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EXPERIMENTAL STUDY ON THE EFFECT OF BIOFILM FOR BED MUD EROSION IN ANNULAR FLUME

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The prediction of fine cohesive sediment erosion is important information for civil engineers. However, to calculate an actual amount of erosion, the necessity for considering the effect by biofilm (EPS) formed on the bed mud surface has been caused. Biofilm formed on the bed mud has a major influence on the erosion phenomenon in estuaries. Therefore, many researchers are grappling from various angles with this problem.

Experiments were carried out in an annular flume at the Water and Environmental System Laboratory of Fukuoka University. Results of an experimental study on the effect of biofilm for fine cohesive sediment erosion in the annular flume are described. The relation between biofilm on the bed mud and the initial rate of erosion were conducted under the condition to adjust the amount of light and water temperature. The thickness of biofilm reached about 2mm in the maximum and 0.5mm in the minimum. In this study, it has aimed to clarify how the amount of bed mud erosion changes by the biofilm experimentally.

Key Words : *bed mud, erosion, fine cohesive sediment, annular flume, diatomaceae, biofilm*

1. INTRODUCTION

Tidal Rivers carry suspended sediment along with them as they flow toward the upward or downward. When the velocity of the stream decreases, it loses energy and the suspended solids settle down to the bottom of the waterways navigation channels or a bank in river. Fluid-mud formation and transport following settling of suspended solids in muddy tidal rivers and estuaries play an important role in narrowing of river cross section and in shoaloing of navigation channels. A shoaling in a navigation channel that causes the bottom to become shallower than is shown on nautical charts is a safety hazard. The periodic dredging that must be done to keep it clear and safe for navigation is called maintenance dredging. Thus, enormous expenses are necessary for maintenance dredging. The prediction of fine cohesive sediment erosions an important information for civil engineers. However, while the erosion behaviour of non-cohesive sand like sediments is well understood and can be predicted by Shields equation (1936). However, the erosion behaviour of fine cohesive sediments is not yet well understood by the complexity of its physical and biological property. Sediment consolidation, grain-size, and biological slimes (EPS:extracellular polymeric substances) were found to be significant factors influencing erosion resistance. Although much work has been done on the physical erosion process [1),2)], fundamental elements involved in the processes such as biological slimes have not been understood yet. EPS is composed major part (95%) of polysaccharides, and the balance is made by protein. The polysaccharides may be constituted of neutral sugars, uronic acids, sulfonated sugars, or ketal-linked pyruvate groups[3),4)]. The clay particles have charged surfaces and are covered with organic matter and nutrients. Because of particles charged nature, the particles adhere to each other (cohesive sediment). Erosion resistance of fine cohesive sediments is mainly controlled by inter-particle forces. The strength of these forces is governed by biofilm and electrochemical properties of clay and moisture content of sediment. In this paper we will consider the processes that lead to the formation of biofilms and the production of EPS and discuss their effect in the stabilization of fine cohesive sediments.

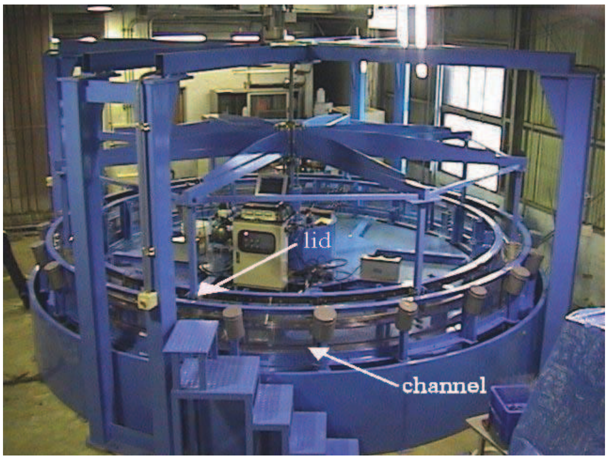

Fig. 1 The outline of annular flume

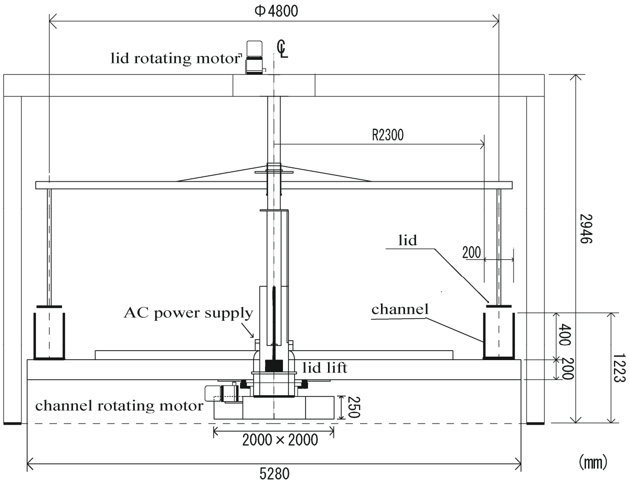

Fig. 2 Cross section view of the annular flume

2. EXPERIMENTAL APPALUTUS

The straight flume, recirculation straight flume and annular flume are given the typical experimental flume which used by the analysis of the fine cohesive sediments erosion and deposition processes. In the last four decades, annular flume has become suitable equipment for the study of fine cohesive sediments phenomena because of their advantages over the traditional straight or straight recirculation flumes. Especially in fine cohesive sediments transport processes, annular flume has been used to determine the critical shear stress for which deposition and erosion of cohesive sediments occur. An annular flume is basically composed of a channel and a lid, and the flow is occurred by the rotation of the flume itself, thus avoiding the use of recirculation pumps. Both parts, channel and lid, rotate in opposite directions so that an endless flow in current direction is generated by the relative velocity between channels and lid. This endless flow is most suitable for experimental study of fine cohesive sediments as no pumps or inflow respectively outflow conditions are disturbing the flocculation processes like in straight flumes. In this way, the aggregates structure is not externally disturbed and all the processes affecting them are only due to their interaction with the flow. Another advantage of annular flumes is that once the flow has been established it is fully developed in the entire flume, producing uniform distributions of bed shear stresses in the tangential direction of the flow.

The annular flume at the Water and Environmental System Laboratory of Fukuoka University, Japan, is a round-form channel with a width of 0.2 m and a mean diameter of 5m, and the maximum water depth of 0.4m. A lid with a width of 0.18m and a mean diameter of 5m that is variable in height so that different flow depths can be adjusted touches the water surface in the channel.

Figure 1 and 2 illustrate the outline of the experimental apparatus. The annular flume consists of a circular channel with a mean diameter of 5 m and a channel width of 0.2 m. The water depth is 0.4 m. A circular lid at the water surface drives the water. In order to minimize the effect of secondary currents near the bottom the channel itself is rotated in the opposite direction. The annular flume is constructed of seawater-resistant materials. The channel and lid are constructed of transparent polyvinyl chloride,

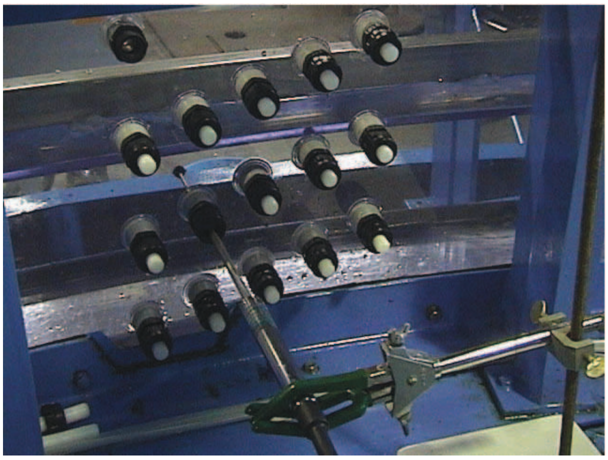

Fig.3 The out line of the measuring point of velocity

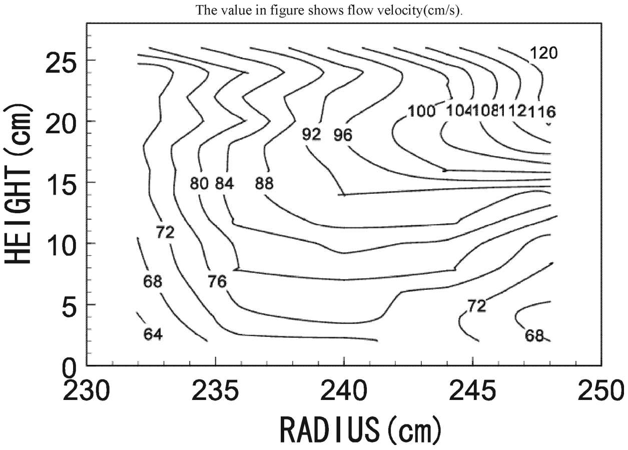

Fig.4 The tangential velocity profile in the flume

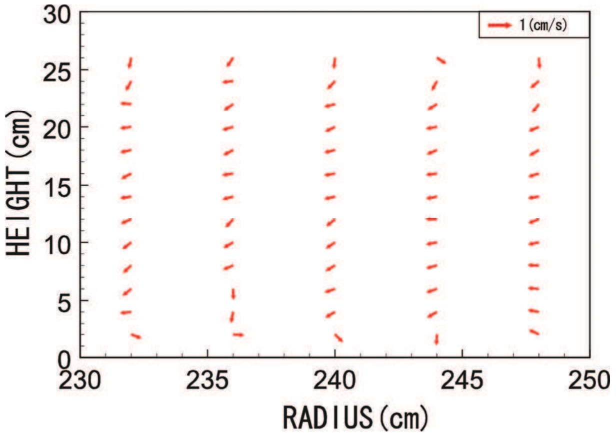

Fig.5 The secondary flow field in the flume

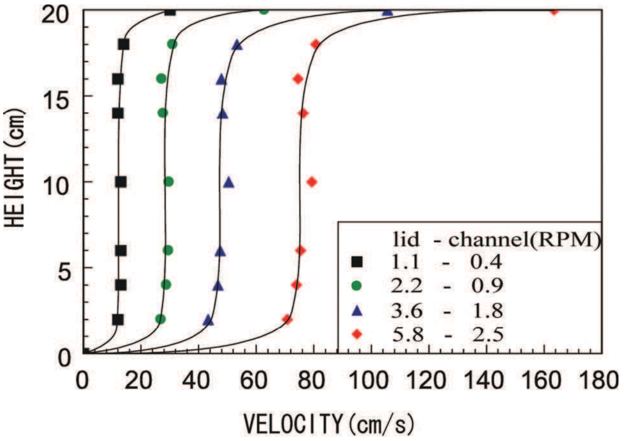

Fig. 6 The vertical profile in the flume at the middle of the channel

which is possible to facilitate access of measurement sensors and sampling devices to the interior of the flume, and light penetrates to a full depth of the channel.

For a preparatory experiment, the profiles of 3D velocity profile were measured in the channel. Velocities in the channel were measured with a 3D-electromagnetic current meter (VM-1001: KENNK Co.). Two measuring point was set on the diagonal, 19 points at a distance 1cm apart from the bottom of the channel (refer to Figure 3). The operational speeds of the lid and the channel are experimentally determined. The optimal ratio of the angular velocities of the upper lid and the channel is also a function of the water depth.

Figure 4 and 5 show the profile of the tangential velocity in the channel. In this figure, plot water depth (cm) in ordinate and the distance from the center of rotation in abscissa. From these figures, the secondary currents on the bottom are minimized. In Figure 4, the tangential flow velocity profile near the bottom reproduce like the velocity profile in the straight channel.

Figure 6 shows the velocity profile at the center(R=2.4m) of the channel. The velocity profile is plotted with tangential velocity (cm/s) as abscissa against the water depth (cm) as ordinate. From this figure, it is possible to consider that the shear stress in the channel occurs only on the bottom and lid surface.

The expression of shear stress is obtained from the momentum transfer theory of Prandtl. Prandtl equation is expressed as equation (1). We estimate the shear stress on the bottom and surface in the channel from this equation, further study will be necessary.

$$\frac{\tau}{\rho}=(\varepsilon+\nu)\left|\frac{d\bar{u}}{dy}\right| \;,\varepsilon=l^2\left|\frac{d\bar{u}}{dy}\right| \;,l=\kappa y \qquad (1)$$

where τ : shear stress on the bottom, ε : eddy viscosity coefficient, ν : kinematic coefficient of viscosity, ρ : the density of water, l : mixture length, κ : von Karman constant. The effect of the molecular viscosity is much smaller than eddy viscosity, and kinematic coefficient of viscosity is negligible.

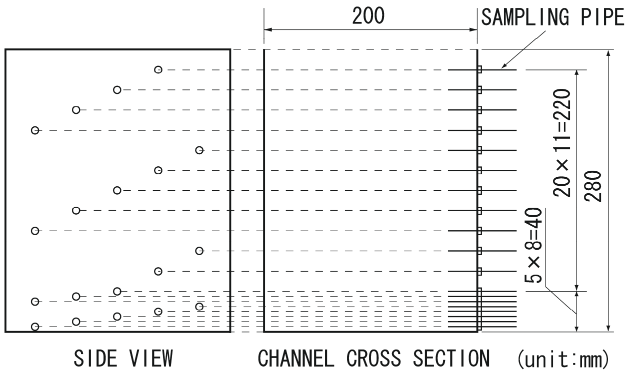

Fig.7 The measuring point of SSC in the channel

3. EXPERIMENTAL METHOD AND CONDITION

(1) Material

The mud material used in this study was obtained at the estuarine region of Rokkaku River in SAGA prefecture located in the western part of Japan where the maximum tidal range is 5m, the largest in Japan. The grain size distribution of mud material was measured under the fully dispersed condition by the hydrometer method. About 78% of mud material was in clay range, 22% in silt range. Its mean diameter, specific gravity, and ignition loss were 1.4 μ m, 2.64, and 18%, respectively. All experiments were conducted in salt water of specific gravity, 1.025. The concentration of suspended solids (SSC) in the channel was used to adjust about 20 kg/m^3.

(2) SSC measurement in the channel

The amount of erosion from the bed mud was measured by using a suspended solids concentration profile in the channel. The sampling device was made of stainless steel pipes. Stainless steel sampling pipes of 2mm diameter were installed in the channel at the distance, 4cm, from the inner channel wall and it is possible to insert only at which the measurements.

Fig.8 The bed mud surface condition after 2 weeks leaving

Figure 7 shows the sampling point of suspension. Suspension sampling was done at 19 points in the channel at the same time. Suspension was sampled through the pipes, and the concentration of suspended solids was measured with a turbidity meter.

(3) Biofilm formation method

Suspension in the storage tank was supplied to the flume to set the water depth in the channel reached 28cm, the suspension in the flume settled down on the bottom and then formed consolidated bed mud on it. After leaving for the prescribed period, biofilm or mats were formed on the bed mud. At the same time, we control the light and temperature conditions. Under the lighten condition, a mercury arc lamp shine light on the bed mud surface throughout the biofilm formation period. On the other hand, under the darken condition, the flume was covered with black vinyl sheet throughout the biofilm formation period. After leaving for the prescribed period as shown table 1, we measured the thickness of biofilem formed on the bed mud at 4 measuring point was set on the diagonal. The growth rate of the biofilm layer was recorded by a video camera with a close-up lens through a wall not to destroy the bed mud layer, and was analyzed on the PC monitor. Figure 8 illustrates the bed mud surface condition after leaving for 2 weeks that form extensive biofilms or mats on the surface of bed mud.

Table1 Experimental conditions

	Initial consentoration of SS (g/l)	Light Condition	Consolidation (days)	Temp (℃)	Thickness of biofilm(mm)
RUN1	20.0	Lighten	19	32.8	1.9
RUN2	21.6	Darken	7	28.9	0.7
RUN3	19.1	Lighten	7	22.2	1.6
RUN4	20.3	Darken	7	19.4	0.5
RUN5	23.4	Lighten	14	17.9	1.0
RUN6	21.5	Darken	14	14.9	0.6

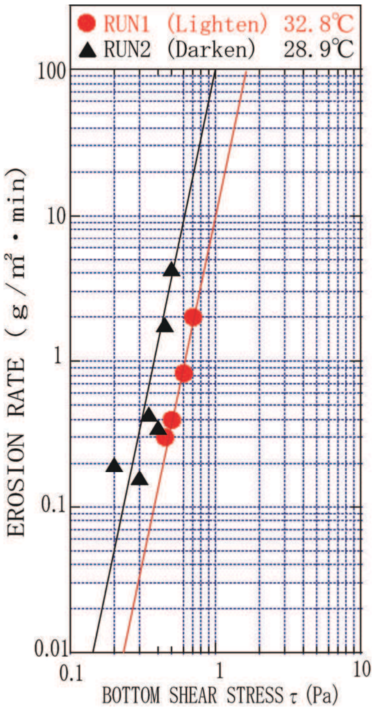

Fig.9 Experimental results at high water temperature region

(4) Experimental conditions

The experimental conditions are given in Table 1. Experiments are started by mixing salt water and sediment in the flume to a suspension with a defined and homogeneous concentration (20 kg/m^3). Before beginning erosion experiments, bed mud layer has to be developed. This can be accomplished by settling of sediment from a homogeneous suspension under no-flow conditions. After a given consolidation time, erosion is initiated by a stepwise increase of bottom shear stresses. Under a regime of climate change condition, RUN1 and RUN2 are e reproduced in summer high water temperature (about 30℃), RUN3 and RUN4 in mild water temperature (about 20℃), and RUN5 and RUN6 in severe winters water temperature (about 16℃).

4. EXPERIMENTAL RESULTS

(1) Experimental results at high water temperature region (comparison RUN1 and RUN2)

The logarithmic relationship between shear stress on the bed mud and erosion rate is shown in figure 9. The depth of biofilme was 1.9mm at lighten condition (RUN1), 0.7mm at darken condition (RUN2). From this figure, the relation indicates the erosion rate at RUN1 is almost one order smaller than it at RUN2. It becomes clear that the production of extracellular polymeric substances (EPS) by algae contributes to this stabilization by forming biofilm on the bed mud surface. The threshold shear stress of erosion is 0.45(Pa) at lighten condition (RUN1) and 0.2(Pa) at darken condition (RUN2).

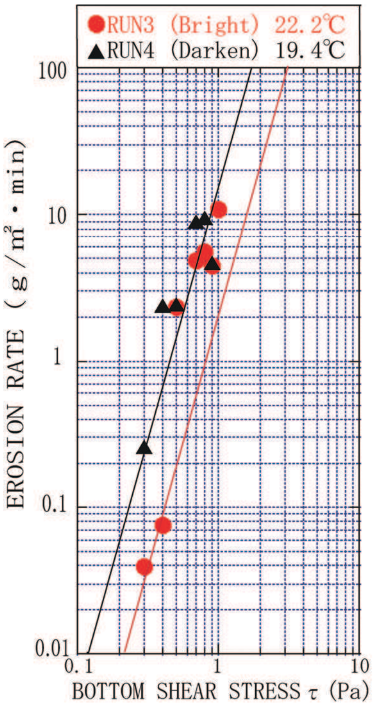

Fig.10 Experimental results at middle water temperature region

(2) Experimental results at middle water temperature region (comparison RUN3 and RUN2)

Figure 10 shows the relationship between bottom shear stress and erosion rate at RUN3 and RUN4. Plots of bottom shear stress versus the erosion rate indicated linear relationships on logarithmic graph paper. From this figure, the erosion rate at RUN3 decreases until the bottom shear stress reached 0.4 Pa. On the other hand, after the erosion rate at RUN3 over 0.4 Pa, the erosion rate at RUN3 is equal to the rate at RUN4. The erosion threshold shear stress is 0.3(Pa) at lighten condition (RUN3) and 0.3(Pa) at darken condition (RUN4).

(3) Experimental results at low water temperature region (comparison RUN5 and RUN6)

Figure 11 indicates the relationship between bottom shear stress and erosion rate at RUN5 and RUN6. Plots of bottom shear stress versus the erosion rate indicated linear relationships on logarithmic graph paper. The biofilm depth at RUN5 (lighten condition) was about 1.0mm which depth was the minimum all over the experiments at this time. This figure shows

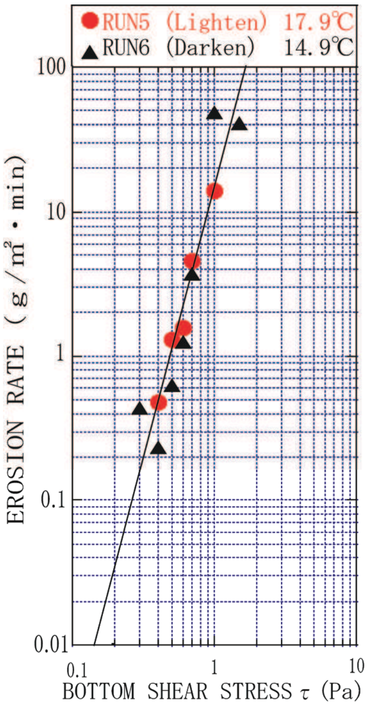

Fig.9 Experimental results at low water temperature region

no difference of the erosion rate at RUN5 and RUN6. It is considered that the biofilm formed at RUN5 (lighten condition) was eroded immediately after the beginning of the experiment The threshold shear stress for erosion is 0.4(Pa) at lighten condition (RUN5) and 0.3(Pa) at darken condition (RUN6).

5. DISCUSSION

Figure 12 illustrates the first stage erosion phenomena at the lighten condition. Surface biofilm erosion occurs gradually when the bed shear stress is slightly greater than a critical erosion stress. In this figure, surface biofilm erosion looks like suspended film in the air. Contrary to this, figure 13 indicates the first stage erosion phenomena at the darken condition. From the observing results on the PC monitor, surface erosion process at the darken condition is quite different from it at lighten condition. It was found that the biofilm depth formed at the darken condition is extremely thin, so the erosion phenomena at the first stage shows the ordinary erosion process.

Figure 14 appears the photograph through a microscope of the eroded biofilm after the experiment. It is considered that the eroded biofilm was mainly consisted of Diatoms and bacteria. Diatoms are microalgae, which form extensive biofilms on the surface of bed mud layer. Thalassiosira genus exude large quantities of extracellular polymeric substances (EPS), which form the matrix on the bed mud surface.[4)]

The effect of biofilem formed on the bed mud surface has an influence to not only a surface section but also some depth. The experimental results at high or middle water temperature region that were shown in figure 9 and 10 appear this biofilm effect.

Erosion rate shifting phenomena are shown in figure 10; this figure indicates the results of middle water temperature region. From this figure, surface erosion occurred gradually from the beginning, and it is considered that all biofilm formed on the surface was eroded at the bottom shear stress reached 0.4 Pa. About the biofilm reached depth, it is necessary to determine quantitatively by other method.

At the middle and high water temperature regions, it was proved that the erosion rate under the biofilm formed over 1mm depth was almost one order smaller than other cases.

At the middle and high water temperature regions, it was proved that the erosion rate under the biofilm depth formed over 1mm was almost one order

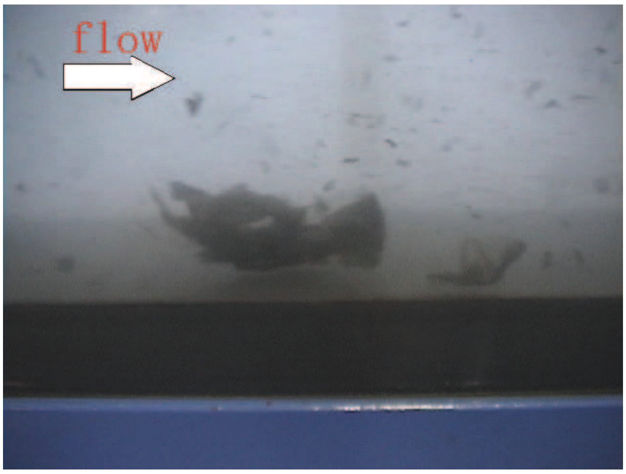

Fig. 12 The first stage erosion phenomena at the lighten

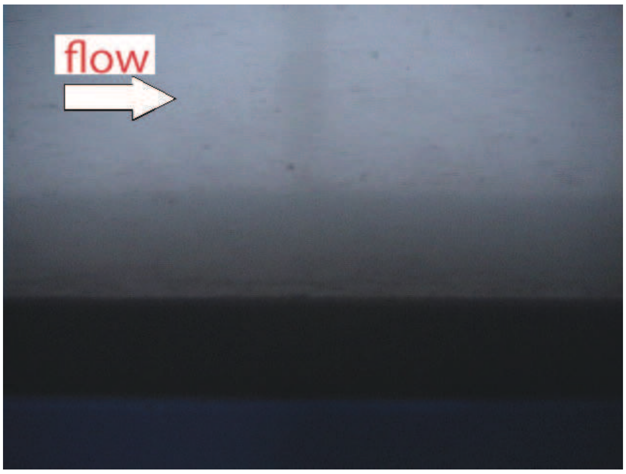

Fig.13 The first stage erosion phenomena at the darken

smaller than other cases. And at the low water temperature region is shown in figure 11, the difference of erosion rate between darken and lighten condition is not exist because of low microalgae activity.

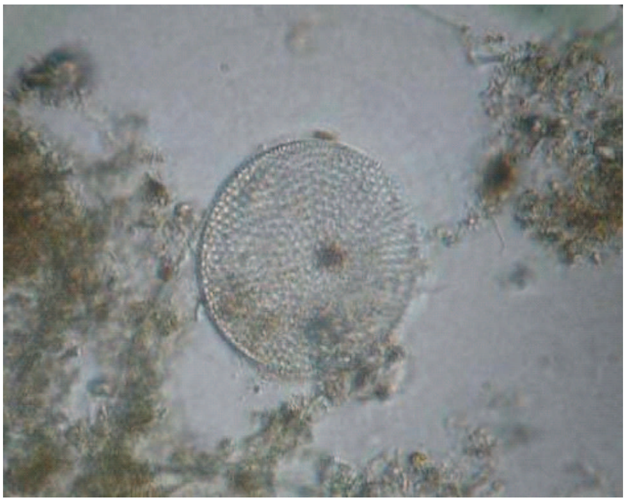

Fig.14 Microscope photograph of the eroded biofilm

6. CONCLUSIONS

In order to discuss the effect of biofilm formed on the bed mud surface, experimental investigations for erosion are performed by using the annular flume at FUKUOKA University. Basis for the comparison of experimental results is 1) the erosion rate under the biofilm depth formed over 1mm was almost one order smaller than it formed under 1mm depth. And Erosion rate shifting phenomena was shown after the surface biofilm layer all eroded, at this time the erosion rate approached the ordinary surface erosion process. 2) under the middle and high water temperature condition, the biofilm depth formed on the bed mud surface was thicker than the low water temperature condition case. And also, the biofilm depth at the lighten condition was thicker than it at the darken condition only in the range of the middle and high water temperature regions. It will be considered that microalgae activity on the bed mud surface declines at the low water temperature condition.

These results indicate the erosion threshold stress at the summer season will be greater than it at the winter season in estuary, and it also means that the erosion rate at winter season will be greater than it at the summer season in estuary region. Further field observations will be necessary to confirm this effect.

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