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Chapter 30

CONSTRUCTION OF BIOLOGICALLY PRODUCTIVE ARTIFICIAL TIDAL FLATS WITH SOLIDIFIED SEA BOTTOM SEDIMENTS

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ABSTRACT

Ago Bay is a typical enclosed coastal sea that is connected to the Pacific Ocean via a very narrow and shallow entrance. The bay has been contaminated by the practice of culturing pearls, which has been occurring for the past 110 years. To address this problem, a new technology — the Hi-Biah-System (HBS) — was introduced in 2005. This product of this system, which dewaters muddy dredged sediments and reduces them to their raw materials, was used to construct a tidal flat. The purpose of this study was to evaluate the environmental conditions of the constructed tidal flat 2 years after it was built. We monitored the physico-chemical (oxidation–reduction potential, acid volatile sulphide, loss on ignition, water content, total organic carbon, total nitrogen, chlorophyll a, and particle size) and biological characteristics of five constructed tidal flats and a natural tidal flat. At the same tidal level, the physico-chemical parameters were similar among the five constructed tidal flats and the natural one. However, the biomass and macrobenthic population were higher in the constructed flat compared to the natural one. We suggest that the muddy dredged sediments generated by the HBS could provide useful materials for enhancing the productivity of the tidal coastal environment.

Keywords: Muddy dredged sediments; Constructed tidal flat; macrobenthos; Total organic carbon; Ago Bay; Japan

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1. INTRODUCTION

Ago Bay is a typical enclosed coastal sea that is connected to the Pacific Ocean via a very narrow and shallow entrance. The bay, which is world-famous for its cultured pearls, lies in the Mie Prefecture, Japan. Over the past 110 years, the practice of culturing pearls in the bay has led to contamination. The expansion of human populations and anthropogenic impacts on sensitive natural systems, such as shallow areas, sea grass beds, and tidal flats, have further increased the input of contaminated materials into Ago Bay, leading to the accumulation of organically enriched sediments on the sea bottom.

In 2000, dredging of the contaminated sea floor sediments was initiated in an attempt to restore the sea environment to a healthier condition and to prevent deterioration resulting from the pearl industry. However, because dredged sea floor sediments tend to emit a horrible smell, finding areas for disposal has become a serious problem. Moreover, the large water content of sediments makes their transport and disposal extremely difficult. The technical feasibility of dredging and disposal, economic and environmental issues, and possibilities for reuse of sediments have not yet been resolved. Thus, the development of an alternative system to treat dredged sea bottom sediments is needed.

The Corps of Engineers manual on beneficial uses of dredged material (USACE, 1987) lists ten broad categories of use: habitat restoration; beach nourishment; aquaculture; recreation; agriculture; land reclamation and landfill cover; shoreline erosion control; industrial use; material transfer for dikes, levees, parking lots, highways; and multiple purposes. Graalum et al. (1999) suggested that dredged material might be useful for manufacturing topsoil, which would help reduce and recycle waste soil and provide an additional alternative for the long-term management of dredge disposal sites by reducing the amount of land needed for disposal facilities.

Using dredged sediment to construct tidal flats is another alternative use of dredge materials. Many tidal flats have been lost as a result of industrial, agricultural, and urban development of coastal areas. According to the Ministry of the Environment, Japan, the total area of natural tidal flats was about 826 km^2 in the 1940s; by the 1980s, approximately 40% of these natural flats were lost (Kikuchi, 1993; Kimura, 1994; Takahashi, 1994). To date, about 70% of the natural tidal flats that existed in Ago Bay in the 1940s have been lost (Kokubu et al., 2004). Tidal flats perform many environmental functions, such as providing a habitat for benthic organisms and playing a role in water purification and biological productivity. Currently, a number of projects are under way to protect and maintain natural tidal flats and wetland ecosystems in Ago Bay. Furthermore, efforts are being made to restore damaged tidal flats and to create constructed tidal flats to mitigate those that have been lost (Miyoshi et al., 1990; Cofer and Niering, 1992; Ogura and Imamura, 1995; Lee et al., 1998).

In the inner area of Ago Bay, large amount of organic matter have accumulated on the sea bed due to eutrophication, which has resulted in the occurrence of oxygen-deficient water from the bottom to the middle layer of water during the summer. This phenomenon has occurred in many enclosed coastal seas, such as Tokyo Bay, Osaka Bay, and Ise Bay (Suzuki and Matsukawa, 1987; Joh, 1989; Omori, et al., 1994), as well as in aquaculture areas (Hirata et al., 1994; Tsutsumi, 1995). The hypoxic (or anoxic) water can lead to environmental impacts, such as blue tide (Aoshio) and red tide (Akashio) (Kakino et al., 1987; Takeda et al., 1991). Shallow-water regions such as tidal flats can mitigate these problems; sea grass and seaweed beds act as water purifiers and they play an important role in preventing habitat deterioration and in promoting fish nursery grounds in the inner-bay environment (Takeda et al., 2007).

The Environmental Restoration Project on Enclosed Coastal Seas in Ago Bay — also called the Ago Bay Project — began in 2004 to deal with efforts to restore the environmental conditions in the bay under the Collaboration of Regional Entities for the Advancement of Technological Excellence (CREATE) program of the Japan Science and Technology Agency (JST). The goal of the project was to improve the natural self-cleaning capability of the bay by forming constructed tidal flats, shallow-water areas, and sea algae and/or sea grass beds inside the bay.In 2005, up-to-date technology for a new in situ solidification system for treating muddy sea bottom sediments (the Hi-Biah-System (HBS)) was developed (Imai el al., 2007; Dabwan et al., 2007). The product of the process — solidified sediments — contain a great deal of mud. This mud was used to construct tidal flats in Ago Bay. To our knowledge, few experimental and monitoring data exist concerning these muddy, enriched, constructed tidal flats. In this study, we continuously monitored the ecosystem and environmental conditions in a constructed tidal flat and compared it to data from a natural tidal flat.

2. MATERIALS AND METHODS

2.1 Study site

The study site is located in Ise-Shima National Park, a semi-enclosed area around the Shima peninsula that is connected to the Pacific Ocean via a very narrow (the width is 1.5 km) and shallow (the water depth is 25 m) entrance called the Fukaya Channel (Fig. 1a). The interior part of the bay is complexly divided into many branch bays. The pearl culture industry uses the whole interior area of the bay and the cultivation rafts are spread out like the reticulation; thus, a large-scale dredger cannot enter these inner parts of the bay.

The natural tidal flat analyzed in our study lies in the inner part of a branch bay in the Tategami area in Ago bay. The amplitude of the flat varies from 0.5 to 3.0 m and its inclination is 1/10 (Fig. 1b). The constructed tidal flat was built in the same area.

2.2 Solidification method for disposal of sediments

Figure 2 shows the in situ solidification system. The detailed information has been described previously (Imai at al., 2007; Dabwan et al., 2007). The HBS consists of a main stock tank of sediments, a coagulant chamber, reactors 1 and 2, and a dewatering section. The treatment capacity was approximately 1~2 m^3/hour. The water content of the dredged sediments was 90% by weight. After treatment with HBS, the content was lowered to 60 wt%.

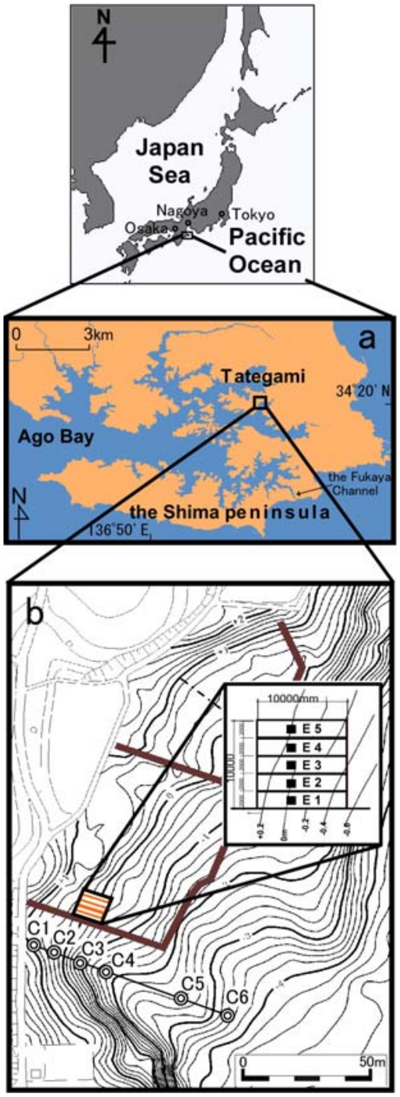

Figure 1. Location of Ago Bay in Mie prefecture, Japan. The stations indicate the artificial tidal flats (E1 to E5) and the natural tidal flats (C1 to C6).

2.3 Building the constructed tidal flat

The constructed tidal flat was settled from February to March 2005 in Tategami, Ago Bay as shown in Figure 1b. It was then divided into 5 sections (E1 to E5), each with an area of 10 m length × 2 m width × 0.5 m depth.

For section E1, the coagulant in the HBS consisted of 1.5 wt% of soil conditioner made of paper sludge ash exhausted from the pulp and paper industry. The chemical components of the soil conditioner were 44.2% CaO, 26.9% SiO_2, 12.7% Al_2O_3, and 12.2 % SO_3. After the water

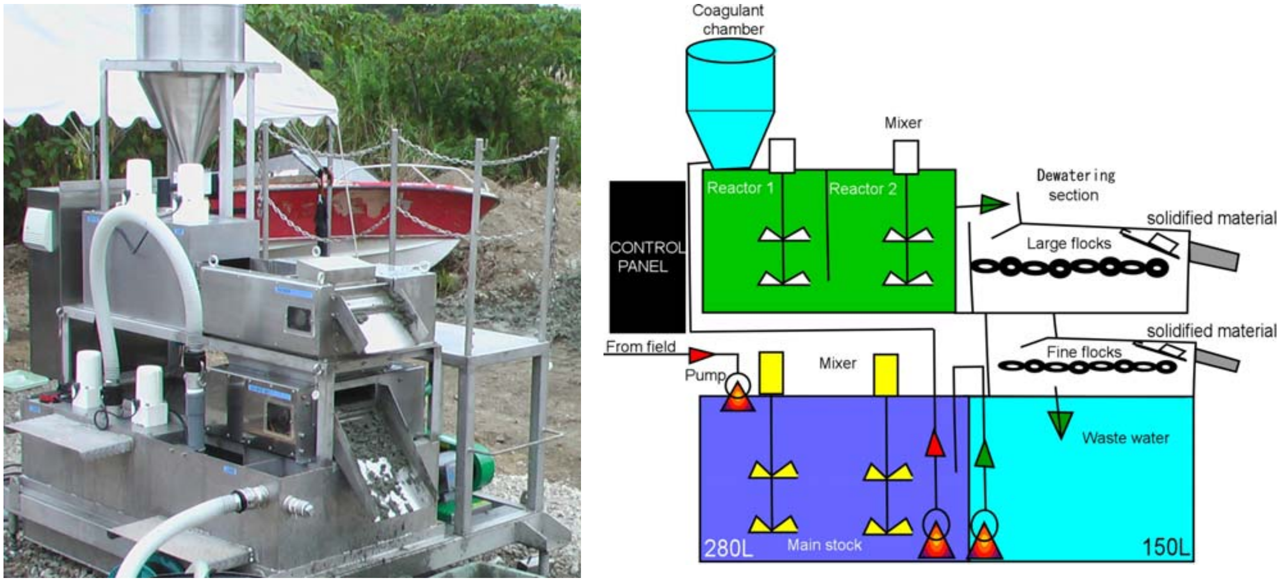

Figure 2. The solidification machine (Hi-Biah-System) developed for treatment of bottom sediments.

content of the sediments was reduced to 60 wt%, they were mixed with sand obtained from Ago Bay at a ratio of 3:7, and then an area of the constructed tidal flat was created from these materials.

For section E2, solidified materials with 60 wt% water content were produced in a similar way: After adding 20 wt% of the same soil conditioner, a pellet was formed with a pelletizer, as illustrated in Figure 3. The shape of the pellet was a column with a diameter of 8 mm and length of 20 mm. The E2 section of the constructed tidal flat was then produced from the pellets mixed with sand (weight ratio 3:7).

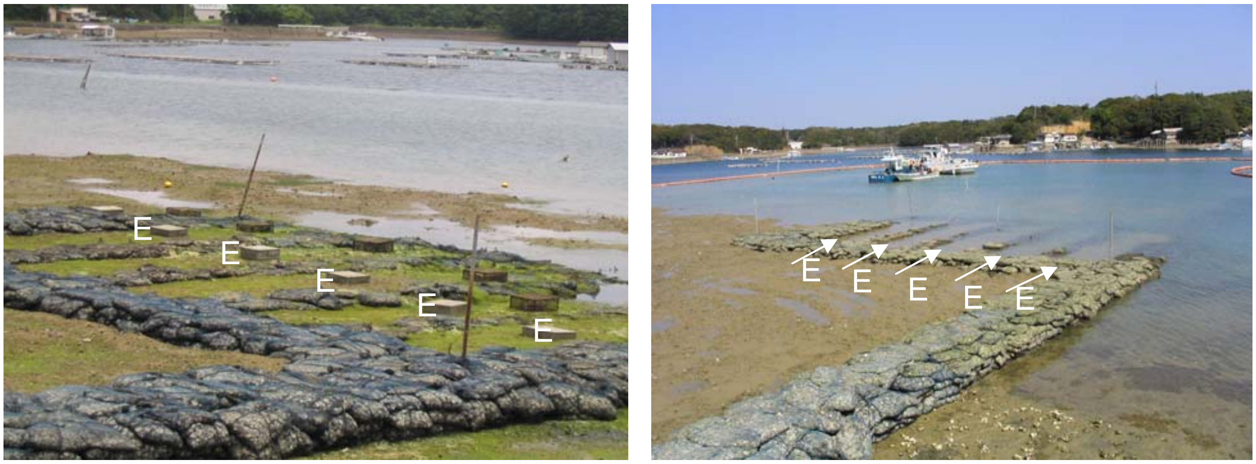

Figure 3. The sections of the artificial tidal flat.

The E3 section of the flat was constructed from sand obtained in Ago Bay. For the E4 section, 5 wt% of coagulant consisting of gypsum was used in the HBS solidification treatment. After dewatering, the sediment water content was reduced to 60 wt%, then the solidified materials were mixed with sand (weight ratio 3:7), and an area of the tidal flat constructed.

For section E5, approximately 2 wt% of poly aluminum chloride (PAC) was added as the inorganic polymer coagulant. After dewatering, the water content of the solidified materials was reduced to 40 wt% and the solidified sediments were mixed with solidification agents consisting of waste steel slag (20% by weight) and then with sand (weight ratio 3:7). The resulting materials were used to construct the E5 area of the tidal flat.

2.4 Monitoring of environmental conditions in the constructed tidal flat

We monitored the physico-chemical parameters and biological characteristics of the natural and constructed tidal flats every 4 months from 28 May 2005 to 20 June 2007. The parameters examined were water content, WC (JIS, 2000a); loss on ignition, LOI (JIS, 2000b); total organic carbon, TOC (Vario MAX CHS, Elementar Analysensysteme GmbH); chemical oxygen demand, COD (JIS, 1998); chlorophyll a (N,N-Dimethylformamide extraction method); acid volatile sulphide, AVS (Gas detector tube, GASTEC); and particle size (JIS, 1999). These physico-chemical parameters were evaluated using soil materials core-sampled from the surface to 12 cm depth. The amount of chlorophyll a was measured in soil materials from the surface to a depth of 1 cm. Particle size was measured at 3 and 16 months in the natural tidal flat and every 4 months in the artificial tidal flat. To evaluate biomass and a population density of macrobenthos, soil samples were collected within quadrats (25 cm x 25 cm x 25 cm). Subsequently, the samples were sieved through a mesh size of 1 mm and the organisms on the sieve were fixed in 10 vol% formaldehyde. Organisms then were sorted, identified, counted, and weighed.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical parameters on the constructed tidal flat

We monitored the physico-chemical environmental conditions on the constructed tidal flat every 4 months for 20 months. Tables 1 and 2 summarize the results of the particle size analysis of the natural tidal flat and the artificial tidal flat, respectively. In the natural tidal flat, the percentage (abundance ratio) of particles with a diameter < 75 μm increased with depth from C1 to C6. At stations C3 to C6 the median particle size was < 75 μm, which illustrates that the natural tidal flat in this study area is a muddy tidal flat. In contrast, only 20–45% of the particles from the artificial tidal flat (not including E3) were < 75 μm. These values were similar to those from stations C1 and C2, but lower than the value from adjacent station C3, which sits at a water depth similar to that of the artificial tidal flat.

Table 1. Particle size analysis of the natural tidal flat.

Time passed[#] (months)		C1	C2	C3	C4	C5	C6
3	< 75 μm[a]	42.1%	48.2%	64.1%	72.9%	83.1%	56.2%
	median[b]	96 μm	83 μm	41 μm	23 μm	4 μm	43 μm
16	< 75 μm	35.7%	47.7%	67.3%	81.4%	69.0%	75.7%
	median	120 μm	80 μm	31 μm	6 μm	10 μm	6 μm

[#] In 2005, monitoring was performed in Apr. (1 month), Jul. (3 months), and Oct. (6 months); in 2006 in Jan. (9 months), Jun. (13 months), Sep. (16 months), and Nov. (18 months); and in Jan. 2007 (20 months).

[a] Percentage of particles with a diameter < 75 μm

[b] Median particle size

No remarkable temporal differences in the muddy fraction percentage in the artificial tidal flat were observed during the 20 months of monitoring. Previous research has documented the movement of fine particles on tidal flats (Yang, 1999; Osborne, 2005; Chang, 2007). Although the effusion of muddy fraction (small particle size fraction) was expected in the artificial tidal flat , these results that no remarkable change in the particles of less than 75 μm were observed may support that this phenomenon was not occurred.

In the estuaries that lie at the interface between freshwater and marine systems, organic matter mineralization processes occur (Middelburg at al., 1996). Thus, when constructing man-made artificial tidal flats, evaluating these processes over time is important. Figures 4 and 5 depict the seasonal variations in each of the examined parameters. The WC (a), LOI (b), TOC (c), and COD (d) were almost constant among the monitoring periods. However, the values of these parameters were lower at stations C1 and C2 in the natural tidal flat and at station E3 in the artificial tidal flat, compared to the other stations of both tidal flats. The value of chlorophyll a increased over time on the artificial tidal flat. This phenomenon also was observed on the natural tidal flat on the deeper side that sat at the same level as the artificial tidal flat.

3.2 Monitoring of macrobenthos on the constructed tidal flat

Evaluating the benthic fauna's response to the constructed tidal flat requires analysis of both abundance changes that occur over space and time (Beukema, 1976; Koh and Shin, 1988; Castel et al., 1989). Figures 6 and 7 depict the population density and biomass of macrobenthos in the natural (a) and constructed (b) tidal flats over time. On the constructed flat, the population density and biomass were close to zero after 1 month, but after 3 months the population density increased relative to that observed in the natural tidal flat (especially at the same depth level station (C3), as shown by the arrows). On the other hand, the biomass of macrobenthos reached a level similar to that of the natural tidal flat after 6 months. After 20 months of monitoring,

Table 2. Particle size analysis of the materials used to construct each section of the artificial tidal flat.

Time passed[#] (months)		E1	E2	E3	E4	E5
1	< 75 μm[a]	35.6%	28.0%	16.9%	36.1%	25.7%
	median[b]	271 μm	292 μm	861 μm	245 μm	636 μm
3	< 75 μm	45.1%	22.6%	28.8%	26.3%	19.3%
	median	111 μm	986 μm	286 μm	529 μm	1963 μm
6	< 75 μm	33.3%	20.0%	15.2%	23.4%	20.3%
	median	210 μm	1504 μm	666 μm	480 μm	631 μm
9	< 75 μm	43.6%	43.3%	29.1%	45.8%	26.0%
	median	107 μm	115 μm	207 μm	109 μm	346 μm
13	< 75 μm	28.0%	36.0%	21.1%	32.5%	26.0%
	median	310 μm	220 μm	340 μm	240 μm	360 μm
16	< 75 μm	33.9%	25.7%	18.3%	31.7%	25.9%
	median	230 μm	330 μm	370 μm	250 μm	340 μm
18	< 75 μm	36.6%	27.5%	20.1%	29.2%	26.0%
	median	210 μm	280 μm	350 μm	240 μm	320 μm
20	< 75 μm	31.2%	31.3%	19.0%	26.0%	22.9%
	Median	240 μm	230 μm	320 μm	260 μm	390 μm

[#] In 2005, monitoring was performed in Apr. (1 month), Jul. (3 months), and Oct. (6 months); in 2006 in Jan. (9 months), Jun. (13 months), Sep. (16 months), and Nov. (18 months); and in Jan. 2007 (20 months).

[a] Percentage of particles with a diameter < 75 μm

[b] Median particle size

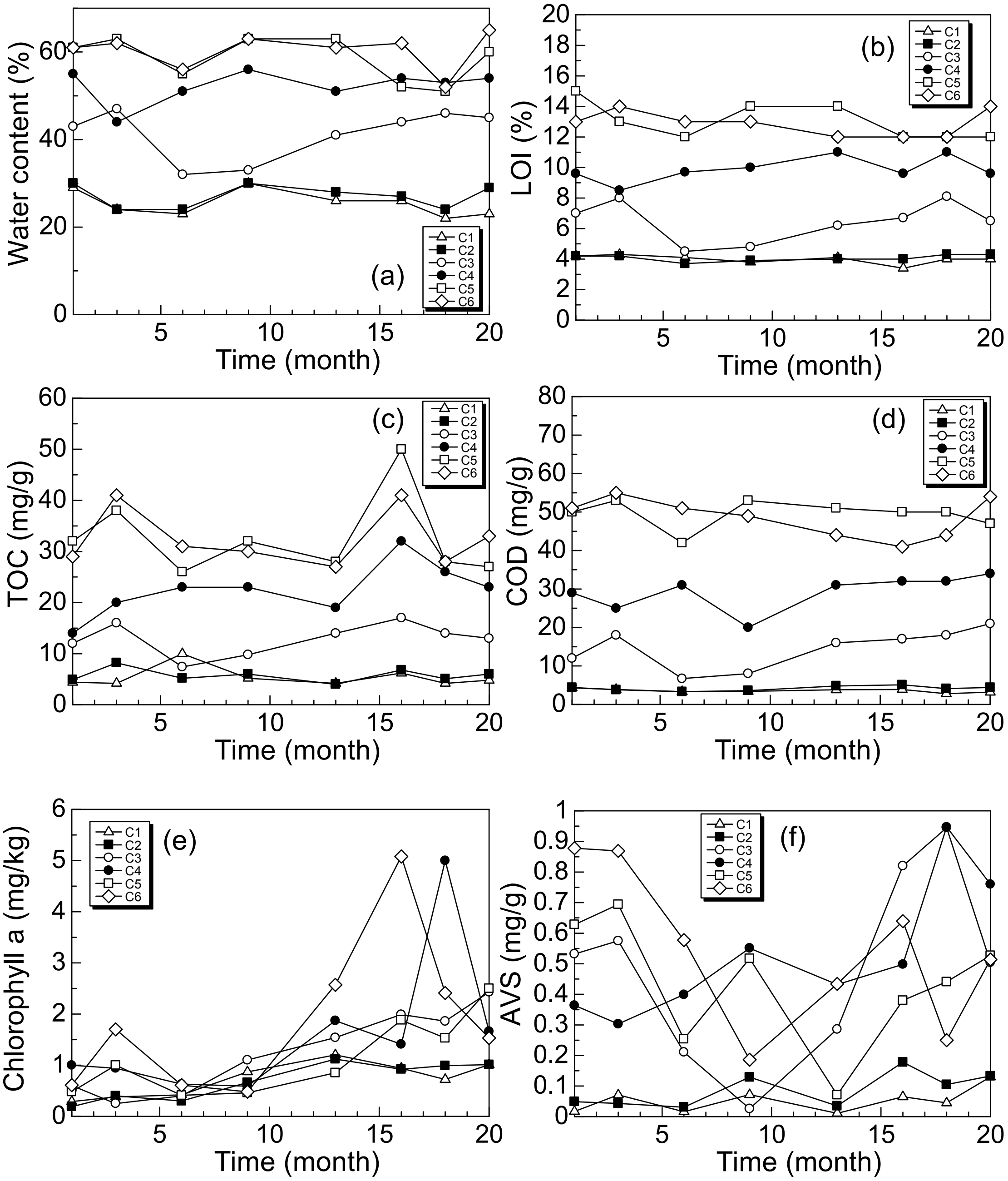

Figure 4. Chemical parameters of the natural tidal flat. See Table 1 for monitoring dates. (a) WC: water content, (b) LOI: loss on ignition, (c) TOC: total organic carbon, (d) COD: chemical oxygen demand, (e) Chlorophyll a, (f) AVS: acid volatile sulphide.

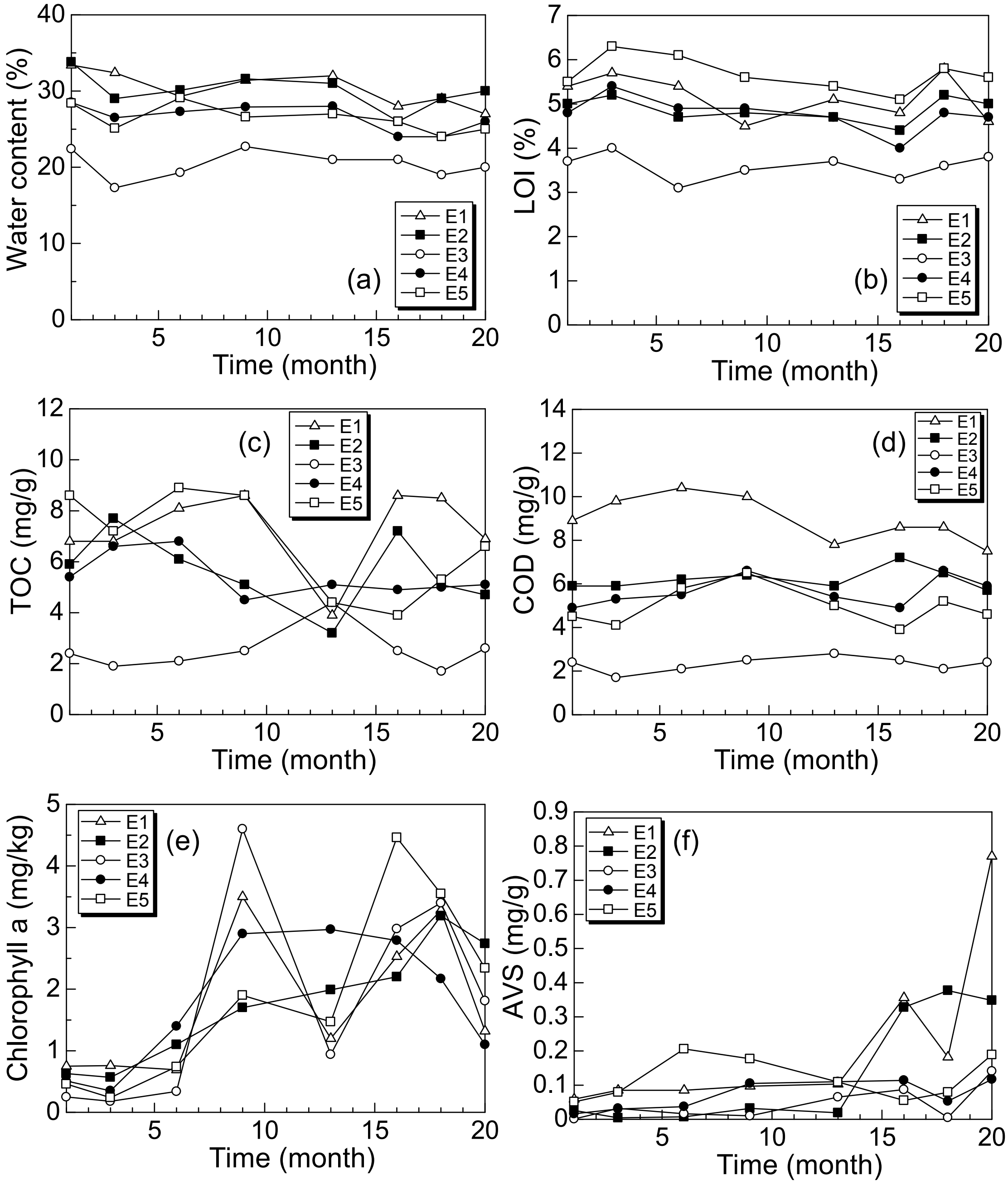

Figure 5. Chemical parameters of the artificial tidal flat. See Table 1 for monitoring dates. (a) WC: water content, (b) LOI: loss on ignition, (c) TOC: total organic carbon, (d) COD: chemical oxygen demand, (e) Chlorophyll a, (f) AVS: acid volatile sulphide.

despite the appearance of increases and decreases, the population density and biomass of macrobenthos in the constructed tidal flat increased relative to that of the natural tidal one. The predominant macrobenthic species in the constructed tidal flat were polychaetes and molluscs. At the deeper stations of the natural tidal flat, the predominant species were bivalves, but the species observed were similar at both tidal flats and the species composition of the two types of flat were not significantly different. These results were similar to data reported previously (Havens et al., 1995; French et al., 2004). These observations for better population and biomass of macrobenthos may be due to the minerals supplied by the solidified sea bottom sediments, which would generate good ecological conditions for benthic animals. However, Herman et al. (2001) reported that the abundance of microalgae is much lower at muddy than at sandy sites, and they hypothesized that high mud content decreases the availability of benthic microalgae. Likewise, Billerbeck et al. (2007) pointed out that benthic photosynthesis was greater in the submerged inner bay with sandy substrate than in the muddy area.

Long-term monitoring is needed to better understand the effects of using these muddy solidified sea bottom sediments to construct tidal flats. To our knowledge, few long-term investigations have been undertaken in the artificial tidal flats (Cammen et al., 1974; Seneca et al., 1976), but the little data available suggest that the habitat functions (e.g., primary production, organic carbon content) on a constructed tidal marsh would be similar to those of a natural tidal one after several years.

Lee et al. (1988) investigated the physico-chemical and biological characteristics of several natural tidal flats and constructed tidal flats with various types of sandy and muddy conditions on the in the semi-closed sea environment. They found no remarkable differences in the population density and biomass of macrobenthos. In contrast, bacterial populations of the sandy constructed tidal flats were remarkably lower than those in the natural flats. However, the population density of samples collected from the constructed tidal flat with high silt content was similar to that of the natural tidal flat. These results indicate that silt particles play an important role in providing habitats for benthic bacteria and biologically productive environments for tidal flats. Ueda (2000) reported that on tidal flats, the sediments were kept oxygenated and accessible to benthic animals throughout the year and the dominant benthic fauna were larger than those found in adjacent inner bay bed.

In the natural tidal flats (Fig. 6a and Fig. 7a), the water depth increased from C1 to C6 and station C3 was at almost the same depth as the constructed flat (E1 to E5). The macrobenthic population density at stations C1 and C2 was lower than at stations C3 to C6 (Fig. 1). C1 and C2 also had lower water content and organic matter content (LOI, TOC, and COD; Fig. 5) than did the other natural stations. These values were lower than those obtained in the constructed tidal flat (not including E3), although the high silt contents was observed in natural tidal flat rather than the artificial tidal flats. These results suggest that it is important to construct artificial tidal flats by considering not only organic matter content but also water depth.

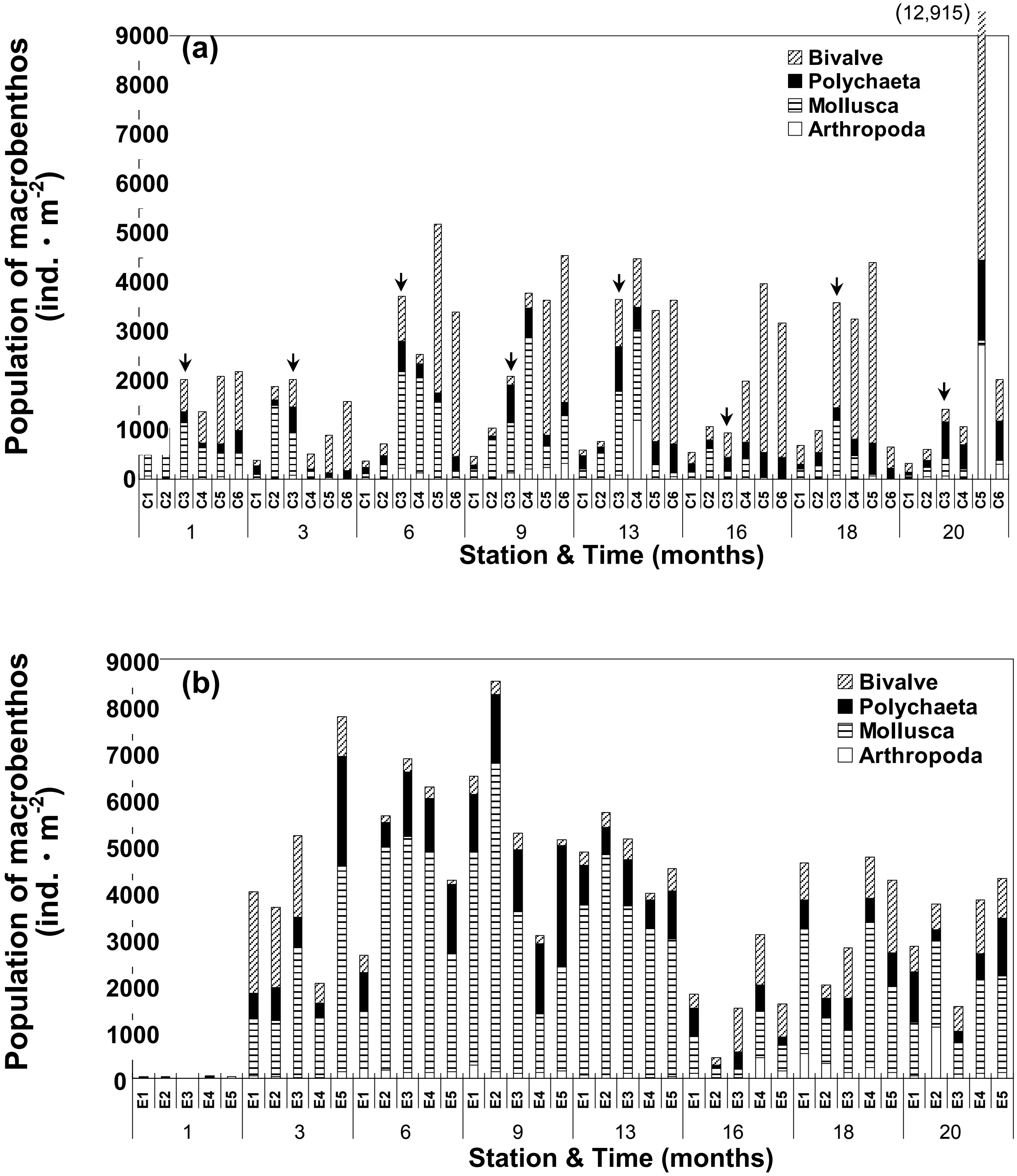

Figure 6. Population of macrobenthos in the natural tidal flat (a) and the artificial tidal flat (b). See Table 1 for monitoring dates. C1 to C6: the natural tidal flat.

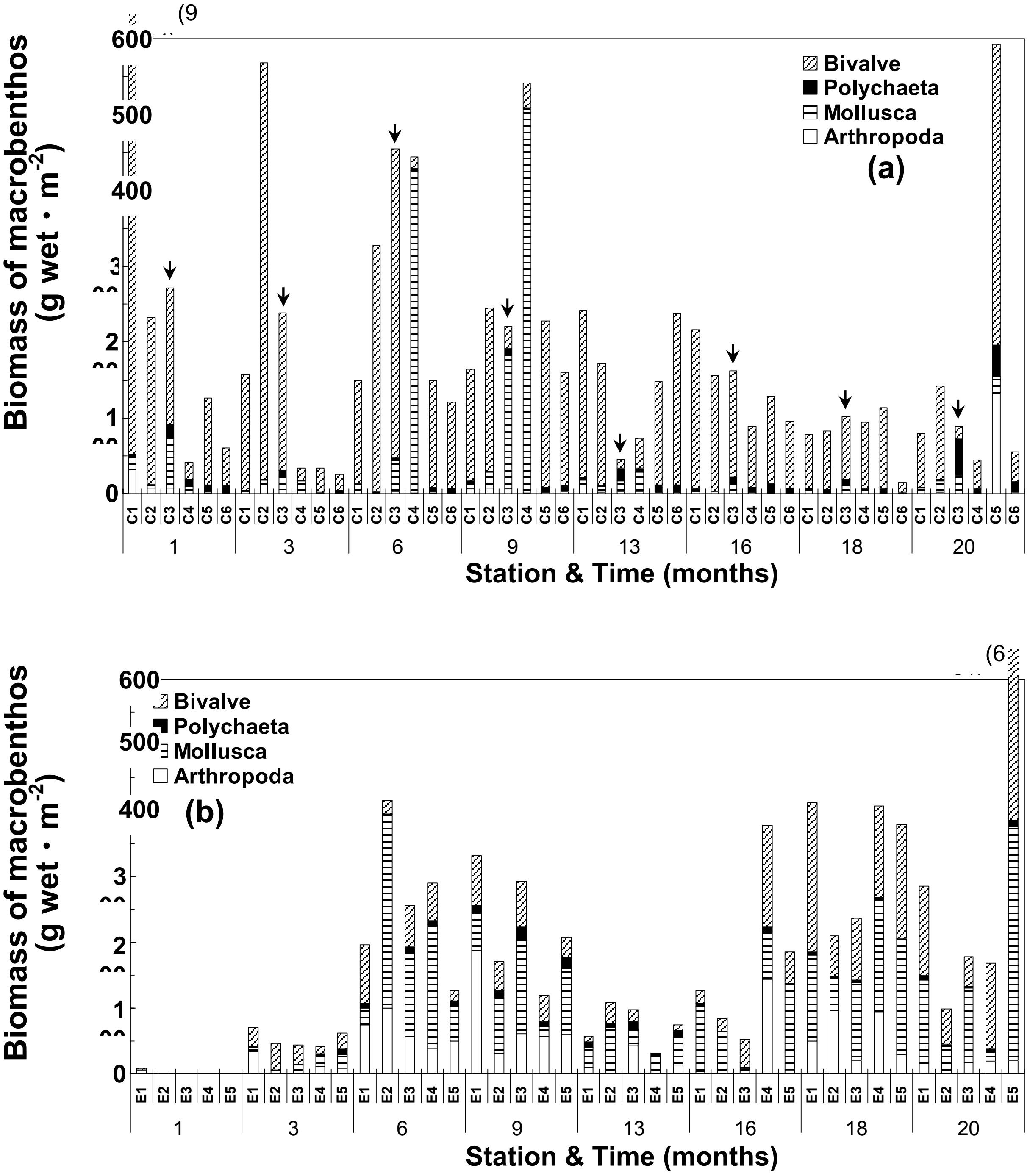

Figure 7. Biomass of macrobenthos in the natural tidal flat (a) and the artificial tidal flat (b). See Table 1 for monitoring dates. C1 to C6: the natural tidal flat.

4. CONCLUSIONS

We developed an in situ solidification system for treatment of sea bottom sediments (the Hi-Biah-System (HBS)). These solidified sea bottom sediments were then used to construct an artificial tidal flat in Ago Bay. The ecosystem and environmental conditions of the constructed tidal flat, which were monitored and compared to a natural tidal flat over the course of 2 years, were found to be very similar and/or superior to those of the adjacent natural tidal flat.

5. ACKNOWLEDGMENTS

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