

## THERMAL ENVIRONMENT OF TIDAL MUD OF ARIAKE SEA

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**ABSTRACT:** A remarkable decrease of catch of shells was observed during the last three decades in the Ariake Sea, Japan. The higher content of acid volatile sulfide (AVS) is responsible for the unfavorable geo-environmental condition of the Ariake Sea. This paper presents an assessment of the thermal environment of the Ariake Sea tidal flat as a part of geo-environmental condition study. To observe the daily and seasonal variation of temperature in different depths, temperature was measured by inserting the thermocouple at various specified depths and at 0.10 m depths interval in the last week of every month at study areas in the Ariake Sea tidal flat, respectively. Thermal properties of the sea mud were measured by using the thermal properties analyzer (KD2). It was observed that during spring and summer heat was transferred from subsurface to the deeper depth however during winter and autumn the opposite phenomena happened. This type of temperature profile in the tidal flat helps to enter the sea laver treatment medicine during winter and consequently deteriorate the mud and again helped to increase remediation of the Ariake sea tidal mud naturally during summer.

**Keywords:** Ariake Sea, geo-environment, tidal mud, temperature, thermal properties

### INTRODUCTION

The Ariake Sea, which is located in the north-western part of Kyushu Island, is one of the best-known semi-closed shallow seas in Japan. Many rivers flow into the eastern coast area of the Ariake Sea and carry  $4.4 \times 10^8$  kg of sediments per year (Azad et al. 2005). Coarse sediments accumulate in the eastern coast, and fine grains brought by the residual current accumulate in the bay head to form vast tidal flats with fine sediments (Kato and Seguchi 2001). The vast tidal flat mud of the Ariake Sea, which is almost 40% of the total tidal flat area of Japan, is famous for its rich fishery products and *Porphyra* sp. (sea weed) cultivation. Different types of shells like *Sinonovacula constricta*, *Atrina pectinata* and *Crassostrea gigas* are important creatures in the Ariake tidal mud. However, a dramatic decrease in the catch of these shells is observed in the tidal flat area. From Fig. 1 it is seen that the catch of *Crassostrea gigas* usually living in the near surface mud, dropped from  $7.99 \times 10^5$  kg in 1976 to only  $1.26 \times 10^5$  kg in 1999; that of *Atrina pectinata*, living in the upper 0.10-0.15 m of the mud, declined from  $1.3395 \times 10^7$  kg in 1976 to  $7.9 \times 10^4$  kg in 1999, and the situation in the case of *Sinonovacula constricta*, living in the depth of 0-0.7 m of the mud, was

even worse:  $1.7 \times 10^5$  kg catch in 1976 dropped to practically nil by 1992.

The acid treatment practice for *Porphyra* sp. cultivation is one of the major causes for this declination of the shells as this practice has made the geo-environmental condition of the Ariake tidal mud unfavorable for the living creatures of the tidal mud (Hayashi and Du, 2005, Moqsud et al. 2007). During the period of the cultivation (December -March), the acid (which is mainly organic chemicals) is used as the disinfectant acid to treat the *Porphyra* sp. cultivated in the sea and also to provide some nutrient phosphorus to it.

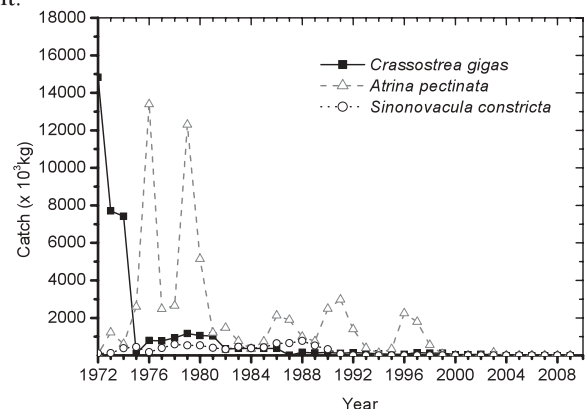


Fig. 1 Decrease in the catch of shells in the Ariake Sea

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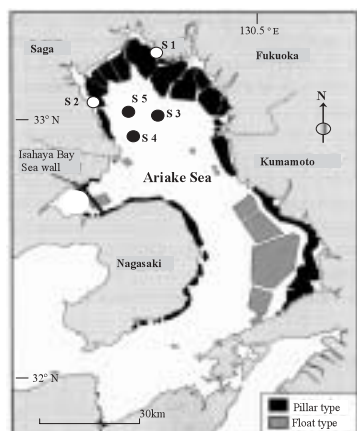


Fig. 2 Map of the Ariake Sea and study areas

This organic acid provides ample of foods for the sulphate reducing bacteria living in the mud and consequently increase the sulfide content in the mud. The generation of sulfide is also influenced by the seasonal temperature and shows a higher value during the summer and the late autumn as bacteria becomes more active in the higher temperature. The higher sulfide content created by acid treatment practice is the main reason for the unfavorable condition for the benthos in the Ariake Sea. Moreover, the activities of the benthos depend strongly on the thermal environment near the sediment surface. Photosynthetic capacity of micro phyto-benthos on an intertidal flat was strongly influenced by mud surface temperature (Blanchard et al., 1997). The filtration rate of bivalves was dependent on the water temperature (Hosokawa et al., 1996). As a result, to evaluate geo-thermal environment is important especially for the acid contaminated Ariake Sea. Thermal properties dictate the storage and movement of heat in soils and as such influence the temperature and heat flux in soils as a function of time and depth (Anandkumar et al., 2001). In recent years, considerable efforts have gone into developing techniques to determine these properties (Ochsner et al., 2001). The propagation of heat in a soil is governed by its thermal characteristics (De Vries, 1963). Main factors influencing soil thermal properties are mineralogical composition, the organic content and water content (De Vries, 1952, Wierenga et al., 1969). No study has been carried out before to get the information about the thermal properties as well as thermal environment of the Ariake sea mud. So the objective of this study is to assess the thermal environment of the tidal mud by getting the information of the temperature distribution in different depths and find a diurnal and seasonal profile of it in the tidal flat region, and finally thermal properties variation with respect to depth for the temperature distribution in different seasons. The thermal properties

of the Ariake Sea mud collected from both tidal flat and inside the deep sea of the Ariake Sea were conducted as a part of thermal environmental studies of the Ariake Sea.

## SAMPLING SITES

Two sampling sites from tidal flat areas sample 1(S1) and sample 2 (S2) and three sampling sites (sample 3 (S3), sample 4 (S4) and sample 5 (S5)) inside the Ariake Sea were selected as the study areas. Figure 2 shows the locations of the two tidal flat areas (Higashiyoka and Iida) and the three different areas inside the sea, along with the two types (pillar type and float type) of *Porphyra* sp. cultivation areas.

The tidal currents sweep into the sea and move northwards along the eastern shoreline and create a counterclockwise water movement. This would sweep the finer suspended particles delivered by rivers on the east side towards the inland end, where sedimentation would occur. Sediments in the Ariake Sea tidal flats are medium sand to silty mud. Medium sand, which accounts for 71% of the total tidal flats, is located mainly in the east and south coast areas (Azad et al. 2005). The silty mud is mainly in the bay head. Higashiyoka tidal flat located in the bay head was chosen as a study area (S1) which is near to Chikugo River (the biggest river in Kyushu Island), Okinohota River as well as other rivers and thought to be affected by the river waters. Another study area in tidal flat was Iida (S2), which seems to be the most affected by the acid treatment practice. The other three study areas are chosen inside the Ariake Sea where all the time they are under water. The sample 1 and sample 2 (Higashiyoka and Iida) were collected during the ebb tide and the tidal flat was exposed to the sun directly. The other three mud samples (S3, S4, and S5 in Figure 2) were collected from under the sea water in different depths in different locations in the Ariake Sea. The sample collection was done in the last week of April 2006. The typical values of basic physicochemical properties of the mud samples collected from five study areas are tabulated in the Table 1. The mud samples were collected from the 0-0.2 m in the Ariake Sea.

## MATERIALS AND METHODS

The vast tidal flat area of the Ariake Sea, which is 40 % of the total tidal area of Japan, is mainly muddy with high water content. The percentage of clay content is much higher than the sand or silt. To evaluate the temperature variation in different depths of the tidal mud,

5 nos. of thermocouples (Tokyo sokki kenkyojo Co., Ltd. Model no. N004853) were installed at 0.10 m, 0.20 m, 0.50 m, 1.0 m and 2.0 m depth which were connected with data logger (TDS- 530) to store the continuous hourly data of the temperature at Higashiyoka tidal flat mud. The sensors were placed about 20 m away from the shore line. The data loggers were kept in a watertight box and put in a small ship which was tied with some anchor and moved upward and downward during the high tide and ebb tide, respectively. Every two days the automatically stored data was collected from the data logger in the ship. This field investigation was carried out from 1<sup>st</sup> April, 2006 to 8<sup>th</sup> April, 2006 at Higashiyoka tidal flat.

In order to measure the seasonal temperature variation, the data were collected from both Iida and Higashiyoka tidal flat, 20 m away from the shore line during the ebb tide once in every month. By inserting the thermocouple (3 m long and 0.96 cm diameter) vertically into the tidal flat upto 3.0 m depth and at each 0.10 m interval the data was measured. The thermocouple was connected with a battery and a digital display. The temperature data was displayed directly in degree Celsius. The mud samples from tidal flat were collected during the ebb tide and about 20 m distance from the shore line. The sample was then sliced into specified layers in the laboratory to measure various properties in each layer. The sulfide content was measured following the standard method prescribed by the Japan fisheries resource conservation association. The instrument which was used to measure the sulfide content is the GASTEC 201L/H which was also used by Wu et al. (2003) to determine the sulfide content of the marine sediments.

In-situ samples were collected by inserting vertically a thin wall steel tube sampler with a diameter of 0.07 m

and a length of 0.90 m at five sites. For sample collection from tidal flat region an amphibious ship was used. The mud samples from tidal flat were collected during the ebb tide and about 40 m distance from the shore line. For sample collection from inside the sea, a ship was used. The ship was stopped in the predetermined location which was fixed by the global positioning system (GPS). The diver dived into the sea and collected the mud samples by inserting the steel tube into the sea bed floor and capped the two openings of the tube. The sample was then sliced into 0.05 m layers in the laboratory to measure the thermal properties in each layer.

The thermal properties analyzer KD2 Decagon Devices, Inc. was used to measure the thermal properties. Thermal conductivity and thermal diffusivity were measured directly from the thermal properties analyzer.

The volumetric heat capacity was calculated by the relation: Volumetric heat capacity = Thermal conductivity/thermal diffusivity

## RESULTS AND DISCUSSION

### Daily Variation of Temperature

Figure 3 shows the variation of the tidal mud temperature in different depths from 1<sup>st</sup> April, 2006 to 8<sup>th</sup> April, 2006. It is seen that at 0.10 m and 0.20 m depth, the fluctuation of temperature was more prominent. However, from 0.50 m to 2.0 m depth, the diurnal variation was not so prominent. In the sub-surface region, the solar radiation affected the soil temperature more than the deeper part of the tidal mud.

Table 1 Basic physicochemical properties of the samples

Physicochemical parameters	S1	S2	S3	S4	S5
Density ( $\times 10^{-3}$ kg m <sup>-3</sup> )	2.71	2.69	2.68	2.69	2.64
Water content (%)	168	235	160	239	253
Liquid limit $w_L$ (%)	130	150	107	149	142
Plasticity index $I_p$	73	87	67	89	88
Ignition loss (%)	11.9	13.3	14.4	12.6	13.7
pH	8.03	7.92	7.60	7.53	7.59
ORP (mV)	-40.7	-121.4	128	130	46.38
Acid volatile sulphide content ( $\times 10^{-3}$ kg kg <sup>-1</sup> dry-mud)	0.16	0.42	0.14	0.30	0.49
Salinity (kg m <sup>-3</sup> )	17	16	20	21	22
Grain size analysis (%)					
Sand	9	7	11	6	6
Silt	36	30	49	46	45
Clay	55	63	36	47	47

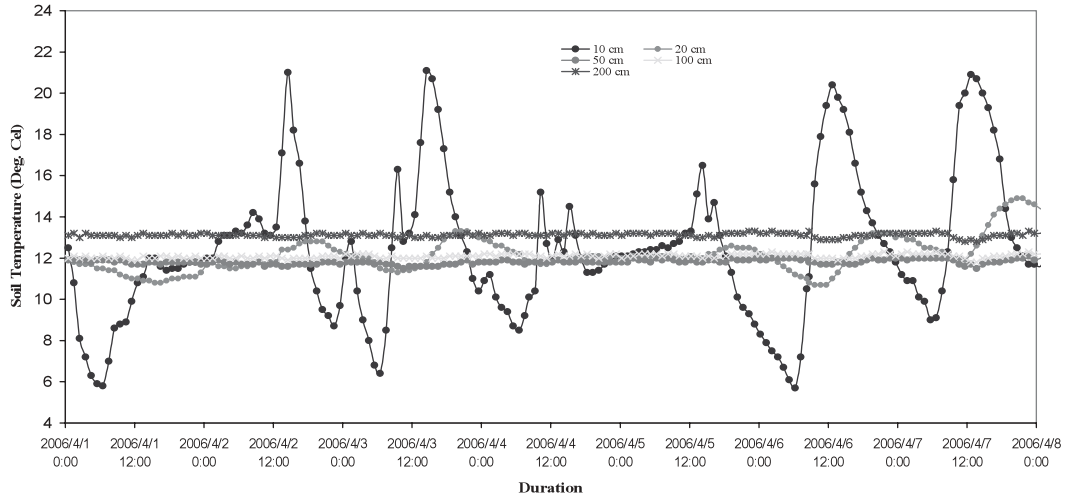


Fig. 3 Variation of diurnal temperature with depth in the Higashiyoka tidal flat

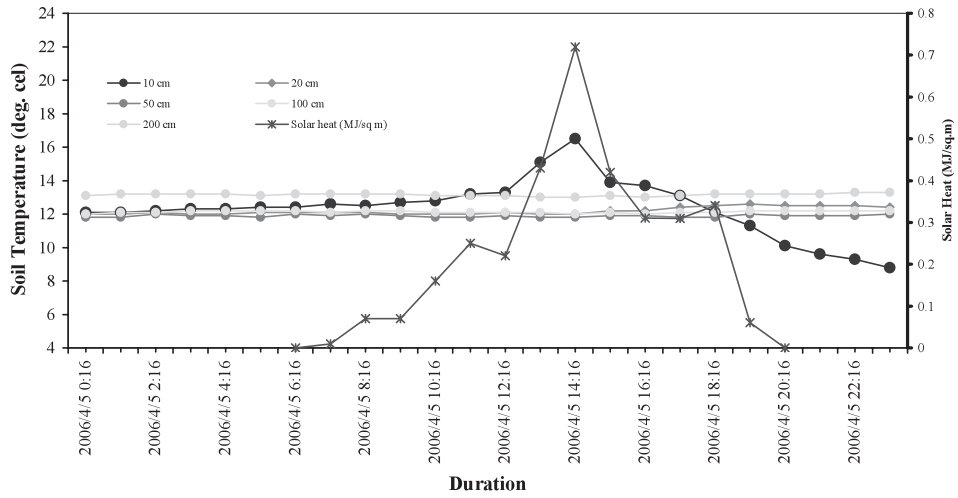


Fig. 4 Effects of solar radiation on the soil temperature in different depths

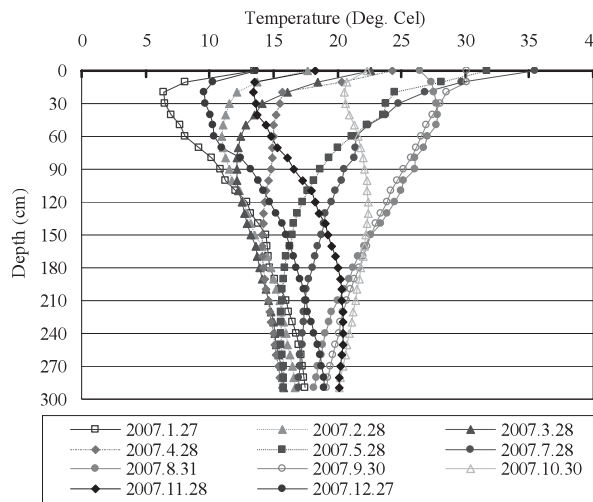


Fig. 5 Seasonal variation of temperature at Higashiyoka tidal flat



This type of diurnal profile of temperature also agrees with the findings in Baeksu tidal flat in Korea (Yan-ki et al. 2005). At 2.0 m depth, the temperature shows higher value than 1.0 m depth. This is probably due to the volumetric heat capacity of the tidal mud and the time lag for absorbing and releasing the heat during the summer and the winter. The peak temperature reached at different time at different depths. During the ebb tide the time lag to reach the peak in different depths is more than the high tide due to infiltration of sea water in the deeper depth.

Figure 4 illustrates one day (24h) variation of tidal flat mud temperature influencing by the solar radiation. It is seen that at 0.1 m depth, the peak value reached when the solar radiation was also peak. At night, the temperature did not show any variation both in the ebb tide and the high tide time. This proves that the tidal mud temperature is only influenced by the solar radiation in the subsurface region. The tidal mud temperature at subsequent depths reaches the peak at different timings, with the time lag increasing with depth. The peak temperature reached about 2:00 PM and the value was about 17 °C at 0.10 m. The temperature at 0.50 m, 1.0 m and 2.0 m remained almost constant around 12-13 °C. It is concluded from this Figure that time lag increased with increasing depth but the rate of increasing decreased with the increasing depth. Thermal properties of the tidal flat mud govern this type of phenomenon.

#### Seasonal Variation of Temperature in Tidal Flat

Figure 5 shows that the seasonal variation of temperature at different depths at Higashiyoka tidal mud in 2007. During the spring and summer the surface temperature shows a higher value than the subsequent depths. During this time, heat was absorbed by the tidal mud and heat was transferred from the surface to the deeper part of the tidal mud. On the other hand, during winter and autumn the surface temperature was lower than the subsequent depths. During this time heat is released to the surface. During April, the variation was not so prominent. It showed almost straight line. Iida site also showed the same trend as with Higashiyoka site during the summer and the winter.

The acid treatment practice started during the winter season (December-February). In winter, the temperature drop down about 5 °C. Due to this type of lower temperature the tidal flat mud showed a contraction tendency. The acid treatment practice and the contraction tendency of the tidal mud occur during the same time. As a result, the chemicals used in the sea laver treatment agent entered into the tidal mud. On the other hand, during the summer the surface temperature reached

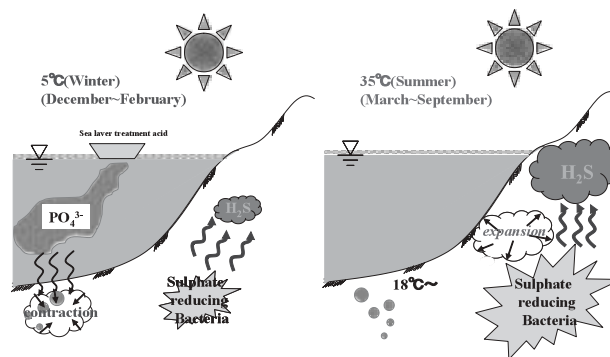


Fig. 6 Seasonal variation of temperature and consequently expansion and contraction tendency and acid treatment practice effects

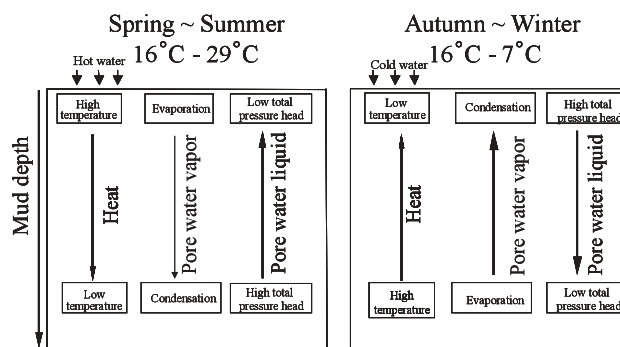


Fig. 7 Proposed concept of coupled heat-pore water vapor-pore water liquid flow in tidal flat

about 38 °C. This type of high temperature shows an expansion tendency of the tidal mud. The tidal mud expansion causes easy movement of some biogenic gases generated inside the tidal mud.

#### Conceptual Image of Seasonal Temperature Effects and Acid Treatment Practice on Tidal Flat

Figure 6 shows the conceptual image of the seasonal temperature variation and the acid treatment practice in the Ariake Sea. The various chemicals which are inside the sea laver treatment medicine enter into the tidal mud during the winter season due to the contraction effect of tidal mud. The chemicals and organic acid supply a lot of foods to the sulfate reducing bacteria. With this ample of foods and the convenient temperature during the spring and summer the sulfate reducing bacteria becomes very active and consequently produces hydrogen sulfide, sulfur di oxide as a result the acid volatile sulfide (AVS) content increased. The AVS content at the Iida tidal flat area shows much higher than the safe limit for the living creatures in the tidal mud. The AVS represents a complex and dynamic biogeochemical system which is not defined simply by analysis of acid volatile sulfide

materials (Richard and Morse, 2005). Actually there are many factors which are liable to produce AVS in some specific regions. However, the laboratory test showed that due to the acid treatment practice the AVS value increased in the tidal flat mud (Moqsud et al. 2007). So the conceptual image of acid treatment practice and the seasonal variation of temperature are thought to be rational.

Proposed Mechanisms of Pore Water Movement

Figure 7 illustrates that the conceptual image of the pore water movement in the tidal mud due to the seasonal variation of temperature. During spring and summer, the temperature at the shallow depth of the Iida tidal mud of the Ariake sea is higher than that of deeper depth, whereas opposite phenomenon was found during autumn and winter. The temperature gradient in the mud causes pore water to move in the vapor phase from a higher temperature site to a lower temperature site. The vapor condensates at the lower temperature area and becomes water which increases the total head and drives the water liquid phase from lower temperature site to the higher temperature site (Nassar et al. 2000). Aforementioned process is titled coupled heat-pore water vapor-pore water liquid flow, as shown in Fig. 7.

Thermal Properties

*Thermal conductivity variation with depth*

Figure 8 shows that the variation of thermal conductivity in different depths in the Ariake sea. In the sample of tidal flats (sample 1 and sample 2), the variation is more prominent than the other samples collected from deep sea. This is probably due to much turbulence of the tidal flat mud in the tidal flat region and introduces various kinds of matter during the tidal water movement as well as the direct exposure to the sun light during the ebb tide. All the samples show great variations in the sub surface (0-0.20 m) region but less variation in deeper region. Thermal conductivity of mud varies with soil texture, water content and organic matter content (Hamdeh and Reeder, 2000, Yadhav and Saxena, 1973). The water content of the Ariake mud is always over 130% in different depths, which indicates that the conductivity of the Ariake mud is not affected by the water content in different depths.

*Thermal diffusivity variation with depth*

Figure 9 shows the variation of thermal diffusivity with depth for all the Ariake mud. It is seen that in the tidal flats (sample 1 and sample 2); the thermal diffusivity

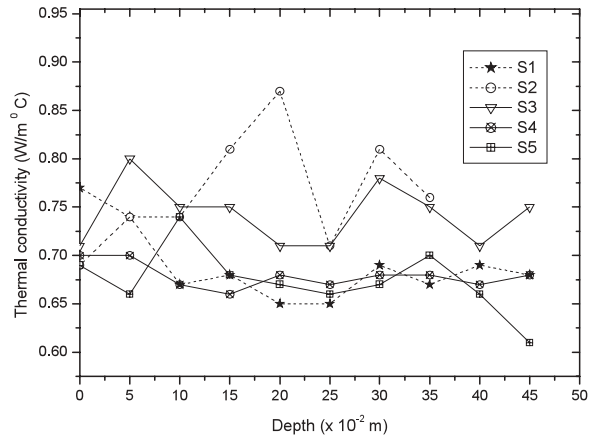


Fig. 8 Variation of thermal conductivity with depth in the Ariake Sea

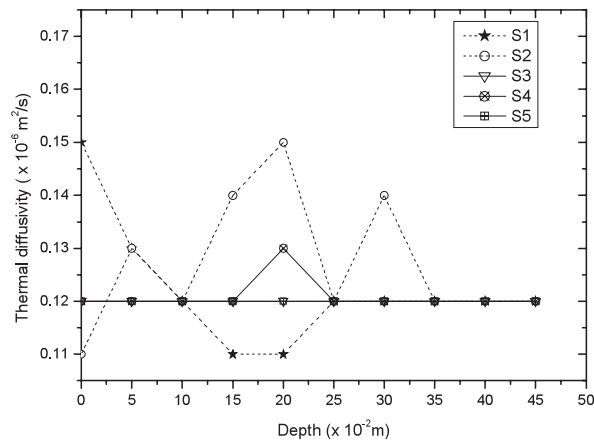


Fig. 9 Variation of thermal diffusivity with depth

is varied much in the different depths. On the other hand in the case of deep sea mud sample (sample 3, sample 4 and sample 5) the thermal diffusivity was constant in different depths. This is due to a small chance of turbulence in the deep sea bed floor. However, in the tidal flat area during the low tide, the tidal mud is exposed directly to the sunlight and during the ebb tide; a lot of foreign matters come and disturbs the homogeneity in the mud of the tidal mud layers. It is seen that in the deep sea mud, the value of thermal diffusivity is always in  $0.12 \times 10^{-6} \text{ m}^2/\text{s}$ . In the tidal flat, the peak reached at  $0.13 \times 10^{-6} \text{ m}^2/\text{s}$  in different depths.

*Volumetric heat capacity variation with depth*

The volumetric heat capacity of the tidal mud refers to the value which indicates the ability to store heat. If the volumetric heat capacity of a soil is high then the

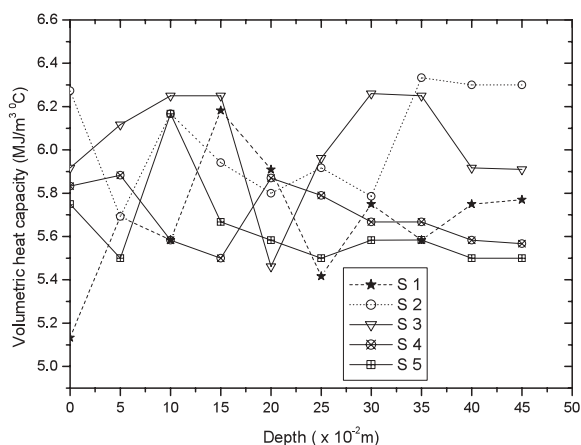


Fig. 10 Variation of volumetric heat capacity with depth

soil is more stable in terms of temperature change or the thermal environment. Figure 10 illustrates the variation of volumetric heat capacity with depth of the various samples. Sample 2 shows a great variation in volumetric heat capacity. The peak shows at 0.35 m depth and value is about  $6.3 \text{ MJ/m}^3 \text{ } ^\circ\text{C}$ . Clay soil generally has higher volumetric heat capacity than sandy soil for the same water content and soil density (Hamedh, 2003, Ekwue et al., 2005). Volumetric heat capacity is very important for the acid infected tidal mud. Sulphate reducing bacteria (SRB) plays an important role in the geo-environmental condition of the Ariake Sea (Holmer and Storkholm, 2001, Rickard and Morse, 2005, Sorensen and Jorgenson, 1987). These Bacteria like the layer where the volumetric heat capacity is higher (Moqsud et al., 2006). Because in that layer it shows the more stable condition which is liked by the bacteria.

The temperature of underground soil is affected mainly by the soil thermal properties (Moqsud et al., 2006 a, Nassar et al., 2000) and these properties play a significant role in the geo-environmental condition in the global environment. The thermal properties of the mud are also induced by the mineralogical matter presence in the mud (Naidu and Singh, 2004). The effects of this mineral matter on the thermal properties of the Ariake sea mud needs further study.

## CONCLUSIONS

The temperature profiles, which result primarily from the molecular diffusion of heat through the sediment, resemble those typical of field soils and their form is similarly dependent on the thermal properties of the mud and the ambient meteorological conditions. The diurnal

temperature variation is more visible near the surface (0.10 m and 0.20 m). The temperature increase gradually from morning, peak at noon and gradually decrease at afternoon. However, at 1.0 m and 2.0 m depth, the variation of temperature was not so prominent. This is due to the volumetric heat capacity and the thermal conductivity of the tidal mud. From the seasonal variation of temperature, it is seen that during late summer, the surface and subsurface temperature is always higher than the deeper depth of the mud while in the winter the opposite phenomenon occurs. The thermal properties of mud collected from tidal flat showed a different trend from the mud collected inside the sea due to the exposure to the sunlight and the tidal wave turbulence in the tidal flat areas. In this study an innovative idea has been adopted to explain the deterioration and the natural remediation of the tidal flat mud in the Ariake Sea. The proposed mechanisms for understanding the transient seepage of pore water liquid of the tidal mud which contributes to the transport of sea laver treatment acid in the tidal mud and also natural remediation of contaminated tidal mud of the Ariake Sea was described clearly. The seasonal variation of temperature and the volumetric heat capacity of the mud have played a significant role for the maintaining the deterioration and natural remediation in the Ariake sea mud.

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