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Cover Page Footnote

This research was partly supported by the Ministry of Education, Culture, Sports, Science, and Technology of Japan. The present work was performed as part of the joint collaboration of research projects titled “Environmental Restoration Project on the Enclosed Coastal Seas, Ago Bay,” supported by the CREATE (Collaboration of Regional Entities for the Advancement Technological Excellence) activity program organized by the Japan Science and Technology (JST) Agency. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the supporting organizations.

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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 organically contaminated by the practice of culturing pearls, which has been ongoing for the past 110 years. To address this problem, a new technology — the Hi-Biah-System (HBS) —, which dewateres muddy dredged sediments and changes the muddy sediments for raw materials of tidal flat, was introduced in 2005. The solidified product from the sediments with the HBS was used to construct the tidal flat. The purpose of this study was to evaluate the environmental conditions of the constructed tidal flat 2 years after its construction. 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 a constructed tidal flat (five sections) and a natural tidal flat (six points). At the same tidal level, the physico-chemical parameters were similar among the constructed and the natural tidal flats. However, the biomass and macrobenthic population were higher in the constructed flat compared to the natural one. According to the findings of this study it can be concluded that the solidified products from the sediments with the HBS could provide useful materials for constructing the tidal coastal environment.

Keywords: Muddy dredged sediments, constructed tidal flat, macrobenthos, total organic carbon, Ago Bay

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 Mie Prefecture, Japan. Over the past 110 years, the practice of culturing pearls in the bay has led to organic contamination associated with the deterioration of sea water and sediments. The expansion of human populations and anthropogenic impacts on sensitive natural systems

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(shallow areas, sea grass beds, and tidal flats) has further increased the input of contaminated materials into Ago Bay. Therefore, their situations lead 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 awful 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 economical and environmental friendly dredging and disposal of contaminated sediments as well as possibilities of reusing the sediments have not yet resolved. Thus, the development of an alternative system to treat dredged sea bottom sediments is required for healthier environment.

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 to reduce and recycle waste soil. Thus it can provide an additional alternative for the long-term management of dredge disposal sites by reducing the amount of land needed for disposal facilities.

Constructing tidal flats is another alternative use of dredged materials. When the dredged sediment with awful smell is treated by the HBS, the solidified materials from them can not emit the smell. Many tidal flats have been destroyed 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 km² in the 1940s. Approximately 40% of these natural flats were destroyed by 1980s (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 activity. 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 remedy the damaged tidal flats and to create constructed tidal flats for restoring environmental conditions (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. It resulted due to the oxygen-deficient water from the bottom to the middle of sea during 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 sea weed beds act as water purifiers and can 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 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.

Hi Biah System (HBS), an up to date technology to treat muddy sea bottom sediments by in situ solidification, was developed in 2005 (Imai et al., 2008a, b; Dabwan et al., 2008). The products by the process, solidified sediments, contain a great deal of mud that was used to construct tidal flats in Ago Bay. Although the condition monitoring in the muddy-enriched, constructed tidal flats play a significant role in the environmental remediation and protection, there is little information on the environmental condition monitoring in the constructed tidal flats. In this study, we continuously monitored the ecosystem and environmental conditions in the five sections of constructed tidal flat and compared it to data from six points of 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 (1.5 km width) and shallow (25 m water depth) entrance of the bay (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 can not 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 flats were 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 (Dabwan et al., 2008; Imai et al., 2008a, b). 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 m³/hour. The water content of the dredged sediments was 90% by weight. After treatment with HBS, the content was lowered to 60 wt%.

2.3 Building the constructed tidal flat

The constructed tidal flat was built 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. Five sections of the tidal flat were constructed by using different materials for exploring the better conditions of artificial tidal flats.

Construction of Artificial Tidal Flats with Sea Sediments

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% SiO₂, 12.7% Al₂O₃, and 12.2% SO₃. After

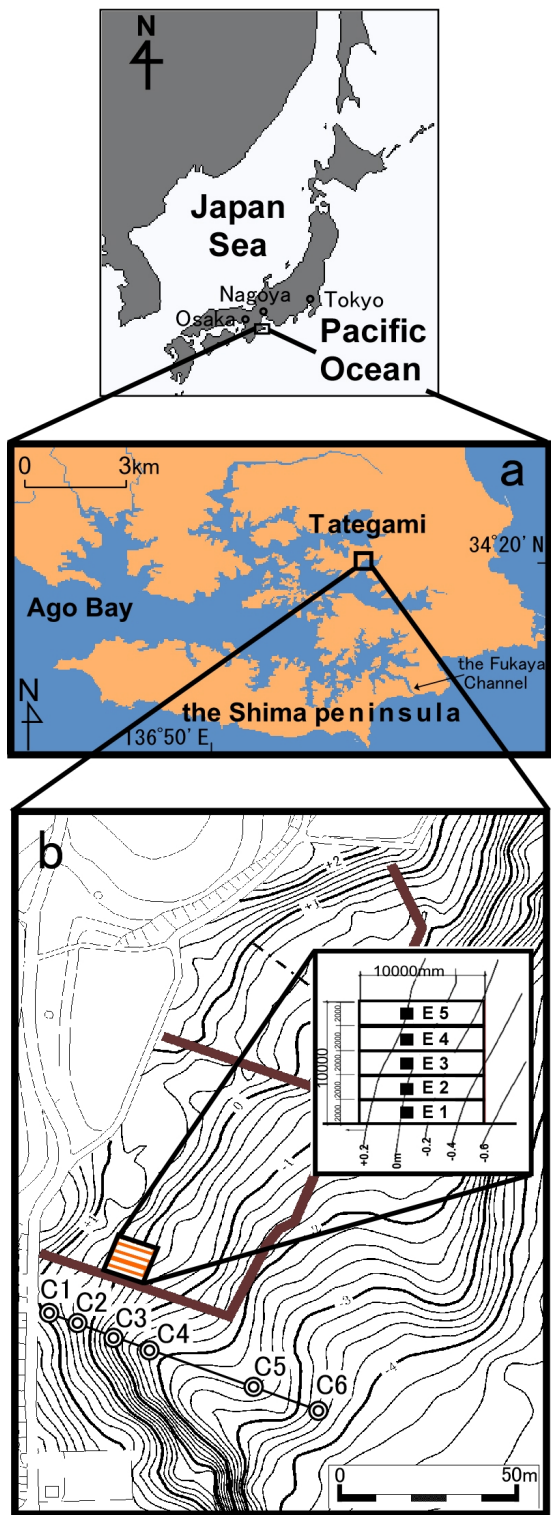


Figure 1. Location of Ago Bay in Mie prefecture, Japan. The stations indicate the artificial tidal flats (E1 to E5) and the natural tidal flats (C1 to C6).

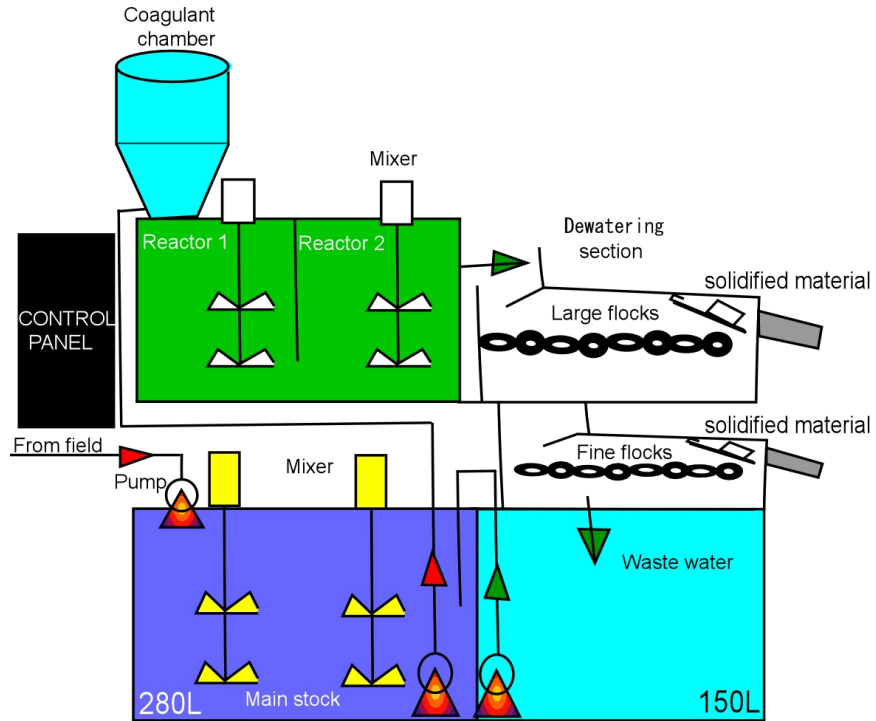


Figure 2. The solidification machine (Hi-Biah-System) developed for treatment of bottom sediments.

the reduction of water content to 60 wt%, the sediments were mixed with sand obtained from Ago Bay at a ratio of 3:7, and then an area of the constructed tidal flat was built 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. 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 built from the pellets mixed with sand (weight ratio 3:7).

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.

Table 1. Brief summary of the procedures for constructing artificial tidal flats.

Section	E1	E2
Procedure	(1) Addition of 1.5wt% soil conditioner. (2) Dewatering to 60 wt%. (3) Mixing of muddy sediment of (2) and sand with a ratio of 3:7. (4) Construction of tidal flat with the material of (3).	(1) Addition of 1.5wt% soil conditioner. (2) Dewatering to 60 wt%. (3) Addition of 20wt% soil conditioner. (4) Formation of pellet. (5) Construction of tidal flat with pellet of (4) and sand with weight ration 3:7.
Section	E3	E4
Procedure	(1) Construction of tidal flat with sand.	(1) Addition of 5wt% gypsum coagulant. (2) Dewatering to 60 wt%. (3) Mixing of muddy sediment of (2) and sand with a ratio of 3:7. (4) Construction of tidal flat with the material of (3).
Section	E5	Natural tidal flat
Procedure	(1) Addition of 2wt% PAC. (2) Dewatering to 40 wt%. (3) Addition of 20wt% solidification agent (waste steel slag). (4) Construction of tidal flat with the material of (3) and sand with weight ration 3:7.	6 points (C1~C6).

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. The procedures for constructing the artificial tidal flats are briefly summarized in Table 1. The sections of the artificial tidal flat illustrated in Figure 3.

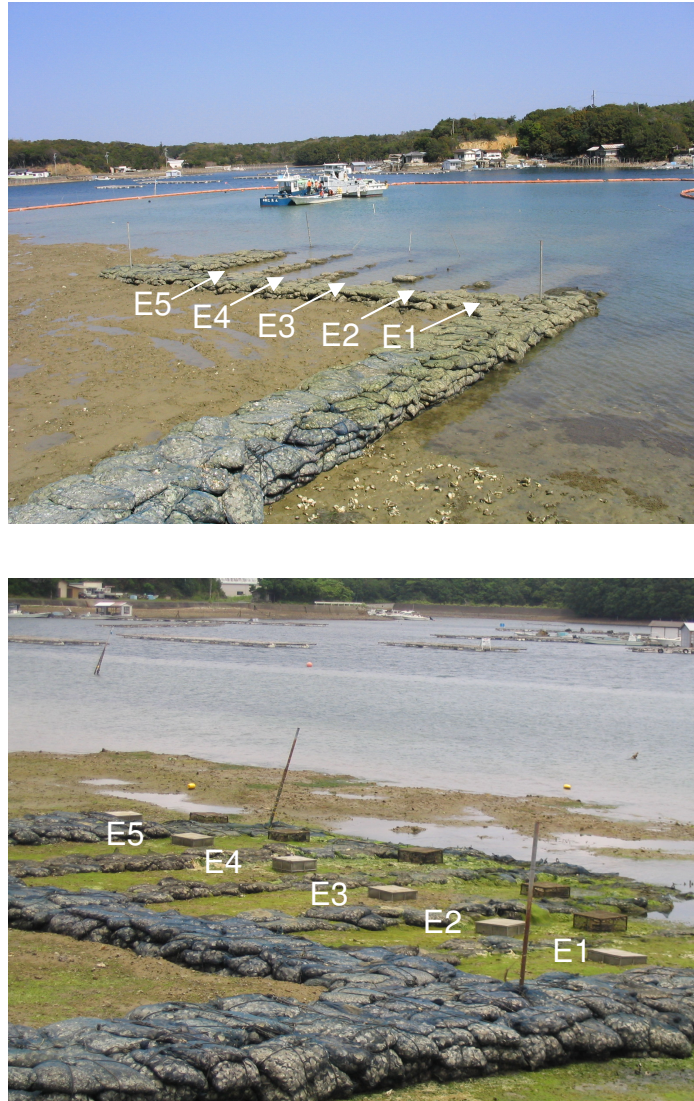


Figure 3. The sections of the artificial tidal flat.

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; Speziale et al., 1984); acid volatile sulphide, AVS (Gas detector tube, GASTEC); and particle size (JIS, 1999). These physico-chemical parameters were evaluated using all of 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 × 25 cm × 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 (Lee et al., 1998). 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 2 and 3 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 had the rough tendency to increase 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 area is a muddy tidal flat. In contrast, only 20–45% of the particles from the artificial tidal flat (except for 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.

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 et al., 2007). Although the effusion of muddy fraction (small particle size fraction) was expected in the artificial tidal flat, the observance of no remarkable change in the particles of less than 75 µm between 1 and 20 months may support that this phenomenon did not occurred.

In the estuaries lying at the interface of freshwater and marine systems, organic matter mineralization processes occur (Middelburg et al., 1996). Thus, evaluating these processes over time is important during the construction of man made artificial tidal flats. 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 lower values for WC, LOI, TOC, and COD at stations C1 and C2 may be attributable to the distance from the edge of sea water. 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. The tendencies of AVS in the constructed tidal flats were different from the natural one. The reason for them could not be clarified.

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 numerous 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, despite the temporal increase and decrease, 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 molluscans. 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 useful organic and mineral substances 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 available data 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.

Table 2. 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

Table 3. 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

Lee et al. (1998) investigated the physico-chemical and biological characteristics of several natural tidal flats and constructed tidal flats with various types of sandy and muddy conditions in the semi-closed sea environment. They found no remarkable differences in the population density and biomass of macrobenthos between the artificial and natural tidal flats. In contrast,

bacterial populations of the sandy constructed tidal flats were significantly 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. Ueda et al. (2000) reported that the sediments containing the silt particles were kept oxygenated and accessible to benthic

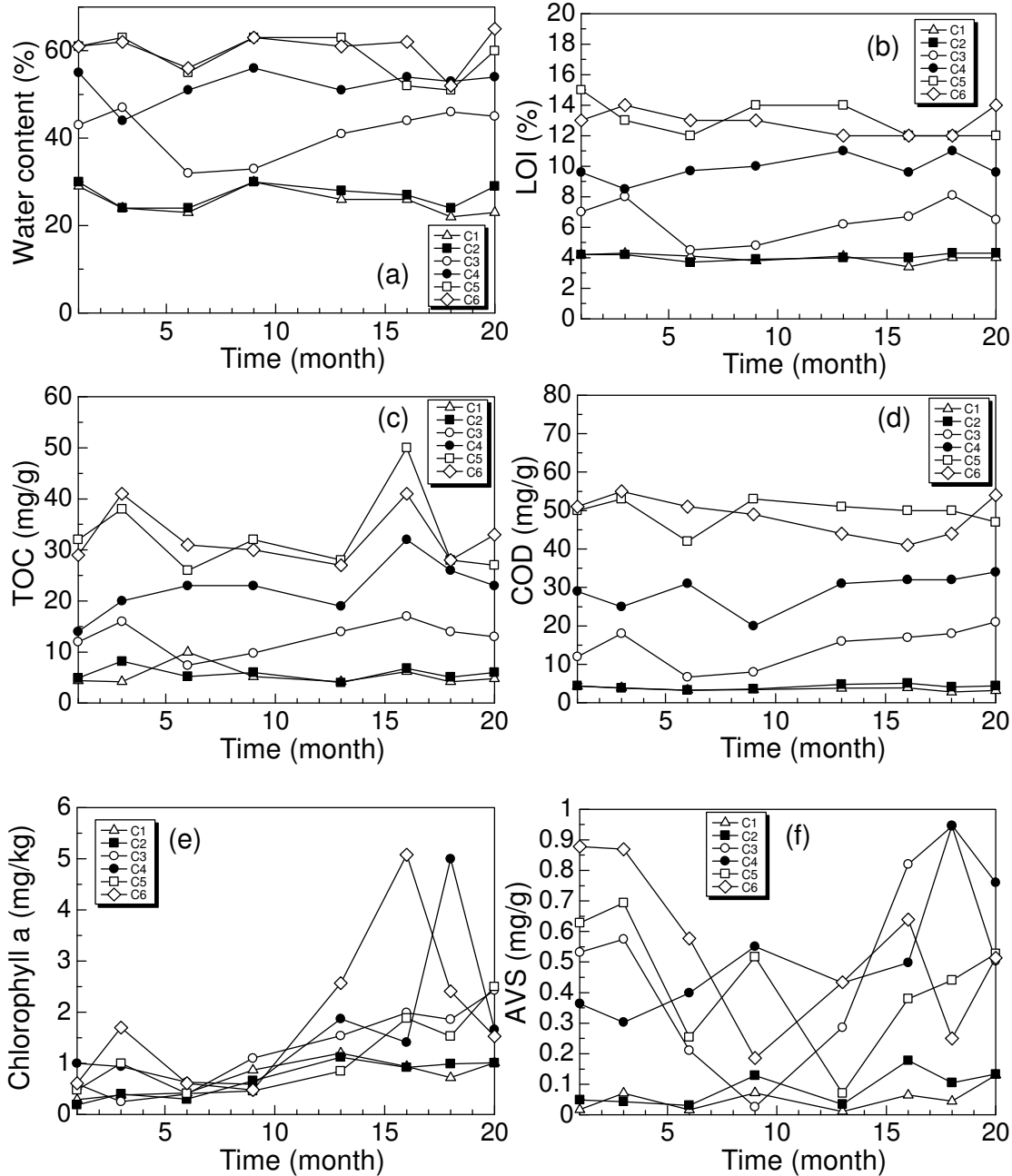


Figure 4. Chemical parameters of the natural tidal flat. See Table 2 for monitoring dates. (a) WC: water content, (b) LOI: loss on ignition, (c) TOC: total organic carbon, (d) COD: chemical oxygen demand, (e) Chlorophyll a, (f) AVS: acid volatile sulphide.

animals throughout the year on tidal flats and the dominant benthic fauna were larger than those found in adjacent inner bay bed. These literature reports and the experimental data in the present work may indicate that silt particles play an important role in providing habitats for benthic bacteria and biologically active environments for tidal flats.

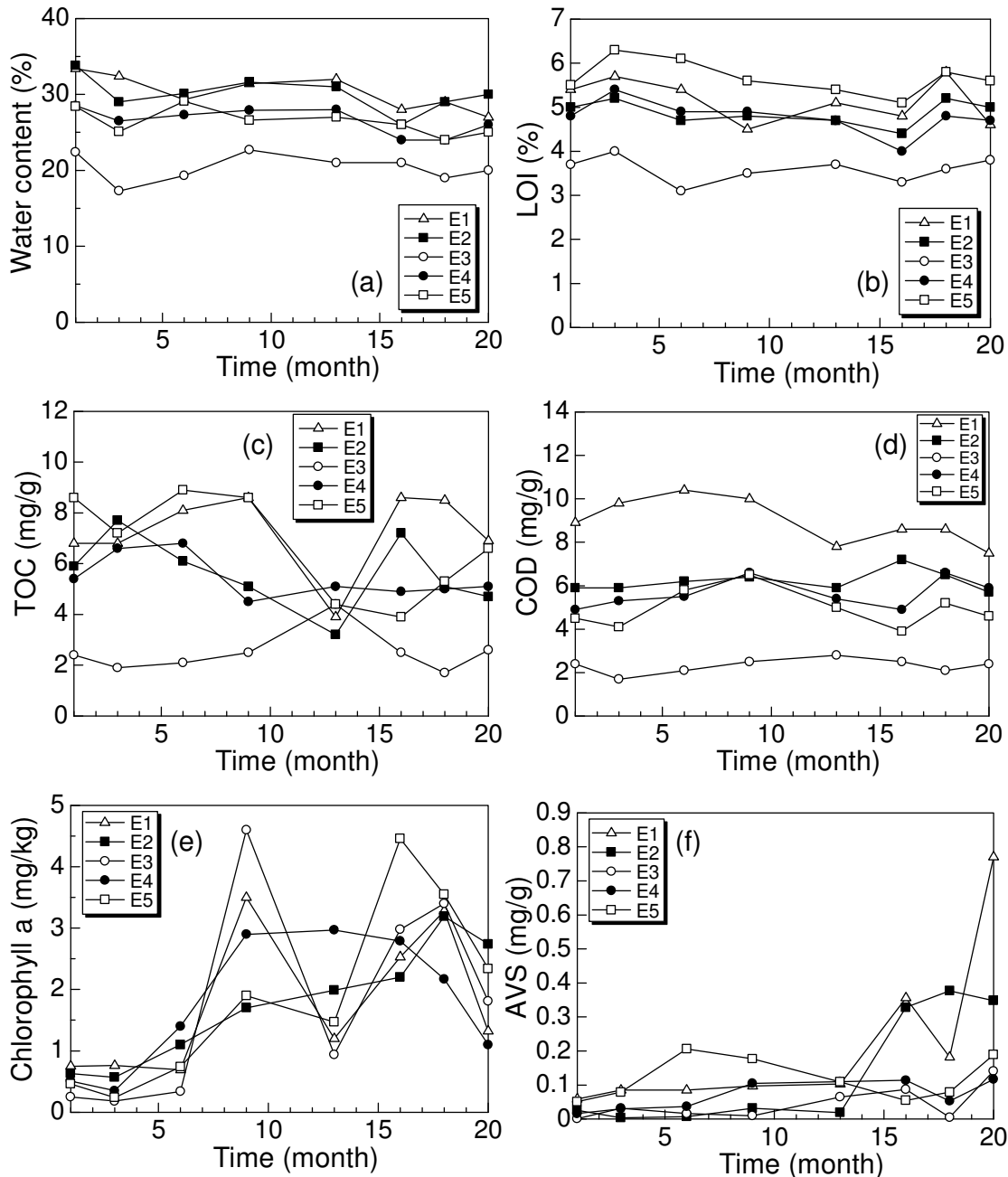


Figure 5. Chemical parameters of the artificial tidal flat. See Table 2 for monitoring dates. (a) WC: water content, (b) LOI: loss on ignition, (c) TOC: total organic carbon, (d) COD: chemical oxygen demand, (e) Chlorophyll a, (f) AVS: acid volatile sulphide.

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. 6). C1 and C2 also had lower water content and organic matter content (LOI, TOC, and COD; Fig. 4) than other natural stations. These values were lower than those obtained in the constructed tidal flat (except for E3), although the high silt contents was observed in natural tidal flat rather than the artificial tidal flats. The character of the constructed tidal flat at station E3 may be attributed that it was made of only the sand. The organic matter content can affect both population density and biomass of macrobenthos. Although little relation of macrobenthic biomass with the organic matter content could be observed in the present study, it was roughly postulated that the organic matter content in the range of 3% to 7% was moderately effective for increasing the macrobenthic population density, based on the comparison between the artificial and natural tidal flats. Consequently, the present results suggest that it is significant to construct artificial tidal flats by considering not only organic matter content but also water depth.

4. CONCLUSION

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 to those of the adjacent natural tidal flat.

5. ACKNOWLEDGMENTS

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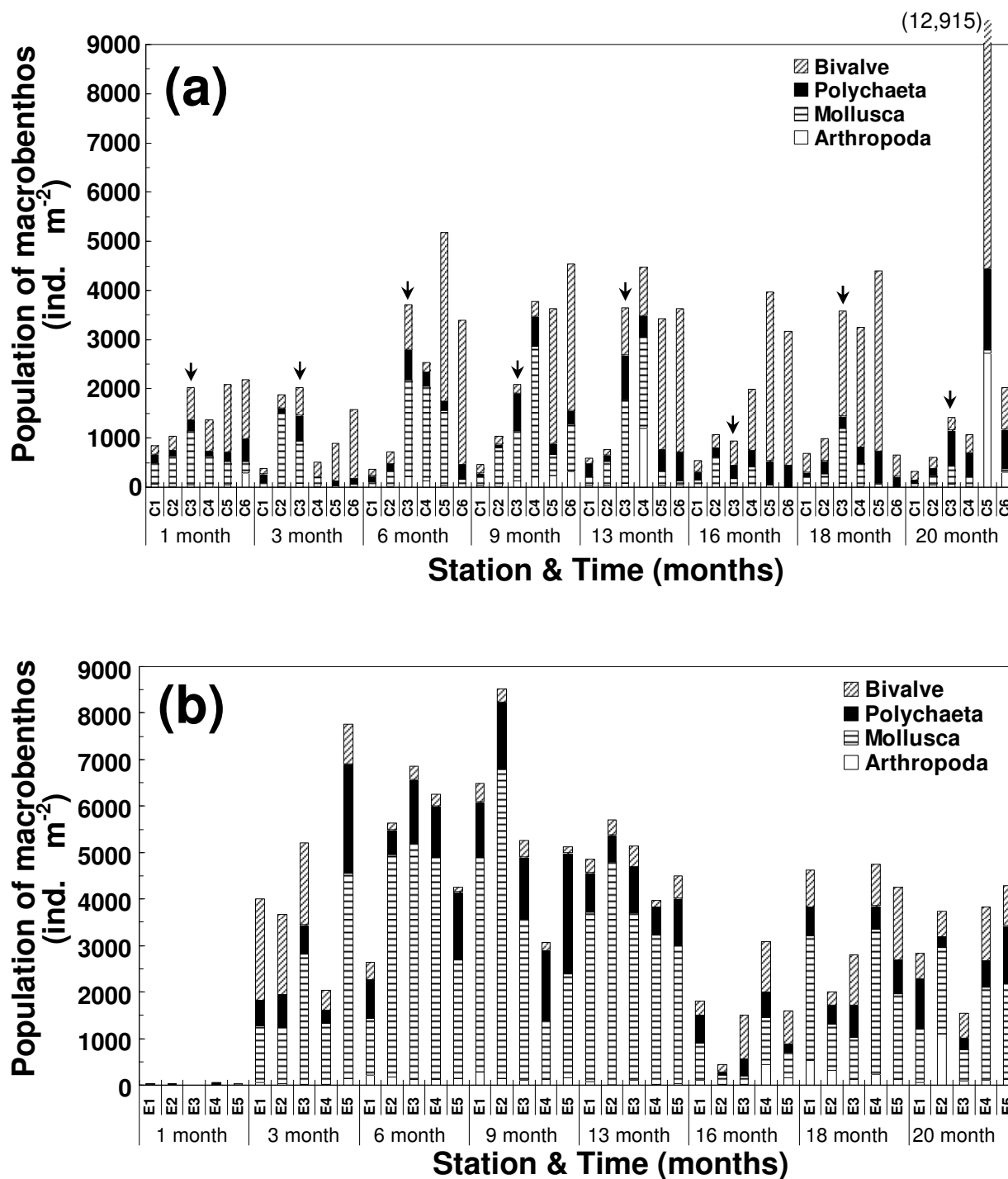


Figure 6. Population of macrobenthos in the natural tidal flat (a) and the artificial tidal flat (b). See Table 2 for monitoring dates. C1 to C6: the natural tidal flat.

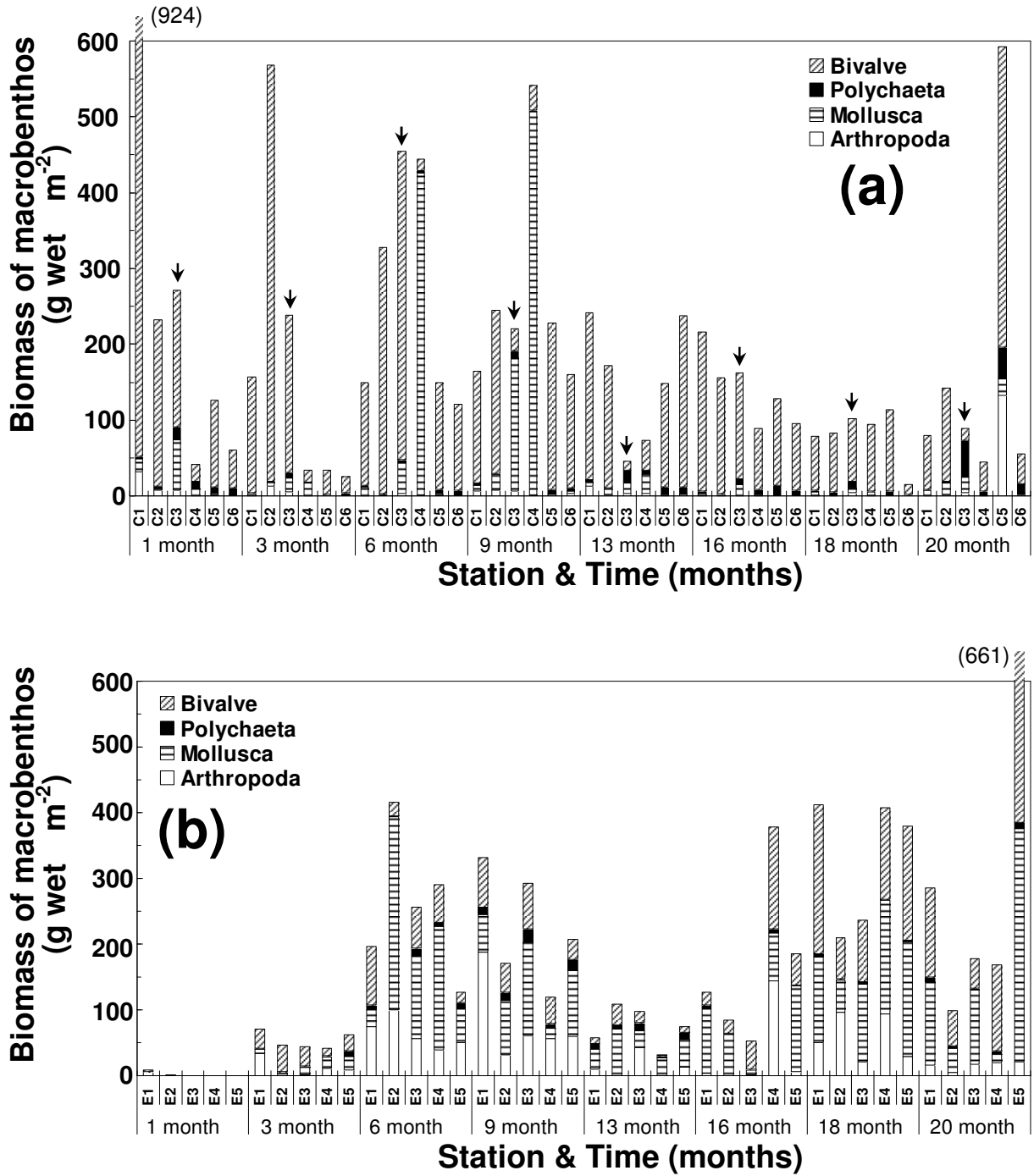


Figure 7. Biomass of macrobenthos in the natural tidal flat (a) and the artificial tidal flat (b). See Table 2 for monitoring dates. C1 to C6: the natural tidal flat.

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