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Iron and Steel Slag Products and New Effective Utilization Technologies†

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Abstract:

Lineup of iron and steel slag products of JFE Steel is introduced. And the development processes of the new technology which is effective for environment restoration and natural material substitution in recent years are also presented.

1. Introduction

Iron and steel slag, which are inevitable byproducts of steel product manufacturing, are processed and sold by steel makers as useful materials called “iron and steel slag products.” Annual sales of iron and steel slag products produced in Japan have reached a huge amount of approximately 40 million tons[1]. As industrially-produced products, the production volume of iron and steel slag products in Japan follows that of crushed stone, crude steel and cement, and is roughly the same as production of gasoline[2].

JFE Steel produces and sells “Iron and steel slag products” which utilize the special properties of iron and steel slag. This paper introduces the properties and applications of each of JFE Steel’s “Iron and steel slag products.”

In addition, JFE Steel is constantly developing the technologies that utilize newly-discovered properties and technologies which greatly improve quality. Recent achievements in these technologies are also reported.

2. Production and Control of Iron and Steel Slag Products

2.1 Iron and Steel Slag Product Production Process

Iron and steel slag is classified as blast furnace slag generated in the ironmaking process, in which pig iron is produced by reducing iron ore in the blast furnace, and steelmaking slag generated in the steelmaking process, in which iron is refined in the converter or electric furnace. **Figure 1** shows the production process of iron

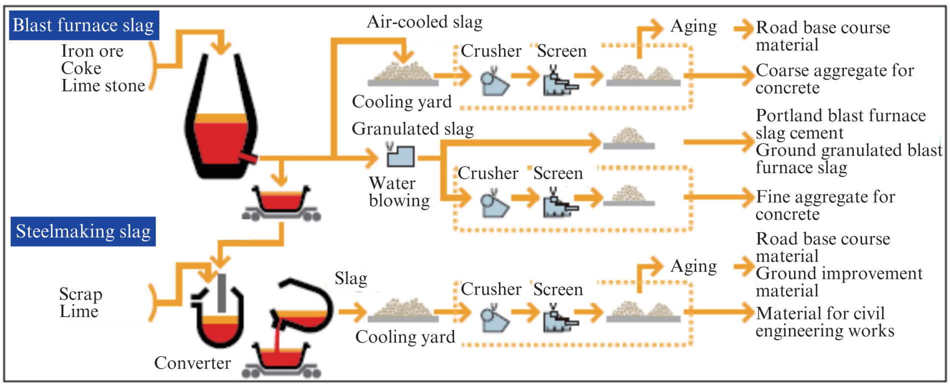

Fig. 1 Iron and steel slag processes

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and steel slag products[3]. Blast furnace and converter operation is basically performed prioritizing the composition and temperature of the molten iron and steel, but the composition of the slag is also adjusted as necessary, depending on the application of the slag products. Next, the cooling and solidification process is classified as air cooling, in which the slag is slow-cooled and solidified in crystalline lumps, and granulation, in which the slag is cooled rapidly by spraying water, resulting in the formation of fine glassy particles. In the crushing and mechanical stabilization process, the size of the slag is adjusted to the particle size distribution range required by the intended application. In the case of road base course materials, aging is performed after crushing and screening. Finally, after inspection of product quality, the products are shipped.

2.2 Management of Iron and Steel Slag Products

Japanese Industrial Standards (JIS) have been established for the main applications of iron and steel slag products, which include aggregate for cement and concrete, road base course material, etc., and quality is controlled in accordance with those standards.

Quality control and sales management of iron and steel slag products are performed in accordance with "Guidelines related to management of iron and steel slag products,"[1] which was formulated by the Nippon Slag Association. Before shipping, environmental safety quality (amount of dissolution and content of heavy metals) is checked. Manuals are also established based on the above-mentioned Guidelines, and investigation before order receiving, explanations to customers, investigation during construction, investigation after construction, etc. are performed.

3. JFE Steel Iron and Steel Slag Products

3.1 Raw Material for Cement

The largest use of blast furnace slag is as a raw material for cement. Nationwide, total sales for domestic consumption and exports are 17.8 million t/y[1]. Blast furnace cement is produced by mixing ordinary Portland cement and ground granulated blast furnace slag, which is produced by grinding water granulated blast furnace slag, as shown in **Photo 1**. JFE Steel sells water granulated blast furnace slag to cement makers in Japan and other countries. As part of the water granulated blast furnace slag produced by JFE Steel, ground granulated blast furnace slag is ground by Chiba Riverment and Cement Corporation and Mizushima Riverment Corporation, which are members of the JFE Steel Group.

Photo 1 Water granulated blast furnace slag and ground granulated blast furnace slag

Photo 2 Iron and steel slag for road construction and example of construction

The quality of the water granulated slag that can be mixed in blast furnace cement is specified strictly by each cement maker. Because the chemical composition is specified by basicity, basicity adjustment of blast furnace slag and selection by basicity are performed, corresponding to the standards of each cement company[2].

3.2 Road Base Course Material

As iron and steel slag road base course materials for road construction, JFE Steel produces and sells "Hydraulic and mechanically stabilized slag HMS-25" and "Mechanically stabilized slag MS-25" for base course (upper subbase) use and "Crusher run slag CS-40 and CS-30" for subbase course (lower subbase) use. These products satisfy "JIS A 5015, Iron and steel slag for road construction."

Photo 2 shows iron and steel slag for road construction and an example of construction.

Iron and steel slag road base course materials can be used as a substitute for natural stone. As sensitivity to the water content is low, it is possible to continue compaction work even when it begins to rain during work. Due to its good compaction property, it is possible to open the road to traffic immediately after construction. Because the hydraulic property appears over a long period after construction, durability is excellent, which means maintenance costs can be reduced. This slag material can also be used as a supplementary material for recycled road base course materials such as concrete and asphalt, etc. In particular, since HMS-25

Photo 3 Steam aging plants (pressure type and ordinary pressure type)

Photo 4 Blast furnace slag fine aggregate

has a hydraulic property of hardening gradually in the presence of water, design is possible with a depth equivalency factor (coefficient of relative strength) of 0.55, enabling road construction with a small amount of material[3].

Blast furnace slag is aged for 3 months or longer to prevent leaching of yellow leachate from air-cooled blast furnace slag, after which a leaching test for blast furnace slag is performed. The product is shipped after confirming that yellow leachate does not form.

In steelmaking slag, which is a high basicity material, lime that was charged in the converter remains in an undissolved form. This lime precipitates out during cooling and exists as free CaO, which then forms $Ca(OH)_2$ in the presence of water. Because free CaO expands, steam aging is performed at a steam aging plant, as shown in **Photo 3**, to saturate free CaO to $Ca(OH)_2$ in advance and thereby prevent expansion. The resulting product is used as road base course material.

3.3 Blast Furnace Slag Fine Aggregate

Water granulated blast furnace slag, as shown in **Photo 4**, is also used as fine aggregate for concrete, or so-called sand. Fine aggregate is the second largest application of water granulated blast furnace slag, with sales of 1.8 million t/yr in Japan[1]. Unlike slag materials for cement, a high density, hard material is required in water granulated slag for fine aggregate. Furthermore, different particle size distributions are considered necessary, depending on the areas where the fine aggregate will be used.

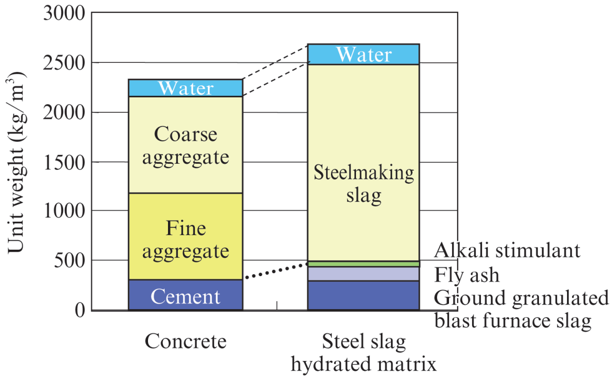

Fig. 2 Mixture of steel slag hydrated matrix

JFE Steel West Japan Works (Fukuyama District) produces blast furnace slag fine aggregate equivalent to medium sand by selecting high density granulated slag, while East Japan Works (Chiba District) has installed a dedicated water granulated slag production plant for fine aggregate and produces coarse, high density blast furnace slag fine aggregate equivalent to coarse sand[4]. At both sites, after grinding to remove sharp corners from the granulated slag, an anticaking agent is added to prevent caking during storage. In recent years, it has been found that concrete using blast furnace fine aggregate has excellent resistance to sulfuric acid, freezing and thawing resistance and resistance to damage by salt attack[5-7].

3.4 Steel Slag Hydrated Matrix

JFE Steel developed and produces a product called Steel Slag Hydrated Matrix[8] using steelmaking slag and ground granulated blast furnace slag as the main raw materials. An example of the mixture of Steel Slag Hydrated Matrix is shown in **Fig. 2**. Steel Slag Hydrated Matrix is produced by kneading, pouring and curing in the same process as ordinary concrete, but using steelmaking slag in place of sand and gravel and ground granulated blast furnace slag as a binder. The alkali stimulation of the Ca ions that leach out of the steelmaking slag brings out the latent hydraulic property of the ground granulated blast furnace slag, and hardening occurs as a result of the hydration reaction[9].

After kneading, Steel Slag Hydrated Matrix can be handled in the same way as ready-mixed concrete. It is used in products formed in a similar manner to concrete blocks using forms, and in the manufacture of Frontier Rock™, as shown in **Photo 5**, by crushing to a rock-like shape after hardening. Steelmaking slag has different compositions and size distributions at each plant and process where it is generated. In order to secure the hardness of the matrix, Hydrated Matrix is manufactured by adjusting the mixture of the steelmaking slag and the ground granulated blast furnace

Photo 5 Frontier rock™

Photo 6 Sand compaction pile method

Photo 7 Various Marine stone™ products

Fig. 3 CaO improved soil

slag corresponding to the slags being used. Because the solubility of the alkali component of Hydrated Matrix is smaller than that of concrete using ordinary Portland cement, this product has the distinctive feature of superior adhesion by marine organisms in comparison with concrete when used in marine areas. Taking advantage of this feature, it is used in stone materials and blocks for port and harbor construction[10,11].

3.5 Steelmaking Slag for Ground Improvement (Use in Sand Compaction Piles)

Steelmaking slag can be used as a material for sand compaction in ground improvement work, utilizing the soil engineering properties of a large unit weight and large shear resistance angle in comparison with natural sand. Because a shear resistance angle of 40°or more can be secured, the ground improvement width can be reduced in comparison with natural sand, enabling a reduction of construction costs.

The range affected by alkaline elution from steelmaking slag is limited to 1 m from the pile, and the fact that there is no effect on the surrounding ground has been confirmed[12].

3.6 Marine Stone™

JFE Steel produces and sells Marine Stone™ as an environmental improvement material for marine areas. Marine Stone is produced by adjusting the particle size of steelmaking slag and is available in products with the three particle sizes in **Photo 7**, Marine Stone 10, Marine Stone 30 and Marine Stone 85. It is a suitable material as a base for shoals and seaweed beds. In actual projects, 242 000 m^3 of Marine Stones was used in the construction of the Iwakuni Air Base seaweed bed and tidelands, and 24 500 m^3 was used in the Yamaguchi Prefecture Tobu Marine Area Seaweed Construction Project and has become a base for adhesion of seaweeds, shellfish and other marine organisms[13,14].

3.7 Calcia (CaO) Improvement Material

Calcia (CaO) improvement material[15] is made by composition control and mechanical stabilization (size adjustment) of converter type steelmaking slag as the raw material. As shown in **Fig. 3**, CaO improved soil, which increases the strength of weak dredged soil by a water absorption effect and hydration reaction, is formed by mixing this material with weak dredged soil. Due to the high viscosity of CaO improved soil, generation of turbidity is remarkably suppressed when it is introduced in water. CaO improved soil also has the characteristic of adsorbing phosphorous and sulfides. Active use in backfilling weak dredged soil with a high water content in shoal and tideland construction, refilling former dredging sites and land reclamation has become possible by improvement to CaO improved soil[16-18].

3.8 Water Granulated Slag for Civil Engineering Works

Water granulated slag is widely used in civil engineering applications such as backfill material behind seawalls, reclamation material, cover material for poor ground, subgrade material, banking and the like. **Photo 8** shows water granulated slag for civil engineer-

Photo 8 Water granulated slag for civil engineering works and example of construction for quay

Photo 9 Steel slag crushed stone for civil engineering works and example of construction for farm road

ing works and an example of construction. As features of water granulated slag for civil engineering works, although this material is lighter than sand, it has a shear resistance angle of 35°or more, and modified CBR has strength equal or superior to that of natural sand, at 20–30%. It also has the hydraulic property of water granulated slag and thus hardens over time, which increases resistance against liquefaction during earthquakes[3)].

3.9 Steelmaking Slag Crushed Stone for Civil Engineering Works

Steelmaking slag for civil engineering works is widely used as a land preparation material, banking load, partitioned dike material, construction road material, etc. Steel slag crushed stone and an example of construction using this material are shown in **Photo 9**.

In comparison with natural crushed stone road base course material, bulk density (mass of unit volume) is large and the shear resistance angle is 40° or more. Quality is specified in the Japan Testing Center for Construction Materials (JTCCM) standard “JSTM H 8001, Steelmaking slag crushed stone for civil engineering works. ” Steelmaking slag crushed stone for civil engineering works is produced by adjusting the size of the slag and controlling environmental safety quality in accordance with the JTCCM standard.

Photo 10 Construction of Marine stone^{TM} in Fukuyama inner harbor

4. Development of New Technologies for Effective Utilization

4.1 Marine Bottom Environment Improvement Materials

In September 2010, JFE Steel received a request for consultation from Fukuyama City regarding the bad odor generated at the inner harbor in Fukuyama, and carried out a field demonstration test of sulfide suppression using Marine Stone^{TM}jointly with Hiroshima University with the aim of solving the problem of the sulfide odor generated from the sludge-like bottom sediments in those waters. As a result, suppression of sulfide generation and bottom sediment improvement effects, including the habitats of benthos, etc., were confirmed[19-21)].

Marine Stone was adopted as a bottom sediment improvement material in the “Fukuyama Port-Port Waters Environment Creation Project (Inner Harbor District)” in Hiroshima Prefecture. Approximately 38 000 tons of Marine Stone was laid in an area of about 66 000 m^2 in the Fukuyama Inner Harbor (Fukuyama City, Hiroshima Prefecture). The condition of construction of Marine Stone at Fukuyama Inner Harbor is shown in **Photo 10**.

The environmental improvement effects of Marine Stone in this closed body of water were highly evaluated, and together with Hiroshima University, JFE Steel received the 12th Eco-Products Awards, Minister’s Prize from the Ministry of Agriculture, Forestry and Fisheries in 2015, and the Nikkei Global Environment Technology Award for Excellence in 2016.

4.2 Ferroform^{TM} Pavement

The loading conditions of roads in a steel works are more severe than those of general public roads because coil carriers and large-scale dump trucks travel on steel works roads, and this leads to early progress of the deterioration of the surface of asphalt/concrete pave-

Photo 11 Ferroform™ pavement by sea water

Photo 13 Continuous solidification process for blast furnace slag PACSS™

Photo 12 Construction of breakwater at Oofunato harbor entrance

Photo 14 Appearance of plate-like solidified slag and developed coarse aggregate

ment. A switchover to concrete pavement is effective for improving durability. Ferroform™ pavement, in which the above-mentioned Steel Slag Hydrated Matrix is substituted for this concrete pavement, has been applied to steel works roads. Like ordinary concrete pavement, Ferroform can be placed by concrete pumping, and construction by a simple finisher is also possible[22].

The seawater mixed concrete technology of Obayashi Corporation has also been applied to Ferroform. **Photo 11** shows a pavement using seawater-mixed Ferroform which was constructed at East Japan Works (Chiba District)[23].The Obayashi Corporation technology "High durability seawater and sea-sand mixed concrete" received the 17th Ministry of Land, Infrastructure, Transport and Tourism (MLIT) Grand Prize for R & D in Construction (MLIT Minister's Award) in 2015.

4.3 Use of Artificial Stone in Tohoku Disaster Reconstruction

The Steelmaking Slag Hydrated Matrix product Frontier Rock™ was adopted as an artificial stone material for port and harbor construction in the reconstruction of the Tohoku region following the 2011 Great East Japan Earthquake and Tsunami disaster. Mainly 1 t size stones were used as armor stones for harbor entrance breakwaters. **Photo 12** shows the construction of a breakwater at the entrance of Oofunato harbor, where 11 000 m^3 of Frontier Rock was used as armor stones, and 14 000 m^3 was also used in the construction of breakwaters at the entrance of Kamaishi harbor, thereby contributing to the reconstruction.

4.4 High Density Blast Furnace Slag Coarse Aggregate

Although air-cooled blast furnace slag is used as coarse aggregate for concrete, the annual sales volume is small, being 219 000 t/y in Japan[1]. Since air-cooled blast furnace slag is porous, its coefficient of water absorption is large and the value of the coefficient also varies greatly. JFE Steel developed the pan-type continuous blast furnace slag solidification process for concrete aggregate, PACSS™, shown in **Photo 13**, which reduces the porosity of blast furnace slag. When molten slag is solidified continuously in cast steel molds, it is possible to obtain dense, plate-shaped slag with a thickness of approximately 25 mm[24]. The coarse aggregate shown in **Photo 14** can be produced by crushing these slag plates. Although the coefficient of water absorption of conventional air-cooled blast furnace slag is 3–4%, the water absorption of the coarse aggregate produced by the PACSS process is 1% or less which is similar to that of natural aggregate. Concrete mixed with this coarse aggregate has drying shrinkage similar to that of limestone[25].

4.5 Future Efforts

JFE Steel is also developing new slag production processes. NEDO project "Environmentally Harmonized Steelmaking Process Technology Development (COURSE50)" has been developing, processes for separating CO_2 gas from blast furnace gas are being studied[26]. In the CO_2 absorption method, which is one separation method, utilization of unused energy in the steel works as energy for separating CO_2 gas from the liquid used to absorb the CO_2 gas is being studied. As one such method, JFE Steel developed a steelmaking slag sensible heat recovery process. This is a process in which the molten slag is solidified in plates with a thickness of about 7 mm by a twin roll-method, and heat exchange with air is performed in a packed bed in order to recovery sensible heat efficiently from steelmaking slag, which has low thermal conductivity[27-29). As a result of experiments with a pilot-scale plant, a sensible heat recovery rate of more than 30% was achieved.

In another NEDO project, JFE Steel is also developing a slag iron source recovery technology in order to recycle the iron remaining in steelmaking slag. In this process, after recovering the metal mixed in steelmaking slag in a high temperature condition, the iron oxide is reduced by a rotary kiln method, and metallic iron is recovered.

Among other efforts, JFE Steel is developing the technology for analysis of f-MgO[30), the ecotoxicological assessment and assessment of the ecotoxicity of iron and steel slag by the bioassay method[31).

5. Conclusion

Although iron and steel slag products are byproducts which are generated when producing iron and steel products, they are also industrials products that are processed and controlled corresponding to the intended application and the quality requirements of the user. In the future, JFE Steel will continue to develop iron and steel slag products which are more useful as materials supporting society.

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