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The "Eco-Block" as a coral-friendly contrivance in port construction

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Abstract. Following observations of natural recruitment of coral colonies to breakwaters in Naha Port, Okinawa Prefecture in 1989, we launched monitoring surveys to explore the processes of coral settlement and growth on concrete armor blocks, along with the development of technology to enhance coral settlement and growth on such structures. The development concept centered on creating rough surfaces on conventionally smooth block surfaces, thus imitating the natural rugosity of reef substrates. In 1999, the findings from these surveys and experiments were then applied to the project "Eco-block", a wave-dissipating block with unevenly processed surfaces to enhance coral recruitment. Since the installation of Eco-blocks, the growth and recruitment of corals on the blocks has been recorded yearly. Eco-blocks with surface abrasions at about 5mm and 10mm in depth and width had higher coral settlement compared to unprocessed blocks.

Key words: coral restoration, port development, artificial structure, surface processing, increased settlement

Introduction

Coral communities are widely recognized for the crucial roles they play in subtropical and tropical coastal ecosystems (Costanza et al. 1997; Moberg et al. 1999). Among the world's coral reef seas, the southern area of Japanese waters surrounding the islands of Okinawa Prefecture has been described as a biological hot spot, an area with high diversity and a multitude of rare species (Roberts et al. 2002). Coral communities found in this area were extensively damaged following a severe bleaching in 1998, which was induced as a result of abnormally high sea temperatures (Hoegh-Guldberg 2000). These corals are now showing signs of recovery; yet, it is crucial to gain an insight into the coral growth and settlement before and after the bleaching event, as well as the development of restoration technologies to facilitate the recovery of corals from bleaching.

The Okinawa General Bureau, the Cabinet Office of Japan, also spare no efforts in promoting port development, in which port or harbor modification should follow "coral friendly" approaches. In 1989, coral colonies were found settled on wave-dissipating blocks of Naha First Breakwater in Naha Port. Every year since 1990, the settlement and growth of corals have been monitored annually on 30 fix quadrates. The results compiled until 2003 were reported by Ooka et al. (2006). In addition, focusing on this phenomenon as a way to make port construction more coral-friendly, we began the development of technology to enhance coral settlement and growth on concrete armor blocks. The development concept centered on creating roughness on conventionally smooth block surfaces, thus imitating natural substrates as near as possible. The initial experiment began in Naha Port in 1990, followed by the second one in 1991. The findings from these experiments were then applied in a project utilizing the "Eco-block" in 1999, a wave-dissipating block with abrasive protrusions on its surface. Since the installation of Eco-blocks, the growth and settlement of corals have been monitored yearly in 36 fixed quadrates placed on them. In this report, we analyzed the findings from these surveys and evaluated the effectiveness of such uneven processing on block surfaces in enhancing coral settlement.

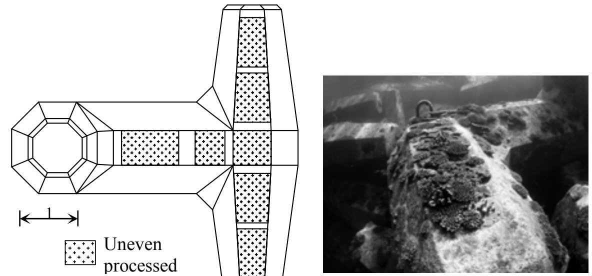
Methods

Monitoring of coral settlement and growth: wave-dissipating blocks without surface processing

The purpose of this monitoring is to explore the coral settlement and growth on the unprocessed, smooth surfaces of artificial substrates. The surveys were conducted around Naha First Breakwater in Naha Port, Japan. Live coral coverage and number of colonies were monitored annually over eight years between 1990 and 1997 at six different water depths C.D.L. (Chart Datum Level) -1, -3, -5, -7, -9 and -12m). The data were collected from three stations set up at each depth, and year-on-year changes were observed and reported (Yoshimi et al, 1998). The monitoring was then resumed in 2000, in response to the coral degradation caused by the bleaching in 1998, an extensive bleaching associated with unprecedented high sea temperatures around the world. The surveys were conducted on the same stations until 2007.

Monitoring of coral settlement and growth on Eco Blocks: experiment to enhance coral recruitment
Eco Block development
To gain an insight into the relationships between substrate properties and coral settlement, we conducted the experiment in two locations using armor blocks with different surface modifications. In 1990, we deployed our blocks with surface protrusions to the height of 1cm onto the side of Naha First Breakwater (primary experiment section), and in the following year of 1991, deployed another type of blocks with triangular or rectangular patterns etched out into the surface onto the side of Naha Breakwater (secondary experiment section). Coral settlement was monitored annually on these blocks by underwater visual observation. The results showed an enhanced attachment of the corals, proving the effectiveness of such modification (Iwakami et al. 1995; Yoshimi et al. 1998). These results in turn saw the development of the "Eco Block," a wave-dissipating block designed to enhance coral settlement, and the launching of an ongoing project using such blocks in Naha Port, from 1999 onwards. The Eco Block's surface (Fig. 1) is unevenly processed in various shapes and patterns when molded in factories.

Monitoring of coral growth on Eco Blocks
The monitoring commenced in 1999 on Eco Blocks placed around Naha Breakwater and continued until 2007. Fixed stations were set up on the top surface of the blocks. Block surfaces were classified into four levels of surface roughness: abrasions in the region of 2mm, 5mm, and 10mm in depth and width, and unprocessed (for control). On the surface of each roughness processed by using some kinds of wood frame while the surface of the concrete was soft, three quadrates (50cm x 50cm) were placed at each depth of C.D.L.-2, -5, and -8m, and the number of colonies, coral cover, number of species and maximum diameter in a quadrate were documented by underwater visual observation.



(8 years after installation)

Figure 1: Eco-block (40t)

Results
Coral settlement and growth on unprocessed blocks
As the fixed monitoring stations were set up on the blocks installed in 1986, the survey marked the twenty-first year in 2007. Figure 2 shows year-on-year changes of coral cover and the number of colonies by water depth. Graphs represent mean values and standard deviation (n=3) of the data obtained from the top surfaces (gradient: 0°).

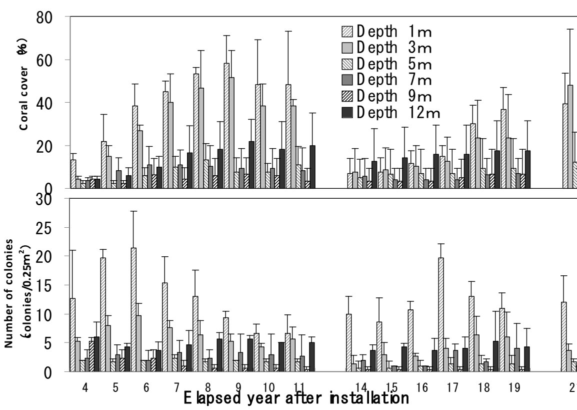


Figure 2: Coral growth on artificial blocks at Naha port.
The blocks were installed in 1986. (Mean+SD: n=3)

Changes in number of colonies
At the depths of C.D.L.-1m and -3m, both the number of colonies and coral cover increased over the period spanning the fourth year (the initial year of the survey) to the sixth year following block installation. Meanwhile, from the seventh to ninth years, the number of colonies was decreasing while the coral cover in the same period was increasing. At the depths of C.D.L.-5m and deeper, the number of colonies remained at relatively low levels, indicating that poorer light conditions in contrast to that at shallower depths (C.D.L.-1 and -3m) slowed coral growth, with minimal competition among the colonies over substrate space.

With regards to the results subsequent to the 1998 bleaching event (the 12th year post installation), no significant changes were observed in colony numbers between the 14th and 16th years. This implies lower rates of larval recruitment immediately after the bleaching. But in the 17th year, the number of colonies increased, especially at the depth of C.D.L.-1m, with the colonies almost doubling in number. In the 18th year, although the number of colonies dropped notably at C.D.L.-1m, the coral cover showed a continued increase, suggesting the growth of the colonies that had settled in the previous year.

Changes in coral cover

From the 14th year of the survey onwards, the coral cover on all wave-dissipating blocks was lower at all depths than the cover recorded prior to this period This could bear evidence of the loss of live coral cover following the worldwide abnormal increases in sea temperature in 1998. The decrease was of particular significance at the depths of C.D.L.-1m and -3m, where increased sea temperatures must have had greater impacts on the corals. Comparing the results of the 19th and the 21st years, a marked increase in coverage was observed at the depths of C.D.L.-1m and -3m in the 21st year. The results also recorded the highest coverage at the depth of C.D.L.-12m between the 14th and 17th years. This phenomenon is attributed to the difference in the dominant coral species at each depth: Acropora (C.D.L.-1m), *Acropora* and *Pocillopora* (C.D.L.-3m), *Pocillopora* (C.D.L.-7m and -9m), and *Porites* (C.D.L.-12m). The year-on-year changes by depth therefore reflect the recovery processes of these corals. At shallower depths, the *Acropora* and *Pocillopora* species had suffered a reduction in coral cover under the increased temperatures, but showed signs of recovery in later years; while at deeper depths, the *Porites* species survived the period of augmented temperature and continued their growth.

Coral settlement and growth on Eco Blocks

Figure 3 and 4 illustrate the results of coral colony number and coral cover by depth and surface roughness. Graphs represent the mean value (n=3) of the data.

Changes in number of colonies

The number of colonies on the Eco Blocks had been on the rise for all levels of surface roughness at the depth of C.D.L.-2m for two years after block installation. The rougher surfaces demonstrated a greater effectiveness in terms of initial settlement of corals. After the third year, the number of colonies began to decrease on the surface with abrasions of 10mm deep, and it leveled off on the surface with abrasions of 5mm deep. However, on the surface with a roughness of 2mm deep, the number of colonies continued to increase before it plateau in the fifth year. In contrast, colonies on the control blocks showed a slow and gradual increase in number. At the depth of C.D.L.-5, the number of colonies had been largely on the rise for all levels of surface roughness until the fourth year. The greater effectiveness was observed for rougher surfaces as seen in the results from the depth of C.D.L.-2m. After the fourth year, the number of colonies showed a decline trend at all roughness, while the colonies on the control blocks again showed a slow but gradual increase for all surveyed years. At the depth of C.D.L.-8m, the number of colonies were also increasing for over three to four years after block installation but its relationship with surface roughness was not clearly observed.

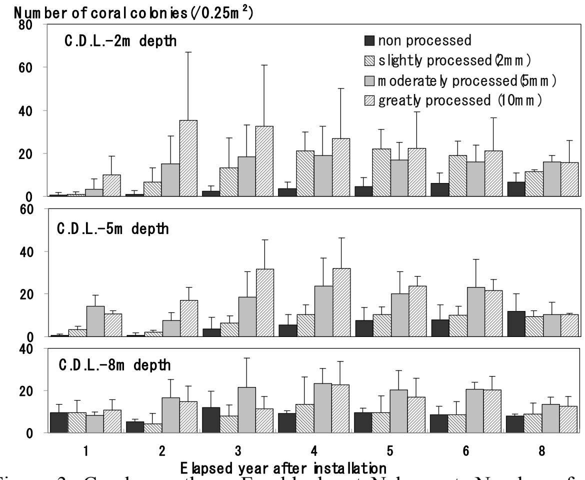


Figure 3: Coral growth on Eco-blocks at Naha port; Number of colonies. The blocks were installed in 1999. (Mean+SD: n=3)

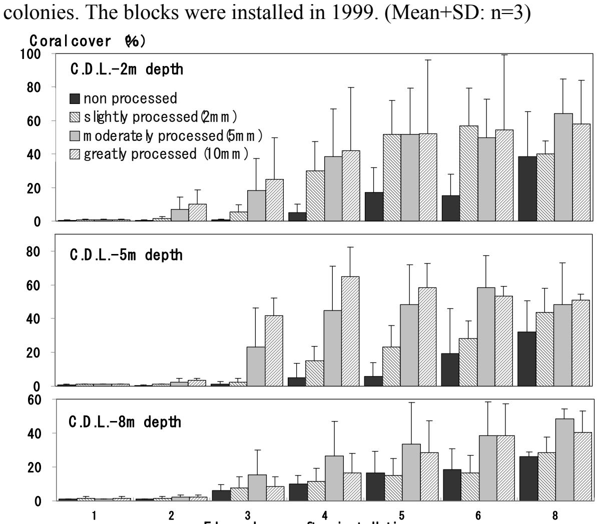


Figure 4: Coral growth on Eco-blocks at Naha port; Coral cover. The blocks were installed in 1999. (Mean+SD: n=3)

Changes in coral cover

At the depth of C.D.L.-2m, the coral cover on the blocks with abrasions of 10mm deep and 5mm deep showed a distinct increase in the third year. In this passage of years, the effects of surface roughness to coral cover were apparent. After the fourth year, the coral cover on the surface with 2mm-deep abrasions also showed an accelerated increase, reaching closer to those on rougher surfaces towards the eighth year. In parallel, the number of colonies on the processed area showed a decrease, which is probably a result of spatial competition among corals during the colonization process, or the fusion of colonies among the same species. At the depth of C.D.L.-5m, the coral cover on the surfaces with abrasions of 10mm and 5mm hovered at moderate to high levels after the fourth year, ranging between 45% and 65%. On the surfaces with abrasions of 2mm and the control, the coverage for both was gradually increasing after the sixth year, almost rivaling each other by the eighth year. The results from the depth of C.D.L.-8m did not show as major an increase in cover as in shallower waters; however, rougher surfaces (abrasions of 5mm deep and 10mm deep) demonstrated a more rapid increase in coral cover than that on slightly processed surfaces (2mm deep) and the control.

Discussion

Coral settlement and growth on Eco Blocks

The data accumulated on coral settlement and growth processes can be expressed as a curve akin to a logistic curve (Yamamoto, et al, 2002). Taking into account the life cycle of corals, the growth process of corals can be classified into four stages as shown in Fig. 5; 1) recruit period– planula larvae settle on substrates, 2) post-settlement stage– attached planulae develop into polyps, 3) exponential growth stage – budding of polyps affords exponential increase in coral cover, and 4) stable-growth stage. We discuss the effects of uneven surface processing of Eco Blocks on coral settlement and growth at each stage.

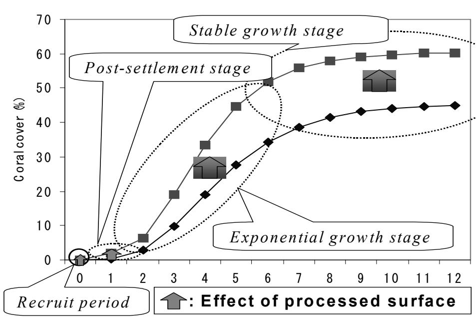


Figure 5: Schematic view of coral growth processes

Larval settlement stage (Recruit period)

Corals release eggs and sperm once in early summer. Fertilized eggs then become planula larvae and drift in surface waters for several days to weeks before attaching themselves to a stable substrate. It is known that the planulae seek out a surface suitable for them to attach to and grow into polyps, and that a top surface of a substrate is seldom sought (Babcock and Mundy 1996). The planula is about 1mm long. Given its tiny dimensions, the uneven processing on the block surface that creates angular sides, if of an appropriate depth, can benefit their settlement to a greater extent than flat surfaces. It is also reported that the roughness on the substrate surface can enhance the attachment of large sea weeds (Terawaki 1988; Watanuki et al. 1990). The reasoning behind this is considered to be the presence of the disturbed flow area and stagnant flow area that are created on the surface with slight abrasions. As such, there is a possibility that these two flow areas created on an unevenly processed surface can physically facilitate the attachment of planulae. This theory could explain the results we obtained in Naha Port, in which larval recruitment and number of coral colonies in the initial growth on the processed area exceeded those on the control.

Initial growth stage (Post-settlement stage)

There is no clear definition that differentiates the initial growth stage from the stable growth stage. However, it has been reported that the growth of newly settled polyps during the initial growth was slow, with higher mortality rates (Wilson and Harrison 2005). The reason behind this is due in part to the presence of predators or competitors in a coral reef ecosystem. Crown-of-thorns and *Drupella* are among the most famous predators, but young polyps are also affected by random grazing by sea urchins such as *Echinometra* and *Diadema* and fish such as parrotfish *Sparisoma viride* (Sanchez et al. 2004) and snail such as *Coralliophila abbreviata* (Williams and Miller 2006).

As these animals also feed on algae that compete with corals for space, some reports have cited that an increase in sea urchins like *Diadema* can result in an increase in coral colonies and coral cover (Macintyre et al, 2005); however, it should be considered that densities of corals, algae and predators dictate their relationships.

With such low chances of survival at this stage, the presence of an unevenly processed surface capable of offering a shelter to newly attached corals against predators, could physically aid in the improvement of survival rates. Also newly-installed structures, which are usually void of large sessile animals or plants that inhibit planula settlement and initial coral growth, could be one of the factors to improve coral settlement and growth.

Exponential growth stage and stable growth stage

Corals grow exponentially at this stage. Therefore, the increase in coral cover seems to depend on coral recruitment in the larval settlement stage and survival rates during the initial growth stage. The results from the monitoring surveys on Eco Blocks in Naha Port also illustrate the growth with the initial increase in colony numbers and subsequent increase in coral cover. With the increase in coral cover, the number of colonies decreases. It has been reported that mature colonies can be detached or fragmented by stormy waves (Madin and Connolly 2006). Against such external forces, an uneven surface processing that affords a larger surface area and thereby a greater friction force, is expected to allow secure attachment for corals, and thus minimizes their detachment from the substrate.

Eco Block as a restoration technology

After the implementation of wave-dissipating blocks in 1986, the coverage of coral communities exceeded 50% in the eighth year and leveled off until the high temperature-induced bleaching brought about extensive damage to coral communities in 1998. The recovery process shown from 1998 until 2007 illustrates a slower growth of the corals at all depths except for C.D.L.-12m, compared to that before the bleaching.

It has also been reported that coral recovery on old wave-dissipating block, on which dead coral skeletons from the bleaching still remained, was slower than that on the new blocks (Ooka et al. 2006). The space within the coral skeleton serves as habitat for new larval recruits, but it also can be utilized as habitat by coral-predators including gastropods and sea urchins. In addition, some researchers have reported a reduction in larval recruitment after the bleaching events (Jinendradasa et al. 2000; Omori et al. 2001).

In other words, the decreased larval recruitment in the post-bleaching period, and the inhibition of initial larval settlement by mobile benthic predators are considered to be the major factors for the slow coral recovery on substrates after the bleaching.

Meanwhile, when the unevenly processed blocks were compared with the non-processed blocks in Naha Port, the processed blocks showed a significantly greater number of coral colonies. This could imply the possible effectiveness of the surface processing in enhancing the settlement of larvae in conditions where larval supply is poor.

Bachtiar (2000) reported a possibility of coral reef restoration using an artificial substrate. Fox (2005) reported her work in Indonesia's Komodo National Park where she placed artificial substrates among coral reefs having been destroyed by blast fishing and confirmed the steady settlement of *Acropora* species four to five years after the placement.

With all these findings and previous reports, we believe that the placement of artificial substrates with unevenly modified surfaces into the waters of coral reefs suffering degradation can facilitate coral recovery and thus aid in the restoration of coral communities.

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