Technical Review

Nippon Steel Corporation's Construction Products and Technologies for Carbon Neutral Buildings and Infrastructures

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Abstract

Steel products offer extremely high recyclability and the highest strength to weight ratio of any building material. These characteristics also have a huge potential to mitigate CO_2 emission in building and infrastructure construction. Pursuing the best combination of high strength/performance steel products and their engineering design technologies as well as innovative processes of steel production could provide a solution for carbon neutral building and infrastructure construction.

1. Social Trends Toward Carbon Neutrality and Carbon Neutrality Initiatives of Nippon Steel Corporation

In October 2020, then Prime Minister Suga delivered a policy speech and declared that Japan would go carbon neutral by 2050. After his declaration, Nippon Steel announced its "Carbon Neutral Vision 2050" in March 2021 and published a roadmap of measures for achieving the carbon neutral goal.[1] Steel products are used in all sectors, including automobiles, energy, social infrastructure, and home appliances. The steel industry accounts for 14% of Japan's total CO_2 emissions (including CO_2 emissions from the generation of electric power used for steel production). It is essential to take initiatives to become carbon neutral while meeting the steel demand that will increase with the increasing population and improving living standards throughout the world.[2]

Nippon Steel's "Carbon Neutral Vision 2050" aims to reduce the total CO_2 emissions by 30% by 2030, starting from 2013, and to become carbon neutral by 2050. With blast furnace steelmaking, CO_2 is inevitably emitted from the iron ore reduction process. It is necessary to change the steelmaking process itself to turn carbon neutral. As specific measures, we will develop and deploy three super-innovative technologies: (1) production of high-grade steel in large electric arc furnaces, (2) COURSE50 (including Super COURSE50), and (3) a 100% hydrogen-based direct reduction process. We will also reduce CO_2 emissions from our existing processes and power plants, build efficient production systems, and introduce outside technologies such as CCU and CCS. We plan to implement these measures based on the roadmap shown in **Fig. 1**. Nippon Steel announced that it would start selling the NSCarbolex™ Neutral steel products certified as having reduced CO_2 emissions through Nippon Steel's carbon neutrality measures.[3] An environment is emerging where steel products sequentially embodying the results of Nippon Steel's carbon neutrality measures can be utilized.

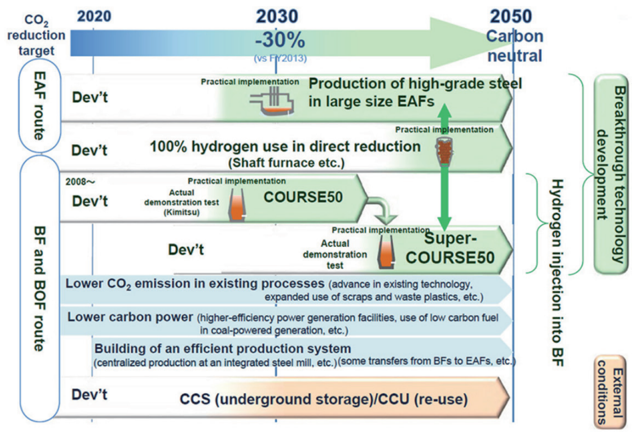

Fig. 1 Roadmap of reduction measures for CO_2 emissions

In the construction sector, measures are implemented to save energy consumption and to introduce renewable energy. In addition to these measures in the operation stage, there are mounting needs to determine and reduce CO_2 emissions throughout the entire supply chain, including the construction stage of buildings and facilities and the manufacturing stage of construction materials. Among these trends, Nippon Steel is required to implement the above-mentioned long-term carbon neutrality measures, to disclose CO_2 emissions

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from the manufacture of current steel and building material products, and to contribute to the reduction of CO_2 emissions from steel structures by employing its unique high-performance steels and utilization technologies. In this article, we present the possibilities of Nippon Steel's high-performance steel products and utilization technologies through the trial calculation of CO_2 emissions from steel structures as technical standpoints towards achieving carbon neutrality by using Nippon Steel's steel and slag products. Our initiatives to utilize steel slag and cement products as construction materials are also introduced.

2. Recyclability and CO_2 Emission Intensity of Steel Products

Almost all steel products are recovered as scrap, removed of most impurities, and reused as substitutes for natural resources. A closed-loop recycling is adopted so that steel products can be recycled and reused any number of times. Recycling is inseparable in the life cycle of steel products. ISO 20915 and JIS Q 20915 specify the methods to consider this recycling effect in the environmental impact calculation. When the recycling effect is considered according to these calculation methods, blast furnace steel and electric arc furnace steel are equivalent in their environmental impact. The emission intensities of greenhouse gases, etc., of Nippon Steel's steel products calculated based on these standards are published by environmental labels or EcoLeaf environmental product declaration (EPD) labels[4] as specified in ISO 14025. CO_2 emission intensities that reflect the recycling effect of Nippon Steel's steel products can thus be reflected in the CO_2 emission assessment of structures built from Nippon Steel's steel products.

Since 2019, Nippon Steel has been acquiring EcoLeaf EPD and now has 41 of them (accounting for more than 80% of Nippon Steel's steel products). The EcoLeaf EPD of steel products disclose the emission intensities of various environmental impact substances from resource mining to product manufacturing and the above-mentioned recycling effect of steel products. These emission intensities are about half of the CO_2 emission intensities from resource mining to manufacturing phase only. ISO 20915 and JIS Q 20915 were standardized in 2018 and 2019, respectively. The Greenhouse Gas Protocol is a de facto standard for calculating greenhouse gas emissions from an organization's supply chain, for example. In the Greenhouse Gas Protocol, however, the offset effects like the recycling effect must not be included in the calculation and must be separately stated. This is the same for many other emission standards. To evaluate the environmental performance of steel more accurately, it is desirable that the recycling effect should be included in the calculation of CO_2 emissions from steel production.

Steel products have high strength in addition to the recyclability described above. When structures of the same strength are built from different materials, they vary greatly in the amount of materials used. For example, the CO_2 emission intensity per unit mass[5, 6] of steel (steel shapes with the recycling effect considered) and ready-mixed concrete is 0.874 ton-CO_2/ton and 0.134 ton-CO_2/ton, respectively, as shown in **Table 1**. The strength of steel is about 10 times that of commonly used concrete, however. When the two materials are compared in terms of the CO_2 emission intensity per unit mass divided by the material strength or by the CO_2 emission intensity per unit strength, it is 0.0037 ton-CO_2/ton·MPa (0.874 ton-CO_2/ton ÷ 235 MPa) for the steel shapes and 0.0056 ton-CO_2/ton·MPa (0.134 ton-CO_2/ton ÷ 24 MPa) for the ready-mixed concrete. In other words, the steel shapes are equally or less polluting than the

Table 1 CO_2 emissions intensity

Materials	CO_2 intensity (ton-CO_2/ton)		
	JISF (2018)[5]		MOE Database[6]
	Including recycling	Without recycling	
Steel shapes	0.874	1.618	–
Steel plates	0.857	2.110	
Steel bars	0.753	1.541	
Ready mixed concrete	–	–	0.134

ready-mixed concrete. When we discuss the CO_2 emissions from structures, we must evaluate the CO_2 emission intensity of steel by considering the recyclability of steel described in this chapter and must have discussions based on the amount of materials used in actual structures. In the next chapter, we describe the possibility of utilizing high-performance steel and utilization technologies through an example of estimation.

3. Contribution of Steel and Utilization Technology to Reduction of CO_2 Emissions from Structures

3.1 Estimation of CO_2 emissions in office building

The CO_2 emissions of buildings are evaluated in the stages of design, construction, operation, renovation, and demolishment. The CO_2 emissions in the construction stage are related to the manufacture of building materials and on-site construction. They account for a proportion that cannot be ignored when considering the environmental impact throughout the life cycle of the building. Nippon Steel has commercialized building material products and technologies that contribute to structural weight reduction of a building and construction rationalization. These can also provide effective measures for reducing the CO_2 emissions in the construction stage. In this section, we estimate CO_2 emissions from a mid-rise office building in the construction stage and describe the direction of efforts to reduce the CO_2 emissions with Nippon Steel's products and technologies. **Table 2** shows details of the studied office building. The studied model is an eight-story office building with a building area of 879 m^2 and a total floor area of 7030 m^2, which was based on the standard office model shown in Reference 5) and redesigned to comply with present design standards.[6] **Figure 2** shows a typical floor plan as well as column and pile layout plans. The building is designed as steel moment resisting frames on both the X and Y planes. The structural members consists of cold press-formed square steel columns (BCP325B) for the columns, hot-rolled H-shaped beams (SN400B and SN490B) for the beams, and rotary press-in steel pipe piles (SKK490) for the foundation.

The CO_2 emissions related to the manufacture of materials in this study are calculated by multiplying the amount of materials used in the structure by their CO_2 emission intensity. The values shown in Table 1 are used as the CO_2 emission intensity values of steel, concrete, and cement. The values published by the Japan Iron and Steel Federation[7] are used as the CO_2 emission intensity values of steel. The CO_2 emission intensity values of steel are studied in two cases with and without consideration of the recycling effect. The CO_2 emission intensity of ready-mixed concrete is determined from the database of the Ministry of the Environment.[8] The CO_2 emission intensity values given in Reference 5) are used as those of materials other than steel and concrete. The CO_2 emission intensity values related to the fabrication and construction of the steel members skeleton are assumed to be 0.025 ton-CO_2/ton and 0.037 ton-CO_2/m^2 by referring to References 9) and 10), respectively.

Figure 3 shows CO_2 emissions in the construction stage of the subject building. When the recycling effect is considered in the CO_2 emission assessment, the CO_2 emissions of the building and piles as a whole are about 65% of the CO_2 emissions when the recycling effect is not considered. As described above, one challenge in assessing the environmental impact of steel products is whether or not the CO_2 emissions from the production of steel are assessed by considering the recycling effect.

Table 2 Details of the studied office building

Location		Tokyo
Use		Office
Structure		Steel MRF structure
Area		Commercial zone, Fire protection zone
Number of stories		8-story
Site area		1125.60 m^2
Building area		879.75 m^2
Total floor area		7030.57 m^2
Typical floor area		879.75 m^2
Building height		30.6 m (PH32.9 m)
Finishing material	Floor	Granite
	Cladding	Aluminum curtain wall, Extraction molded cement panel
	Roof	Asphalt waterproofing layer

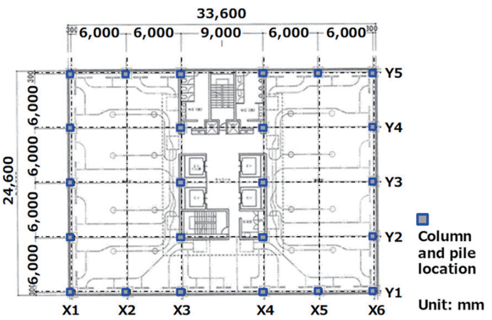


Fig. 2 Typical floor plan and column location based on reference 6)

3.2 Estimation of CO_2 emissions from bridge foundation piles

In this section, we introduce estimation examples[11)] of CO_2 emissions in the construction stage of bridge foundation piles. From 2013 to 2016, the Ministry of Land, Infrastructure, Transport and Tourism worked on the development of a method for quantitatively determining the CO_2 balance throughout the life cycle and summarized the results in a report.[11)] The guide appended to the report[11)] (hereinafter referred to as "the guide") compares bridge foundation construction methods in the approximate design stage and describes their total CO_2 emissions and CO_2 emission sources.

The study results of the guide are summarized in **Table 3**. The subject bridge foundation is the foundation of a high reinforced concrete (RC) pier in a bay area bridge section. Five methods, or inner-excavation steel pile, steel-concrete composite pile, soil-cement composite steel pile, cast-in place pile, and screw pile methods, are compared. As shown in Table 3, the five methods differ in the required diameter and number of piles depending on their design characteristics. Accordingly, they also vary in the size of the foundation footing. The estimation of CO_2 emissions covers the entire foundation construction process from the collection of materials to the completion of construction and applies to one bridge foundation. **Figure 4** shows the estimation results. The CO_2 emissions derived

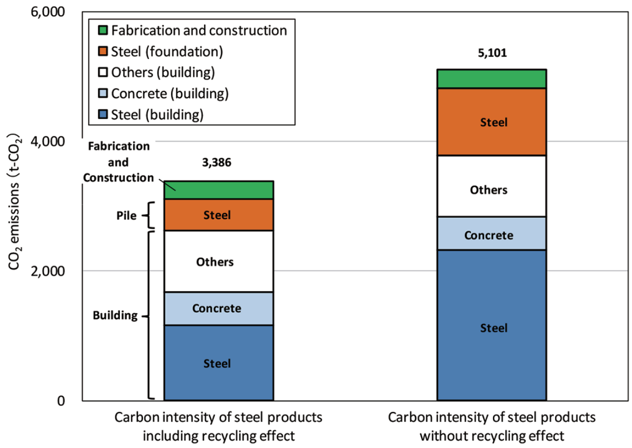


Fig. 3 CO_2 emissions from the studied office building

Table 3 Specifications and CO_2 emissions for each method based on reference 11)

	Inner-excavation steel pile	Steel concrete composite pile	Soil-cement composite steel pile	Cast-in-place pile	Screw pile
Pile dimensions					
Pile diameter	ϕ1000	ϕ1000	ϕ1200	ϕ1500	ϕ1200
Pile length	19.5 m	19.0 m	19.0 m	18.5 m	19.0 m
Pile number	32	32	16	16	18
Footing size					
TR direction	14.5 m	14.5 m	11.0 m	14.3 m	14.4 m
LG direction	14.5 m	14.5 m	11.0 m	14.3 m	11.4 m
Height	3.5 m	3.5 m	3.5 m	3.5 m	3.5 m
CO_2 emissions					
Footing	243	243	140	236	190
Piles	282	455	267	234	171
Sum	525	698	407	470	361

from materials account for about 90% of the total CO_2 emissions for all five methods. The guide uses 0.799 ton-CO_2/ton as the CO_2 emission intensity for steel products. This value is close to the above-mentioned CO_2 emission intensity with consideration of the recycling effect. We think that there is no problem in interpreting it as an estimation with recycling considered.

When the five methods are compared, the CO_2 emissions are smallest at 361 ton-CO_2/foundation for the screw pile method, followed by 407 ton-CO_2/foundation for the soil-cement composite steel pile method, and 470 ton-CO_2/foundation for the cast-in place pile method. These three methods characteristically use a small number of piles per foundation or about half the number of piles used by the inner-excavation steel pile method and the steel-concrete composite pile method. In the guide, the soil-cement composite steel pile method with the second lowest CO_2 emissions is selected as the best method by taking its economic efficiency into account. The soil-cement composite steel pile method produces about 13% more CO_2 emissions than the screw pile method with the lowest CO_2 emissions but helps to reduce CO_2 emissions by 42% as compared to the steel-concrete composite pile method with the most CO_2 emissions.

This study confirms that most of the CO_2 emissions from the installation of the foundation piles are derived from materials and that the CO_2 emissions greatly vary with the pile construction method selected. The selection of construction methods and technologies, not limited to foundation construction, has been determined mainly based on initial construction costs, site conditions, and construction period. The CO_2 emissions will be considered in the future selection of construction methods and technologies.

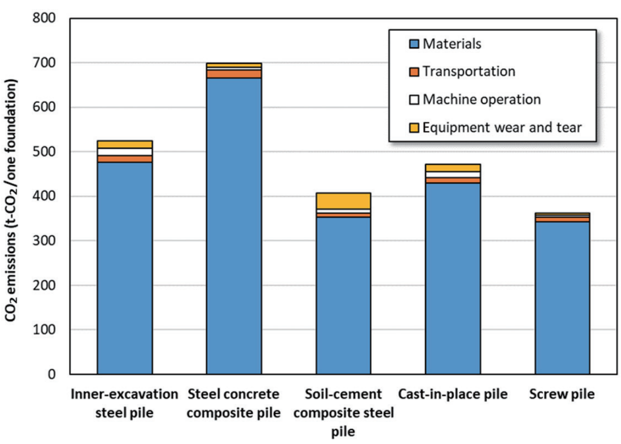
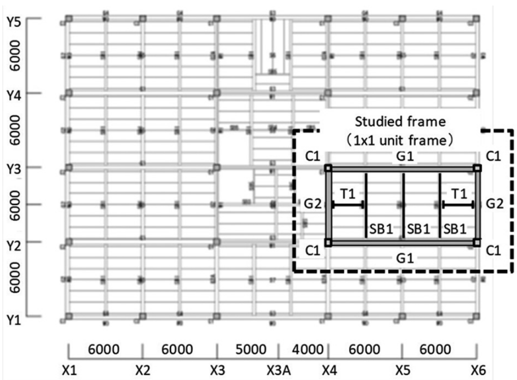


Fig. 4 CO_2 emissions of 5 pile methods and its sources[based on reference 11)]

3.3 Possibilities of high-performance steels and utilization technologies

The application of Nippon Steel's high-performance steel and utilization technologies can be expected to further reduction of the CO_2 emissions from the steel structures described in the previous section.

For steel frame buildings such as office buildings, the CO_2 emissions can be reduced first by reducing steel weight. NSHYPER BEAM™ H-shaped beams with constant outside dimensions and used as beams are available in more sizes than JIS-sized H-shaped beams. Optimum cross sections can be selected to suit design requirements. NSYP™345B has a specified design strength 20 N/mm^2 higher than that of the conventional standard SN490B beams. NSHYPER BEAM™ features an excellent weight efficiency with thin webs and compact flanges. The beam end web stiffening method and the lateral bracing elimination method can make the most of the performance of NSHYPER BEAM™. The weight of girder members can be reduced further by the combination of NSHYPER BEAM™ with these methods. The steel weight can also be reduced by use of high-strength cold press-formed square steel columns UBCR365 and cold press-formed square steel columns BCHT385 and BCHT440 as column members and by use of welded light-weight H-shaped beams SMart BEAM™ as beam members. The lateral bracing elimination method reduces the steel weight by eliminating the lateral buckling stiffeners of girders. This method can also be expected to reduce the CO_2 emissions by rationalization of steel frame fabrication and on-site construction, such as reduction of bolted and gusset plate connections and reduction of the number of lifting operations on the construction site. NSHYPER BEAM™ and cold press-formed square steel columns can eliminate the assembling and welding operations required for built-up H-shaped beams and welded built-up box columns. The CO_2 emissions in the steel fabrication stage can be reduced by the reduction of welding material usage and reduction of fabrication operations. **Figure 5** shows an example of the study of CO_2 emission reduction achieved over a 1 × 1 span of the structural members in the office building described in Section 3.1. The weight of steel members (columns, girders, and beams) used in the subject structural frame and the CO_2 emissions associated with the steel members are reduced by about 13% each by application of the above-mentioned high-performance steel products and utilization technologies. In the future, we will proceed with



Members	Designation	Original design	Proposed design
Girder	G1	HY-700×300×12×25 (SN490B)	HY-800×250×12×25 (SN490B) *Stiffened beam-end web construction method
	G2	HY-550×300×16×28 (SN490B)	HY-600×300×12×25 (NSYP345B)
Beam	SB1	H-400×200×8×13 (SS400)	LH-450×200×4.5×9 (SWH400)
Lateral brace	T1	H-250×125×6×9 (SS400)	– *Lateral stiffener omission construction method
Column	C1	□500×22 (BCP325B)	□500×19 (UBCR365)
Steel weight		12 134 kg	10 521 kg (13% reduction)
CO_2 emissions		10 529 kg-CO_2	8 190 kg-CO_2 (13% reduction)

Fig. 5 A case study of CO_2 emissions reduction utilizing high performance steel products and technologies

quantitative evaluation of these CO_2 emission reduction effects.

In the examples of bridge foundation piles discussed in Section 3.2, the steel pipe pile methods were confirmed to be relatively effective in reducing CO_2 emissions. Nippon Steel has NS ECO-PILE™ as a screw pile method with the lowest CO_2 emissions. The NS ECO-PILE™ method can reduce the environmental impact with no soil removal, no vibration, and low noise. The Gantetsu Pile™ method is available as the best soil-cement composite steel pile method in terms of economic efficiency and has been employed in very many construction projects. The TN-X method is available as an inner-excavation method in the building sector. An enlarged bulb with a maximum height of 2400 mm is formed at the bearing end to deliver a maximum bearing capacity of 17900 kN. The TN-X method is effective in further reducing the number of piles used and the CO_2 emissions generated.

In this section, we have presented estimations of CO_2 emissions in the construction stage for several structures and showed the possibilities of reducing CO_2 emissions from the structures by use of Nippon Steel's high-performance steel products and utilization technologies. The CO_2 emissions can be effectively reduced further by use of high-performance steels that meet the needs of improving the safety of steel structures and of reducing the steel weight of steel structures and by application of the utilization technologies that make the most of these characteristics. In addition to the reduction of CO_2 emissions by the innovation of steelmaking processes, it is important to provide solutions to minimize the CO_2 emissions from steel structures by combining high-performance steel products and utilization technologies. We will tackle the reduction of the steel weight of steel structures and the reduction of steel fabrication and on-site construction operations as measures for reducing the CO_2 emissions, advance steel products and utilization technologies, expand the application of steel products and utilization technologies, and fulfill the needs for reducing the environmental impact to realize carbon neutrality.

4. Contribution to Low-Carbon Society by Use of Steel Slag and Cement

Steel slag is a by-product of the process where iron is reduced from iron ore and refined. In recent years, about 38 million tons of steel slag has been produced per year and 99% is used as steel slag products for construction materials, agricultural fertilizers, etc.[12] The history of steel slag utilization in Japan spans about 100 years. We have developed applications for steel slag to suit the social environment. Some steel slag products, including blast furnace cement and road base course material, are designated as specified procurement items for public works (products conducive to environmental impact reduction) in the Act on Promotion of Procurement of Eco-Friendly Goods and Services by the State and Other Entities. This act was enforced in 2001. In recent carbon neutrality policies, steel slag products for marine areas are noted as materials that contribute to the creation of blue carbon by regenerating seaweed beds so that more seaweeds can absorb and fix CO_2. In this section, we introduce steel slag products as construction materials contributing to carbon neutrality.

Blast furnace cement is produced by pulverizing and mixing blast furnace slag without firing. As shown in **Table 4**,[13] blast furnace cement type B has CO_2 emissions of 323 kg/t-cement less than Portland cement. Cement increases in strength with age.[14] When compared in terms of strength per CO_2 emission according to the data of Reference 14), blast furnace cement is much better as shown in **Fig. 6**. In Japan, blast furnace cement shares only about 20% of the cement market. Blast furnace cement is low in carbon and highly resistant to alkali-silica reaction and salt damage. Its demand as a construction material is thus expected to increase further.

We next introduce materials contributing to blue carbon as shown in **Fig. 7**. In recent years, CO_2 that seaweeds absorb during photosynthesis has now been highlighted as blue carbon. Japan has the sixth longest coastline in the world. Blue carbon is expected to be an effective CO_2 emission reduction measure. Three products are shown below for the formation of blue carbon from grown seaweeds. In the first group are Vivary™ bags and Vivary™ boxes. These products provide marine fertilizers that supply iron, a component necessary for seaweed growth, and proliferators for seaweeds that absorb CO_2. The second is an artificial stone made of hydrated steel slag. This serves as an epiphytic base material for seaweeds

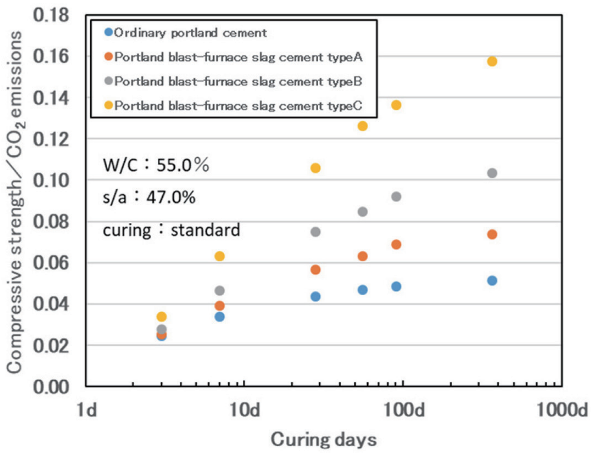


Fig. 6 Compressive strength per cement emission CO_2

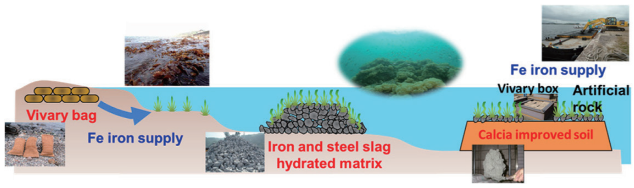


Fig. 7 Overview of steel slag products

Table 4 CO_2 emissions per ton of cement[13]

(unit: kg)

CO_2 emission source	Ordinary Portland cement ① CO_2 emissions	Portland blast-furnace slag cement type B ② CO_2 emissions	CO_2 reduction amount ①−②	CO_2 reduction rate (%)
Limestone	480	273	207	43
Electric power energy	286	171	115	40
Total	766	443	323	42

that absorb CO_2. The third is slag-improved soil, a ground material made by solidifying and improving dredged soil. It is used as material to raise the sea bed to such a water level that sunlight can reach the seaweeds.

The Vivary™ bags were tested on the coasts of Mashike Town and Tomari Village, Hokkaido, among other regions, and proved effective in alleviating the seaweed depletion. The Vivary™ bag technology is described in the "Revised Isoyake Countermeasures Guidelines (in Japanese)" published by the Fisheries Agency of Japan. The artificial stones can be used as algae reef material. They were used as armor stones on the breakwaters at the entrance of Kamaishi Bay in a restoration project after the Great East Japan Earthquake. The artificial stones are used as civil engineering materials as well and are expected to help seaweeds to grow on harbor structures. The slag-improved soil is used not only for elevating seaweed beds, but also for building underwater embankments at the back of breakwaters as breakwater reinforcements.[15] Seaweed beds formed on the top of the underwater embankments can be utilized.

The Ministry of Land, Infrastructure, Transport and Tourism focuses on blue carbon as one of its carbon neutral port policies. Blue carbon projects are expected to advance along with dredging projects to maintain port functions and along with port facility reinforcement projects to build national resilience. In 2020, the Japan Blue Economy Association was inaugurated and started the certification of CO_2 sequestration with J-Blue Credits in Japan. Under these circumstances, we would like to contribute to carbon neutrality by accelerating the use of steel slag products to reduce CO_2 emissions in public works.

5. Conclusions

Steel is an extremely recyclable material. The idea of CO_2 emission intensity by considering the recyclability of steel is standardized by ISO and JIS. The CO_2 emission intensities of Nippon Steel's steel products are disclosed with EcoLeaf, one of the environmental product declaration (EPD) labels. With the EcoLeaf labels, the CO_2 emission intensity of steel reflecting its recycling effect can be reflected in the assessment of CO_2 emissions from steel structures. Steel with excellent strength and steel slag are low in CO_2 emissions per unit of strength, so that they help to reduce the quantity of construction materials to be used and hence to reduce the CO_2 emissions from construction projects.

It is important that the CO_2 emissions should be reduced by innovating the steelmaking process. It is also important to pursue the combinations of high-performance steel products having superior shape and strength properties with utilization technologies that make the most of such properties and accordingly to provide solutions to minimize the CO_2 emissions from steel structures. The rationalization effects of reducing the steel weight of steel structures and of reducing the steps of steel fabrication and on-site construction will be understood as the effects of CO_2 emission reduction. We will increase the sophistication of steel products and utilization technologies and will expand the applications of steel products and utilization technologies to meet the needs for further reduction of the environmental impact. This is the direction we should take to achieve carbon neutrality in the building and infrastructure construction.

Steel slag is a material that contributes to blue carbon when used to help seaweeds to absorb and fix CO_2, and has historically been used for cement and roadbed materials. In recent years, it has come to be used in diversifying applications, just a few of which we have introduced in this article. Steel slag is a material expected to contribute to carbon neutrality. The development and deployment of more diversified applications for steel slag are essential.

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