Development of Manufacturing Process for Blast Furnace Slag Coarse Aggregate with Low Water Absorption†

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Abstract:

Due to the high porosity of blast furnace slag coarse aggregate (BFG), it is difficult to control the water content of the concrete where the BFG is used. JFE steel has been developing a pan type continuous slag solidification (PACSS^{TM}) process to reduce water absorption ratio of BFG under 1%. In this process, molten slag is poured into mold, and the slag is solidified at the thickness of 20 mm to 30 mm before the gas in the slag is generated and produced. The process results in the reduction of the porosity of slag. A pilot plant was constructed, and production of BFG under 1% became possible using this plant.

1. Introduction

Due to the high porosity of blast furnace slag coarse aggregate (BFG), its water absorption is high (approximately 4%), and it is extremely difficult to control the water content of the aggregate when BFG is mixed with concrete. It has been reported that clogging of the pipe occurred during concrete pumping with 100% BFG, and pumping was impossible[1)]. Although BFG is included in the standard "JIS A 5011, Slag aggregate for concrete, " use is still extremely limited. However, because the current coarse aggregate market depends on natural resources, manufacture of artificial coarse aggregate using iron and steel slag as raw materials has a large significance from the viewpoints of the problem of depletion of good quality natural aggregate and prevention of the environmental destruction associated with extraction of crushed stone.

JFE Steel developed a continuous blast furnace slag solidification process called PACSS^{TM} (Pan-type Continuous Slag Solidification)[2)] in order to reduce the water absorption of BFG to less than 1%, which is the same level as that of natural aggregate. In this process, the porosity of the solidified slag is reduced by pouring molten blast furnace slag into molds to a thickness of 20–30 mm, and solidifying the molten slag before the gas is generated from the slag and expands to form pores[3)].

A practical-scale PACSS pilot plant was constructed, and large-volume manufacture of plate-shaped solidified slag was performed by continuous solidification of molten blast furnace slag. The manufactured solidified slag plates were crushed to the size of BFG, and the quality of the product was evaluated. This report describes the construction of the pilot plant, the results of test production of solidified slag and the results of an evaluation of the slag.

2. Development of PACSS^{TM}

2.1 Outline of PACSS^{TM} Pilot Plant

A schematic drawing of the PACSS^{TM} pilot plant is shown in **Fig. 1**, and the specifications of the plant are shown in **Table 1**. The plant consists of 50 molds arranged in a circular shape on mold bogies, a slag pit where the solidified slag is recovered and water-cooling nozzle units for spray cooling of the molds. The molds

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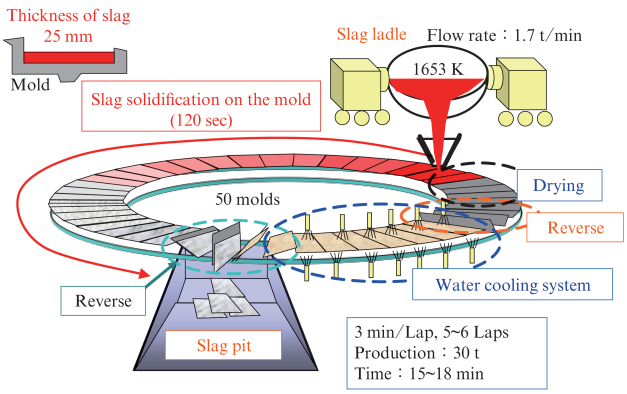

Fig. 1 Schematic drawing of PACSS™ pilot plant

Table 1 Specifications of PACSS™ pilot plant

Dimensions of mold	W (0.66 m×1.0 m)×L2.7 m Depth 0.1 m
Number of mold	50
Mold material	SC450
Mold weight	1 280 kg

Table 2 Specification of Nozzle

	Water flow rate L/min/m²	Angle of spray
Nozzle A	343	60°, 90°
Nozzle B	62	65°

are trapezoidal in shape and have dimensions of 0.66 m in the upper base, 1.0 m in the lower base, 2.7 m in length and 0.1 m in depth. The system is designed to move at a speed of 1 revolution/3 min and produce slag with a solidified thickness of 20–30 mm at a slag flow rate of approximately 2 t/min. The slag that flows onto the molds solidifies in a plate-like shape after cooling for 2 min, and is then dropped into the slag pit by inverting the molds. After cooling, the molds are dried naturally by air drying, and then receive the next molten slag. This plant processes the content of one slag ladle, which is approximately 30 t, as one batch in 5–6 revolutions.

2.2 Design of Spray Water-Cooling System

The selection of spray nozzles was carried out with the aim of designing the optimum spray water-cooling system. The specifications of the nozzles used in the selection process are shown in **Table 2**. Nozzle A was a type of nozzle that has a high water flow rate density, and has a narrow elliptically-shaped cooling range with a spray angle of 90°in the short direction and 60° in the long direction. Nozzle B was a type with a low flow rate density and a wide circular cooling range with a spray angle of 65°.

To evaluate the cooling capacities of the two nozzles, temperature measurements were performed by

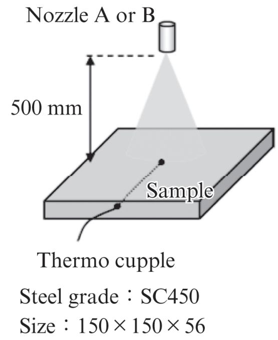

Fig. 2 Measurement of water-cooling capacity

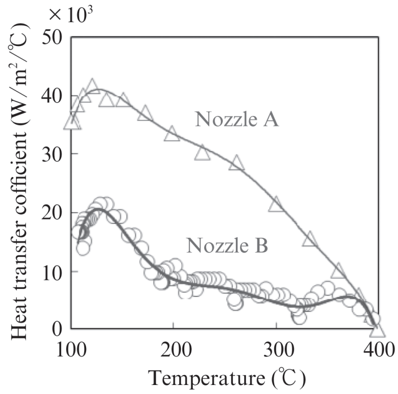

Fig. 3 Relationship between surface temperature of Steel plate and heat transfer coefficient

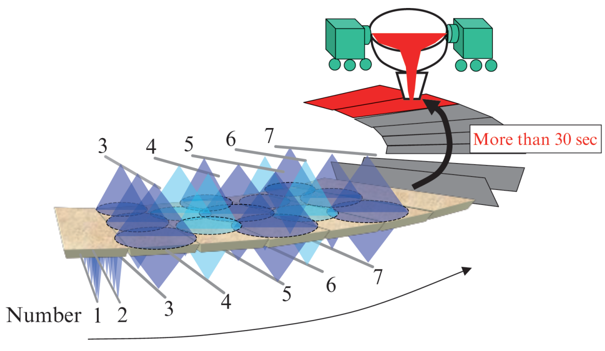

Fig. 4 Schematic drawing of water-cooling system

spraying water on a heated steel plate. The experimental method is shown in **Fig. 2**. Water was sprayed on a SC450 steel plate (150×150×56) which had been heated to 400°C in an electric furnace, and the heat transfer coefficient was obtained from the temperature decrease per unit time, which was measured with a thermocouple set at a depth of 2 mm in the SC450 plate.

The relationship between the surface temperature of the steel plate and the heat transfer coefficients of the two nozzles is shown in **Fig. 3**. Nozzle A had a high heat transfer coefficient of 20 000 W/m²/°C at 300°C. The heat transfer coefficient of Nozzle B was 10 000 W/m²/°C or less at around 200°C and was 5 000 W/m²/°C or less at temperatures over 300°C.

Figure 4 shows the dimensions of the spray water-cooling system that was designed based on these experi-

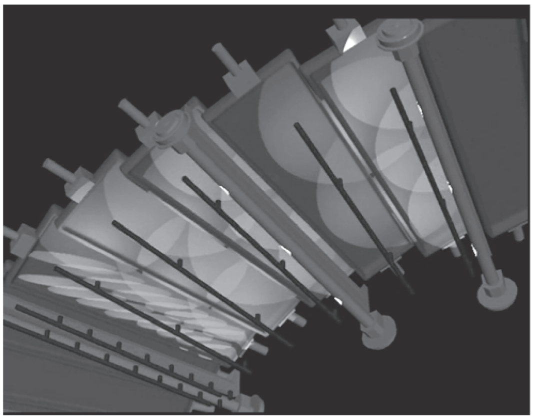

Fig. 5 3D-CAD of water cooling system

Photo 2 PACSS^{TM} pilot plant experiment

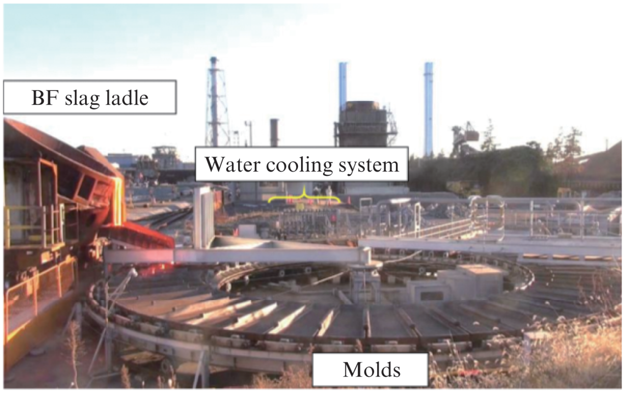

Photo 1 PACSS^{TM} pilot plant

Photo 3 Plate-like solidified slags

mental results. The water-cooling system comprises a 7-nozzle unit. Nozzle A was used in the first two units, and was arranged only under the molds. From the 3rdnozzle, Nozzle B was arranged on both the top and bottom sides of the molds. Because the surface temperature of the molds after discharging the slag was assumed to be 300°C or higher and the pilot plant was constructed outdoors, rusting of the molds was a concern. Therefore, the concept of the nozzle arrangement was to increase the cooling capacity at the initial mold positions, and then to cool the molds uniformly after reducing the mold surface temperature. The time between the end of water spraying and receiving of the molten slag was set at 30 s or longer to enable complete drying of the molds after spraying, before receiving the next molten slag.

Because the beams that form the axis of rotation of the molds are an obstacle to water spraying in the pilot plant, the condition of spraying was reproduced from the design drawing of the pilot plant by using 3D-CAD. **Figure 5** shows an example of a 3D-CAD analysis of the condition in which the nozzles unit is arranged perpendicular to the ground surface in the designed spray water-cooling system. The water spray is shown by light. An arrangement in which the nozzle units were inclined by several 10°was also tried, but it was found that the least interference with the water spray occurred when the nozzle units were arranged perpendicular to the ground surface.

2.3 Results of PACSS^{TM} Pilot Plant Experiment

The PACSS^{TM} pilot plant is shown in **Photo 1**. The pilot plant experiment was carried out by the following procedure. Slag that had solidified on the surface of the blast furnace slag ladle during transportation from the blast furnace was broken up with heavy equipment, and the mouth of the blast furnace slag ladle was arranged directly facing the slag runner of the pilot plant. The ladle was then tilted so as to obtain a constant slag flow rate, and the molten slag was supplied to the molds by way of the runner. **Photo 2** shows the condition of the pilot plant experiment. The molten slag can be seen spreading on the mold. After this, the solidified slag was transported by the molds and dropped into the slag pit. After the molds were cooled by water spraying or radiation, molten slag was poured again. **Photo 3** shows the solidified slag in the slag pit. On the molds, the molten slag is cooled from the surface in contact with the air and from the surface in contact with the mold. As a result, after the slag is dropped into the slag pit, the interior of the slag is red-

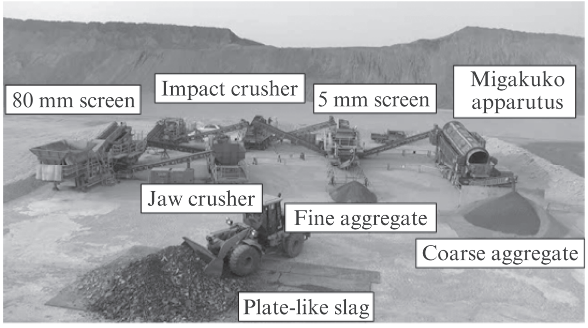

Photo 4　Mobile crushing plant

Photo 5　BFG with low water absorption

hot, and the slag is still partially unsolidified. In the pilot experiment, about 30 t of solidified slag plates were produced from 1 ladle, and a total of approximately 410 t of solidified slag was produced.

The mobile crushing plant is shown in **Photo 4**. This plant consists of an 80 mm screen, an impact crusher, a 5 mm screen and an ore polishing machine. The crushing procedure is as follows. The solidified slag plates are introduced into the 80 mm screen, and the +80 mm is crushed by a jaw crusher to obtain −80 mm. The −80 mm solidified slag plates are then introduced into the impact crusher and crushed to a size of 25 mm or under. After this, crushed slag with a size of < 5 mm is classified as fine aggregate by the 5 mm screen, and slag with a size of 5 mm or more is separated and recovered as coarse aggregate after processing through the ore polishing machine. The coarse aggregate with low water absorption is shown in **Photo 5**. It’ s appearance is the same as that of natural stone.

Table 3　Quantity of BFG and fine aggregate

Course aggregate	Fine aggregate
351 t (86%)	57 t (14%)

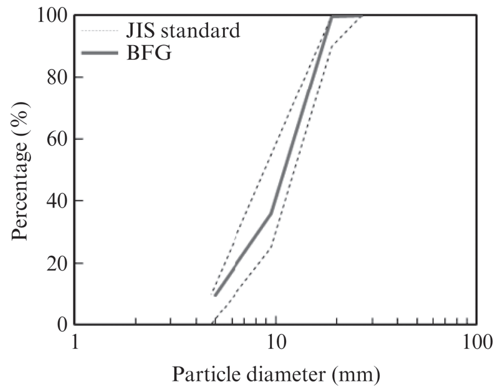

Fig. 6　Particle distribution of BFG

The quantities of coarse aggregate and fine aggregate manufactured by this process are shown in **Table 3**. When approximately 410 t of solidified slag was crushed, it was possible to manufacture 351 t of coarse aggregate. Thus, the yield ratio was 86%.

The particle size distribution of the coarse aggregate is shown in **Fig. 6**. The developed product is within the particle size range provided in the JIS standard.

2.4 Quality of BFG with Low Water Absorption

Table 4 shows the chemical composition of the blast furnace slag coarse aggregate with low water absorption. All of the components specified in the JIS standard are within the standard values.

To evaluated the quality of the BFG with low water absorption, the density in the absolutely dry condition, density in the saturated surface dry condition, water absorption, mass per unit volume (bulk density), fine

Table 4　Chemical composition of BFG

	CaO	SiO_2	T.S	SO_3	FeO
Composition (%)	41.6	34.5	0.74	0.11	0.04
JIS standard	≦45.0	—	≦2.0	≦0.5	≦3.0

Table 5　Comparison of quality of BFG and limestone aggregate

	BFG	JIS standard	Limestone	JIS standard
Density in saturated surface dry condition (g/cm^3)	2.83	—	2.69	—
Density in absolutely dry condition (g/cm^3)	2.82	≧2.4	2.68	≧2.5
Water absorption (%)	0.73	≦4.0	0.30	≦3.0
Bulk density (kg/L)	1.72	≧1.35	1.66	—
Amount of material passing test sieve 75 μm (%)	0.20	< 5.0	2.30	< 5.0
Amount of abrasion loss (%)	11.8	≦35	18.3	≦35
Solid volume percentage for shape determination (%)	61.2	—	61.6	—

Table 6 Elution of BFG

	Cd	Pb	Cr^{6+}	Hg	As	Se	F	B
Elution (mg/L)	< 0.005	< 0.001	< 0.01	< 0.0005	< 0.002	< 0.002	0.09	0.03
JIS standard (mg/L)	≦0.01	≦0.01	≦0.05	≦0.0005	≦0.01	≦0.01	≦0.8	≦1

Table 7 Content of BFG

	Cd	Pb	Cr^{6+}	Hg	As	Se	F	B
Content (mg/kg)	< 10	< 10	< 10	< 1	< 10	< 10	500	67
JIS standard (mg/kg)	≦150	≦150	≦250	≦15	≦150	≦150	≦4 000	≦4 000

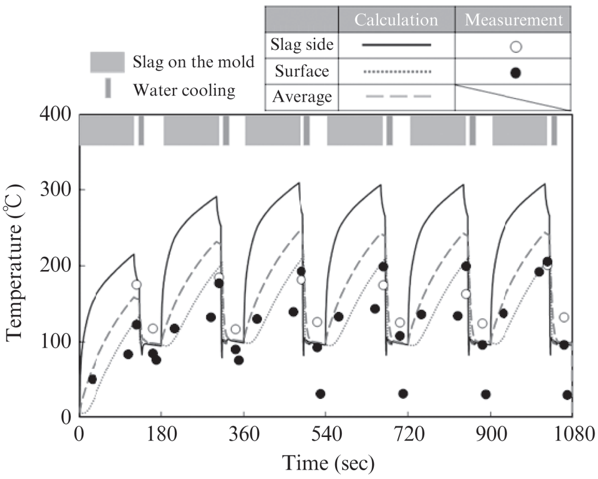

Fig. 7 Mold temperature in the pilot plant

particle (< 75 μm) content, abrasion loss and solid volume percentage for shape determination were measured. **Table 5** shows the results, together with the results for limestone. The water absorption of the developed BFG with low water absorption was 0.73%, achieving the target of 1% or less. The abrasion loss of the BFG with low water absorption was also low, at 11.8%, showing that this product has excellent abrasion resistance.

Environmental safety quality standards for BFG are established under JIS standards. Therefore, elution and the content of chemical substances were measured in accordance with JIS K 0058–1 and JIS K 0058–2, respectively. The respective results are shown in **Table 6** and **7**. Both elution and the content of chemical substances satisfied the JIS standards.

2.5 Evaluation of Mold Cooling during Experiment

In order to control the temperature of the molds in the pilot plant, a non-steady 1-dimensional heat transfer analysis was performed as a simulation of the temperature history of the molds during the pilot plant test. The temperature of the molten slag was assumed to be 1 380°C, and the initial temperature of the molds was assumed to be 20°C. One cycle was 180 sec. The slag was cooled on the molds during the period of 0–120 sec, and the molds were then water cooled or air cooled from 120–180 sec. This cycle was repeated 6 times in operation during the pilot experiment. Temperature measurements were performed by installing radiation thermometers at various positions. **Figure 7** shows the calculated results of the temperature change of the molds in the pilot plant, together with the measured values. Here, “Slag side” indicates the temperature of the surface where the slag was actually placed on the mold, and “Surface” indicates the temperature of the back side of the mold. As shown in this figure, the temperature changes of the molds during the experiment could be inferred approximately by the non-steady 1-dimensional heat transfer analysis. It was estimated that the surface temperature of the mold exceeded 200°C in the 1^{st} cycle and exceeded 300°C in the 2^{nd} cycle. However, by performing appropriate water cooling, it was possible to control the surface temperature of the molds to approximately 300°C or less, which is the guideline for avoiding deformation of the mold.

3. Conclusion

The pan-type continuous blast furnace slag solidification process PACSS™ was developed, and a pilot plant was constructed. It was possible to manufacture blast furnace slag coarse aggregate (BFG) with water absorption of less than 1% by using the pilot plant equipment. Various quality evaluations of the BFG were performed, and satisfactory results were obtained. A mold cooling system was also designed, and the optimum spray water-cooling system was proposed.

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