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# SEDIMENT CHARACTERISTICS AND OXYGEN CONSUMPTION VELOCITY OF TIDAL FLATS IN ARIAKE SEA

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The sediment characteristics and the velocity of sediment oxygen consumption (SOC) were investigated using the intact cores sampled from the bed surface at 22 sites in the Ariake Sea. The vertical distributions of the sediment characteristics indicate that the silt tends to accumulate easily a large amount of organic matter and to make the sediment environments deteriorate. The values of AVS along the west coast tend to be lager than that along the east coast, because the grain of sediment along the east coast is coarse. The experimental results of SOC and the theoretical consideration showed that the values of dissolved oxygen decreased exponentially with time and the SOC velocity depends linearly on the sum of chlorophyll a and pheophytin concentrations. The SOC velocity increased with the water temperature and the threshold of biological activity was near 5 °C in the Ariake Sea.

***Key Words*** **:** *Sediment characteristics, sediment oxygen consumption, Ariake Sea*

## 1. INTRODUCTION

Hypoxic events, i.e., the phenomena that the dissolved oxygen (DO) in water decreases to less than about 2 mg/l[1)], give a severe impact to the ecosystems in the water area. The events not only cause the extinction of organisms, but also affect living resources and habitat. The behaviors of DO with time have been investigated to preserve the coastal ecosystems. As a result, it has been revealed that the generation of hypoxic water mass is significantly related to the human activities. The inputs of anthropogenic nutrient break the balances of coastal ecosystems and often induce high oxygen consumption. The consumption processes of DO in coastal ecosystems can be divided into those occurring in the water mass and those caused by sediment. Rutherford et al.[2)] concluded that the sediment oxygen consumption (SOC) might account for 90 % of the total oxygen consumption[2)]. The quantification of SOC, therefore, is very important to predict the generation of hypoxic water mass.

The SOC in a coastal region has been studied since the early 1960s[3-5)]. Three different methods are used generally for the SOC estimation: (1) incubation method with an intact core in a laboratory[6)]; (2) in situ measurements with a bell jar[7)]; (3) estimation method on diffusive oxygen fluxes calculated from the vertical profiles of DO near the sediment surface[8)]. Although the in situ measurements and the diffusive methods are often used, in recent years, the incubation method is the most popular because of its simplicity.

In this study, the sediment characteristics in the Ariake Sea have been investigated. The SOC velocity has been estimated by means of laboratory experiment and discussed on the basis of the sum of chlorophyll a concentration and pheophytin concentration, which is a representative index of easily decomposable organic matter. The water temperature dependence of the SOC velocity has also been investigated.

## 2. EXPERIMENTAL METHODS

### 2.1 Field sampling

The Ariake Sea is semi-closed sea located in Kyushu Island of Japan, and forms a unique ecosystem. It has the bay axis of 96 km, the area of 1,700 $km^2$ and the average width of 18 km as shown in Fig. 1. The water is 20 m deep on an average. Many rivers run into the east coast and the total area of tidal flats developing in the Ariake Sea is approximately 207 $km^2$. Recently, it is said that the decrease of tidal flats due to the reclamation, the reduction of tidal exchange and so on accelerate the deterioration of coastal ecosystems. Many researchers point out that hypoxic water mass generates frequently in summer and its frequency and spatial scale are increasing year by year.

The sediment sampling in the Ariake Sea was conducted in summer of 2005 to 2008 at 22 sites shown by red dots in Fig. 1. The number after the sampling site name means the number of sampling sites in the same area. Three intact sediment cores at each site were sampled by using a cylindrical acrylic tube shown in Fig. 2. The tube was 50 cm high and the inner diameter was 11 cm. The sediment cores higher than 15 cm were sampled. Two core samples were used for the experiments of SOC. The other one was used for the analysis of the sediment characteristics. The core samples were kept cool in a chest filled with ice and were carried to the laboratory. Seawater used for the SOC experiments was also sampled at each site.

### 2.1 Sediment analysis

Sediment core was sectioned at 0.5 cm intervals to 10 cm to analyze the sediment characteristics. The grain size of every section was measured by using the Particle Size Analyzer (HORIBA, L-920). The concentrations of chlorophyll a (Chl.a) and pheophytin (Pheo.) in each section were measured using standard spectrophotometric techniques after extraction of sample in 90 % acetone[9]. The acid volatile sulfide (AVS) in the dry sediment was obtained by converting the value of AVS in the wet sediment measured by using a gas detector (GASTEC, GV-100S).

### 2.3 SOC experiments

Fig. 3 shows the experimental set-up of SOC. To measure the values of SOC, the sampled seawater was first pretreated by filtering with Whatman GF/F and aerated for more than 1 h in a dark room. The pretreated seawater was superposed slowly on the sediment core so as not to suspend the bed materials till the water depth becomes 25 cm. The oxygen consumption due to bacterial respiration in the 25 cm column of pretreated seawater was measured as a reference. The water surface was sealed with thin liquid paraffin to suppress the transfer of oxygen through the air-water interface. Throughout the experimental period, the water column was slowly stirred by a stirrer to suppress the formation of stratification. The DO concentration was measured by using a calibrated DO electrode (TOADKK, OE-570BA) and obtained at 5-min intervals during 12 h. The experiments were conducted in an incubator (SANYO, MIR-253). The inside of the incubation was kept dark to suppress the primary production and was set to maintain the water

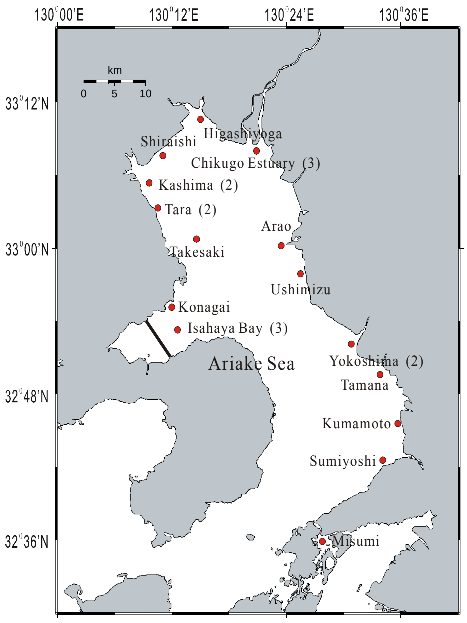


**Fig.1** Sampling sites of sediment cores in Ariake Sea.

**Fig.2** Sampled sediment core.

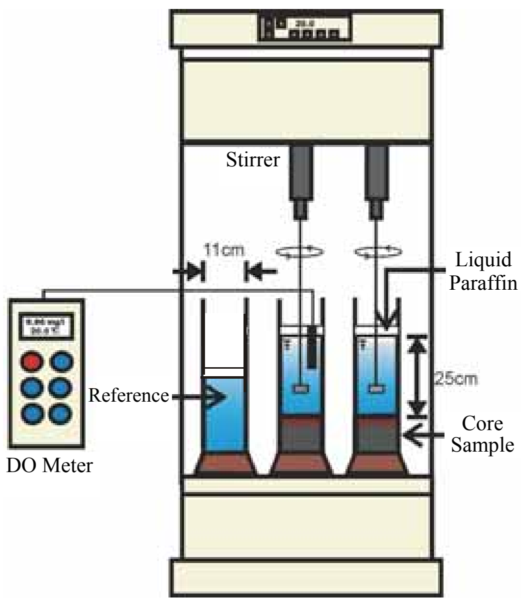


**Fig.3** Experimental set-up for SOC measurements.

temperature at 20 °C except for the experiments of the temperature dependence of SOC. In order to investigate the effect of temperature on SOC, intact cores sampled from Isahaya Bay were used. The water temperature was changed at intervals of 5 °C in the range of 5 to 25 °C.

## 3. RESULTS AND DISCUSSION

### 3.1 Sediment characteristics

Three east sites (Sumiyoshi, Yokoshima -1 and Ushimizu), two west sites (Takesaki and Kashima-1) and Chikugo Estuary -1 are selected as typical sampling sites. The vertical profiles of their sediment characteristics are shown in Fig. 4. As the AVS experiments could not be carried out at the Yokoshima site, the AVS data are not shown in Fig. 4 (d).

The grain sizes are converted to the values of median diameter phi (Md ϕ). As shown in Fig. 4 (a), Md ϕ at the 6 selected sites are in the range of 2.5 to 7.2. The profiles of Md ϕ at Kashima, Takesaki and Chikugo Esturary are almost uniform in the vertical direction and vary between 6 and 7. These sediments belong to silt. The sediment at Ushimizu and Sumiyoshi is sandy and the grain size tends to decrease with the depth. At Yokoshima site, Md ϕ suddenly decreases from 6.4 to 2.4 at 50-55 mm sediment layer. This means that the layer of silt accumulates on the sand of the lower layer.

Figs. 4 (b) and (c) show the vertical profiles of Chl.a concentration and Pheo. concentration, respectively. In both silty and sandy layers, the values of Chl.a are almost uniform in the vertical direction and are lower than 5 μg/gwet except for the surface layer at Yokoshima. The values of Chl.a in the surface layer at Yokoshima decrease rapidly with the depth and it suggests the accumulation of large amount of phytoplankton. Generally speaking, the tendency that the Pheo. concentration decreases with depth and depends on the grain size of sea bed is seen. As shown by the vertical profile at Yokoshima, the Pheo. concentration in the silt of upper layer is much higher than that in the sand of lower layer. Since the sediment at Kashima and Takesaki is silt, a large amount of Pheo. is included.

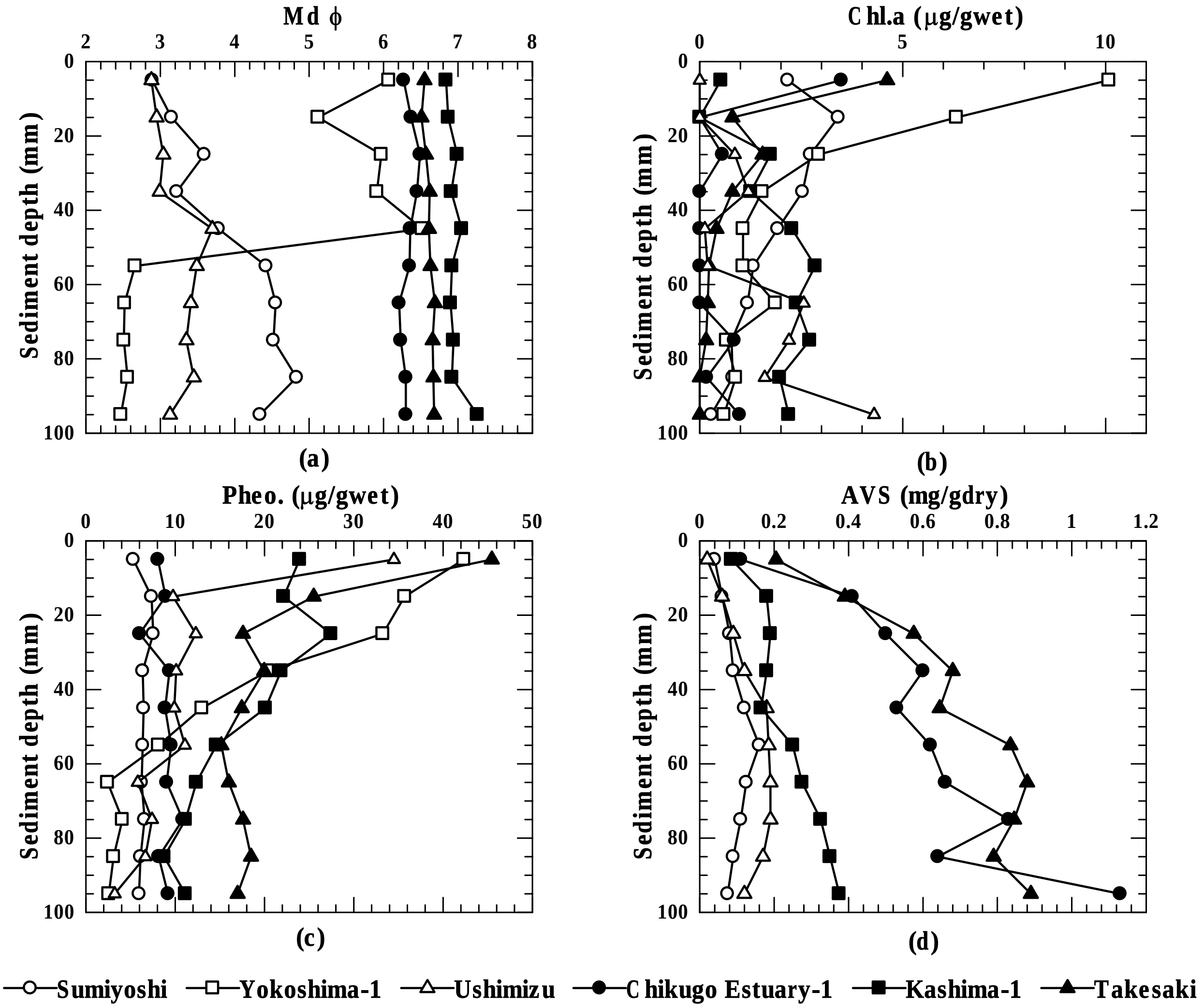


**Fig.4** Vertical profiles of sediment characteristics at typical sampling sites.

**Table 1** Average values of sediment characteristics.

| | Site | Md Ø | Chl.a (μg/gwet) | Pheo. (μg/gwet) | AVS (mg/gdry) |
|---|---|---|---|---|---|
| W | Isahaya Bay-1 | 6.54 | 6.44 | 30.46 | 0.33 |
| E | Isahaya Bay-2 | 6.57 | 7.82 | 4.61 | 0.28 |
| S | Isahaya Bay-3 | 5.97 | 6.05 | 10.38 | 0.52 |
| T | Konagai | 6.27 | 1.29 | 2.10 | 0.12 |
| | Takesaki | 6.53 | 2.63 | 32.49 | 0.35 |
| C | Tara-1 | 6.62 | 8.35 | 18.21 | 0.01 |
| O | Tara-2 | 6.60 | 2.02 | 5.82 | $9.75\times10^{-3}$ |
| A | Kashima-1 | 6.85 | 0.46 | 23.47 | 0.15 |
| S | Kashima-2 | 6.52 | 2.83 | 7.86 | $2.50\times10^{-2}$ |
| T | Shiraishi | 6.91 | 2.94 | 17.01 | 0.14 |
| | Higashiyoga | 6.52 | 0.60 | 5.91 | 0.00 |
| E | Chikugo Estuary-1 | 6.35 | 1.35 | 7.67 | 0.34 |
| A | Chikugo Estuary-2 | 6.14 | 1.43 | 10.16 | $1.80\times10^{-2}$ |
| S | Chikugo Estuary-3 | 6.69 | 0.45 | 4.58 | 0.00 |
| T | Arao | 6.31 | 0.00 | 9.73 | 0.38 |
| | Ushimizu | 2.94 | 0.35 | 19.60 | 0.05 |
| C | Yokoshima-1 | 5.55 | 7.18 | 38.75 | — |
| O | Yokoshima-2 | 6.53 | 4.65 | 8.74 | 0.16 |
| A | Tamana | 6.85 | 0.19 | 5.16 | $5.03\times10^{-2}$ |
| S | Kumamoto | 5.77 | 0.59 | 15.70 | 0.00 |
| T | Sumiyoshi | 3.05 | 2.83 | 6.43 | 0.05 |
| | Misumi | 2.76 | 1.47 | 8.31 | 0.02 |

The sediment at Sumiyoshi and Ushimizu is sand and the Pheo. concentration is very low. The concentration at Chikugo Estuary is also very low though the sediment is silt. This may be attributed to that the decomposition of organic matter has already advanced under the anaerobic condition as seen in Fig. 4(d).

The AVS concentrations varied between around 0 mg/gdry and 1.2 mg/gdry as shown in Fig. 4 (d). The AVS concentrations are less than 0.2 mg/gdry in the upper 5 mm layer of the all sites. The AVS concentrations at Takesaki and Chikugo Estuary increase rapidly with the depth and the sediment environment is in anaerobic situation. On the other hand, the concentration of AVS at Kashima is much smaller than that at Chikugo Estuary. However, considering that a large amount of Pheo. is included in the sediment at Kashima and the grain size at Kashima is much smaller than that at Chikugo Estuary, we can conclude that the sediment environments at Kashima will deteriorate more in future. The AVS values at Ushimizu and Sumiyoshi are almost uniform in the vertical direction and the sediment environments are in relatively good condition. This may be caused by that the sediment at Ushimizu and Sumiyoshi is sand.

The sediment characteristics for all the 22 sampling sites are given in Table 1. Here, the characteristic quantities are averaged over 3 cm thickness from the surface. Generally speaking, the values of AVS along the west coast tend to be lager than that along the east coast, because the grain of sediment along the east coast is coarse. Ushimizu, Sumiyoshi and Misumi take the small values of Md $\phi$ and AVS. These results mean that the sediments are sand and the sediment environments are under an aerobic condition. Especially, we can infer that the sediment layer at Ushimizu is in a good condition and the aerobic decomposition takes place though the value of Pheo. is very large. At Isahaya Bay, Takesaki, Chikugo Estuary-1, Arao, the value of AVS is larger than 0.2 mg/gdry and the sediment environments are in the deteriorated situation. Especially, the Pheo. concentration is also very large at Isahaya Bay-1 and Takesaki, we can infer that the sediment environments will progress to the worse situation. It is interesting that the value of AVS at Tara-1, -2, Kashima-2 and Tamana is relatively small and the sediment environments are in good condition though the sediment is silt.

### 3.2 Sediment oxygen consumption

The DO-depletion profiles are shown in Fig. 5. [DO]* is dimensionless quantity defined by $DO/DO_0$, where $DO_0$ is the initial value of DO. The profile at Yokoshima-1 decreases most rapidly with time because a large amount of organic matter is included in the sediment as shown in Fig. 4 (c). On the other hand, [DO]* decreases very slowly at Misumi, Chikugo Estuary-2 and Sumiyoshi since the organic matter in the sediment is small.

The time-variation of [DO]* is given by

$$V\frac{d[DO]^*}{dt} + S\,v[DO]^* = 0\,, \tag{1}$$

where $V$ is the volume of water, $S$ is the surface area of the sediment core and $v$ is the oxygen consumption velocity. By dividing the both side by $V$,

$$\frac{d\,[DO\,]^*}{dt} + \frac{v}{h}\{\,[DO\,]^*\} = 0 \tag{2}$$

is obtained. Here, h is the height of water column i.e., 0.25 m. The solution of Eq. (2) is given by

$$[DO]^* = \exp\left\{-\frac{v\,t}{h}\right\}. \tag{3}$$

Fig. 5 shows the profiles of DO depletion by the intact cores sampled at all the observation sites. These depletion profiles were obtained by subtracting the quantity of the oxygen consumption by the reference from one by the intact sediment core. In the figure, the theoretical curves are drawn to fit to the experimental data. We can see a good agreement between the experimental data and the theoretical curves.

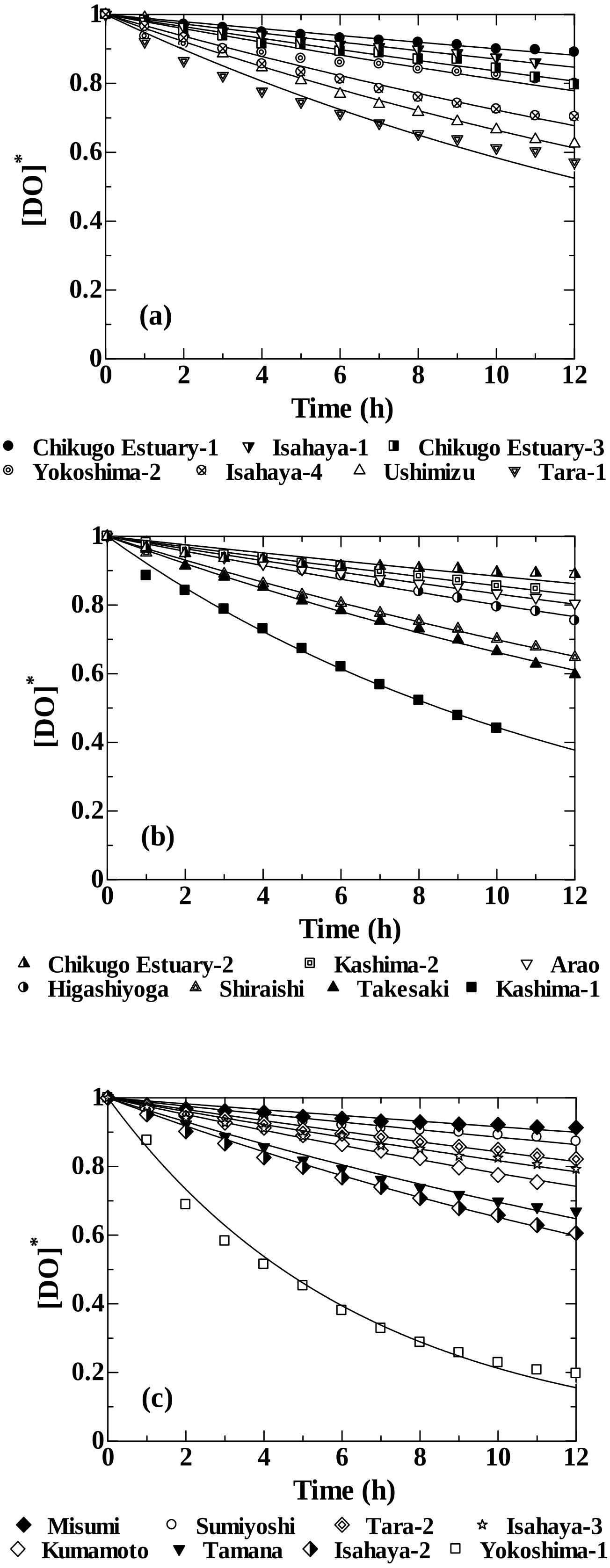


**Fig.5** DO-depletion profiles.

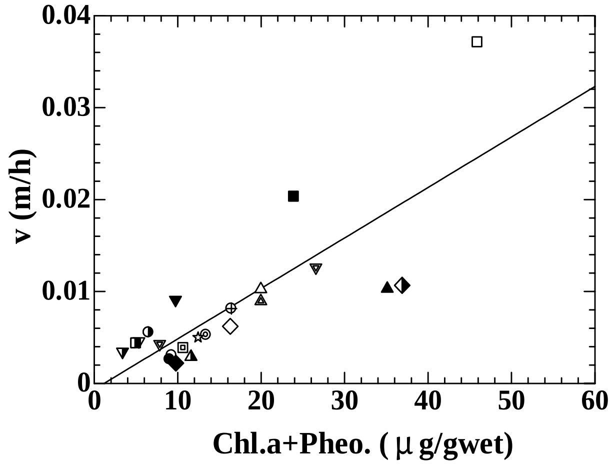


**Fig.6** Relationship between SOC velocity and pheophytin concentration. (See legend in Fig. 5)

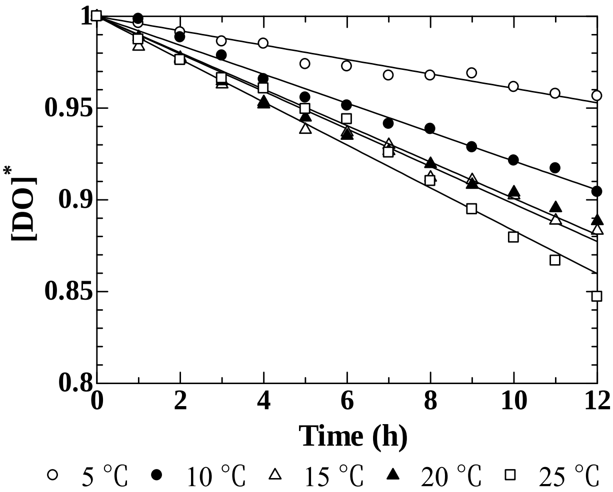


**Fig.7** DO-depletion profiles obtained by varying water temperature. The sediment core were sampled from Isahaya Bay.

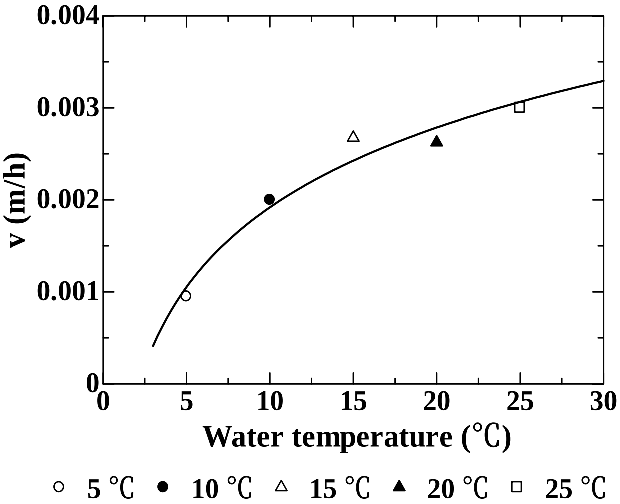


**Fig.8** Relationship between SOC velocity and water temperature.

### 3.3 SOC velocity

By superposing Eq. (3) to the data at each sampling site, we can estimate the values of the SOC velocity v. Fig. 6 shows the relationship between the SOC velocity and the sum of Chl.a concentration and Pheo. concentration. Here, the concentrations of Chl.a and Pheo. are averaged over 3 cm thickness of the sediment surface layer and their sum is used as a representative index of easily decomposable organic matter. From the figure, we can find that the SOC velocity tends to increase linearly with the increase of the concentration of <Chl.a + Pheo.>.

### 3.4 Temperature dependence of SOC velocity

Fig. 7 shows the depletion profiles obtained by changing the water temperature from 5 °C to 25 °C. We can see that the value of [DO]* decreases with the increase of temperature. The solid lines are fitting curves obtained by superposing Eq. (3) on the experimental data. Fig. 8 shows the relationship between the SOC velocity and the temperature. The SOC velocity increases monotonically with the temperature, though the increasing rate becomes smaller with the increase of temperature. Though it was reported by Seiki et al.[4] that the temperature threshold of SOC was 10 °C in Hiroshima bay, that in the Ariake sea is near 5 °C.

## 4. CONCLUSIONS

We investigated the sediment environments in the Ariake Sea and quantified the SOC velocity. The values of AVS along the west coast tend to be lager than that along the east coast, because the grain of sediment along the east coast is coarse. Ushimizu, Sumiyoshi and Misumi take the small values of Md $\phi$ and AVS. These results mean that the sediments are sand and the sediment environments are under an aerobic condition. Especially, the sediment layer at Ushimizu is in a good condition and the aerobic decomposition takes place though the value of Pheo. is very large. At Isahaya Bay, Takesaki, Chikugo Estuary-1, Arao, the value of AVS is larger than 0.2 mg/gdry and the sediment environments are in the deteriorated situation. Especially, the Pheo. concentration is also very large at Isahaya Bay-1 and Takesaki, therefore the sediment environments will progress to the worse situation. It is interesting that the value of AVS at Tara-1, -2, Kashima-2 and Tamana is relatively small and the sediment environments are in good condition though the sediment is silt.

The DO-profiles decrease exponentially with time and can be expressed by the theoretical solution. The SOC velocity tends to increase linearly with the increase of the concentration of <Chl.a + Pheo.> averaged over 3 cm thickness of the sediment surface layer and increases monotonically with the water temperature. The threshold of biological activity is near 5 °C in the Ariake Sea.

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