Reproduction Technology of Coral Reefs Using "MARINE BLOCK®"†

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Abstract:

In tropical to subtropical marine areas, coral bleaching frequently occurs probably due to environmental destruction and global warming, and coastal ecosystems are degrading. JFE Group is engaged in technological development for restoring coral reefs, which have been damaged due to bleaching, etc., by combining the coral-implanting tool, which was developed by Tokyo University of Marine Science and Technology to prepare the substrate for coral larvae, and the carbonic solid of iron-steel slag " MARINE BLOCK®. " This paper reports on the healthy growth of young coral on Marine Block in the ongoing test in the actual sea.

1. Introduction

Coral reefs are widely distributed in oceans from the tropics to the subtropics, and are extremely important as a site of primary production in ecosystems. In human life, they are a supplier of fishery and leisure resources, and at the same time, also have the vital function of protecting land areas from typhoons, tsunamis, and other natural threats. However, the coral reefs of the world are exposed to serious danger due to the inflow of sediments from land, explosive growth of *Acanthaster planci* (common name: crown-of-thorns starfish) and other predatory life forms, and rising ocean temperatures accompanying global warming.

In Japan, awareness of environmental protection is continuing to rise as these conditions become widely known among the general population. As a result, measures to reduce CO_2 emissions and reuse resources, such as the Basic Law for Establishing the Recycling-based Society, Law for the Promotion of Nature Restoration, and others have been enforced, and various governmental agencies require environmental protection and recycling by methods of effective utilization of resources and energy saving.

Against this background, the JFE Group developed a coral reef reproduction technology by combining its MARINE BLOCK®[1,2] product, which is a carbonic solid of iron-steel slag that JFE originally established as a CO_2 fixing technology using iron and steel slag, and a coral implanting tool (settlement device) developed by Tokyo University of Marine Science and Technology, with the aim of practical application. This paper discusses the development of this technology, with particular attention to issues related to the environment, ports and harbors, and fisheries, among others.

2. Necessity of Reproduction of Coral Reefs

Coral reefs created by coral over long periods of time are distributed in oligotrophic (nutrient-poor) waters from the tropics to the subtropics. Here, a rich coral reef ecosystem (food chain), which has been called a "marine tropical rain forest," is formed by photosynthesis of *Zooxanthellae* that coexist with the coral.

The topography of a coral reef consists of a base of rock (limestone), which is the reef proper, and a sandy area (coral sand and Foraminifera) on the inner side of the reef, which is called a lagoon.

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Because the reef faces the outer ocean and forms a good environment for seawater exchange, table-shaped and covering-type corals breed intensively in this part of the reef. Around many of Equatorial islands which are affected by subsidence accompanying subduction of sea bottom plates, coral plays a role of compensating for sinking of the islands by raising the level of reefs. Reefs also have a breakwater function, and coral prevents erosion of reefs by growing and continuing build up reefs.

A lagoon is a gentle body of water which is protected from waves. In sandy waters, branching corals intertwine, creating a beautiful undersea landscape. These areas support diverse forms of marine life, and also provide an area for raising their young.

The global scale bleaching and accompanying extinction of coral in 1998 is considered to have been caused by rising ocean surface water temperatures due to global warming. Bleaching was also observed thereafter in many areas. Because damage by bleaching increases in shallower waters, this phenomenon had a catastrophic impact on many of the corals that had grown luxuriantly on the upper surfaces of reefs. Moreover, in closed lagoons, the rise in the seawater temperature was remarkable, causing extinction of many corals (**Photos 1** and **2**).

The effects of coral extinction are serious, as represented by subsidence of islands and erosion of reefs, and are accelerated by rising water surface temperatures due to global warming. Thus, the development of a detailed coral reproduction technology corresponding to reef topography was urgently needed in order to respond to this situation.

Photo 1 Coral reef 7 years after 1998 bleaching (March 2005, Miyako Island)

Photo 2 Lagoon 8 years after 1998 bleaching (February 2006, Sekisei Lagoon)

3. Materials Used

The materials used in the development of this technology were “MARINE BLOCK®,” which is a carbonic solid manufactured from iron and steel slag, and a “coral settlement device,” which enhances the implantation rate of coral larvae.

3.1 Marine Block

Marine Block has the following features[1,3).

(1) Material manufactured using only slag (main component: lime), which is produced as a byproduct of iron and steel production processes, and carbon dioxide.

(2) Absorbs and fixes CO_2 (1–7wt%) as calcium carbonate during manufacturing.

(3) Porous block with porosity of 20–40%, with a coating layer consisting mainly of calcium carbonate, which is the same substance as shells and coral.

(4) No pH change seawater.

3.2 Coral Settlement Device

The coral settlement device was developed by Tokyo University of Marine Science and Technology. Manufactured from ceramic material, the device has a diameter of 40 mm and height of 26 mm, and is engraved so that implantation of coral larvae are enhanced and that the larvae are protected from predation by sea urchins and fish (**Photo 3**).

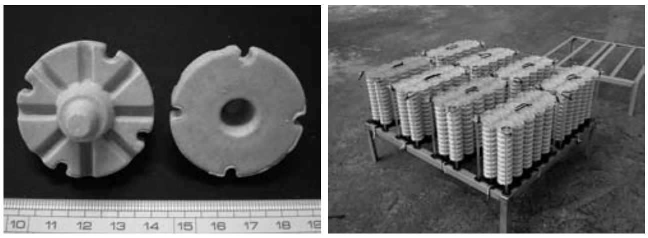

Photo 3 Coral settlement devices

Photo 4 Installation of a base frame supporting coral settlement devices

After developing from eggs to larvae, coral float near the surface for approximately 3–7 days, then settle on an artificial base (rock, coral reef, etc.) and begin to grow. A case (base frame) containing settlement devices is deployed (**Photo 4**) in waters where a coral reef exists during the coral spawning (around May to June), and coral larvae will also settle on the settlement devices during this time.

4. Research Results

4.1 Coral Larvae Settlement Test

From 2001 to 2003, an experiment was carried out to investigate the coral larvae settlement rate using Marine Blocks and ordinary concrete plates at Akajima (Aka Island) in Okinawa Prefecture, Japan (**Photo 5**)[4)]. In an actual sea experiment in 2002, approximately 2 times as many coral settled on the slag plates as on the concrete plates in all fields. These results proved that Marine Block has high biological affinity (**Fig. 1**).

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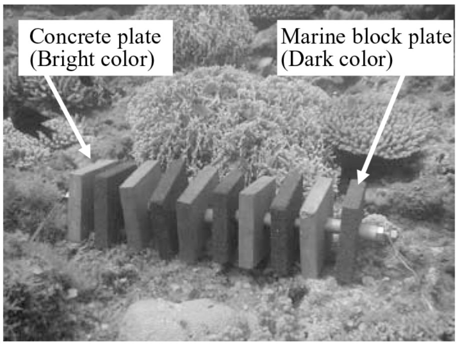

Photo 5 Field test of Marine block plates and concrete plates

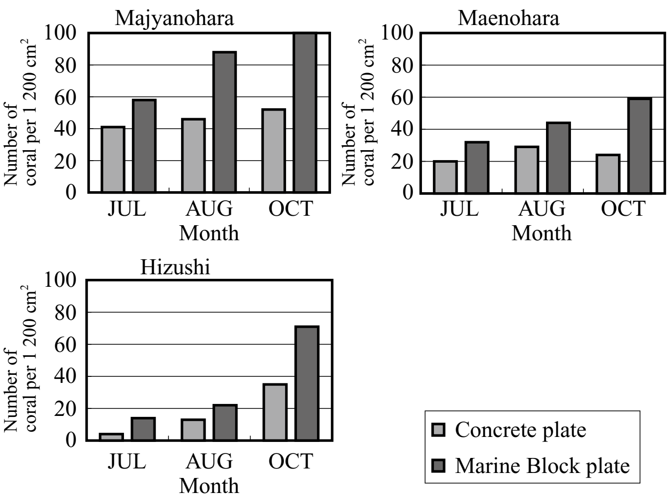

Fig. 1 Numbers of implanted coral on different plate materials (2002)

4.2 Test of Transplantation of Coral to Marine Block

Based on the results of the research at Akajima, in June 2003, coral settlement devices were deployed at the Sekisei Lagoon in the Southern Ryukyu Islands with the aim of securing young coral by sexual production. In August, part of the settlement devices were fixed on a Marine Block which was used as an artificial base for coral transplantation. All work was performed in the water. The settlement devices were installed in holes drilled in advance in the Marine Block using an underwater bond.

At the stage of June 2003, coral could not be observed with the naked eye on any of the settlement devices used in transplantation. In May 2004, settlement of coral could be observed visually on some of the settlement devices, but in all cases, these were small colonies with a size of several millimeters. In August, the condition of growth of these coral was checked, and the size exceeded 5 mm. Growth of the coral was checked again in February, and the largest had grown to a size of approximately 5 cm (**Photo 6**, **Fig. 2**).

These results proved that Marine Block does not hinder the growth of coral and can function as an artificial

Photo 6 Overview of Marine Blocks and close views of grown coral

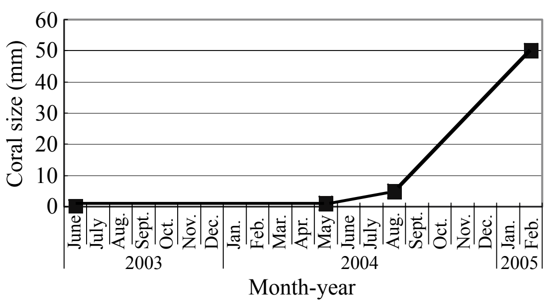

Fig. 2 Growth rate of coral on Marine Block (*Acropora sp.*)

base for coral transplantation[3)].

4.3 Practical Application of Coral Reproduction Technology

Beginning in 2003, the JFE Group also started development of a coral reproduction technology using Marine Block at Miyakojima. The objective of this work was to develop a technology at the actual level with the aim of practical application, based on the results of the prior research at Akajima and research carried out in parallel at Sekisei Lagoon[5)].

In this technical development, the aim was to restore a former coral reef where dead coral had accumulated like debris (so-called "rock field") using a combination of Marine Blocks and settlement devices, and to enable

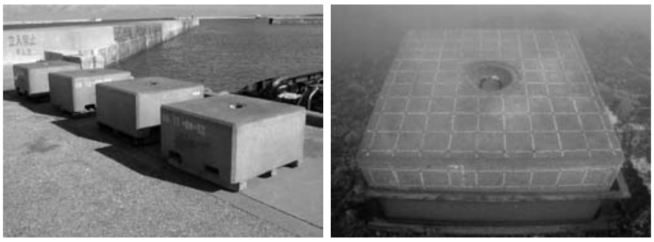

Photo 7 Marine Blocks (Artificial base for coral reefs)

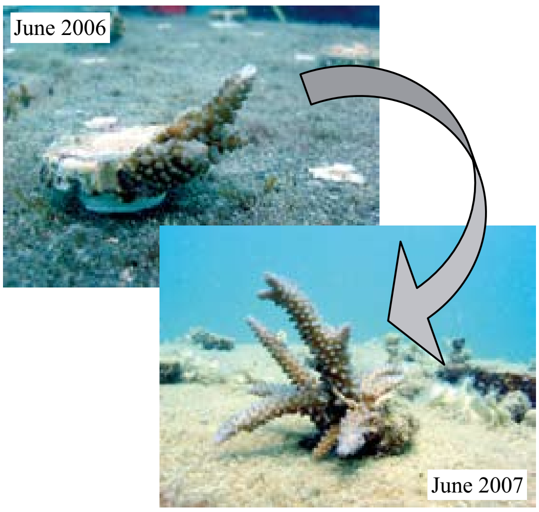

Photo 8 Coral growth on Marine Block (*Acropora sp.*)

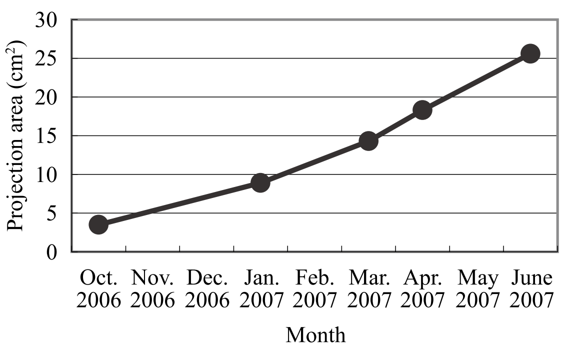

Fig. 3 Development of coral growth (projection area)

Photo 9 Coral growth on Marine Block (*Acropora sp.*)

completion within the local waters. Restoration of coral at reefs of this type had been considered difficult. In order to secure young coral for sexual reproduction, each year beginning in 2005 coral settlement devices were deployed in the waters around Miyakojima. Four 1-ton type Marine Blocks (**Photo 7**) as an artificial base for transplantation were sunk in the Toriver District at Hirara Port in October 2005. Coral transplantation was performed by the method of installing coral settlement devices, where growth of young coral had been previously, on the Marine Blocks. Full-scale coral transplantation began in October 2006.

Steady growth of the transplanted coral was confirmed by June 2007. Examining the degree of growth of the *Acropora sp.* shown in **Photo 8** by the overhead projection area, growth was 3.5 cm^2 in October 2006. In 2007, the coral grew steadily from 8.9 cm^2 in January, to 14.3 cm^2 in March, 18.3 cm^2 in April, and 25.6 cm^2 in June (**Fig. 3**). Furthermore, the growth of the transplantation coral spreading on the Marine Blocks was confirmed (**Photo 9**).

5. Ecology of Coral and Reproduction Scenario

Reproduction of coral occurs by two mechanisms, asexual reproduction, in which limbs of coral which have been broken off as a result of a typhoon or the like drift until they take root and grown in a suitable area, and sexual reproductions, in which a new individual is produced by insemination of an egg by a sperm.

Furthermore, there are two types of sexual reproduction, one called "broadcast spawning," in which all gametes (eggs and sperm) are released at once on the night of a full moon, and "brooding," in which the coral produces larvae that it eventually release. The former is represented by *Acropora sp*. Nearly 100 species release bundles of eggs and sperm over an area of several square kilometers. These bundles burst open at the ocean surface, and fertilization occurs as countless eggs and sperm float near the ocean surface. Fertilized eggs develop into larvae in less than 2 days, and settle and become established if they find a suitable location on a reef within 3–7 days after birth. Because larvae are dispersed and moved by tidal currents and ocean currents, it is thought that very few are able to settle and establish. Brooding type reproduction is represented by *Pocillopora sp*. In this case, larvae settle within a very close area within 1 day after release.

5.1 Coral Reproduction Method

At present, with coral populations rapidly dwindling, use of transplantation by breaking off polyps from an adult (use of asexual reproduction) in large-scale works is not desirable. For this reason, the authors developed a coral reproduction technology utilizing sexual reproduction, beginning in 2002, and conducted coral reproduction experiments in various parts of Japan using a combination of coral settlement devices and Marine Blocks. As a result of experiments with numerous species, it was possible to create a scenario for a coral reef reproduction technology using the settlement devices and Marine Blocks. It is thought that this technology can be used in reproduction of coral reefs not only in Japan, but also around islands in tropical areas.

5.2 Function of Settlement Device and Method of Use

The settlement device provides a new settlement area to the numerous species and extremely large number of individual coral which are born as a result of simultaneous broadcast spawning and also provides grown coral for transplantation. In the design of the device, consideration was given to use in large quantity in the sea and methods of transplantation work.

A large number of individual settlement devices are stacked on a base frame, and a sea area with a high population of established larvae is selected for deployment of the devices. First, the date of broadcast spawning of the coral is predicted, and larvae of *Acropora sp*. are settled by deploying the settlement devices from a week prior to that date until the predicted date. As *Pocillopora sp.* releases its larvae from time to time thereafter, an even larger settlement can be expected. Because coral can be confirmed in the sea 1 year after establishment, in transplantation, it is possible to select and use the necessary number of settlement devices appropriately.

Coral is reproduced by fixing settlement devices to a rock base or Marine Blocks at a rate of 10 devices per 1 m^2, and then continuously taking care of the devices (a device is replaced if an individual dies, etc.). Although the devices are left in place in the sea while waiting for the coral to grow, transplantation between sea areas is easy in this stage. For example, in cases where bleaching is expected due to high water temperature, it is possible to evacuate the coral temporarily to slightly deeper water, where the temperature is lower, and in cases where the suitable area for settlement of the larvae is an area with strong waves, the coral can be moved to calmer waters after settlement.

The procedure developed for the coral reef reproduction technology using Marine Blocks and the coral settlement devices is introduced in the following.

(1) Deployment of Settlement Devices to Secure Larvae (May–June)

The settlement devices are deployed in the object waters timed to spawning of the coral. Study of the optimum location, spacing, installation method, and installation cost of the settlement devices is necessary.

(2) Placement of Settlement Devices

Settlement devices deployed in spring may be washed away by typhoons, etc. In order to avoid this risk, the settlement devices are moved to a safe location in deeper water, etc., before typhoon season. When moving the settlement devices, consideration is necessary to avoid damaging recently settled coral; in particular, it is necessary to avoid contact with the air and rapid changes in water temperature.

(3) Growth of Settled Coral (approximately for 1 year)

Coral are grown for approximately 1 year in the location to which the settlement devices were moved in summer. As a result, it is possible to obtain young coral which have survived the process of natural selection. Because coral of larger size can also be expected, the possibility of predation is reduced.

(4) Installation of Marine Blocks

Marine Blocks are sunk in the waters where the coral reef is to be reproduced. In areas with severe conditions such as high waves, a stability calculation is made, and countermeasures such as anchoring or fixing of the frames are taken. It is desirable to drill the holes for installation of the settlement devices in the Marine Blocks in advance, before the blocks are sunk.

(5) Transplantation of Settlement Devices

The settlement devices are removed from the frame, and coral which have grown on the devices are selected. After selection is completed, the devices in which the young coral are established are transplanted to the Marine Blocks. However, the number is adjusted so that the final density of the coral colony is on the order of 10 colonies per 1 m^2.

(6) Confirmation of Effect of Transplantation and Monitoring

The condition of growth of the coral on the transplanted settlement devices is observed periodically, the effects thereof are evaluated, and the necessity of movement to a new transplantation location or additional transplantation in the existing location is judged. In combination with this, water quality and the condition of surrounding habitats are monitored, and data are collected as material for future countermeasures.

5.3 Function of Marine Block and Method of Use

The natural base for fixing the settlement devices is a reef. However, there are large lagoons where the branching coral in the coral reefs has died and been reduced to the condition of debris. In such locations, there is no alternative but to place an artificial base for transplantation of the settlement devices. Furthermore, at reefs where the environmental load from the land is large, lush growth of microalgae on the surface due to eutrophication is a problem. When these algae capture fluid mud and the reef is coated with a this muddy material, it becomes impossible for coral larvae to settle. Use of an artificial base is necessary in location of this kind also.

For an artificial base for reproduction of coral reefs, the material as such must be suitable for the settlement and growth of coral. As described in section 4.1, because coral larvae settle well on Marine Block itself, it is a suitable material on this point.

There are two different methods of using Marine Block in the reproduction of coral reefs. One is a method in which Marine Block is used as an artificial base for transplantation of the settlement devices on which coral has grown and continuous control thereafter. The second is a method of use as an artificial reef, in which the coral larvae are settled and grown on the Marine Block.

When using Marine Block as an artificial base for transplantation of settlement devices, the Marine Blocks only become necessary in the stage when the coral has grown on the settlement devices. Accordingly, it is possible to respond by installing the blocks in advance in order to create a coral reproduction site, or to deploy the necessary number immediately before transplantation. In other words, in this case, the timing of installation is not an issue.

When Marine Block is used as an artificial reef, consideration is required, including drilling holes in advance, setting the timing of installation to the same schedule as the settlement devices, etc.

(1) Coral Settlement on Natural Reef

In the natural world, coral larvae (*Acropora sp.*) settle in shaded places such as small holes or crevices in reefs. Approximately 1 year later, the coral has grown to a diameter of about 10 mm and protrudes from the hole, and thereafter it grows rapidly. Use of holes as a habitat is considered to be a self-defense measure to prevent predation by sea urchins (Echinometra mathaei), etc.

For larvae of coral to settle in these kinds of holes, the holes must be clean. Furthermore, during the period when coral grow slowly, the settled coral will die in the hole in environments where the hole is buried under algae or red soil.

Photo 10 Underwater inspection of corals on the coral settlement devices (CSD) 26 months after deployment (June 2004, Sekisei Lagoon)

When a settlement device (**Photo 10)** is used, the fact that these are stacked to create horizontal openings, and coral larvae settle on the undersurface of the settlement disc part, takes into account the survival mechanism of coral in the natural world during the first year of life. Furthermore, deployment of these devices in the sea immediately before broadcast spawning is intended to avoid fouling of other organisms to the surface of the settlement device.

(2) Coral Settlement on Marine Block

In cases where Marine Block is used as an artificial reef, if the block surface is left smooth, any larvae that settle there will be devoured immediately by other organisms, and in virtually all cases, growth will be difficult. Considering the ecology of coral which settle and grown on natural reefs and settlement devices, it is necessary to create an environment which settled larvae can inhabit safely for a period of 1 year.

The processing for this purpose is simple, and can be accomplished by drilling holes with a diameter of 10 mm in the Marine Blocks immediately before broadcast spawning of the coral. These holes can be drilled on land, and the blocks can then be placed immediately before spawning, or the holes can be made immediately before spawning in blocks already placed in the water.

On Marine Blocks in which 10 mm diameter holes are made in advance and which placed immediately prior to spawning, the coral larvae settle in the holes and achieve a diameter of roughly 10 mm in 1 year, in the same manner as in natural reefs (**Photo 11**). Thus, Marin Block is material which is capable of showing the same function as natural reefs on which coral larvae settle and grow.

5.4 Scenario of Coral Reef Reproduction

Using a combination of coral settlement devices

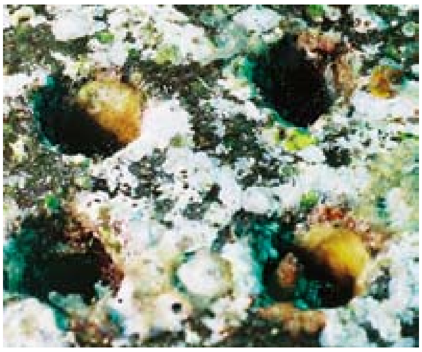

Photo 11 13 months old Acropora settled in the 10 mm diameter holes (at the upper right and the lower left) on the Marine Block (June 2007, Sekisei Lagoon)

and Marine Blocks, it is possible to reproduce coral reefs with no impact of any kind on coral or the natural environment. Considering the ecology of coral, utilizing the opportunity of large-scale broadcast spawning is quite reasonable. This is because more than 99% of the innumerable coral larvae which are born will be carried away from the seas where coral reefs are found, and will die without finding a suitable place to settle. By providing settlement devices in these locations, it is possible to save a tiny fraction of the larvae that would otherwise die and use them to reproduce a coral reef. Moreover, in coral reefs, which are vital sites of biodiversity, it is important to reproduce the environment using larvae of the various species of coral in the same ratios as in the existing coral colony.

When using Marine Blocks, which are large in size, the blocks are placed in the water immediately before spawning, and are difficult to recover or move after placement. Because the settlement device can be used more flexibly, use of Marine Blocks in combination with the settlement device can be considered a new development in coral reproduction technology.

All transplanted coral do not necessarily grow smoothly. The coral are implanted at a rate of 10 per 1 m^2, and individual coral that die are replaced. By continuing this kind of cares, it is possible to cover Marine Blocks with various species of coral which grow to a diameter of approximately 40 cm in 5–6 years after transplantation.

6. Conclusion

Several new experiments were carried out as part of the development of a coral reproduction technology using settlement devices and Marine Blocks. In addition to clay ceramics, a settlement device of a new material was developed by molding and calcinating iron and steel slag. This material has a satisfactory surface profile and high strength, and can be fixed to reefs and protective structures in areas with rough waves.

The number of coral larvae is decreasing due to the worldwide decline in live coral. As a solution to this problem, attempts are being made to collect coral larvae, taking advantage of the features of the compact, lightweight settlement device, and establish the larvae on settlement devices in the sea.

Because the water quality is comparatively good at Sekisei Lagoon, coral which had died due to bleaching are showing a tendency to recover in many sea areas. However, in the area around Ishigakijima, there are locations where coral do not reproduce due to the environmental load from the land. In order to determine the cause of this problem, “Developmental research on a biological evaluation unit for coastal areas” is now being carried out in Nagura Bay.

In tropical countries, coral is in the same state of crisis as in Japan. Because information on the ecology of the coral in these waters is extremely limited, an advance evaluation of the coral reproduction capacity is critical when considering coral reproduction projects. For this, “Developmental research on an advance evaluation system for coral reef reproduction areas,” combining settlement devices and Marine Blocks, is being conducted in the Bunaken (Manado) National Park in Indonesia.

Reproduction of coral reefs requires a detailed response in each ocean area. The settlement device and Marine Block described in this paper are powerful tools for reproducing coral reefs as they exist in nature that are compatible with the development of coral, which only grows 10 mm in 1 year.

The JFE Group hopes to contribute to the protection of the natural environment, beginning with the ecosystem, and the preservation of Japan’s own land, making full use of the innovative technology described in this paper.

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