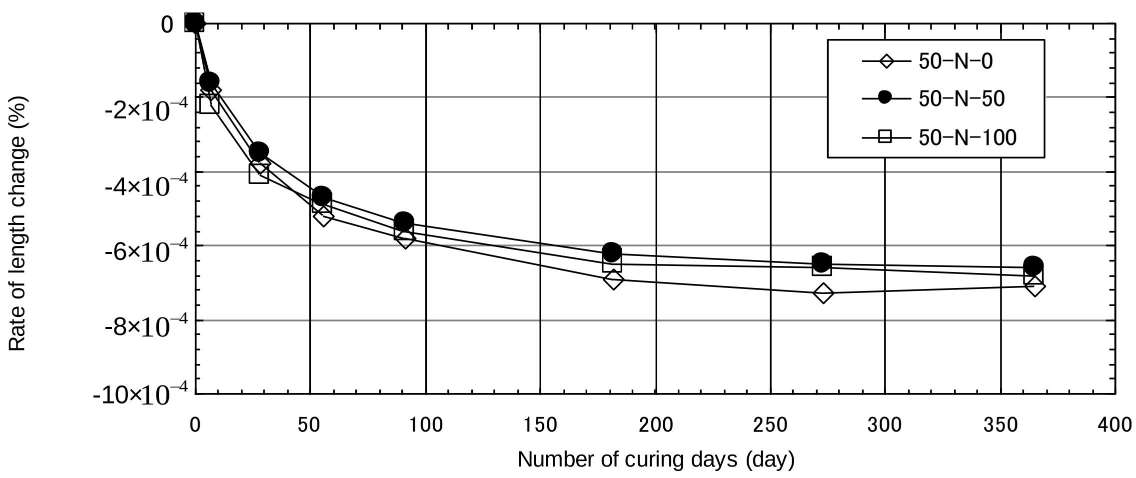
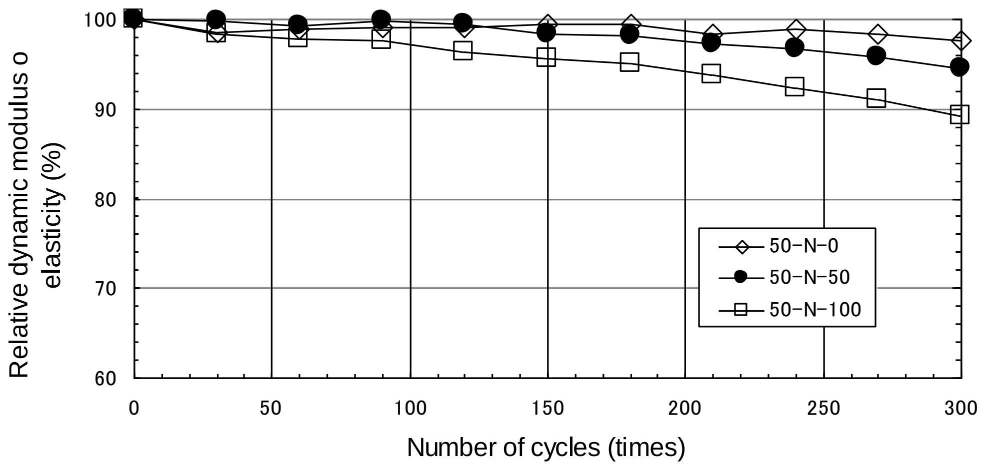
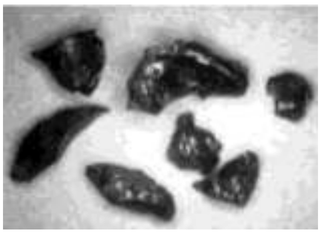


Figure 7: Freeze-thaw test results



Picture 1: Example of EG slags discharged from the EAGLE



Complete view

Closeup

Picture 2: EG slag shape after grinding treatment

Before grinding treatment

After grinding treatment