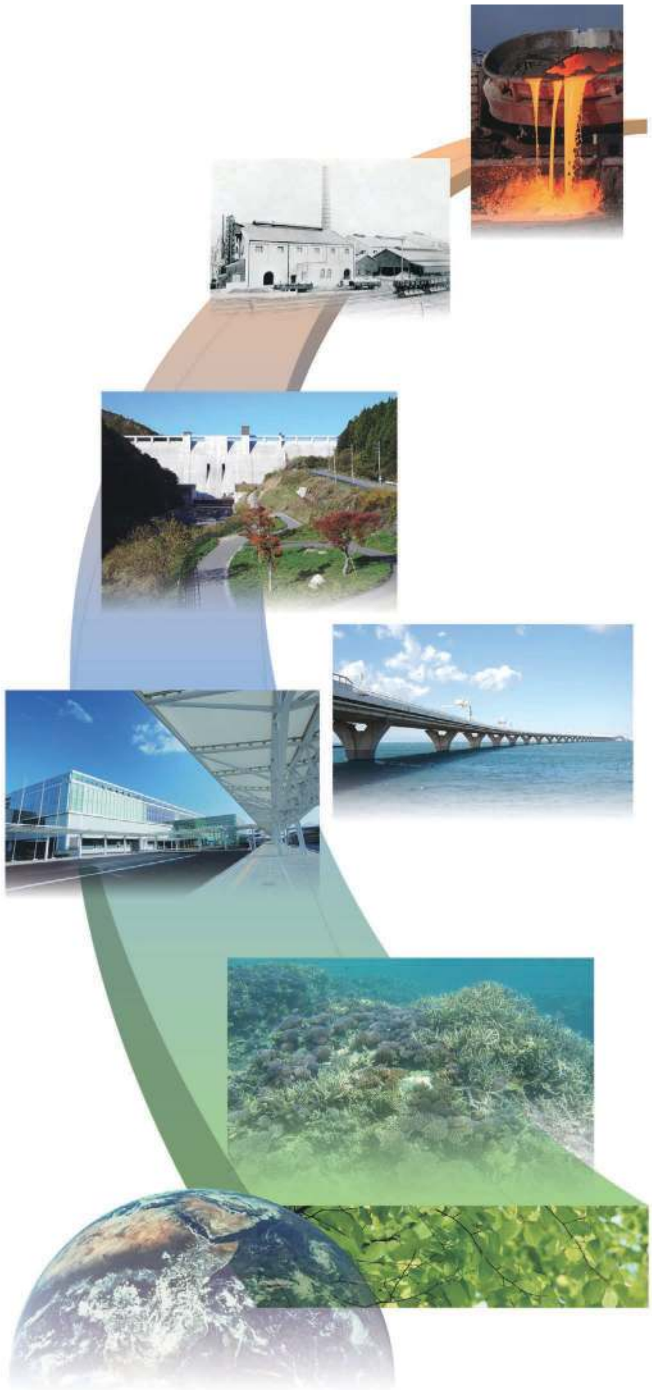
I Development of Application Technologies Gaining Attention in the Environmental and Global Era

Iron and Steel Slag: The Environmental Material for the Future



The development of iron and steel slag utilization technologies has been ongoing for about a century, primarily in the fields of cement and road construction. However, with the maturation of the economy and industry and the declining trend in new investments in social infrastructure, it is essential to develop applications and markets for iron and steel slag in order to create stable demand that meets societal needs, ensuring its continued effective use in the future. In addition to furthering the conventional use of iron and steel slag, the Nippon Slag Association is advancing development to realize the various potentials of iron and steel slag, considering the following perspectives as increasingly important.

- Utilizing the environmental restoration effects of iron and steel slag. While the application of iron and steel slag has primarily focused on reclamation in marine areas, future development themes should also include measures to address natural disasters in port areas and the restoration of lost natural marine environments. Research has shown that the iron and mineral components of iron and steel slag are effective in the environmental restoration of marine areas.
- Focusing on the importance of utilizing iron and steel slag to achieve a carbon-neutral society, and maximizing its energy-saving and CO_2 reduction effects. For example, further CO_2 reduction through the use of ground granulated blast furnace slag as a binder, as seen in blast-furnace slag cement, is expected to be one of the key measures for realizing carbon neutrality.
- Pursuing hybrid effects through the combination of various types of iron and steel slag, as well as combining iron and steel slag with other materials. These combinations will generate various advantages that cannot be achieved by individual materials alone, and are expected to be practically applicable across multiple fields.

The expansion of such uses will contribute to further advancing Japan's recycling-oriented society and promoting sustainable development. The Nippon Slag Association and its member companies will actively work to promote and expand the use of iron and steel slag, not only in public works but also in various other projects. This will be achieved with the support of various organizations, including the government, local municipalities, universities, and research institutes, while gaining the understanding of stakeholders. The following introduces recent examples of iron and steel slag utilization technology development.

1 Contribution to Marine Environment Improvement and Restoration: Creating a Rich Marine Environment with Steel

Blocks and Artificial Stone Materials Made by steel slag hydrated matrix (JFE Steel Corporation and Nippon Steel Corporation)

The steel slag hydrated matrixx were developed as an alternative to cement concrete. These recycled products are made by replacing cement with ground granulated blast furnace slag as the binder, and using steelmaking slag in place of natural stone and sand as aggregates, with the optional addition of alkaline activators or admixtures as needed. By using recycled products for nearly all raw materials, the hydrated matrix are expected to reduce CO_2 emissions during cement production and minimize the environmental impact associated with the extraction of natural aggregate.

Steel slag hydrated matrix are essentially produced using the same processes as concrete products. Mixed and poured into formwork using equipment similar to that used in concrete plants, blocks of any shape can be produced. Additionally, by crushing them after curing, hydrated matrix can be processed into stone materials of various sizes. As a result, they have been applied in port construction for wave-dissipating blocks, armor blocks, and as alternative stone materials. The track record of hydrated matrix includes block installation work by the Ministry of Land, Infrastructure, Transport and Tourism, Haneda Runway D construction, revetment restoration work following the Great East Japan Earthquake, and revetment works at various steelworks. The total usage reached over 1.4 million m^3 (as of FY 2016). The artificial stone materials (Frontier Stone® and Frontier Rock®) made by steel slag hydrated matrix have received Verification and Evaluation Report No. 22002 for port-related private technologies from the Coastal Development Institute of Technology and have been selected as designated procurement items under the Act on Promoting Green Procurement. The characteristics of steel slag hydrated matrix are as follows.

(1) Density

The density of artificial stone materials made by Steel Slag Hydrated Matrix ranges from 2.1 to 2.9 t/m^3, depending on the raw materials used and the mix design. Additionally, blocks made by Steel slag hydrated matrix typically have densities of 2.3 to 2.6 t/m^3 in the standard mix design (compared to the density of ordinary Portland concrete, which is approximately 2.3 t/m^3), giving them excellent wave stability.

(2) Mechanical characteristics

Steel Slag hydrated matrix exhibit a 28-day strength of 9.8 N/mm^2 or more, which is equivalent to natural stone categorized as semi-hard stone. With modifications to the mix design, strengths of up to 30 N/mm^2 can be achieved. As a result, they show greater potential for long-term strength development compared to ordinary concrete. In terms of bending and tensile strength, they are comparable to ordinary concrete with the same compressive strength. Additionally, they have a lower abrasion coefficient than ordinary concrete, offering superior wear resistance.

Overview of Blocks and Artificial Stone Materials Made by Steel Slag Hydrated Matrix

Item		Blocks made by steel slag hydrated matrix	Artificial stone materials made by steel slag hydrated matrix
Main uses		Deformed blocks, foot protection blocks, rubble blocks, superstructures (unreinforced concrete), etc.	Crushed stone (armor stone for mild slope revetments), backfill stone, reclamation material
Density		2.3 to 2.6 ton/m^3 (Unit volume mass)	2.1 to 2.9 ton/m^3 (Density in saturated surface-dry condition)
Compressive strength ＊28-day strength (with standard curing)		18 N/mm2 or higher is available *)	
Environmental compatibility	pH	9.0 or less **)	9.0 or less **)
	Biofouling properties	Equivalent to or greater than ordinary Portland concrete	Equivalent to natural stone materials

＊) Design strength of general deformed blocks **) Seawater as the solvent with a solid-to-liquid ratio of 1:10

(3) Low alkalinity
Since the main binder is made from ground granulated blast furnace slag, there is minimal leaching of alkaline components into seawater.
(4) Excellent biofouling properties
Since steelmaking slag, the raw material, contains many essential elements for organisms, such as iron and silica, studies have shown a tendency for it to attract a greater number and larger biomass of attached organisms compared to other materials in marine environments.
(5) Availability of stone materials in any shape and grading
In response to requests from clients and users, hydrated matrix can be produced with specified sieving and grain size distributions. For example, by adjusting the grading distribution, a shear resistance angle (φ_0) of more than 35° can be ensured, and by keeping the 10% passing sieve size (D10) at no more than 2 mm, they can be used as non-liquefiable materials.

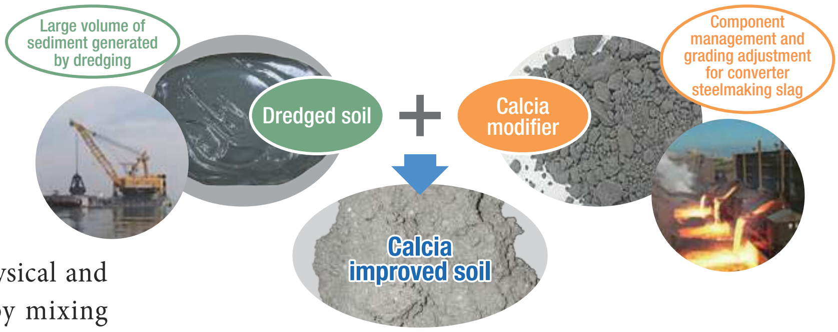
Port Repair Work Using Frontier Rock®

Revetment Reinforcement Work Using Blocks Made by Steel Slag Hydrated Matrix

Frontier Rock® before Shipping

Seaweed Attachment to Frontier Rock® and the School of White Croakers Observed

Utilization Technologies for Soft Dredged Soil (Calcia Improved Soil)



Calcia improved soil is a material whose physical and chemical properties have been improved by mixing soft dredged soil, which is generated in large quantities during waterway dredging and other works, with a Calcia modifier. This modifier is made from converter steelmaking slag that has undergone component control and grading adjustment.

When mixed with Calcia modifier, the silica and alumina components in the dredged soil react with the calcium component from the Calcia modifier through hydration and solidification, forming calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (AFm), which improve the strength of the dredged soil.

Additionally, when mixed with dredged soil, the Calcia modifier instantly absorbs the moisture in the dredged soil and acts to suppress material separation. As a result, even when Calcia improved soil is placed in seawater immediately after mixing, the generation of turbidity is reduced.

Furthermore, Calcia improved soil possesses the following characteristics, making it suitable for a wide range of applications.

• Can be shaped to form stable slopes
• Resistant to liquefaction
• Exhibits long-term durability without deterioration in seawater

For example,

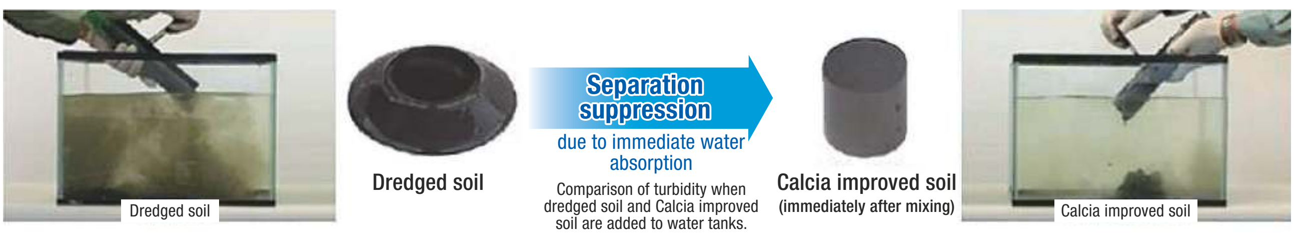
(1) When used for reclamation to construct artificial ground in the sea, Calcia improved soil allows for a shorter reclamation period due to its rapid strength development and minimal consolidation settlement.

(2) When used for shallow area and tidal flat foundation development, which serves as both a breeding and nursery ground for organisms and a site for biological water purification, Calcia improved soil allows slopes similar to those of natural shorelines to be created. Furthermore, its strength ensures that habitats for organisms (such as covering sand, artificial reefs, etc.) established on the surface remain stable.

(3) When used for partition dikes to divide a large reclamation area into sections for efficient construction, Calcia improved soil allows dredged soil to be effectively utilized not only as reclamation material but also as a replacement for the natural stone traditionally used in partition dikes.

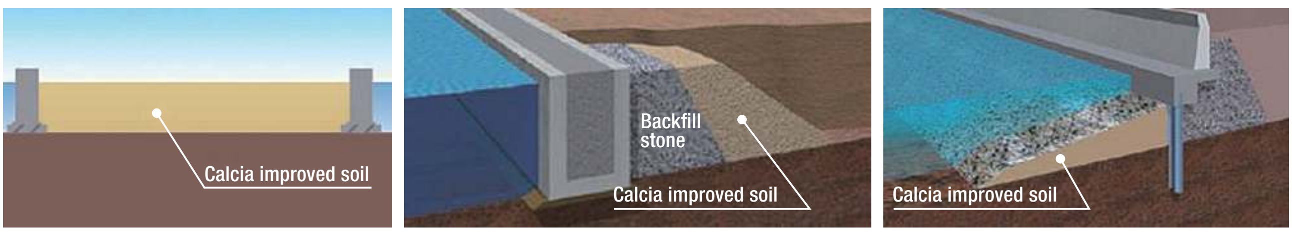
(4) When used for revetment widening to expand the rear of a revetment in order to increase its stability, Calcia improved soil not only suppresses liquefaction of the ground behind the revetment but also prevents the washout of backfill material without the need for sand protection sheets, thanks to its low permeability.

Comparison of Turbidity Suppression Effect

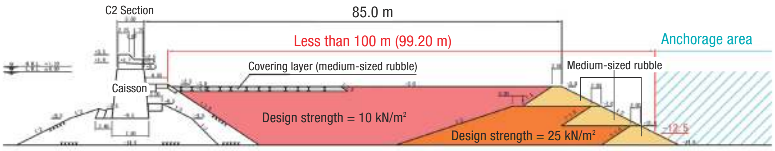


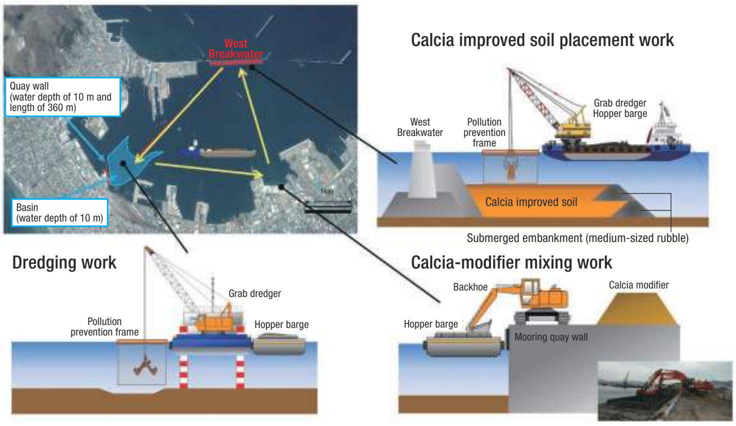
Application Examples of Calcia improved soil

(Left: reclamation material, Center: revetment widening material, Right: shallow-area and tidal flat foundation material)



Overview of 2019 Dredging Work for –10 m Basin at Wakamatsu District in Hakodate Port, Dredging Work at Wakamatsu District in Hakodate Port, Dredging Work for –10 m Basin in Hakodate Port, Dredging Work for Basin in Hakodate Port, and 2020 Dredging Work for Basin at Wakamatsu District and Other Works





Dredged soil generated in the dredging area is transported by a hopper barge to a location where it is mixed with Calcia modifier. After loosening the dredged soil with a backhoe, it is mixed with the Calcia modifier. Calcia improved soil is then placed into the concave areas behind the West Breakwater and within the dredging area. The design strength of Calcia improved soil placed behind the West Breakwater is shown in the diagram on the left.

Construction name: 2019 Dredging Work for –10 m Basin at Wakamatsu District in Hakodate Port, Dredging Work at Wakamatsu District in Hakodate Port, Dredging Work for –10 m Basin in Hakodate Port, Dredging Work for Basin in Hakodate Port, and 2020 Dredging Work for Basin at Wakamatsu District and Other Works; **Construction location:** Area 2 in Hakodate Port for dredging, and Asano and Minato Towns, Hakodate City for Calcia improved soil production, Area 2 in Hakodate Port and the area off the coast of Benten Town, Hakodate City (West Breakwater) for Calcia improved soil placement; **Construction details:** dredging work, soil modification work, soil transportation work, soil disposal work * Dredging work and Calcia improved soil mixed with Calcia modifier used for backfilling the concave areas and for constructing rear embankment; **Construction volume:** Approximately 206,000 m^3 of Calcia improved soil; **Client:** Hakodate Development and Construction Department, Hokkaido Regional Development Bureau, the Ministry of Land, Infrastructure, Transport and Tourism; **Contractor:** Toyo-Fuji Salvage Ordinary Construction Joint Venture and Sapporo Branch of Penta-Ocean Construction; **Construction period:** June 2019 to December 2020.

Calcia improved soil Placement Work Procedures Associated with Dredging Work at Wakamatsu District in Hakodate Port

1 Dredging was carried out down to a depth of 10 meters using a grab dredger. **2** The dredged soil was transported to the mixing site, where it was first loosened and then mixed with Calcia modifier. During the first of the five construction phases, a trial mixing operation was conducted over approximately one month. Based on the results, the method was revised from full-dose modifier mixing to a staged addition and mixing process, reducing the mixing time to approximately 60 minutes and improving operational efficiency. **3** A pollution prevention fence was installed around the area of Calcia improved soil placement.

The development of Calcia improved soil began with fundamental research conducted by the Japan Iron and Steel Federation as part of a subsidized project by the Ministry of Economy, Trade and Industry from FY 2004 to 2007. The usefulness and safety of Calcia improved soil, which had been confirmed through laboratory and tank tests, were also verified in actual practice through the construction of a 3,000 m^3 mound and subsequent monitoring conducted at the North Basin in Sakai City, Osaka Prefecture. The technical knowledge gained from this project was compiled in the Handbook for Utilizing Converter Steelmaking Slag in Marine Areas and its supplementary volume, Technical Data on the Method for Improving Dredged Soil by Mixing with Converter Steelmaking Slag. Furthermore, the additional knowledge gained through the large-scale 500,000 m^3 reclamation project carried out in FY 2012 contributed to the accumulation of further insights, ultimately leading to the publication of the Design and Construction Manual by the Calcia improved soil Study Group.

Since then, with the accumulation of further construction experience, the reliability of the Design and Construction Manual was validated. In FY 2016, the Coastal Development Institute of Technology published the Coastal Technology Library: Technical Manual for the Utilization of Calcia improved soil in Ports, Airports, and Coastal Areas. Following the publication of this manual, additional manuals have been developed, including the Report on Review and Evaluation of Private Technologies Related to Fisheries and Public Works: Calcia-Modification Technology, published in FY 2017 by the Association for Innovative Technology on Fishing Ports and Grounds, and the Cost Estimation Manual for the Calcia-Modified Soil Method, published in FY 2018 by the Calcia improved soil Study Group.

Calcia improved soil has now begun to be adopted in projects by the Ministry of Land, Infrastructure, Transport and Tourism. In the earthquake-resistant quay wall construction carried out by the Shikoku Regional Development Bureau in the Chuo District of Toyo Port, Saijo City, Ehime Prefecture, it was used as backfill material behind the quay wall, offering liquefaction resistance equivalent to that of miscellaneous stone. Additionally, in the dredging work carried out by the Hokkaido Regional Development Bureau at the Wakamatsu District of Hakodate Port in Hakodate City, Hokkaido, Calcia improved soil was used to construct the embankment behind the existing breakwater and to backfill concave areas.

Iron Content Supply Unit Vivary® Unit (Nippon Steel Corporation)

In recent years, a phenomenon known as “rocky-shore denudation” has been occurring along coastal areas throughout Japan, causing significant damage to coastal fisheries. Rocky-shore denudation refers to a condition in which large seaweeds such as kombu and kajime die off and disappear from rocky shores, and instead, unarticulated and articulated calcareous algae cover the rock surfaces, turning the area entirely white.

It is said that rocky-shore denudation occurs due to a combination of factors, including the rise in seawater temperature, excessive activation of herbivores caused by higher temperatures, water quality degradation, and other complex causes. One factor that is also mentioned is the decrease in the supply of humic acid iron to the sea through rivers. Iron fulvic acid was originally generated in humus formed by the accumulation of fallen leaves, but deforestation in upstream river areas has led to a reduction in its supply.

Focusing on the characteristics of steelmaking slag, which contains a high amount of water-soluble iron, Nippon Steel Corporation developed the Vivary® Unit, a system for producing humic acid iron by bagging a mixture of steelmaking slag and fermented waste wood chips. By utilizing this unit, the company is working on the restoration of “sea forests” in coastal areas where iron deficiency has made it difficult for seaweed to grow.

In order to confirm the iron supply effect of the Vivary® Unit, the Marine Greening Association, which promotes industry-academia research on sea forests, has conducted real-world sea area experiments for marine greening across the country, starting with the experiment in Mashike Town, Hokkaido, in 2004, in collaboration with the University of Tokyo and other institutions. In the experiment in Mashike Town, it was confirmed that the Vivary® Unit helped kombu grow abundantly on the sea bottom, which had previously been covered entirely by unarticulated calcareous algae, turning the sea bottom completely white. Within about six months of placing the unit, kombu was seen thriving as far as 30 meters offshore. Additionally, in the subsequent large-scale demonstration project, the Vivary® Unit successfully helped kombu grow along a 300-meter stretch of coastline, extending up to about 50 meters offshore. As a result of this marine greening, it was confirmed that the sea urchin catch nearly doubled, contributing to the promotion of fisheries.

Furthermore, in the report published by the United Nations Environment Programme (UNEP) in October 2009, the carbon incorporated into coastal ecosystems, such as the sea forests created by the Vivary® Unit, was named “blue carbon.” Since then, the Vivary® Unit has gained attention as a new carbon dioxide absorption strategy aimed at achieving carbon neutrality. Currently, Nippon Steel Corporation is conducting research on blue carbon, focusing on how the sea forests that the Vivary® Unit has created can contribute to the realization of carbon neutrality.

Growth of Kombu after the Experiment

Large-scale Demonstration Project in Mashike Town, Hokkaido

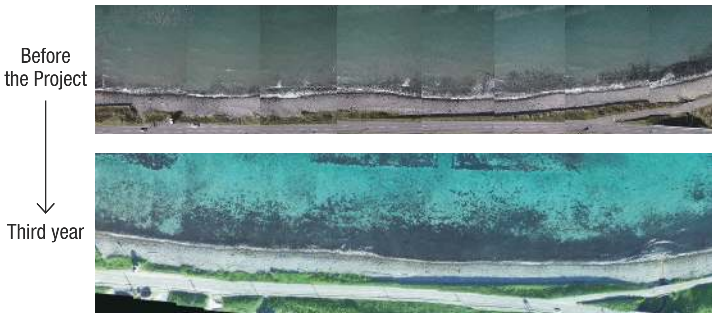
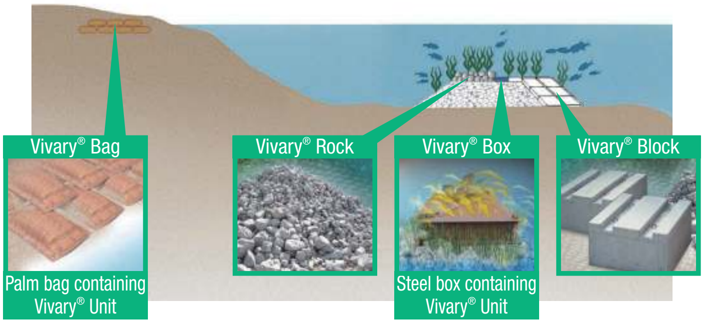


Image of Seaweed Bed Formation Utilizing Iron and Steel Slag Products Including Vivary® Unit



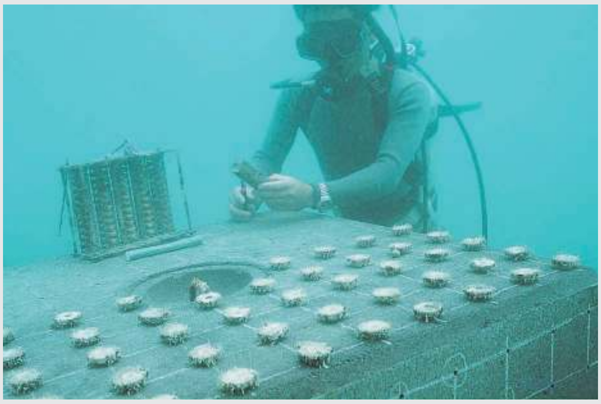
Iron and Steel Slag Carbonated Matrix Marine Block® (JFE Steel Corporation)

Marine Block® is a solidified block produced by exposing steelmaking slag to CO_2-containing gas, causing calcium carbonate to form through the reaction between calcium oxide in the slag and CO_2, which then binds the slag particles together. As calcium carbonate is a component of seashells and coral, Marine Block® is highly compatible with marine organisms and is expected to be used in the creation of artificial coral reefs and seaweed beds. Additionally, by using CO_2-containing gas during production, Marine Block® can contribute to CO_2 emission reduction.

In recent years, coral reefs worldwide have been facing a serious crisis due to factors such as the inflow of sediment from land, the explosive increase in predators like the crown-of-thorns starfish, and the rise in seawater temperature associated with global warming. Using artificial coral reefs with coral larval attachment tools fixed to Marine Block®, JFE Steel Corporation has conducted demonstration research on coral reef restoration. In the demonstration experiment on Miyako Island, it was confirmed that coral larvae had attached to Marine Block®, and coral (Acropora formosa), which had grown to about 20 cm in size after 3.5 years, was present. Additionally, as Marine Block® is porous and steelmaking slag, the raw material for the block, contains nutrient components such as iron and silica, its effectiveness as a substrate for seaweed attachment has been confirmed. Therefore, JFE Steel Corporation is promoting efforts to expand the use of Marine Block® as a substrate material that contributes to the creation and restoration of underwater forests and the enhancement of fishery resources.

Regarding the basic characteristics of Marine Block®, the Waterfront Vitalization and Environmental Research Foundation has published the “Manual for Iron and Steel Slag Carbonated Matrix,” which is used as a guide for its application.

Efforts to Restore and Improve Marine Environments Using Marine Block®



Installation of Coral Larval Attachment Tools on Marine Block®

Growth of Kajime on Marine Block®
(Jogashima, Kanagawa Prefecture)

Tropical Fish Gathering Around “Pocillopora Coral”
(Miyako Island, Okinawa Prefecture)

Acropora formosa Growing to a Diameter of 20 cm
(Miyako Island, Okinawa Prefecture)

2 Contribution to a Low Carbon Society

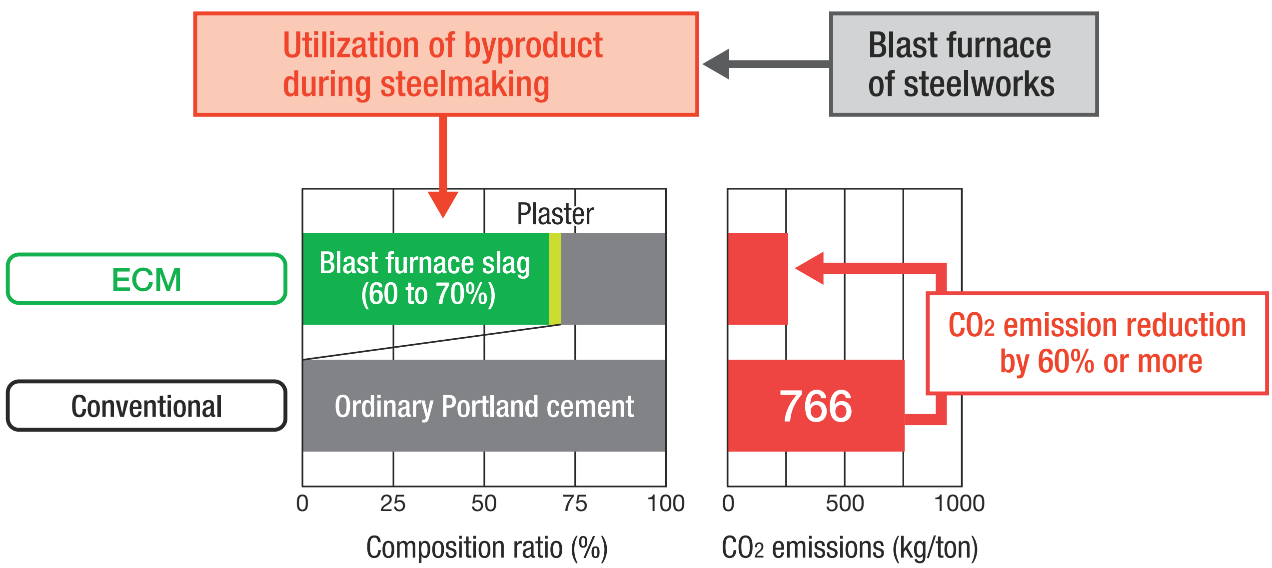
ECM (Energy and CO_2 Minimum) Cement and Concrete Systems

It is estimated that approximately 4% of all greenhouse gas emissions in Japan are derived from the cement industry, with the majority of these emissions occurring during the production of clinker, an intermediate product of Portland cement, through the calcination of limestone. Therefore, in order to reduce the environmental impact of concrete construction as a whole, there have been efforts to reduce energy consumption during cement production by replacing Portland cement with low-environmental-impact materials such as ground granulated blast furnace slag or fly ash, thereby significantly lowering the clinker content in cement. The ECM Cement and Concrete Systems introduced here are examples of low-environmental-impact cement. Efforts to use admixtures as environmental measures in the construction industry are summarized in the brochure titled "Toward the Popularization and Promotion of Low-Carbon Concrete" (*1) published by the Japan Federation of Construction Contractors.

The ECM Cement and Concrete Systems refer to a system for producing and constructing concrete using ECM (Energy and CO_2 Minimum) cement, in which ground granulated blast furnace slag accounts for approximately 60 to 70% of the cement and serves as the primary raw material for hydration. Conventionally, using cement with a high ground granulated blast furnace slag content presented challenges in terms of workability and quality. Therefore, in the development of the ECM Cement and Concrete Systems, ground granulated blast furnace slag was not simply mixed in as a material. Instead, the development focused on a comprehensive solution to the challenges by integrating cement technologies to adjust the chemical composition and grading distribution of ground granulated blast furnace slag, optimizing admixtures, and advancing construction technologies using these innovations. This development was carried out by an industry-academia research team (*2) as a NEDO subsidy project. As a result, the ECM Cement and Concrete Systems succeeded in reducing energy consumption and carbon dioxide (CO_2) emissions in cement production by more than 60% compared to conventional cement production.

Additionally, beyond the reduction in energy consumption and CO_2 emissions, the ECM Cement System has the following characteristics, which have made it applicable to underground building structures, civil engineering structures, ground improvement materials, and other uses.

Estimated CO_2 Emission Reduction by ECM Cement



(1) ECM Cement and Concrete Systems have low hydration and heat generation compared to conventional blast-furnace slag cement, making them highly resistant to thermal cracking.
(2) ECM Cement and Concrete Systems have low drying shrinkage, effectively suppressing shrinkage cracks.
(3) ECM Cement and Concrete Systems have high chemical resistance to chlorides and acids, making them suitable for structures in areas affected by seawater or those using anti-freeze agents.

As a result, the ECM Cement and Concrete Systems have received several awards, including the National Land Technology Development Award from the National Institute for Land and Infrastructure Management, and their widespread adoption is expected to continue growing in the future.

Placement of ECM Concrete

ECM Concrete, which can extend the service life of reinforcing bars by 1.5 times against corrosion due to salt damage, was applied to the concrete structure constructed on the quay wall.

Example of a Pile Using ECM Cement and Concrete Systems

Example of Applying ECM Cement and Concrete Systems to Slab

(＊1) The Environment Committee of the Japan Federation of Construction Contractors, April 2016, http://www.nikkenren.com/publication/detail.html?ci=237

(＊2) Tokyo Institute of Technology, Takenaka Corporation, Kajima Corporation, DC Corporation, Nippon Steel & Sumitomo Metal Blast Furnace Slag Cement (Currently Nippon Steel Blast Furnace Slag Cement, Taiheiyo Cement, Nippon Steel and Sumitomo Metal Cement (Currently Nippon Steel Cement)), and Takemoto Oil & Fat