ASSESSMENT OF THERMAL PROPERTIES OF MUD OF THE ARIAKE SEA, JAPAN

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Abstract: *Thermal environment of the mud is one of the major parts of the acid-contaminated geo-environment of the Ariake Sea. The activities of marine ecosystem both in tidal flats and inside the deep sea mud depend strongly on the thermal environment. In order to investigate the thermal properties of the Ariake sea mud, a portable thermal properties sensor and probe (KD2, Decagon Devices, Inc.) was used. Thermal conductivity, thermal resistivity, thermal diffusivity and volumetric heat capacity of the mud samples collected from both the tidal flat and inside the deep sea were measured. The thermal properties of mud collected from tidal flat showed a different trend from the mud collected from inside the sea due to the enough exposure to the sunlight and vigorous exchange of sea water in the tidal flat in different depths. Thermal conductivity of the Ariake mud was reduced 85-90% after it was oven dried and was increased up to 30% after the ignition loss test. Thermal resistivity of the Ariake mud increased dramatically after oven dried and it was less affected by the organic matter content. Thermal diffusivity was decreased 10-30% after oven dry however it was increased up to 40% after the ignition loss test. The volumetric heat capacity of the Ariake mud was reduced up to 90% and 40% after the oven dry and ignition loss, respectively.*

Keywords: *Thermal conductivity, thermal resistivity, thermal diffusivity, tidal mud, volumetric heat capacity*

1. Introduction

The Ariake Sea is one of the best-known semi-closed shallow seas in Japan. The vast tidal flat 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. However, a dramatic decrease of catch of shells, such as *Sinonovacula constricta*, *Atrina pectinata* and *Crassostrea gigas* is observed both in the tidal flat and inside the deep sea mud in the Ariake Sea for the last 3 decades. According to Saga agricultural and forestry statistical society (SAFSS),Japan 2006, *Crassostrea gigas*, usually living near the surface mud, dropped from 7.99 x 10^5 kg in 1979 to only 1.26 x 10^5 kg in 1999; that *of Atrina pectinata,* living in the upper 0.10-0.15 m of the mud, declined from 1.34 x 10^7 kg in 1976 to 7.9 x 10^4 kg in 1999 and the situation in the case of *Sinonovacula constricta,* living in the depth of 0-0.70 m of the mud , was even worse: 1.7 x 10^5 kg catch in 1976 dropped to practically nil by 1992. The cause for the declination of the fishery products is the unfavorable geo-environmental condition of the Ariake Sea created by acid treatment practice for the *Porphyra* sp. (sea weed) cultivation [10,13]. The *Porphyra* sp. is a favorite food for the people of Japan and Korea and it is the main earning source of the huge population near the Ariake Sea area. During the period of the cultivation (December -March), the acid (which is mainly organic) is used as the disinfectant acid to treat the *Porphyra* sp. cultivated in the sea and also to provide some nutrient phosphorus to it. This organic acid provides ample of foods for the sulphate reducing bacteria living in the mud and consequently increase the sulphide content in the mud. The generation of sulphide 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 [11]. The higher sulphide 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 phytobenthos on an intertidal flat was strongly influenced by mud surface

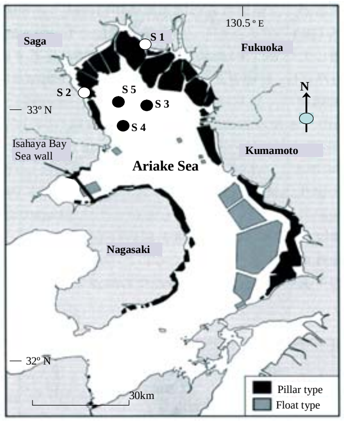

Fig. 1 Map of the Ariake Sea indicating the sampling sites and different types of *Porphyra* sp. cultivation areas

temperature [4]. The filtration rate of bivalves was dependent on the water temperature [12]. 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 [1]. In recent years, considerable efforts have gone into developing techniques to determine these properties [17]. The propagation of heat in a soil is governed by its thermal characteristics [6]. Main factors influencing soil thermal properties are mineralogical composition, the organic content and water content [5, 17, 18]. No study has been carried out before to get the information about the thermal properties of the Ariake sea mud. The objective of the study is to evaluate the thermal properties of the Ariake Sea mud collected from both tidal flat and inside the deep sea and to observe the influence of water content and organic content on the thermal properties of the Ariake Sea.

2. Study areas

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 1 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 [2]. 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 1) 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.

3. Materials and methods

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. Briefly, the measurement was done by inserting the entire needle of the probe completely into the samples. The KD2 sensor needle contains both a heating controller computes the thermal conductivity and diffusivity using the change in temperature and time data. Thermal resistivity is computed as the reciprocal of thermal conductivity. The data of thermal conductivity, thermal diffusivity and thermal resistivity are shown directly in the digital display of the thermal properties analyzer. When the measurement begins, the microcontroller waits for 90 seconds for temperature stability, and then applies a known amount of current for 30 seconds to a heater in the amount of power supplied to the heater.

The volumetric heat capacity was calculated by the relation:

Volumetric heat capacity = Thermal conductivity/thermal diffusivity

Water content test was conducted to observe the effects of water on the thermal properties of the mud samples by following ASTM D 2216. Loss-on-ignition test was conducted for organic content effects on the thermal properties of the mud by following the standard methods of soil analysis [3].

4. Theory of thermal properties measurement

The equation describing the conductive heat transfer in one-dimensional isotropic medium is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

Where T is the temperature, t is time, α is thermal diffusivity and z is the depth.

The equation for radial heat conduction in a homogeneous, isotropic medium is given by

$$\frac{\partial T}{\partial t} = \alpha \left\{ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} \right\} \qquad (2)$$

Where r is radial distance

Table 1: Basic Physicochemical properties of the Ariake Sea mud samples

Physicochemical parameters	S 1	S2	S3	S4	S5
Density (x 10^{-3} kg m^{-3})	2.71	2.69	2.68	2.69	2.64
Water content (%)	168	235	160	239	253
Liquid limit w_L (%)	130	150	140	149	142
Plasticity Index Ip	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)	98	-121.4	128	130	46.38
Sulphide content (x 10^{-3} kg kg^{-1} dry-mud)	0.16	0.42	0.15	0.30	0.49
Salinity (kg m^{-3})	17	16	20	21	22
Grain size analysis (%)					
Sand	10	10	11	6	6
Silt	45	30	49	46	45
Clay	45	60	36	47	47

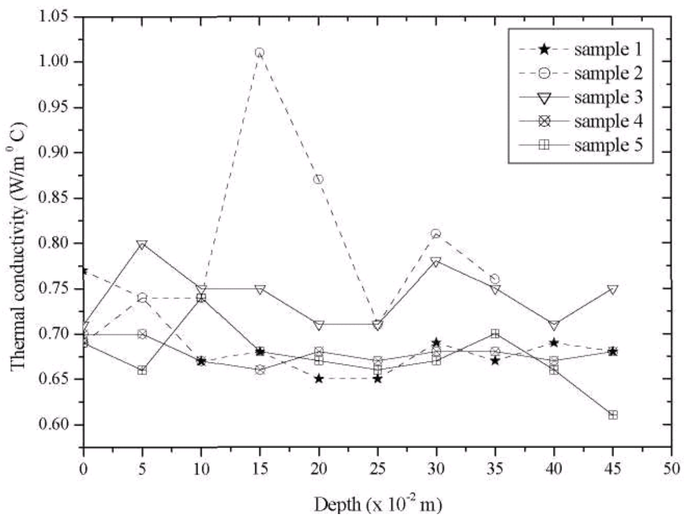

Fig. 2 Variation of thermal conductivity of the samples in different depths

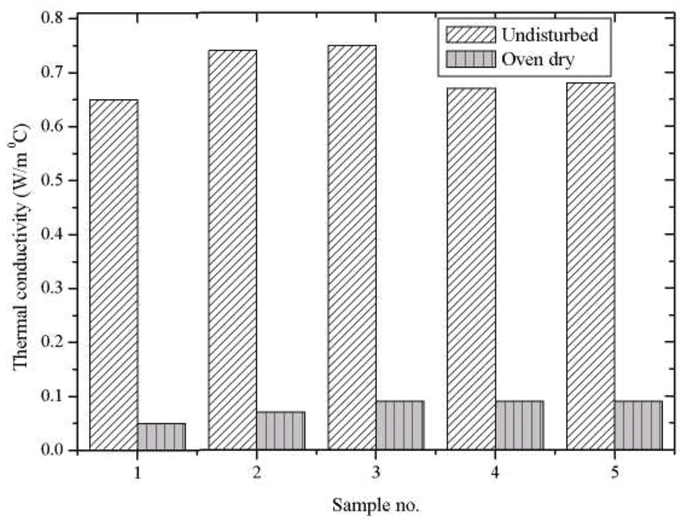

Fig.3 Variation of thermal conductivity of the samples after oven dry

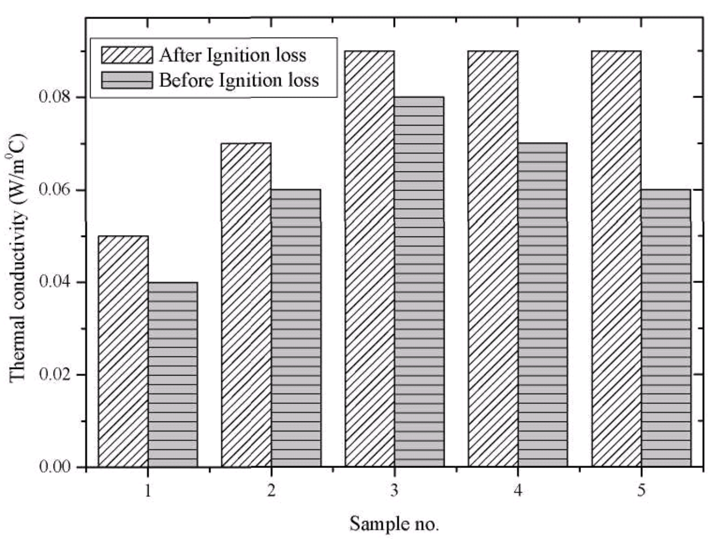

Fig.4 Variation of thermal conductivity of the samples after ignition loss

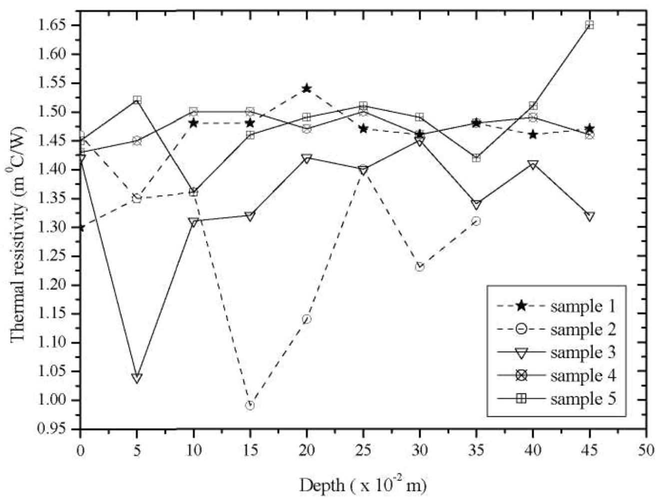

Fig. 5 Variation of thermal resistivity of the samples at different depths

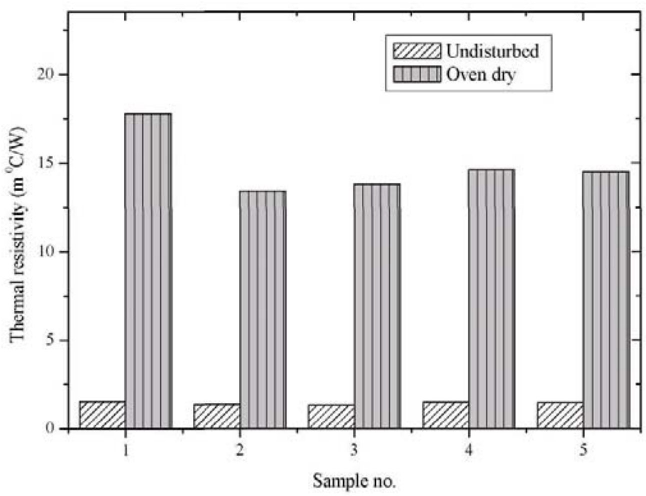

Fig.6 Variation of thermal resistivity of the samples after oven dry

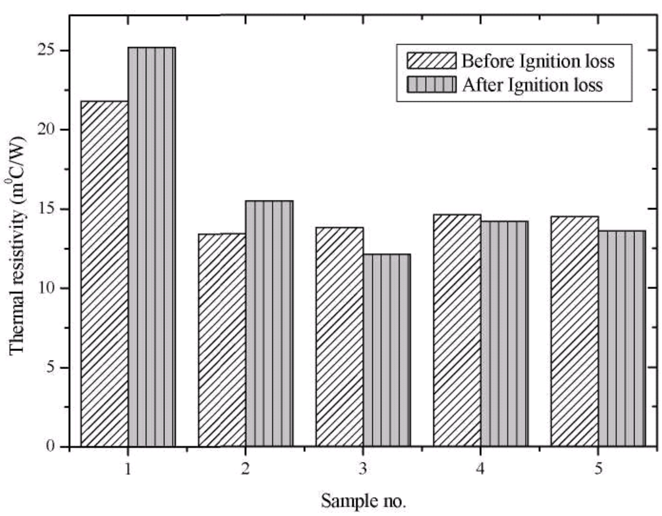

Fig. 7 Variation of thermal resistivity of the samples after ignition loss

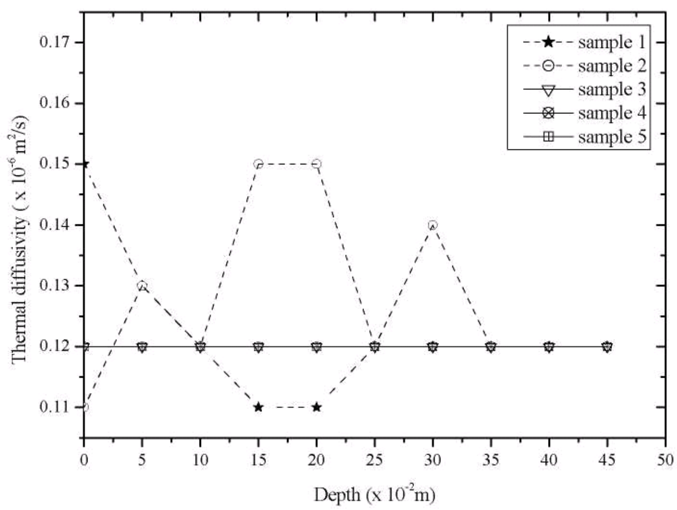

Fig. 8 Variation of thermal diffusivity of the samples at different depths

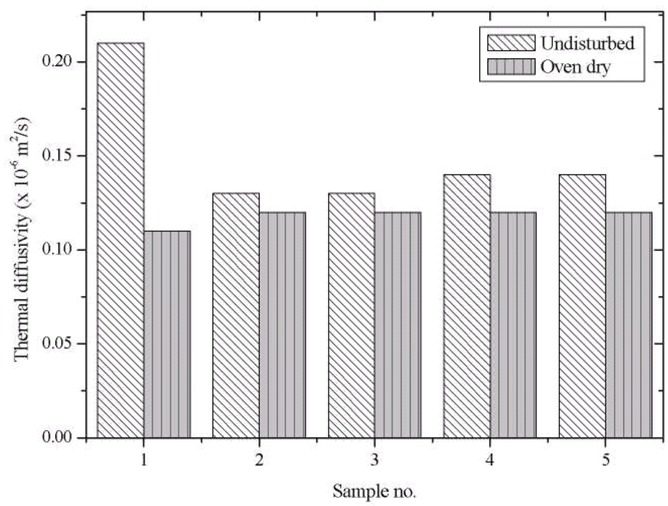

Fig.9 Variation of thermal diffusivity of the samples after oven dry

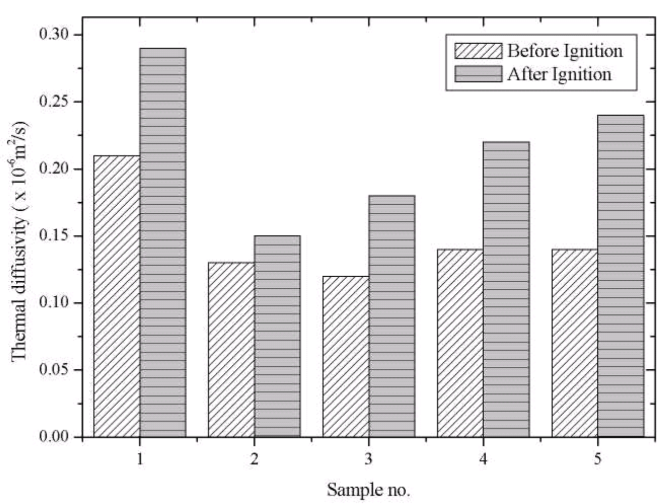

Fig. 10 Variation of thermal diffusivity of the samples after ignition loss

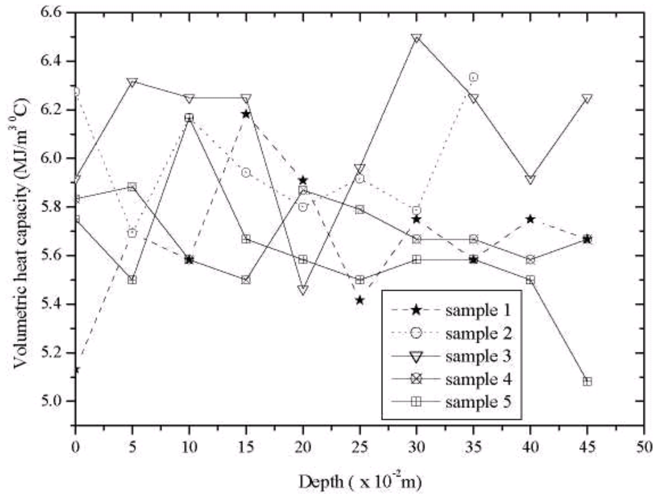

Fig.11 Variation of volumetric heat capacity of the samples in different depths

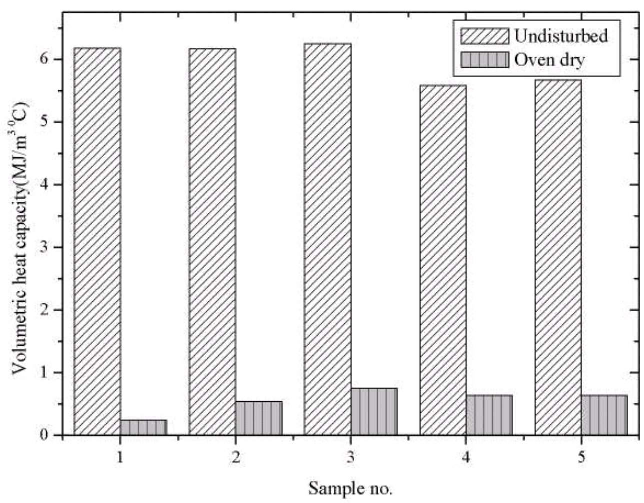

Fig. 12 Variation of volumetric heat capacity of the samples after oven dry

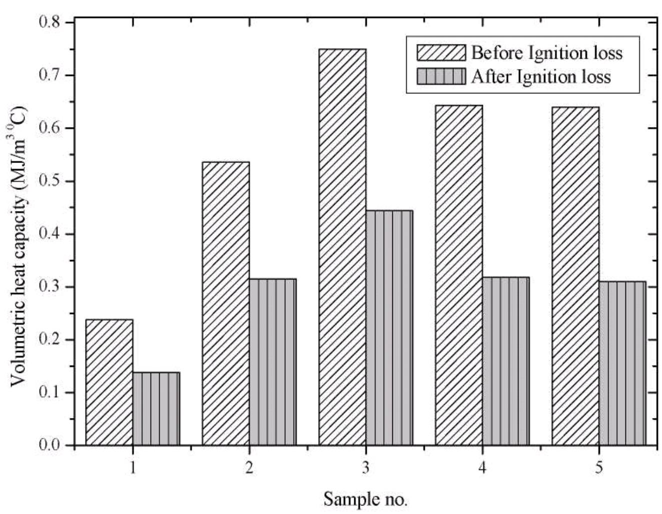

Fig. 13 Variation of volumetric heat capacity of the samples after ignition loss

When a long, electrically heated probe is introduced into a medium, the rise in temperature from an initial temperature T_0, at some distance, r, from the probe is

$$\frac{T-T_0}{1}=\left\{\frac{q}{4\pi\lambda_n}\right\}Ei\left\{\frac{-r^2}{4\alpha t}\right\} \qquad (3)$$

Where q is the heat produced per unit length per unit time, λ_n is the thermal conductivity of the medium and *Ei* is the exponential integral function.

5. Results and discussion

Figure 2 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 turbulation 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 [9]. 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 conductivity of soil is become almost constant after reaching above 120-125% of water content [8]. In Figure 2, it is seen that in sample 3 at 0.15 m depth the value is the highest (1.02 W/m°C). This is probably due to some difference in the mineralogy or organic content from the consequent layers. Figure 3 shows that thermal conductivity of the Ariake mud is reduced 85-90% after it was oven dried (0% water content).Sample 3 shows the peak value of conductivity of 0.75 W/m °C. However, mud samples from Higashiyoka tidal flat shows the lowest value of 0.65 W/m °C. Figure 4 shows that the thermal conductivity was reduced after the ignition loss. The values increase 10-30% after the ignition loss to remove the organic matter. The effects of organic matter on thermal conductivity of the tidal flat mud or inside sea mud were not much studied before. So we were unable to compare our results with others from previous studies. Figure 5 shows that the variation of thermal resistivity with depth. The thermal resistivity is an important part for the thermal environment of the tidal flat as well as for the deep sea mud [15]. The thermal resistivity is varied much in the sub-surface (0-0.2 m) region and it showed a relative stable value in the deeper region. Iida tidal flat mud shows the lowest peak (less than 1 m ° C/W) value in 0.15 m depth. Except sample 3, the mud-samples collected from inside the sea show a relatively small variation in the thermal resistivity. For sample 2, at 0.15 m depth the resistivity shows the minimum value and this is due to the same reason as it showed the highest value of thermal conductivity in that layer (Figure 2). However, after oven dry, the mud samples show a dramatic increase of the thermal resistivity. The water content in the mud increases the thermal conductivity and consequently decreases the thermal resistivity. The dry mud particles have less contact area for heat transfer as well as air has 20 times more thermal resistivity than water which influences the value. For this reason, the thermal resistivity increase after oven dried of the mud samples. However, the thermal resistivity was not affected by the organic content of all the mud samples collected from the Ariake Sea. A small amount of thermal resistivity decrease after ignition loss for the samples collected from inside the sea. On the other hand, a small amount increase shows after the ignition loss for the samples collected from tidal flat mud (Fig 7).

Figure 8 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 is varied much in the different depths. But in the case of deep sea mud sample (sample 3, sample 4 and sample 5) the thermal diffusivity was almost constant in different depths. This is due to a small chance of turbulation in the deep sea bed floor. However, in the tidal flat region during the ebb tide, the tidal mud is exposed directly to the sunlight and during the high 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 x 10^{-6} m^2/s. But in the tidal flat, the peak reached at 0.17 x 10^{-6} m^2/s.Thermal diffusivity is decreased 10-30% after oven dry for the different samples (Fig. 9). To observe the effect of the organic matter content to the thermal diffusivity of the Ariake mud, ignition loss test was performed. It is seen that after ignition loss, thermal diffusivity increased 10-40% in different samples (Fig. 10). Figure 11 illustrates the variation of volumetric heat capacity with depth of the various samples. Sample 3 shows a great variation in volumetric heat capacity. The peak shows at 0.30 m depth and value is about 6.5 MJ/m^3 °C. Clay soil generally has higher volumetric heat capacity than sandy soil for the same water content and soil density [8]. Volumetric heat capacity is very important for the acid contaminated tidal mud. Sulphate reducing bacteria (SRB) plays an important role in the geo-environmental condition of the Ariake Sea. These Bacteria like the layer where the volumetric heat capacity is higher [14]. Because in that layer it shows the more stable condition which is liked by the bacteria. Figure 12 shows that volumetric heat capacity reduces about 80-90% after it was oven dried. Again, after ignition loss it reduced about 30-50% than before ignition loss. Organic content influence the thermal properties as well as the volumetric heat capacity of the soil. With increasing the organic content, the volumetric heat capacity decreases [7].The temperature of underground soil is affected mainly by the soil thermal properties [16] 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. The effects of this mineral matter on the thermal properties of the Ariake sea mud needs further study.

6. Conclusions

The thermal properties of the mud of the acid contaminated Ariake Sea was investigated through laboratory studies. The thermal properties of mud collected from tidal flat showed a different trend from the mud collected from inside the sea due to the exposure to the sunlight and the tidal wave turbulation. Thermal conductivity of the Ariake mud was reduced 85-90% after it was oven dried and was increased by 10-30% after the ignition loss test. Thermal resistivity of the Ariake mud increased dramatically after oven dried and it was less affected by the organic matter after ignition loss. Thermal diffusivity was decreased 10-30% after oven dry however it was increased 10-40% after the ignition loss test. The volumetric heat capacity of the Ariake mud was reduced by 80-90% and 30-40% by the water content and organic content, respectively.

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