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New Applications of Iron and Steelmaking Slag Contributing to a Recycling-oriented Society†

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Abstract:

Iron and steelmaking slag are byproducts of the iron-making and steelmaking processes. To date, these types of slag have been widely used in cement and as aggregate for civil works. This paper introduces new products developed by the JFE Steel Group as materials for improvement of coastline and coastal marine environments, including an environment-friendly block "Ferroform," which is made mainly from slag and absolutely free from natural aggregate, a sand capping material made from granulated blast furnace slag, and a large carbonated slag block, "Marine Block," made from steelmaking slag, and a water-retaining pavement material which mitigates the urban heat island phenomenon.

1. Introduction

Global warming and environmental destruction have become manifest problems in recent years, heightening concern about global environmental issues, and a change-over from the mass-production, mass-consumption, mass-waste society of the past to a zero-emission society is now viewed as important. The iron and steel industry produces extremely large amounts of slag as byproduct of the ironmaking and steelmaking processes, and is therefore continuing to develop slag reduction and recycling technologies and intermediate treatment technologies.

The Japanese steel industry produces 36.58 million tons of iron and steelmaking slag in 2003. There are two main types of slag, blast furnace slag and steelmaking slag. The former is produced as byproducts in the process of manufacturing pig iron in the blast furnace, and the latter is byproducts of steelmaking processes in the basic oxygen furnace (BOF), electric furnace, and so on. The respective amounts of these two types are 24.35 million tons of blast furnace slag and approximately 12.22 million tons of steelmaking slag.

As useful recycled materials, iron and steelmaking slag are mainly used in fields related to civil engineering, for example, in cement, roadbed material, and concrete aggregate. Their recycling ratio is close to 100%, making an important contribution to the creation of a recycling-oriented society. However, public works projects, that is strongly related to recycled fields, tend to be reduced recently and, more over, other recycled materials, such as reused roadbed materials and fly ash, become competitor of slag in the fields. Thus, the development of new application technologies has become an urgent matter.

The JFE Steel Group has developed and sells the following as new use technologies for iron and steelmaking slag: (1) an environment-friendly block, "Ferroform," which can be used as a substitute for concrete, (2) materials for restoration of coastal and marine environments, "Marine Block" and "Marine Base," and (3) a water-retaining pavement material which reduces the urban heat island phenomenon. This report introduces these new application technologies of iron and steelmaking slag which are contributing to a recycling-oriented soci-

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2. Development of Environment-friendly Block, "Ferroform," Using Iron and Steelmaking Slag

An environment-friendly block was developed using ground granulated blast furnace slag as a binder and fly ash, which is a byproduct of coal-fired thermal power plants, as a compounding material[1-3].

In comparison with conventional concrete, this block, named "Ferroform" (iron and steelmaking slag hydrate solid), has the following advantages: (1) high density, (2) low solubility of alkali components, (3) high wear resistance, and (4) excellent adhesion of biofouling organisms in coastal environments. Ferroform has been positively developed as special-shaped blocks such as wave-dissipating blocks and covering blocks, superstructures for caissons, substitute material for ballast, and other materials for port and harbor civil works. This chapter introduces the properties of the environment-friendly block "Ferroform" and an example of application in port and harbor construction.

2.1 Basic Properties of Ferroform

2.1.1 Manufacturing method

An example of the composition of Ferroform in comparison with that of normal-weight concrete is shown in **Fig. 1**. In Ferroform, the binder materials which correspond to the portland blast-furnace slag cement in concrete are ground granulated blast furnace slag (GGBFS), fly ash, and an alkali activater (lime dust, slaked lime, cement, etc.), and the material corresponding to the fine aggregate and coarse aggregate is steelmaking slag. Ferroform is manufactured by mixing, placing, and curing these materials. Because this process is the same as with concrete, concrete manufacturing equipment can be used without modification.

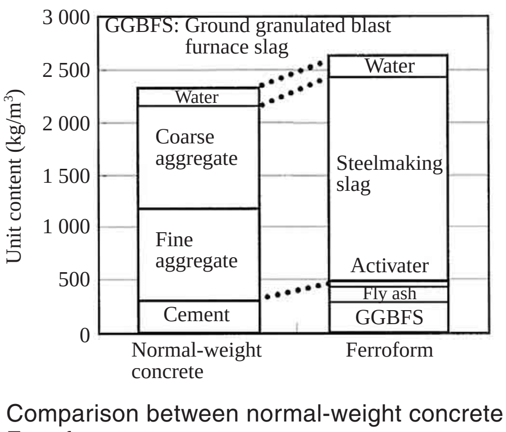

Fig. 1 Comparison between normal-weight concrete and Ferroform

Steelmaking slag, which has a higher density than natural aggregate (density in saturated surface-dry condition: steelmaking slag, 2.8–3.6 g/cm^3, natural aggregate, 2.7–2.8 g/cm^3), is used as a material for Ferroform, the block has a greater mass per unit of volume than concrete, at 2.4–2.7 t/m^3 for the standard mixture in comparison with approximately 2.3 t/m^3 for normal-weight concrete. As a result, Ferroform has great advantage used in dynamic structures, for example excellent stability against waves in coastal environments.

2.1.2 Properties after curing

The relationship between compressive strength and the curing period is shown in **Fig. 2**. Like normal-weight concrete, the strength development behavior of Ferroform increases with material age. The strength of Ferroform after curing for 91 days is approximately 1.3 times greater than after 28 days, and its strength also continues to increase after 91 days, showing a larger long-term strength increase than concrete[4]. The reason for these is considered to be that the curing reaction continues over a longer period.

Other properties are shown in **Table 1**. Both flexural strength and tensile strength are on the same level as concrete of the same compressive strength. The static

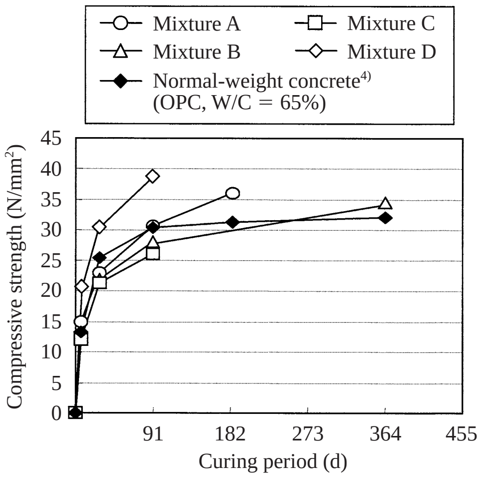

Fig. 2 Relation between compressive strength and curing period

Table 1 Comparison of mechanical properties between Ferroform and normal-weight concrete

Item		Ferroform	Normal-weight concrete
Modulus of elasticity*	(N/mm^2)	21 500–31 000	26 100
Tensile strength*	(N/mm^2)	2.14	2.22
Flexural strength*	(N/mm^2)	3.89	4.05
Abrasive coefficient*	(cm^3/cm^2)	0.043	0.095
Density	(kg/m^3)	2 400–2 700	2 300
Median pore size	(μm)	0.02	0.09

* Compressive strength: 30 N/mm^2

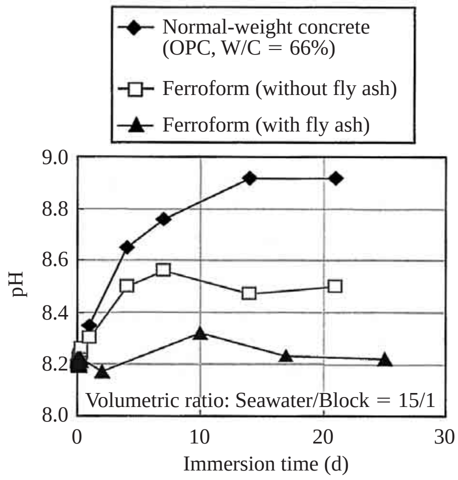

Fig. 3 Change in seawater pH observed after immersion of the test blocks in the laboratory

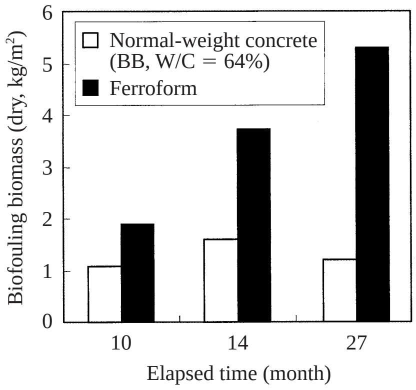

Fig. 4 Change in biomass of biofouling organisms on the Ferroform block and normal-weight concrete block when exposed to the sea

modulus of elasticity is somewhat smaller, that suggests Ferroform is a somewhat softer material than concrete. The abrasive coefficient is small, at approximately 1/2 that of concrete, so that excellent durability against wear due to drift sand in coastal environments can be expected. In addition, because Ferroform has dense structure with a small median pore size, it has the advantage of resistance to salt penetration.

The change in the pH of seawater after samples 100 mm in diameter × 200 mm in height were immersed in artificial seawater is shown in **Fig. 3**. With Ferroform, the increase in seawater pH is small in comparison with concrete made using ordinary portland cement, indicating that leaching of alkali components from Ferroform is slighter than that from concrete. In particular, there is virtually no increase in pH when fly ash is included in the composition. As the reasons for this, the ground granulated blast furnace slag which is the main binder has lower alkalinity than ordinary Portland cement, and the main component of fly ash is SiO_2, which has lower alkalinity.

2.1.3 Adherence of biofouling organisms in coastal environments

In Dec. 1999, 5 t type breakwater blocks approximately 2.0 m in height were manufactured from Ferroform and concrete. These blocks were exposed in the tidal at Mizushima Port, Okayama Pref. in Seto Inland Sea in Feb. 2000. Square sections of biofouling organisms with an area of 20 cm × 20 cm were cut respectively from four locations on the wave-dissipating blocks and dried at 60°C for 24 h. The biomass of the specimens was then measured, and the species of the organisms were identified.

The changes over time in the biomass of the biofouling organism are shown in **Fig. 4**. The biomass on the concrete showed virtually no change over time, but increased with time on the Ferroform. The number of species of biofouling organisms on the concrete was small, reaching only 17 after 10 months, and then increased gradually with time, whereas a large number of species (32) were identified on the Ferroform blocks at the 10 month stage.

Ferroform is considered to provide a more suitable environment for the growth of biofouling organisms than concrete because Fe, Si, and other elements essential for the growth of organisms are contained in steelmaking slag, which is the main material of Ferroform, and the solubility of alkali components is slight.

2.2 Example of Application to Large-scale Construction

Artificial stones and cover blocks using Ferroform were manufactured and placed in a shore protection repair project at JFE Steel's West Japan Works (Kurashiki) between Sept. 2000 and Sept. 2002. A continuous-type mixer was used in mixing the materials, and the cover blocks were manufactured by pouring into forms and curing in the same manner as with ordinary concrete blocks. The artificial stones were manufactured by breaking Ferroform which had been cast in the yard into large pieces.

An example of the condition of work in the shore protection repair project is shown in **Photo 1**. In this project, the installation area covered a total length of 652 m fronting the Inland Sea. First, 36 000 t of artificial stones were deposited from the sea surface by a grab ship, and finishing forming was performed by divers. A crane ship then placed 776 cover blocks weighing approximately 10 t each. It was possible to handle the Ferroform artificial stones and cover blocks in the same manner as natural stones and concrete blocks.

When the condition of spaces between the artificial stones was investigated underwater 2 months after completion, a large number of organisms was found living in the stones. Further, 1.5 years after completion, a

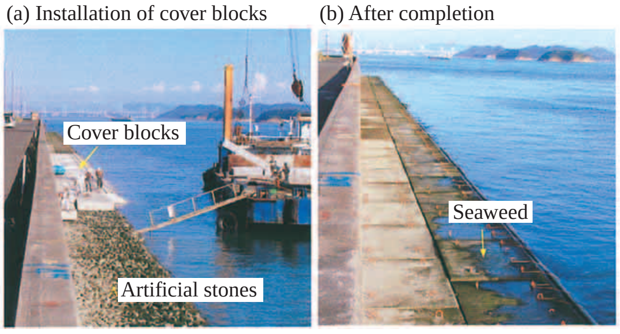

Photo 1 Execution of port and harbor construction using artificial stones and cover blocks

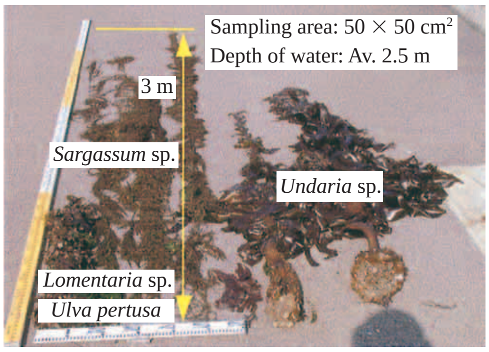

Photo 2 Adhered seaweeds on coverblock made from Ferroform at 1.5 years after completion

seaweed bed consisting mainly of sargassos (*Sargassum*) and *wakame* seaweed (*Undaria*) had formed, as shown in **Photo 2**, demonstrating that Ferroform materials are not only effective in shore protection repair, but also have a large effect in restoring the environment.

In Mar. 2003, a Manual on Steel Slag Hydrated Matrix[5)] was published as Coastal Development Institute of Technology Library No. 16. As of this writing, 170 000 t of Ferroform products have been manufactured and placed, including 2 projects under the direct control of the Ministry of Land, Infrastructure and Transport, and popularization as an environment-conscious block is expected.

3. Coastal Environment Improvement Technologies Using Iron and Steelmaking Slag

To deal with deterioration of marine and coastal environments, including sharp decreases in seaweed beds and a large reduction of marine resources resulting from overdevelopment of coastal areas accompanying high economic growth, nationwide efforts are being made to restore beautiful marine environment of Japan. As part of this, the Diet has also enacted Law for the Promotion of Nature Reclamation (law No. 148, 2002). In the Seto Inland Sea, there has been heightened interest in protecting and restoring precious nature and ecosystems occasioned by the problem of extraction of sea sand. For the future, the development of new environment restoration/creation measures corresponding to the special features of local areas is demanded.

This chapter introduces a granulated blast furnace slag sand capping material called "Marine Base" and seaweed bed substratum, "Marine Block," and an environmental improvement technology by construction of coastal shallows using a combination of iron and steelmaking slag products.

3.1 Granulated Blast Furnace Slag Sand Capping Material, "Marine Base"

3.1.1 Effect in suppressing H_2S generation

The results of measurements of the hydrogen sulfide (H_2S) concentration in slag interstitial water, etc. when granulated BF slag was placed on the sea bottom with bottom sediment[6)] are shown in **Fig. 5**. Over a 2-year period, the H_2S concentration in the slag interstitial water tended to shows smaller values than the bottom interstitial water and beach sand interstitial water. With the granulated BF slag, the pH of the interstitial water trended between 8.2 and 8.6[6)], and is therefore considered to have weakened the activity of sulfate-reducing bacteria[7)], thereby suppressing the reduction of sulfur ions in the seawater by these sulfate-reducing bacteria. This suggests that granulated BF slag has the excellent property of suppressing the generation of H_2S and thus has a greater effect than natural sand in suppressing blue tide.

3.1.2 Silicate supply effect

Granulated BF slag was placed on the sea bottom where bottom sediment had accumulated, and was covered with a container. The silicate concentration of the seawater in the container was then measured. The results showed that the silicate concentration was higher in the area where the granulated BF slag was placed than in the bottom sediment, revealing that the slag supplies silicate to the seawater[7)]. Moreover, it has been pointed out that diatoms have possibility to prevent red tide, because

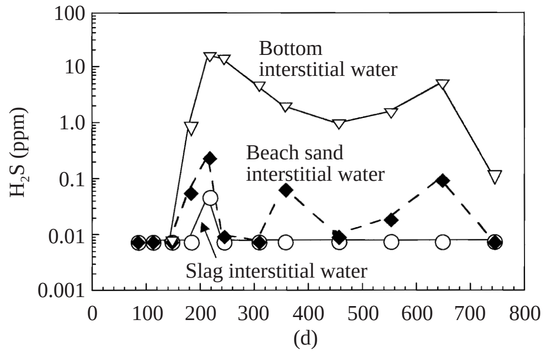

Fig.5 Change of H_2S in seawaters

they are competing species with Dinophyceae[8]. Thus, the silicate supply effect of granulated BF slag has the potential to improve marine productivity and prevent red tide caused by Dinophyceae.

3.2 Seaweed Bed Substratum, "Marine Block"

The seaweed bed substratum "Marine Block" is manufactured by molding steelmaking slag as a raw material and injecting CO_2 into the formed blocks. The microstructure of Marine Block is shown in **Photo 3**. A coating layer consisting mainly of calcium carbonate, which is the same materials as corals and seashells, exists around the slag particles with thickness of tens to hundreds micro meter. This microstructure forms a network structure that extends through the block. The mass per unit of volume of this block is 2.0–2.4 t/m^3, its porosity is 25–42%, and its compressive strength is 10–19 N/mm^2, which are similar to the properties of general porous concrete[9].

Beginning in 1997, comparison tests between Marine Block and concrete blocks were conducted at 10 marine areas throughout Japan in order to evaluate the functions as a seaweed bed substratum. A seaweed growth effect of Marine Block exceeding that of concrete blocks was confirmed in all the marine areas. **Photo 4** shows the appearance of a Marine Block placed in ocean at Jyogashima, Kanagawa Pref. photographed in July 2002, 7 months after the blocks were placed. Seaweed has grown on the Marine Block so thickly that it is impossible to see the block surface. In contrast, no seaweed has grown on the upper surface of the concrete. This phenomenone indicate that Marine Block has larger bio-affinity of the calcium carbonate on the surface.

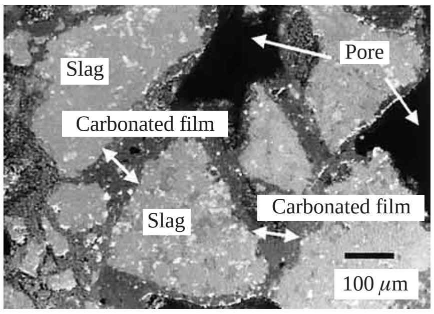

Photo 3 Microstructure of "Marine Block"

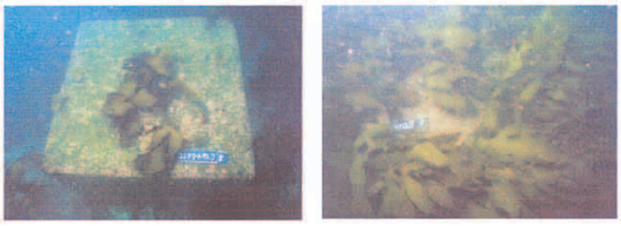

Photo 4 Comparison between "Marine Block" (1 × 1 × 1 m) and portland cement concrete block in ocean at Jyogashima, Kanagawa Pref.

3.3 Construction of Coastal Shallows Using Iron and Steelmaking Slag

3.3.1 Construction of shallows

The Mukuura area of Innoshima City, Hiroshima Pref. was used as the marine test area. In Mar. 2002, a shallows approximately 30 m × 20 m was created by laying lumps of steelmaking slag and the granulated BF slag, "Marine Base," and then 20 Marine Blocks were placed on this base (**Fig. 6**). The biological growth was then verified over a period of approximately 2 years. The construction of this model shallows was carried out as a subsidized project of the Hiroshima Pref. Environmental Industries Creation Promotion Council in fiscal year 2001.

3.3.2 Biological growth on shallows

Figure 7 shows the transition in the number of organisms, wet weight, and number of species in the granulated BF slag area and the bottom sediment area outside the shallows along with time. In the granulated BF slag sand capping area, the total number of individual observed organisms, wet weight, and number of species all greatly exceeded those in the bottom sediment

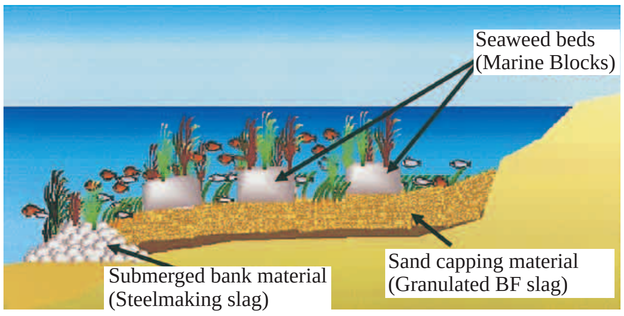

Fig. 6 Scheme of coastal environment restoration model by using steelmaking slag

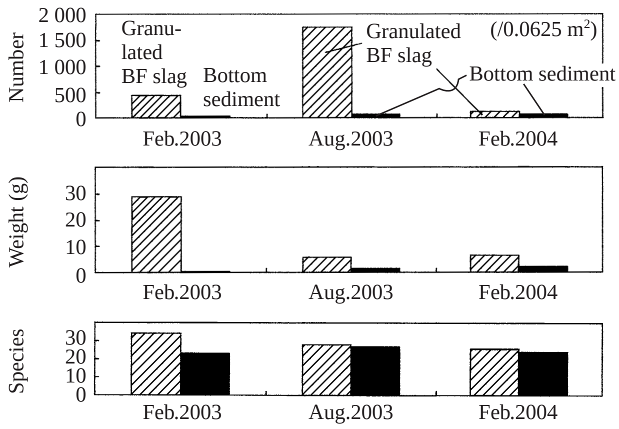

Fig. 7 Observational results of benthonic organisms

area outside the shallows.

On the other hand, a total of 12 species of seaweed was observed on the Marine Blocks, including *Sargassum horneri*, *Enteromorpha intestinalis*, *Dilophus okamurae*. In Feb. 2003, the large annual seaweeds *Sargassum horneri*, *Sargassum filicinum*, and *Sargassum muticum* had grown so large that they could be easily observed on water surface. In Feb. 2004, the *Sargassum horneri* and *Sargassum filicinum* had regrown, and large perennial brown algae (*Phaeophyceae*), *Sargassum macrocarpum* and *Ecklonia kurome* could also be observed.

These results demonstrated that coastal shallows using granulated BF slag and Marine Blocks have excellent properties for creating environments for diverse organisms, almost sam as natural shallows.

4. Water-retaining Material for Use as Heat Island Phenomenon Mitigating Pavement

The heat island phenomenon, in which the ambient temperature in urban areas is higher than that in suburban areas, is becoming a serious urban environmental problem. Artificial structures covering the ground surface, including buildings and asphalt pavement, are considered to be one of the leading causes. It has been estimated that the area and time with temperatures exceeding 30°C can be reduced by approximately 21% by countermeasures such as replacing 50% of the existing asphalt pavement with a road structure which retains water internally of it (water-retaining pavement)[10]. The JFE Steel Group developed a water-retaining material using blast furnace slag as a raw material. This material is poured into the voids in drainage-type asphalt pavement partially, that makes it possible to have water-retaining property with drainable one.

Raw materials of, water-retaining material consisting of a combination of BF slag powder and submaterials are added and mixed with water, and the resulting water-retaining slurry is placed after cured, the slurry solidifies a solidified containing innumerable pores in it. This solid has the following features.

(1) Porosity is 0.6–0.65 m*l*/g and shows a sharp pore size distribution at around 1 μm, resulting in an excellent cooling effect of road surface and its continuousness.
(2) The material is an environment-friendly recycled product made from iron and steelmaking byproducts, and harmful components do not leach out.

4.1 Partially Slurry Filled Water-retaining Pavement

Pavement produced by partially filling voids in drainage-type asphalt pavement with slurry (partially filled asphalt-slag complexed pavement, illustrated **Fig. 8**) is expected to maintain rainwater drainage and reduce noise because voids are retained in the pavement. The relationship between the slurry filling factor and water permeability is shown in **Fig. 9**. It was found that permeability is maintained up to a slurry filling factor of about 70%, but permeability is lost when the slurry filling factor exceeds 80%.

Figure 10 shows the relationship between the slurry filling factor and temperature difference between the asphalt-slag complexed pavement and a dense graded asphalt pavement. The temperature difference of them is roughly constant with the slurry filling factor exceeds 60%, and the cooling effect of 60% filling is substantially the same as with 100% filling.

A partially filled asphalt-slag composite pavement and completely slurry filled pavement in which the voids in drainage-type pavement were filled approximately 100% with the water-retaining material were constructed, and sound absorption was measured (**Fig. 11**).

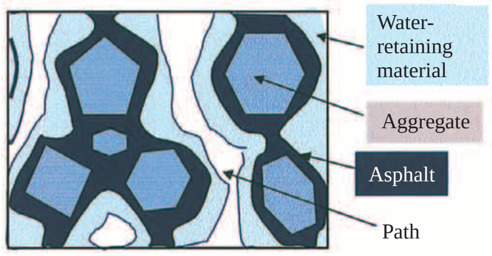

Fig. 8 Cross sectional pattern diagram of partially slurry filled asphalt-slag complexed pavement

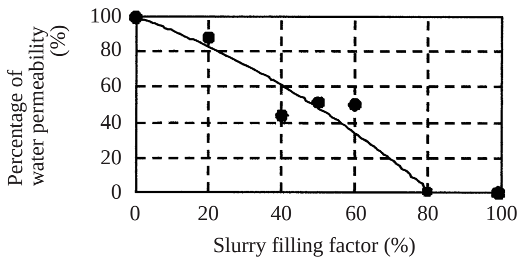

Fig. 9 Relation between slurry filling factor and water permeability

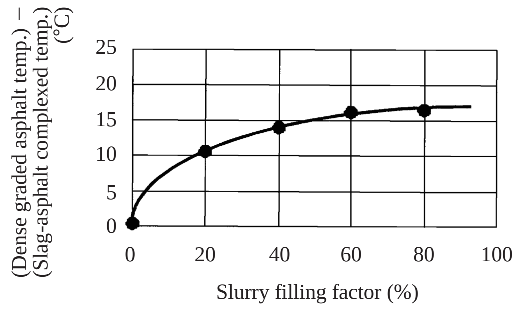

Fig. 10 Relation between slurry filling factor and temperature difference

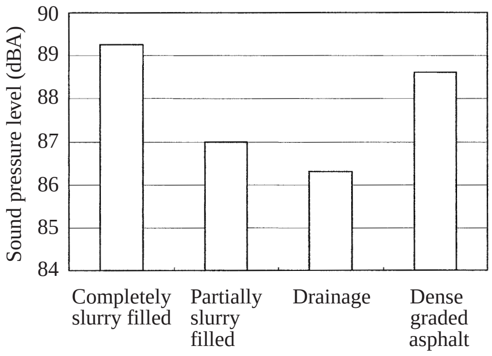

Fig. 11 Sound absorption test results of various pavements (velocity 40 km/h)

With the completely filled asphalt-slag complexed pavement, the sound pressure level showed no difference from that with dense graded asphalt pavement, but with the partially filled pavement, the sound pressure level decreased by approximately 2db, showing that a noise reduction effect is maintained.

4.2 Test of Water-retaining Pavement on Actual Road

In Mar. 2002, water-retaining pavement has been laid out to improve the road environment at the East Exit Plaza from Chiba Station of East Japan Railway Company. The workability of the water-retaining material was satisfactory, and the road was reopened to traffic 2 h and 30 min after completion of the work. Partial filling (60%) of the voids in drainage-type pavement was performed. **Photo 5** shows the appearance of the road after completion.

Thermocouples were installed in the asphalt-slag complexed pavement section and a comparison dense graded asphalt pavement section, and the road temperature was measured. The measured results on July 11, approximately 4.5 months after the construction was completed, are shown in **Fig. 12**. The maximum temperature difference of 13°C was recorded around 11:00

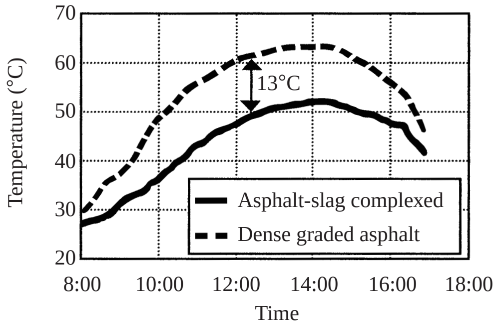

Fig. 12 Temperature surveyed at the bus lane in front of Chiba Station

a.m., and a temperature difference of more than 10°C was maintained until after 3:00 p.m., demonstrating high water-retaining performance.

As of June 2004, this material had been adopted by Tokyo, Osaka, the Japan Highway Public Corporation, and others, and further expansion is expected.

Photo 5 Asphalt-slag complexd pavement

5. Conclusion

The Japanese iron and steel industry produces approximately 36.6 million tons of iron and steelmaking slag annually. With the advent of a recycling-oriented society, effective use of this slag is becoming increasingly important.

The JFE Steel Group will continue to promote the new applications described in this paper as part of its contribution to a recycling-oriented society.

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