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State of the Art in the Technology of Using Blast Furnace Slag Gravel for Concrete Members

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Abstract

More than twenty years has already passed since the establishment of JIS for blast furnace slag gravel. However, the annual quantity of use accounts for only 1.5 million tons because of the very few examples of big construction projects. On the other hand, the needs for recycling and saving construction materials have been highlighted recently because of the serious shortages of new natural resources. This report introduces two examples of experimental uses of blast furnace slag gravel in current technological developments. One use is as an aggregate for underground concrete tank-pit in the construction of an LNG facility. The technical method explained keeps the pumpability of fresh concrete mixed with blast furnace slag gravel. It also focuses on the evaluation of the strength of slag grave in extremely low temperatures. The other example deals with the effective use of blast furnace slag gravel as a fine aggregate by mixing it with natural sand. The study explains the measures for an adequate delay in the hardening of a fine slag aggregate after air-cooling. Moreover, an effective method is proposed in mixture of a fine slag aggregate and natural sand.

1. Introduction

Blast furnace slag is produced as a by-product in the process of pig iron production in a blast furnace at a rate of about 300 kg per ton of pig iron, thereby amounting to over 23 million tons in total annual production domestically[1]. As **Fig. 1** shows, blast furnace slag is classified into two categories: one being an air-cooled category, produced by discharging molten slag into a pit or yard, and the other being a granulated category produced by blowing water into molten slag. The former looks like crushed stones while the latter is sandy. Coarse blast furnace slag gravel, used for concrete as an aggregate, is produced by crushing air-cooled slag and adjusting its particle size, while fine slag is produced by adjusting the particle size of granulated slag.

The technology for using blast furnace slag gravel (both coarse and fine ones) for cement has been developed since the 1970's, accompanied by JIS A 5011 in 1977 and JIS A 5012 in 1981, wherein both "Coarse blast furnace slag gravel for cement" and "Fine blast furnace slag gravel for cement" were specified, respectively. Two kinds of blast furnace slag were later integrated into "Blast furnace slag gravel in Part of Slag Gravel for Cement, JIS A 5011-1". In 1980, 3.51 million tons of blast furnace slag gravel were used throughout the country. Its use, however, continued to decrease, subsequently,

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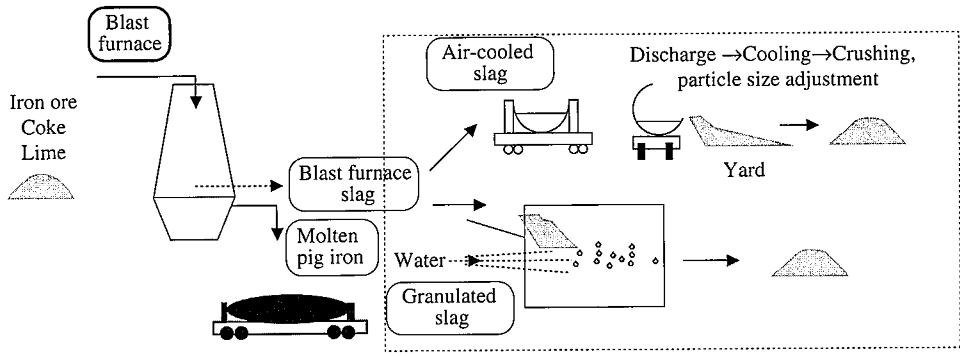

Fig. 1 Blast furnace slag production flowchart

where at one time it reached nearly 1 million tons, annually. However, thanks to a growing demand for recycling in response to movements to protect the environment, as seen, for instance, in the regulations on the collection of sea sand, and to the rapid depletion of our natural resources, the expectation of the expanded use of blast furnace slag resulted in an increase to approximately 1.5 million tons in fiscal 2000.

This paper introduces the efforts being made to expand upon current developments and to accumulate technologies relative to the recent utilization of blast furnace slag gravel by referring to the examples of its application in a large-scale underground LNG tank and to the study of a technology of utilizing blast furnace slage as a substitute for natural sand.

2. Technology of using coarse slag aggregate

2.1 Problems posed for the application of blast furnace slag aggregate to an underground LNG tank

In its expansion works now under way since May, 1998, Futtsu Thermal Power Plant, Tokyo Electric Power Co. is trying to use crushed slag for a coarse concrete aggregate, used for an underground LNG tank and a discharge canal, as a substitute for natural crushed stones for the purposes of cost reduction and effective utilization of resources[2-4]. As **Photo 1** shows, two underground LNG tanks, 73.5 m in diameter, 43.6 m in height, and 125 thousand kl in capacity, are to be constructed, with a 6.0-m-thick bottom plate, and a 1.8-m-thick side wall. The total concrete volume amounts to as much as 82,000 m^3, out of which some 41 thousand tons of coarse blast furnace slag aggregate are used.

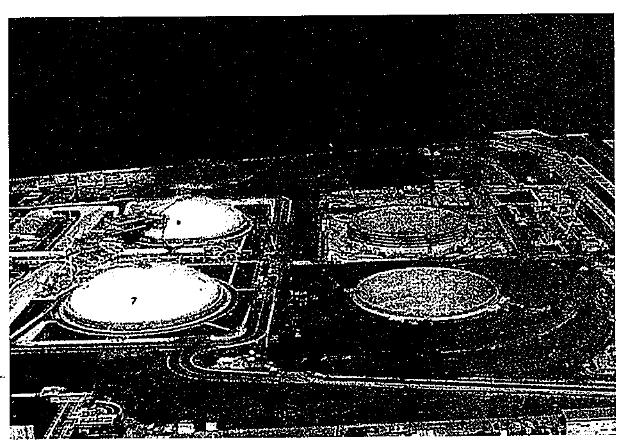

Photo 1 Underground LNG tank under construction

Before using coarse blast furnace slag aggregate for this underground concrete LNG tank, two problems, relating to its porosity and high water absorption, were posed for discussion, shown below.

1) Confirmation of concrete pumpability and formulation of countermeasures

Concrete pumping at high pressure becomes necessary for pumping concrete in the bottom plate construction works of the underground LNG tank because of a long piping extending to about 150 m. It is feared, therefore, that blast furnace slag aggregate absorbs water in the concrete, thereby blocking the piping because of a decline in concrete fluidity. This makes it necessary to study a component material and blending of concrete to avoid the blocking of pipes while pumping concrete.

2) Evaluation of cryogenic strength of concrete mixed with blast furnace slag aggregate

Concrete used for the bottom plate and side wall of the underground LNG tank is exposed to very low temperatures of approximately −70°C when liquefied natural gas is stored therein. These temperatures, however, are raised to nearly normal temperatures when the tank is opened for inspection during its service periods. Then, the concrete is subjected to a great temperature change of freeze-melting[5]. Generally, when a porous aggregate is used for the concrete that undergoes freeze-melting, the aggregate absorbs so much water that it swells when frozen again. This is likely to lead to the concrete cracking. Because of its porosity and high water absorption in comparison with natural aggregate, blast furnace slag aggregate is susceptible to freeze-melting, making it inevitable to confirm its durability when using it for concrete.

Therefore, the influence of mixing blast furnace slag aggregate in concrete was studied on the basis of the test in which comparison was made between two kinds of concrete with each using coarse blast furnace slag aggregate and natural coarse aggregate.

2.2 Influence of blast furnace slag aggregate on pressurized pumping

A pressurized pumping test was carried out to evaluate the influence of water absorption of blast furnace slag aggregate during pressurized pumping on concrete casting. **Table 1** shows the materials used and **Table 2** gives blending conditions. GS-0 in Table 2 is a kind of concrete composed completely of coarse natural aggregate, GS-50, having coarse blast furnace slag aggregate and coarse natural aggregate mixed at a ratio of 50 to 50, and GS-100, composed completely of coarse blast furnace slag aggregate.

As **Photo 2** shows, the test was carried out by casting concrete

Table 2 Blending of concrete used for tests

Symbol	W/C	s/a	Designed value			Unit volume (kg/m^3)					
			f' ck (28)	Slump	Air volume	Water	Cement	Fine aggregate	Coarse aggregate G		Admixture
	(%)	(%)	(N/mm^2)	(cm)	(%)	W	C	S	Natural	Slag	AD
GS-0		42		12		159	289	758	1,104	–	0.723
GS-50	55	45	24	± 2.5	4.5	159	289	808	520	492	0.723
GS-100		47		15	± 1.5	170	310	821	–	921	0.775

Table 1 Materials used

Material item	Materials used	Quality
Cement	Blast furnace cement, grade B	Density : 3.04g /cm^3 Specific surface area : 3,990 cm^2/g
Fine aggregate	Fine natural sand	Density in saturated surface-dried condition : 2.60g /cm^3 Water absorption : 1.70% Fineness modulus : 2.73
Coarse aggregate	Crushed limestone	Density in saturated surface-dried condition : 2.71g/cm^3 Water absorption : 0.71% Maximum particle diameter : 20mm
	Crushed blast furnace slag	Density in saturated surface-dried condition : 2.58g/cm^3 Water absorption : 2.68% Maximum particle diameter : 20mm
Admixture	AE water-reducing agent	Standard type (I)

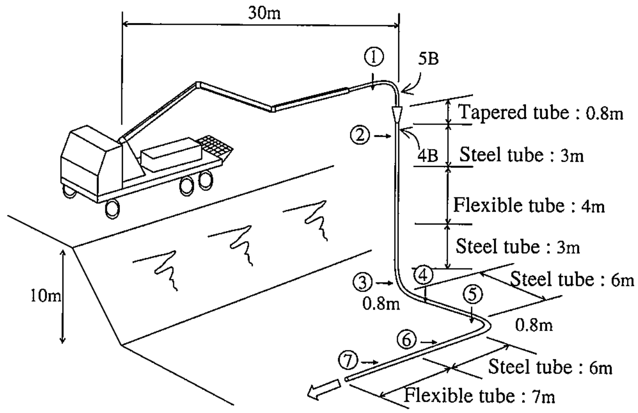

Fig. 2 Outline of pressurized pumping test

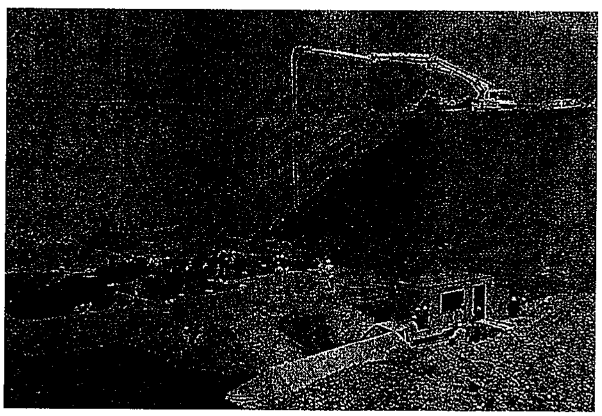

Photo 2 Pressurized pumping test conditions

from the fill-up ground about 10 m high into a piping 62 m in total length where pumpability changes can be found by measuring the pressure inside the pipe at 7 places. **Fig. 2** shows in line with the measurement of a slump and an air volume before and after pressurized pumping.

As a result of pressurized pumping, GS-0 and GS-50 could be cast smoothly without blocking the piping, whereas GS-100 blocked the piping at a tapered part as shown ② in Fig. 2, despite a fluidity rendered higher than others with a slump of 15 cm. If the cause is attributable to the absorption of water by coarse blast furnace slag aggregate, phenomena should be observed wherein there is an increase of pressure inside the pipe because of declined fluidity or declined slump after pressurized pumping. However, no significant difference can be found between the formulations of GS-100 and the other two, as evidenced in the changes of pressure inside pumping as

Table 3 Changes in concrete quality before and after pressurized pumping

Symbol	Before pressurized pumping			After pressurized pumping		
	Slump	Air volume	Compression strengt	Slump	Air volume	Compression strengt
	(cm)	(%)	(N/mm^2)	(cm)	(%)	(N/mm^2)
GS-0	10.5	5.2	31.3	10.5	5.9	29.1
GS-50	8.0	5.1	27.1	9.0	6.0	27.0
GS-100	16.0	5.0	26.4	14.5	4.6	25.0

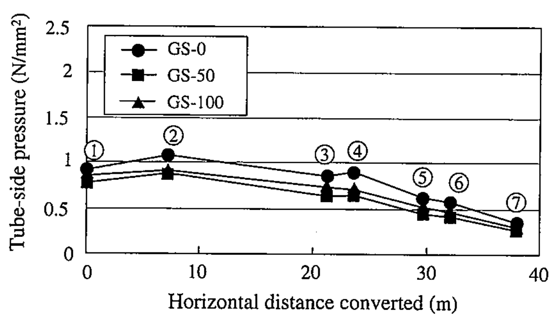

Fig. 3 Results of measurement of tube-side pressure

Table 3 shows. This indicates that the pipe was blocked not only by the pipe, as **Fig. 3** shows, or changes in slump before and after pressurized absorption of water by coarse blast furnace slag aggregate but also by the influence of blocking of the aggregate inside the pipe because of the form and the coarseness of coarse blast furnace slag aggregate.

Based on the findings of this test, it was decided to use a kind of concrete with a coarse blast furnace slag aggregate and a coarse natural aggregate mixed at a ratio of 50 to 50 for the construction of this LNG tank for maintaining workability.

2.3 Freeze-melting property of concrete for which coarse blast furnace slag aggregate is used

Since open inspection is expected of this underground LNG tank at least 5 times during its service period of 50 years, it was decided to conduct a freeze-melting test on the assumption that the temperature of concrete will undergo five cycles from a very low temperature of –70°C to normal temperatures of +16°C. **Table 4** shows the blending conditions. It is to be noted that in this test, a freeze-melting test was conducted in the following manner using trinity cement having a fly ash mixed:

1) A sample (10cm × 10cm × 40cm), cured in water until 28 days of its material age, was put in a steel vessel, which was then immersed in a solution tank of denatured alcohol at the normal temperature of 16°C.
2) Liquefied nitrogen was poured in until the denatured alcohol in the solution tank was cooled down to –70°C, and the sample was kept in that state for a certain amount of time from when it was cooled to –70°C.
3) After that time had passed, the steel vessel was taken out and was left standing until the temperature of the sample returned to normal (16°C).
4) The above procedure was counted as one cycle, and repeated five times. The dynamic elastic modulus of the sample was meas-ured at the 1st, 3rd, and 5th cycles.

Fig. 4 shows the finding of the test. The findings clearly show that although the dynamic elastic modulus decreased to about 75% due to the influence of freeze-melting with a temperature difference of about 90°C, almost no difference was observed between MBF in which coarse blast furnace slag aggregate is mixed by 50% and MBF-0 composed of natural aggregate alone. Accordingly, it was clarified that in the freeze-melting accompanied by the changes in temperature from a cryogenic state to a normal state, coarse blast furnace slag aggregate mixed experienced no adverse effects only if it was mixed to the extent of 50% in volume.

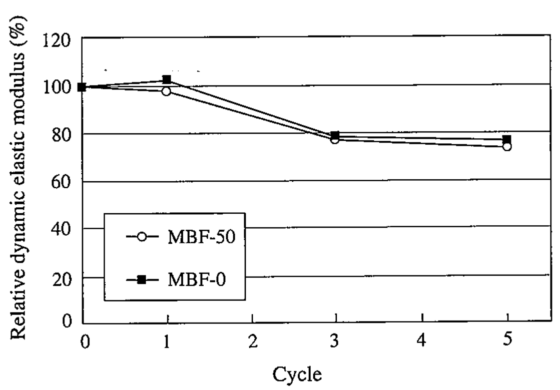

Fig. 4 Results of freeze-melting test at cryogenic temperature

2.4 Conclusion

By taking a series of steps as above-described, it was revealed that if only coarse blast furnace slag aggregate is mixed in concrete with less than 50% of the total volume, the concrete acts in the same manner as the one composed completely of natural aggregate in pressurized pumping and in freeze-melting properties at a very low temperatures.

3. Technology of using coarse aggregate

3.1 Problems posed when blast furnace slag is used for fine concrete aggregate

Fine blast furnace slag aggregate is produced mostly by the front-furnace method in which molten blast furnace slag, separated by specific gravity, is granulated on the operation floor after the production of pig iron in the blast furnace. However, it is also produced by the out-of-furnace method in part of the factories in which molten slag is placed in a ladle, transported to an exclusive plant where it is granulated. Fine blast furnace slag aggregate, thus produced, consists of needle-like granules with latent hydraulic properties. To use it, the following two problems remain to be solved:

1) Development of technology of retarding hardening during storage

Because of the latent hydraulic properties, fine blast furnace slag aggregate hardens sometimes depending on its storage conditions. Most of the complaints against it from users are related to its hardening qualities. Therefore, it is necessary to find out a simple method of preventing hardening.

2) Establishment of concrete utilization technology

Fine blast furnace slag aggregate, with a vitreous surface, is in bad shape. When used for cement, it has an adverse effect on cement[6]. For example, there is an increase in unit water volume and bleeding. This makes it necessary to establish a technology to use it in the same manner as a natural material by the method of making the most of its features and by accumulating technical data.

Hereinafter is a discussion of efforts taken to resolve this situation.

3.2 Technology of retarding hardening

3.2.1 Grasping of hardening phenomenon

To understand the phenomenon relating to the hardening of fine blast furnace slag aggregate, samples with each differing in surface water rate were packed in a cyclindrical vessel, 10 cm in diameter and 20 cm in height, and subjected to the changes in atmospheric temperature so that changes in hardening over time could be investigated. Hardening was then evaluated with a Proctor penetration resistance tester used for the concrete setting test. **Fig. 5** shows one example of a sample with a surface water rate of 4%. The figure indicates that hardening is accelerated, because time becomes shorter before penetration resistance begins to increase when atmospheric temperature is higher. A hardened part was observed in a sample

Table 4 Blending conditions for freeze-melting test

Blending No	f' ck(91) (N/mm²)	Slump (cm)	W/C (%)	s /a (%)	Air volume (%)	Unit volume (kg/m³) Water	Cement	Fine aggregate	Coarse aggregate Natural	Slag	Admixture
MBF-50	24	15	55.0	48.0	4.5	158	285	868	491	467	0.712
MBF-0		±2.5		45.0	±1.5	149	270	828	1,060	–	0.738

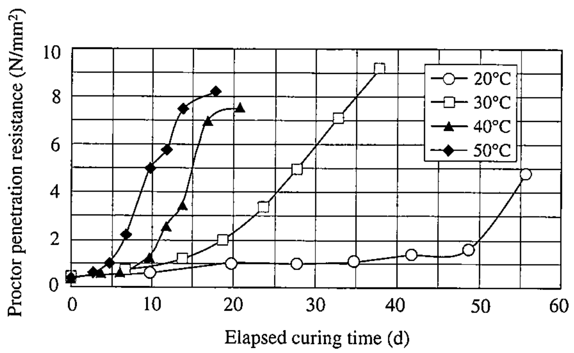

Fig. 5 Influence of curing temperature on granulation hardening

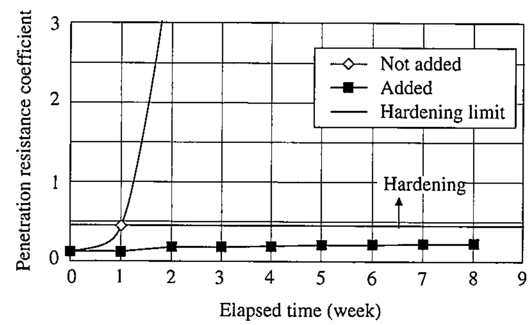

Fig. 6 Effect of hardening retarder at actual field test

when a penetration resistance value slightly exceeded 1.5 N/mm². In a similar manner, tests were conducted by changing surface water rates and by applying a sustained load. However, no significant influence was observed in either case. Atmospheric temperature was thus found to have a greater influence on hardening. This supports an empirical fact that the hardening phenomenon in the actual field tends to occur in the summer.

3.2.2 Development of a technology of retarding hardening

It is known by analogy that lowering temperature is effective for retarding the hardening of fine blast furnace slag aggregate. However, this is not realistic based on the facts that products are stored in a big pile and that it is difficult to request the user to control temperature after shipment. Therefore, it was decided to spray chemicals that will retard hardening as a countermeasure.

A slag hydrate yields ettringite when it contains sulfates, and C-S-H, C_2ASH_8, C_4AH_X and hydrotalcite with a low C/S ratio when it contains no sulfate[7-9]. If fine blast furnace slag aggregate is considered hardened with those hydrates, a setting retarder of cement that cures by hydration in a similar manner can be assumed to be effective for retarding hardening. Accordingly, chemicals among cement setting retarders were selected after due consideration to cost and to their effects on the environment. Their effects were evaluated. **Table 5** shows the findings. The findings revealed that all of them are effective for retarding hardening except for D-2, a polysaccharide, and E-1, an inorganic substance. Particularly worth noting is that A-1, a monoxycarboxylate containing Na, was effective even with a small addition of 0.015%, and found optimal in terms of cost.

Table 5 Results of tests of evaluation of hardening retarders

Symbol	Classification	Addition quantity (%)	Proctor penetration resistance (N/mm²)				
			0d	7d	14d	28d	40d
N	Not added	–	0.2	0.6	3.0	9.0	13.0
A-1	Monoxycarboxylate	0.015	0.2	0.2	0.2	0.2	0.4
		0.030	0.2	0.2	0.2	0.2	0.3
A-2	Monoxycarboxylate	0.030	0.2	0.2	0.2	0.2	0.3
B-1	Trioxycarboxylate	0.015	0.2	0.2	0.4	0.4	0.5
		0.030	0.2	0.2	0.2	0.3	0.5
C-1	Dioxycarboxylate	0.015	0.2	0.3	0.3	0.4	0.5
D-1	Monosaccharides	0.030	0.2	0.2	0.2	0.4	0.8
D-2	Polysaccharides	0.030	0.2	0.2	0.5	1.0	4.0
E-1	Inorganic substance	0.015	0.2	0.3	0.8	1.4	5.4

Therefore, A-1 in the actual field test was used to confirm its effect. **Fig. 6** shows the findings, which indicate that its efficacy was confirmed, because hardening started after about one week when it was not added, whereas no hardening occurred even after 8 weeks when it was added. It has been confirmed that the use of fine blast furnace slag aggregate onto which a hardening retarder was sprayed presents no problem in quality and that hardening can be prevented by mixing with natural sand, such as mountain sand, in a fixed proportion even when a hardening retarder is excepted[10-11].

3.3. Technology of using concrete

3.3.1 Influence of the ratio of mixing of granulated slag with natural sand

With the intention of learning the basic physical properties of concrete for which fine blast furnace slag aggregate is used, various kinds of natural sand with fine blast furnace slag aggregate were mixed to conduct tests under the conditions of a water-to-cement-ratio of 55% and a targeted slump of 12 cm. **Fig. 7** shows the relationship between a slag mixing ratio and a slump. The Figure indicates that no definite relation exists between a slag mixing ratio and a slump and that compatibility depends on the kind of natural sand to be mixed with slag as seen in the cases where a slump increases in proportion as a slag mixing ratio increases and where a slump increases when a slag mixing ratio remains at around 50%.

Therefore, there was an investigation in to the relationships between the percentage of the absolute volume of fine aggregate and a slump. **Fig. 8** shows the findings. They indicate that the relation between the two are in direct proportion and that the use of fine blast furnace slag aggregate is positively affected when the percentage of

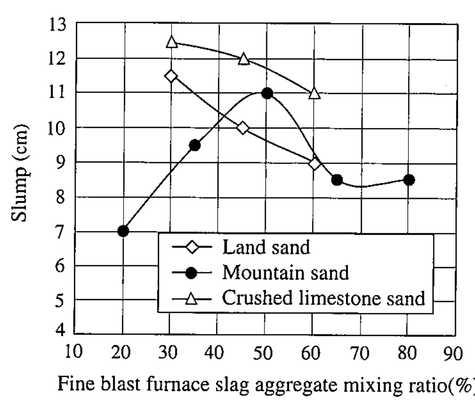

Fig. 7 Fine blast furnace slag aggregate mixing ratio and slump

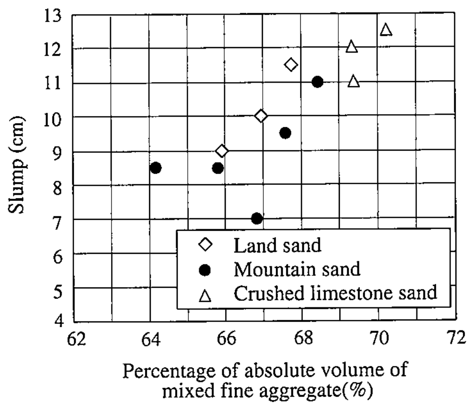

Fig. 8 Percentage of absolute volume of fine aggregate and slump

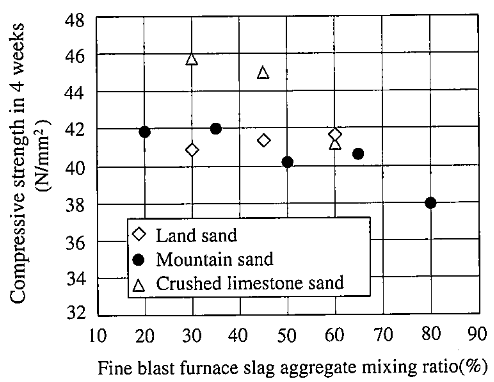

Fig. 9 Fine blast furnace slag aggregate mixing ratio and compressive strength in 4 weeks

absolute volume can be rendered greater against natural sand alone by mixing fine blast furnace slag aggregate.On the other hand, **Fig. 9**, which shows the relationship between a slag mixing ratio and compressive strength, indicates that no constant relation exists between the two and that an optimal mixing ratio exists depending on the kind of natural sand to be mixed therewith.

3.3.2 Study of the method of using natural sand for particle size improvement

A case in which fine blast furnace slag aggregate was mixed by 30% to improve the particle size of fine natural sand was studied. **Table 6** shows the quality of fine aggregate while **Table 7** gives the formulation of cement. The improvement of particle size of natural sand by mixing with fine blast furnace slag aggregate increased the percentage of absolute volume against natural sand alone by 1.8%, accompanied by a decrease in unit water volume by 7 kg/m^3. **Table 8** shows the physical properties of fresh concrete. The difference in physical properties between when fine blast furnace slag aggregate was mixed and when natural sand was used alone is almost the same, and a significant increase in bleeding as generally believed was not observed. **Table 9** shows the physical properties of cured cement. No significant difference between the two cases was observed in dry shrinkage and freeze-melting resistance, the indices of durability. It was confirmed from the foregoing that in those examples concrete performed better when fine blast furnace slag aggregate was mixed than when natural sand was used alone.

3.4 Summary

1) As a factor of the influences of fine blast furnace slag aggregate when stored on hardening, it was clarified that atmospheric temperature has the greatest influence, and effective and cheap measures against hardening by spraying a hardening retarder were developed.
2) Factors influencing quality when fine blast furnace slag aggre-

Table 6 Quality of each fine aggregate

	Natural sand (fine)	Slag (coarse)	Natural sand:70% Slag : 30%
Absolute dry density (kg/l)	2.51	2.66	2.56
Density in saturated surface-dried condition (kg/l)	2.58	2.72	2.62
Water absorption (%)	2.90	2.41	2.75
Bulk density (kg/l)	1.61	1.60	1.69
Percentage of absolute volume(%)	64.0	60.3	65.8
Fineness modulus	2.09	3.25	2.44

Table 8 Physical properties of fresh concrete

Natural sand (%)	Slag (%)	Measuring item	Elapsed time after kneading (min) 0	30	60	90	Bleeding volume (cm^3/cm^2)
100	0	Slump	17.8	13.3	10.5	7.1	0.30
		Air volume	5.8	4.5	4.3	3.9	
70	30	Slump	17.9	12.3	10.0	8.5	0.26
		Air volume	5.6	4.3	3.9	3.7	

Table 9 Physical properties of cured concrete

Natural sand (%)	Slag (%)	Compressive strength (N/mm^2) 7d	28d	91d	Tensile strength (N/mm^2) 28d	Dry shrinkage (×10^{-4}) 365d	Freeze-melting (%) 300 Cycle
100	0	27.5	35.9	43.9	2.91	−8.52	91.2
70	30	27.4	37.4	44.7	3.17	−7.95	90.4

Table 7 Concrete blending when fine blast furnace slag aggregate was used as material of supplementing the particle size of fine natural sand

Slump target (cm)	Aire volum target (%)	Kinds of fine aggregate: Natural sand	Fine slag	Slag mixing ratio (%)	Blending conditions: Water-to-cement ratio (%)	Fine aggregate ratio (%)	Blending volume per 1-m^3 concrete(kg/m^3): Water	Cement	Fine aggregate: Natural sand	Fine slag	Coarse aggregate
18	4.5	Fine	Coarse	0	55.0	47.0	185	336	805	0	957
				30	55.0	47.0	178	324	573	259	972

gate is mixed with natural sand were identified, and a limit ratio of mixing with natural sand within an applicable range was attained. The mixing of fine blast furnace slag aggregate for improvement of the particle size of natural sand was also studied in further detail, and it was found that concrete performs better when fine blast furnace slag aggregate was mixed than when fine natural sand was used alone.

4. Conclusion

As above-described, work proceeded to expand the use of blast furnace slag aggregate for concrete.

Nowadays, as a shift to a recycling-oriented society is often a heated topic, an effective use of recycled materials is now considered more seriously than ever before. Despite the fact that blast furnace slag aggregate is a useful recycled material with a history of more than 20 years since it was incorporated in JIS, it is not well known to the market yet, and thus some time is needed before this material will find general market acceptance. Therefore, it is necessary to respond to the social needs by developing the applications and demands of blast furnace slag aggregate and by perpetually trying to innovate its production process.

Acknowledgments

This conveys the sincerest appreciation and gratitude to those in Futtsu Thermal Power Station construction office, Tokyo Electric Power Co., Kajima-Shimizu Joint Venture, Okumura-Hazama Joint Venture, and neighboring ready-mixed concrete plants, and to those in Taiheiyo Cement for their whole-hearted cooperation in the application of coarse blast furnace slag aggregate, introduced in this paper, and in the technical development of the technology of using fine blast furnace slag aggregate, respectively.

References

1) Steel Slag Association: Annual Statistic Report, (Actual Result of 2000), 2001
2) Hukuda, Uehara, et al.: Application of Concrete with Blast Furnace Slag Gravel to Facilities of Civil Engineering in the Thermal Power Plant (Part 1). The 55th Annual Meeting of Japan Society of Civil Engineers, VI Session, 2000.9
3) Tutiyama, Sakata, et al.: Application of Concrete with Blast Furnace Slag Gravel to Facilities of Civil Engineering in the Thermal Power Plant (Part 2). The 55th Annual Meeting of Japan Society of Civil Engineers, VI Session, 2000.9
4) Akashi, Yokosaka, et al.: Application of Concrete with Blast Furnace Slag Gravel to Facilities of Civil Engineering in the Thermal Power Plant (Part 3). The 55th Annual Meeting of Japan Society of Civil Engineers, VI Session, 2000.9
5) Hasegawa, et al.: Class Room III, Durability (Part 5) — Freezing Damage — . Concrete Engineering. 25 (5), (1987)
6) Japan Society of Civil Engineers: Concrete Library No.76. 1993
7) Hiroshima, et al.: Annual Report of Cement Technology. (73), 89 (1983)
8) LOU Zonghan et al.: Proc. 8th Int. Congr. Chem. Cement. Rio de Janeiro. Vol. IV, 1986, p.30
9) Utikawa, H.: Cement & Concrete (484), 81 (1987)
10) Kanaya,M. et al.: Caking of Granulated Blast Furnace Slag Sand and Its Suppressive Technique. Journal of Inorganic Materials Association. 301 (2000)
11) Matsui, A. et al.: Properties of Concrete Using Granulated Blast Furnace Slag Sand That was Treated with Suppression of Caking. Architectural Institute of Japan, Annual Meeting of the Year 2000, A-1, 2000, p.475