Environment-Friendly Block, "Ferroform," Made from Steel Slag†

MATSUNAGA Hisahiro[*1] TANISHIKI Kazuho[*2] TSUZIMOTO Kazuhito[*3]

Abstract:

A new environment-friendly block, called " Ferroform," consisting mainly of steelmaking slag (corresponds to aggregate), ground granulated blast furnace slag (corresponds to binder) was developed. Ferroform has the same strength and durability as concrete. It can be used a substitute for concrete blocks, natural stones and fresh concrete. In repair work at Mizushima Port, 150 000 t of Ferroform were used as cover blocks and artificial stones.

1. Introduction

In Japan, the Basic Law for Establishing the Recycling-based Society was enacted in 2000, which is intended to restrict consumption of natural resources and reduce environmental loads comprehensively and systematically by encouraging the efficient reuse and recycling of resources, and thus help turn today's social framework based on mass production, mass consumption and mass waste towards an environmentally sustainable society. In response to these environmental concerns, the Japanese steel industry is striving to reduce the production of steel slag, which is a byproduct of the process of steel manufacturing, and to conduct R&D on technologies for recycling this slag.

Steel slag is classified into two types according to production process: steelmaking slag and blast-furnace slag. 24.97 million tons of blast-furnace slag and 14.4 million tons of steelmaking slag were generated in Japan in fiscal 2007[1)]. Efficient recycling of blast-furnace slag has already been achieved: today, 100% of this slag is used as charge stock of Portland blast-furnace slag cement and roadbed materials, among others. Recycling of steelmaking slag, on the other hand, has made little progress even though its effective recycling rate is as high as 98%, as this slag is used for relatively low value-added applications such as temporary road materials for civil works[1)] .

Under these circumstances, JFE Steel has successfully developed a new environment-friendly steel slag hydrated matrix, called "Ferroform," consisting mainly of steelmaking slag (aggregate) and ground granulated blast-furnace slag (binder)[2,3)]. Ferroform can be used as a substitute for concrete blocks and natural stones. To date, Ferroform has been used by JFE Steel as cover blocks and artificial stones instead of ripraps in various port repair works. In addition, a technical manual[4)] describing Ferroform was published in 2003 by the Coastal Development Institute of Technology based on the results of a joint research project conducted among JFE Steel, Nippon Steel Corp., the Coastal Development Institute of Technology and the Port and Airport Research Institute. A working group on "Research on Technical Improvement of Steel Slag Hydrated Matrix" was established at the Coastal Development Institute of Technology in 2006, and a revised edition of the technical manual incorporating new knowledge was published in 2008[5)]. Artificial stone made of crushed Ferroform pieces was awarded the Certificate of Validation and Evaluation of Non-governmental Port Technology by the Coastal Development Institute of Technology in November 2007. This artificial stone was developed under a joint project among JFE Steel, Nippon Steel Corp. and Toa Corp.

This paper outlines the application technologies of

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*1 Senior Researcher Manager,
Slag & Refractories Res. Dept.,
Steel Res. Lab.,
JFE Steel

*2 Staff Manager,
Civil & Construction Sec.,
Planning Dept.,
West Japan Works,
JFE Steel

*3 Staff Manager,
Civil Engineering Materials Sec.,
Construction Materials Sales Dept.,
Construction Materials & Services Center,
JFE Steel

Ferroform in port construction works, including the underlying characteristics of this new recycling-oriented material.

2. Fundamental Properties of Ferroform

2.1 Manufacturing Process

Figure 1 shows an example of the composition of Ferroform in comparison with that of normal-weight concrete (hereafter, concrete). In Ferroform, steelmaking slag is used instead of the fine and coarse aggregates in concrete, and ground granulated blast-furnace slag (granules of molten blast-furnace slag obtained through a process of quenching, grain refining, drying and pulverizing), fly ash, and alkali activator (lime dust, slaked lime, cement, etc.) are employed instead of the cement in concrete. Of these materials, steelmaking slag, ground granulated blast-furnace slag, and water are essential. If recycled water is used, Ferroform can be manufactured entirely from recycled materials.

Ferroform is manufactured by mixing, placing and curing these materials. Since this process is the same as with concrete, concrete manufacturing equipment can be used as is without modification.

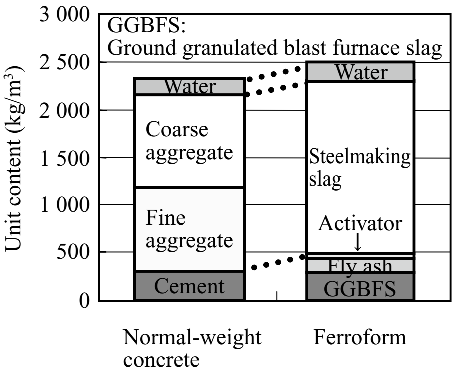


Fig. 1 Comparison between Normal-weight concrete and Ferroform

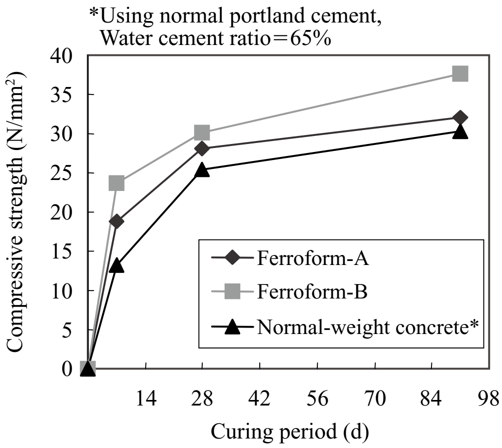


Fig. 2 Relation between compressive strength and the curing period

2.2 Strength and Density

The mixture proportions of Ferroform used in this study in **Table 1** and the relationship between the compressive strength of Ferroform and its curing period is shown in **Fig. 2**. Like concrete, the strength of Ferroform increases with age, most probably because the curing reaction of ground granulated blast-furnace slag and fly ash, which are binder materials, continues over an extended period. It is commonly known that the compressive strength of concrete is correlated to water cement (w/c) ratio[6]. The compressive strength of Ferroform can be controlled in the same way as with concrete, using the mixing proportions of its materials (ground granulated blast-furnace slag, fly ash, alkali activator, and water) as indicators[5]. The compressive strength of Ferroform can be designed up to around 35 N/mm^2 at age of 28 days. This level of strength corresponds to that of normal-weight concrete and semi-hard stones.

The mechanical properties of Ferroform, such as tensile strength, flexural strength, Young's modulus, and abrasive coefficient, also are correlated with its compressive strength in the same way as with concrete. These properties of Ferroform are shown in **Table 2** below. The tensile strength, flexural strength and other

Table 1 Mixture proportions of Ferroform used in this study

Number	Slump (cm)	Air (%)	Unit content (kg/m³)						Water reducing agent (g/m³)
			Water	GGBFS	Activator		Fly ash	Steel-making slag	
					CH	NP			
A	17.5	2.2	202	300	0	50	97	2 019	2 682
B	19.5	2.8	187	300	0	50	130	2 019	4 796
C	—	2.0	173	413	0	83	83	1 920	5 780
D	22.0	3.0	186	371	37	0	273	1 527	2 700
E	18.0	3.1	245	420	42	0	210	1 470	2 520

GGBFS : Ground granulated blast furnace slag
CH : Calcium hydroxide NP : Normal portland cement

Table 2 Comparison of various properties between Ferroform and normal-weight concrete

Item		Ferroform	Normal-weight concrete
Young's modulus*	(kN/mm²)	24	25
Tensile strength*	(N/mm²)	2.2	1.9
Flexural strength*	(N/mm²)	4.0	3.4
Abrasive coefficient**	(cm³/cm²)	0.04	0.09
Density	(t/m³)	2.4–2.6	2.3
Median pore size	(μm)	0.02	0.09

*Compressive strength 24 N/mm² **30 N/mm²

strength values indicated in the table are those measured at a compressive strength of 24 N/mm², which is the common proportioning strength of blocks. Because the values of tensile strength, flexural strength and Young's modulus of Ferroform are on the same level as those of concrete, its design strength can be the same as with concrete.

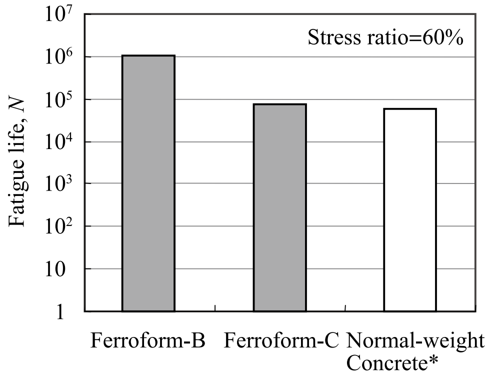
In addition, as steelmaking slag, which has a higher density than natural aggregates (density in saturated surface-dry condition: 2.8–3.6 g/cm³ for steelmaking slag; 2.7–2.8 g/cm³ for natural aggregates), is used as a material for Ferroform, it has a greater mass per unit volume than concrete, being 2.4 to 2.6 t/m³ for the standard mixture as compared with 2.3 t/m³ for normal-weight concrete. This feature of Ferroform is very advantageous when used in dynamic structures for marine applications, as it can provide excellent stability against waves in coastal environments.

2.3 Durability

When Ferroform is used in port structures, wear due to drift sand and wave impact must be considered as characteristics of durability in addition to its strength. For this purpose, the authors conducted tests to determine the abrasion resistance and flexural fatigue characteristics of Ferroform and concrete for comparison according to ASTM C418-98(ASTM: American Society for Testing and Materials).

As can be seen in Table 2, Ferroform has an abrasive coefficient smaller than concrete, and so excellent durability against wear due to drift sand can be expected in coastal environments.

Figure 3 compares flexural fatigue life characteristics between Ferroform and normal-weight concrete. In this test, fatigue life was determined by applying repeated stress equivalent to 60% of the respective flexural strength values at 7 Hz. The results showed practically equivalent flexural fatigue life characteristics for Ferroform and normal-weight concrete, therefore, it is considered that they have equivalent durability against wave impact, too.



*Using portland blast-furnace slag cement (Class B), Water cement ratio=60%

Fig. 3 Comparison of fatigue life of flexure between Ferroform and normal-weight concrete

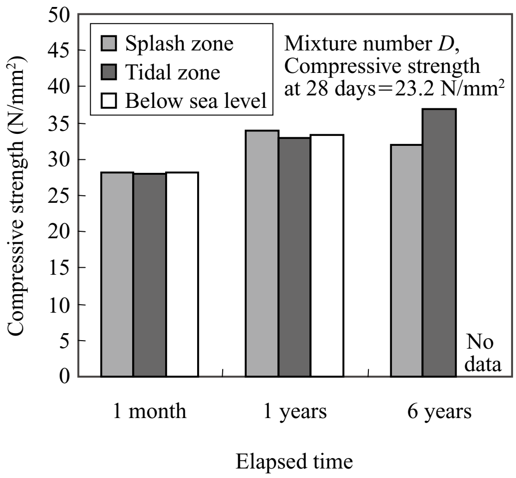


Fig. 4 Change in compressive strength of Ferroform blocks when exposed to the sea

Figure 4 shows the change in compressive strength of Ferroform test blocks (Φ125 × 250 mm) when exposed to the sea in three different conditions: splash zone, tidal zone, and below sea level[5)].

It is shown that starting from one month after exposure and during the first year, the compressive strength of test blocks increased nearly step for step in all three conditions. Then, during the second year to the sixth year of exposure their compressive strength remained practically unchanged. These results prove that Ferroform has the required durability in coastal environments.

2.4 Environmental Impact

Figure 5 shows the change in pH value of seawater after test blocks of 100 mm in diameter and 200 mm in height were immersed in artificial seawater in the laboratory (volumetric ratio; seawater : block = 10 : 1). As compared with concrete made of normal Portland cement and Portland blast-furnace slag cement, the increase in seawater pH is small with Ferroform, indicating that leaching of alkali components from Ferroform is less than from concrete. This means that Ferroform produces

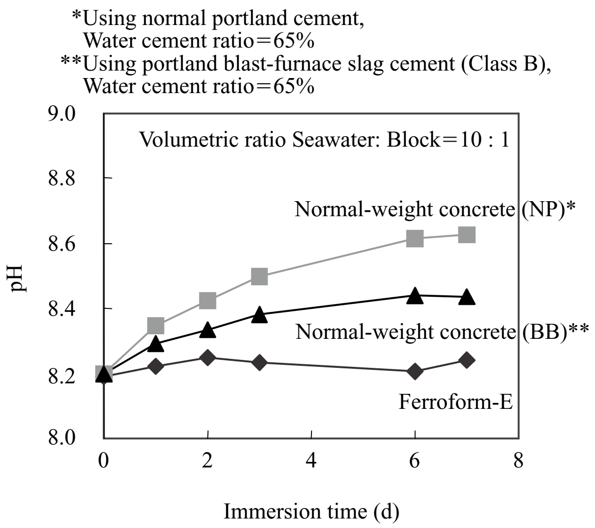


Fig. 5 Change in artificial seawater pH observed after the immersion of the test blocks in the laboratory

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

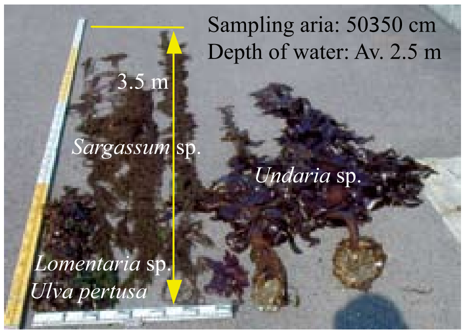


Photo 2 Adhered seaweeds on coverblock made from Ferroform at 1.5 years after completion

less environmental burden. The low level of leaching alkali components is most probably attributable to the fact that the ground granulated blast-furnace slag, which is the main binder of Ferroform, has lower alkalinity than normal Portland cement and Portland blast-furnace slag cement.

As to leaching of hazardous substances, it has been verified that both the finished Ferroform and steelmaking slag, its principal material, meet the requirements for water bottom sediments according to the criteria set forth in the Marine Pollution and Maritime Disaster Control Act of Japan.

3. Examples of Typical Application

3.1 Substitutes for Concrete Blocks and Natural Stones

About 150 000 t of artificial stones and cover blocks of Ferroform in total were manufactured and placed in a repair project of Mizushima Port, JFE Steel’s Kurashiki District, West Japan Works (construction period: 2000 to 2002). Continuous mixing equipment was used for mixing the materials, and the cover blocks (9.8 t/block) were manufactured by pouring into forms and curing in the same way as with ordinary concrete blocks. The artificial stones (10 to 200 kg/stone) were manufactured by breaking Ferroform previously cast in the yard into large pieces.

Photo 1 shows the port repair work during construction. The project covered a construction area extending for a total length of 652 m fronting the open sea. After depositing 36 000 t of artificial stones from the sea surface by a grab dredger, finishing forming was performed by divers and finally, a total of 7 760 t of cover blocks (10 t/block) were placed using a floating crane. The Ferroform artificial stones and cover blocks could be handled in the same manner as natural stones and concrete blocks during this repair project.

According to the underwater inspection we conducted in the project area after 1.5 years of completion, the formation of a natural seaweed bed mainly consisting of sargassos (*Sargassum sp.*) and wakame seaweed (*Undaria sp.*) was verified, as shown in **Photo 2**. A large number of organisms (about 15 kg/m^2 in wet weight) were found living among stones and blocks underwater in the area, including small aquatic animals, proving that Ferroform is not only useful for adherence of seaweeds but also has the effect of restoring the coastal environment through the formation of seaweed beds.

In another example of application, large slope protection blocks of Ferroform, each having dimensions of 1 000 mm × 1 000 mm × 200 mm, were used in a seawall construction project in the area of JFE Steel’s Kurashiki District, West Japan Works (construction period: 2005 to 2006). About 12 000 blocks were manufactured in four months by vibration and pressure forming and steam curing in a plant (**Photo 3**[5)]). The formability of these blocks was identical to those of concrete. As can be seen in **Photo 4**, the finished blocks were installed on the face of the slope of the seawall extending for a total length of 1 500 m.

As this example reveals, mass production of large Ferroform products is also possible using the vibration and pressure forming process.

Forming After steam curing

Photo 3 Production of Ferroform blocks for seawall

placing by concrete pump On placing

Photo 5 Execution of fill in the basement by using fresh Ferroform

Photo 4 After completion of seawall construction using Ferroform blocks

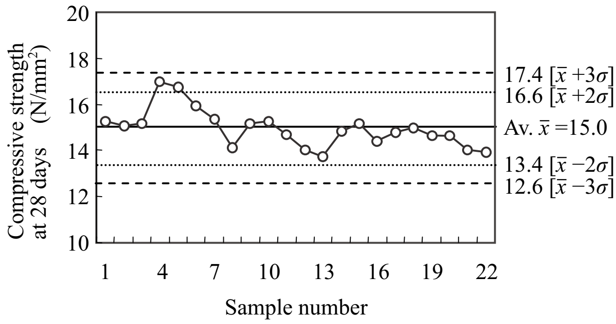


Fig. 6 Fluctuation of compressive strength at 28 days

3.2 Alternative to Fresh Concrete

Ferroform was used as an alternative to fresh concrete in the basement filling project in the area of JFE Steel’s Chiba District, East Japan Works (2003). A total volume of 3 492 m^3 of Ferroform was mixed and shipped in 13 man-days (269 m^3/day on average).

After mixing, fresh Ferroform was pumped up and fed under pressure to the site of placing at a delivery rate of 60 m^3/h and horizontal conversion distance of 150 m and using a pipe having a diameter of 125 mm, as shown in **Photo 5**. The set slump was 210 mm, which although high, did not cause separation and good pumpability was maintained.

Fluctuation in compressive strength of the fresh Ferroform used for this project, at age of 28 days, is shown in **Fig. 6**[5)]. When the proportioning strength is 15 N/mm^2, the average compressive strength is 15.0 N/mm^2 with coefficient of variation of 5%. Since the common coefficient of variation is 10% or less in a well-controlled ready-mixed concrete factory[6)], it is expected that the strength of Ferroform can be controlled to a level similar to that of concrete.

In addition to the use as substitutes for concrete blocks and natural stones in port construction works, Ferroform can also be used as an alternative to fresh concrete in basement filling projects as illustrated in this section.

4. Conclusion

The newly developed steel slag hydrated matrix, Ferroform, consisting mainly of steelmaking slag (aggregate) and ground granulated blast-furnace slag (binder), has strength and durability characteristics equivalent to those of concrete. In addition, leaching of alkali components from Ferroform is less than from concrete.

Ferroform has already been used as a substitute for concrete blocks and semi-hard natural stones in various port construction works. In addition, it can be used as an alternative to fresh concrete in basement filling projects.

The JFE Steel Group will continue to conduct research and development on new applications of steelmaking slag to help create a recycling-oriented society.

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