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Behavior of Electro-osmotic Dewatering of Biological Sludge with Salinity

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ABSTRACT

The salinity effect on electro-osmosis dewatering was investigated by measuring the solid content of sludge after dewatering. Three levels of salinity were studied, 5,000, 10,000, and 12,500 ppm. Coagulant chemicals such as alum, ferrous sulfate, and organic polyelectrolytes were used for some tests. Increasing the salinity from 5,000 to 10,000 ppm and 10,000 to 12,500 ppm was found to increase the sludge solid content about 88 and 28%, respectively. A 2 V/cm increase in voltage intensity can also increase the solid content about 46%. The effect of chemicals is evident at low salinity. At 5,000 and 10,000 ppm, addition of chemicals in average can enhance the sludge solid content about 44 and 16%, respectively. Because of the electrolysis of salt solution and the release of chlorine gas, the pH of the sludge increased. Consequently the zeta potential of the sludge increased, which in turn results in an increase in dewatering rate.

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Therefore an S-shape solid content–time curve was observed for most of the operating conditions, contrary to the conventional shape of a linear increase followed with a decrease of rate before reaching zero rate.

INTRODUCTION

Electro-osmosis dewatering was found effective to dehydrate hardly dewaterable sludge such as very fine particles and gelatinous materials whose diameter is about 10 μm.[1–3] During electro-osmosis dewatering, the negatively charged solid particle tends to migrate toward the anode located at the top of the sludge sample. Cations include Na^+, Ca^{2+}, and Mg^{2+} in the sludge move toward the cathode, which is located at the bottom of the sludge and connected to a drainage system. Water is transported together with these cations by viscous interaction, molecular collision, or hydration sheath, and finally passes through the filter medium and drains away. The movement of sludge solid to the upper anode can delay the onset of cake formation on the lower filter medium and hence leads to enhanced water flow.[4,5]

Based on Helmholtz–Smoluchowski theory, the dewatering rate in electro-osmosis dewatering is mainly dependent on the zeta potential and specific conductivity of sludge.[6] It is commonly known that salt and chemical coagulants can compress the electrical double layers and hence reduce the zeta potential of sludge solid. The ions or charge particles produced from them can also affect the electrical conductivity of sludge.[7,8] Therefore, it is believed that salt and chemical coagulants can give certain effect to the electro-osmosis dewatering of sludge. Although there are a lot of literatures related to electro-osmosis dewatering, the effects of salinity and the chemical addition to it are not many.[2,5,9,10] Salinity effect on electro-osmosis dewatering is not only academically interesting but also important in practice. To take Hong Kong for example, the salinity in sludge is high as seawater is partially used for toilet flushing. Thus, the objective of the present study is to investigate how the salinity and chemical coagulant affect the electro-osmosis dewatering.

MATERIALS AND METHODS

Sludge Collection and Its Characteristics

The activated sludge was collected from the sludge digestion tank of Tai Po sewage treatment plant, which has a capacity of 94,300 cubic meters of sewage per day. The plant is designed to treat the municipal and industrial sewage generated from Tai Po New Town and Tai Po Industrial Estate. During the thickening process, a certain amount of anionic polyelectrolyte was added into sludge for coagulation and flocculation. The collected samples were stored in a refrigerator at 4°C and it was kept for under one month. The sludge characteristics were shown in Table 1 together with the standard analytical methods adopted.[11] As expected, a high salinity was found for the present sludge. The values of a typical activated sludge from the United States were listed in order to have a comparison.[8]

Sludge Preparation and Chemical Dosage

In this study, the salinity of sludge was varied in three levels 5,000, 10,000, and 12,500 ppm, which corresponds to half of, equal to, and one and a quarter times of the averaged value of the sludge collected, respectively. In preparing sludge with 5,000 ppm salinity, 800 mL of original sludge was centrifuged (Allegra™ 6 Centrifuge, Beckman) at 1,000 rpm for 30 minutes to separate the sludge into two layers, the supernatant and the concentrated sludge.[12] The supernatant was replaced with an equal amount of deionized water. Then the salinity of the 800 mL centrifuged sludge was measured with a salinity meter (YSI #85/10 FT). The amount of salt required to adjust 1,000 mL of sludge to 5,000 ppm was calculated and dissolved in 200 mL of deionized water. Finally, the 200 mL salty water was mixed with the 800 mL of centrifuged sludge to produce 1,000 mL of sludge. The sludges with 10,000 and 12,500 ppm salinities were prepared by mixing 200 mL of salt solution with right concentration to 800 mL of original sludge. The sludge mixing was obtained by using a blade impeller with 6.5 cm diameter (Heidolph RZR1) at 60 rpm for 5 min.[13] The mixture was maintained static for 15 min to reach equilibrium before any test.[14] The solid content of the sludge at different salinity levels with and without chemical addition was all fixed at 2.5%.

Widely used sludge conditioning chemicals alum, iron (II) sulfate (copperas), and polyelectrolytes (cationic, anionic, and nonionic)[7] were selected to test their mutual effect with salt. The alum (CAT# 22761-7) produced from *Aldrich Chemical Company* is a 98 + % A.C.S. reagent whereas ferrous sulfate (LOT# 2115A) was made by *Riedel-deHaën Company* and has 99.5% purity. Organic polyelectrolytes were all manufactured from *Polysciences Company*. Cationic polyelectrolyte (CAT# 21743) is in solution form, and its molecular weight is 50,000. Anionic (CAT# 18545) and nonionic polyelectrolytes (CAT# 02806) are in powder form, and their molecular weights are greater than 10,000,000 and between 5,000,000 and 6,000,000,

Table 1. The characteristics of sludges from Hong Kong and the United States.

Parameters	HK activated sludge	Typical U.S. sludge	Standard methods
Moisture content (%)	97.3	99.1	Drying in oven at 104°C for 24 hrs
Total solids (ppm)	27,360	9500	Drying in oven at 103 to 105°C for 24 hrs
Volatile solids (ppm)	15,296	7313	Drying in oven at 103 to 105°C for 24 hrs & burning in furnace at 500 ± 50°C for 1 hr
VS to TS (%)	55.8	73.5	
SS (ppm)	18,400		Applying vacuum filtration & drying in oven at 104°C for 24 hrs
Salinity (ppm)	11,200		Electrical conductivity method
Ammonia (ppm)	5.53		Distillation and phenate method
Nitrate (ppm)	4.36		Ion chromatography
Phosphate (ppm)	8.47		Vanadomolybdophosphoric acid colorimetric
Total phosphate (ppm)	267.0	686.55	Sulfuric acid–nitric acid digestion & vanadomolybdophosphoric acid colorimetric method
Organic N (ppm)	993.0	368.15	Semi-micro-Kjeldahl method
Potassium (ppm)	224.5		Microwave-assisted digestion & ICP method
Nickel (ppm)	6.99	80	Same as above
Zinc (ppm)	32.6	1,700	Same as above
Copper (ppm)	20.7	800	Same as above
Lead (ppm)	19.7	500	Same as above
Cadmium (ppm)	3.01	10	Same as above
Chromium (ppm)	18.2	500	Same as above

All data are done in triplicate, expressed on a wet basis.

respectively. For each type of chemical the dosage is at the optimal value for similar activated sludge.[15] When chemicals were added into sludge, mixing was first performed at 220 rpm (0.6–0.9 m/s) for 5 min using a blade impeller. Then the sludge was stirred at 50 rpm for 5 min. Finally, it was left static for 20 min.[8,16]

Electro-osmosis Dewatering

The electro-osmosis dewatering apparatus is shown in Fig. 1. It is mainly composed of four parts: electrodes, a dewatering cylinder holding the sludge sample, D.C. power supply, and a device for water collection. In conducting electro-osmosis dewatering experiments, the cathode support plate with filter paper (Whatman#1) on the cathode was screwed onto the acrylic cylinder and then was fixed on the metal stand with a beaker below. The bed height, which is the distance between the anode (upper) and the cathode (lower), was adjusted to 2.5 cm. This spacing corresponds to 150 mL of sludge. After 10 min gravitational drainage to eliminate the effect of press from the weight of the iron ring used to keep the anode in close contact with the dewatering sludge, the D.C. power supply (PD 110-5AD, Kenwood TMI, Yukohama,

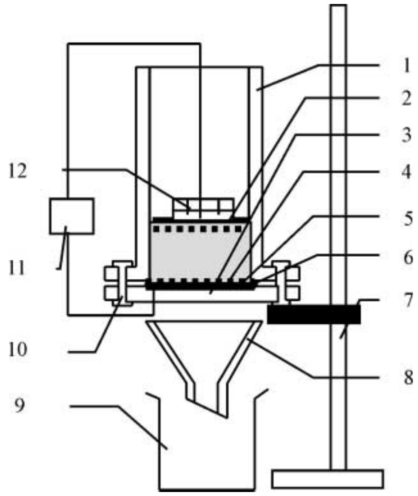

Figure 1. Experimental apparatus. 1) Acrylic cylinder; 2) Ti/Sb-Sn-Ir anode; 3) Cathode support; 4) SS cathode; 5) Filter paper; 6) O-ring; 7) Metal stand; 8) Funnel; 9) Beaker; 10) Screw; 11) Power supply; 12) Iron rings.

Japan) that provided constant voltage was switched on and the voltage was adjusted to either 5, 10, or 15 V, which corresponded to the voltage intensity of 2, 4, or 6 V/cm, respectively. The amount of water collected was weighed by balance and recorded every 10 min for 4 hrs.

Smoluchowski theory Eq. (1) stated that the rate of water released from electro-osmosis dewatering V_w is mainly dependent on zeta potential, ξ, conductivity σ, viscosity of sludge η, and surface area of electrode $A_{electrode}$.

$$V_w = \frac{\varepsilon\zeta}{\eta} \times \frac{I}{\sigma \times A_{electrode}} \tag{1}$$

with ε being permittivity.[17,18] During electro-osmosis dewatering, electrolysis occurs at both anode and cathode as shown below.

Anode Reactions

$$\mathrm{Me} \rightarrow \mathrm{Me}^{n+} + \mathrm{ne} \tag{2}$$

$$6\mathrm{H_2O} \rightarrow \mathrm{O_2(g)} + 4\mathrm{H}^+ + 4\mathrm{e} \tag{3}$$

$$2\mathrm{Cl}^- \rightarrow \mathrm{Cl_2} + 2\mathrm{e} \tag{4}$$

Cathode Reactions

$$2\mathrm{H_2O} + 2\mathrm{e} \rightarrow \mathrm{H_2} + 2\mathrm{OH}^- \tag{5}$$

$$2\mathrm{H}^+ + 2\mathrm{e} \rightarrow \mathrm{H_2} \tag{6}$$

Oxygen, chlorine, and hydrogen gases are released from the electrodes, and anode is corroded when the current passes through the sludge. The titanium anode with Sb–Sn–Ir coating was used to protect the anode from severe corrosion and increase its electrical conductivity. Moreover, it is useful to note that hydrogen and hydroxide ions are generated from anode and cathode, respectively. Therefore, there is high acidity of sludge around the anode, and high alkalinity of water is collected from the cathode.[5,17]

RESULTS AND DISCUSSION

Figure 2 shows the effects of salinity and voltage intensity on electro-osmosis dewatering. At the voltage intensity of 2 and 6 V/cm, the salinity

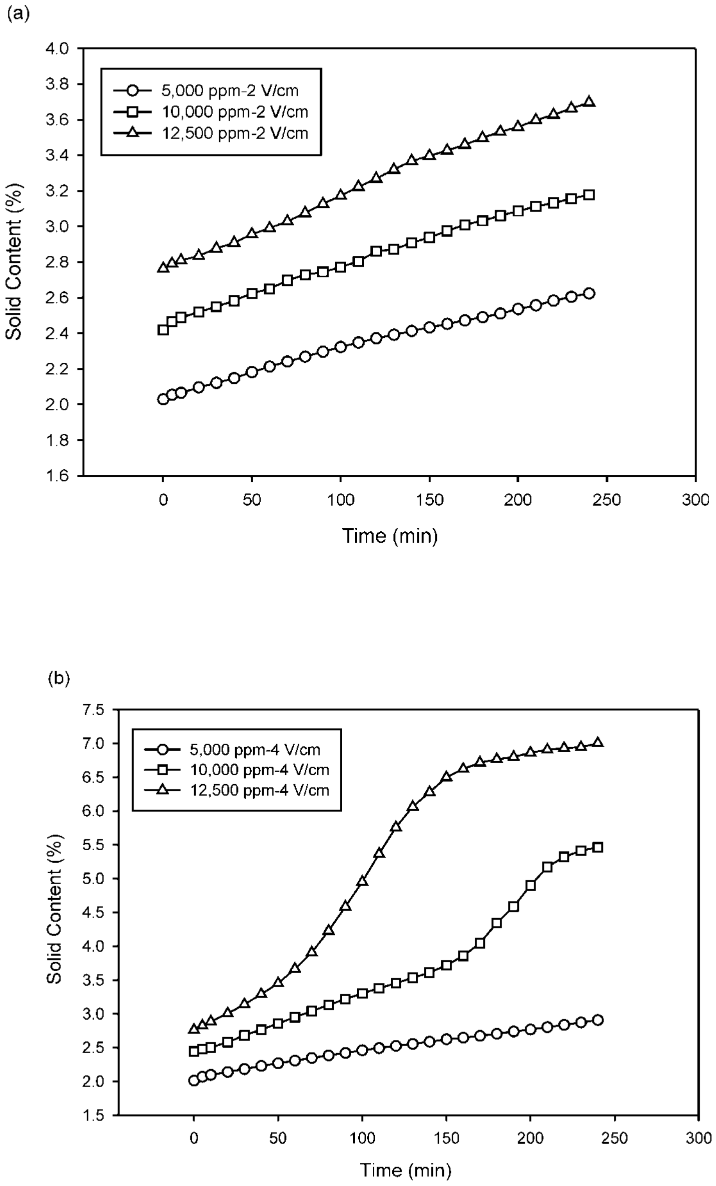

Figure 2. The salinity effect on electro-osmosis dewatering at electric field strength, (a) 2 V/cm; (b) 4 V/cm, (c) 6 V/cm.

(continued)

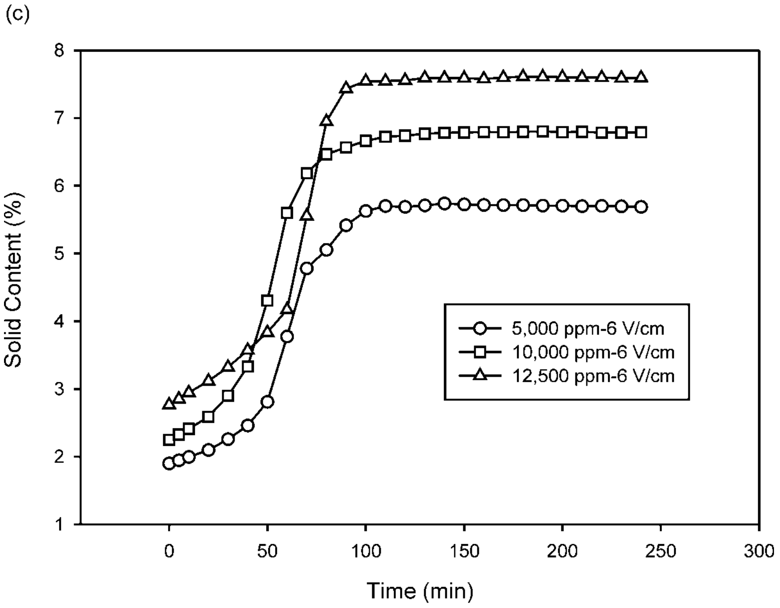

***Figure 2*.** Continued.

effect on electro-osmosis dewatering is insignificant. It can be seen that the curves of different salinity levels are parallel to each other. The difference in sludge solid content among the sludge with different salinities after dewatering is due to the difference in initial sludge solid content. The higher the initial solid content, the higher sludge solid content is obtained after dewatering. At a voltage intensity of 4 V/cm, the salinity effect on electro-osmosis dewatering becomes essential and doubling the salinity can bring 2–3% increase in sludge solid content after electro-osmosis dewatering. In fact, increase in the salinity from 5,000 to 20,000 ppm causes the sludge solid content to increase from 3 to 7%.

It is known that the addition of salt can reduce the zeta potential and increase the conductivity of sludge. Based on Eq. (1), decreasing of zeta potential and increasing of sludge conductivity can decrease the rate of water removed from electro-osmosis dewatering. The finding here seems to oppose the Smoluchowski theory. Ju et al. (1991) found that the Helmholtz–Smoluchowski theory did not agree with the experimental results for the effects of electrolyte concentration.[6] In fact, the water removal in electro-osmosis dewatering increases with increasing salt concentration up to an optimum and decreases with further salt addition. The initial increase in water removal is due to an increase in the current passing through the sludge, and the later decrease is due to the decrease in zeta potential of sludge.[1] This finding is consistent with that reported by Lockhart that adding a small amount of salt is beneficial to EOD.[10]

Apart from the salinity effect, as expected, the solid content of sludge after electro-osmosis dewatering increases with the voltage intensity. In other words, the higher the applied voltage, the more quickly the water is removed from the sludge near the cathode. Hence for conditions of 6 V/cm, limiting solid contents were reached, whereas for 2 V/cm condition, the EOD is still in the initial fast rate stage. It is interesting to note that an S-shaped curve exists for most of the conditions shown in Fig. 3. Specifically, the EOD does not proceed as a fast rate initial period followed with a decreasing rate transient period before reaching the limiting value of solid content. Instead, there is an increase in dewatering rate after the initial EOD period. This phenomenon may be due to the electrolysis of salt solution and resulting release of chlorine gas, which in turn increases the pH of the sludge. The increased pH will cause the zeta potential to increase.

With chemical addition, the amount of water removed from electro-osmosis can be enhanced for low electric field strengths; see Fig. 3. The results shown in Fig. 3c were obtained with very vigorous bubbling in the EOD cell due to the high ion concentrations in the sludge. Therefore this part of the results can only be considered with caution. Now come back to Fig. 3(a) and (b), the organic chemicals seem more effective to enhance electro-osmosis dewatering than the inorganic ones. It is because organic polyelectrolytes can undergo flocculation, whereas inorganic chemicals mainly carry out coagulation. The flocculated floc produced by organic polyelectrolytes is usually larger, more loosely packed than the coagulated flocs produced by inorganic chemicals.[19] It is speculated that the surface properties of the flocculated particles may have changed, especially the zeta potential. The better performance for the organic chemicals suggests that the magnitude of the zeta potential increased. The best performance of the cationic polyelectrolyte supports this hypothesis. Because of the high salinity content, the zeta potential cannot be measured with the available zeta potential meter in our laboratories. The better performance of anionic polyelectrolyte may be rooted from its high molecular weight or long polymer chain. Because nonionic polyelectrolyte does not have charge group and extremely high molecular weight to promote flocculation, less and small flocculated flocs were formed. The better performance of alum than iron (II) sulfate may be because of polymerization of Al to produce a long polymer chain.

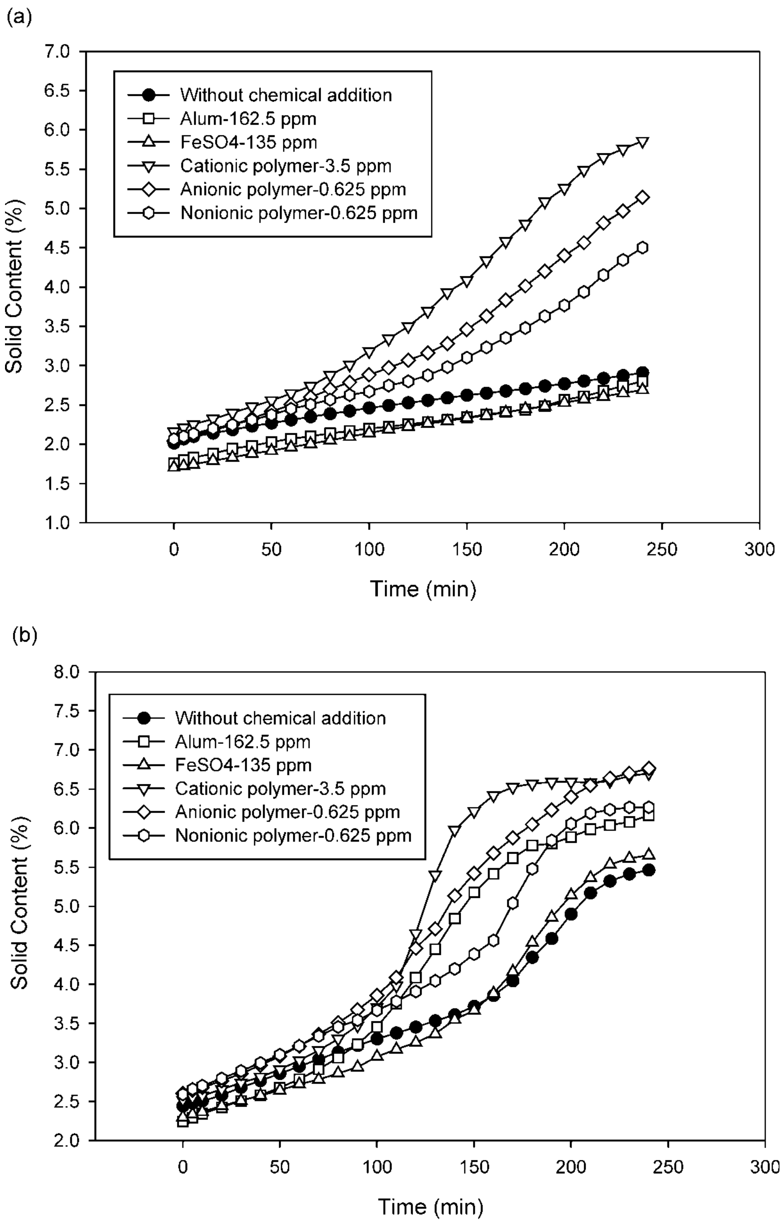

Figure 3. The effect of chemical addition at electric field strength of 4 V/cm, with (a) 5000; (b) 10000; (c) 12500 ppm.

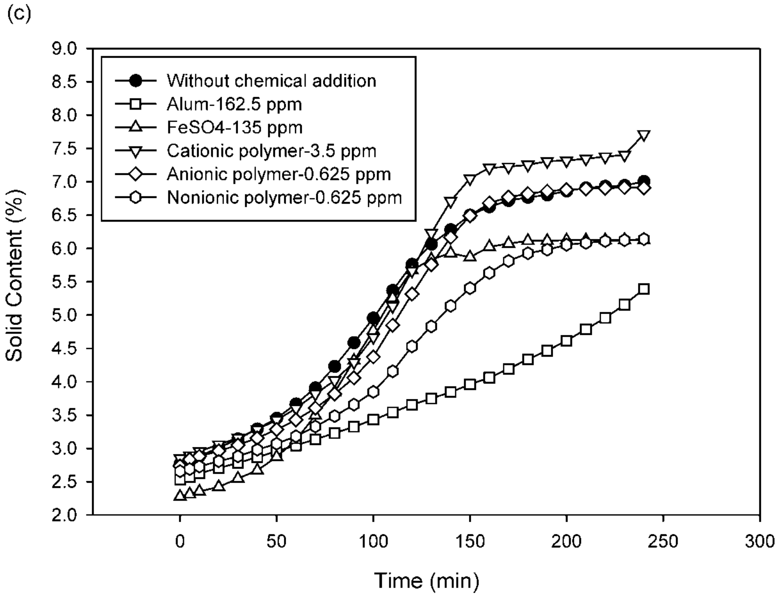

Figure 3. Continued.

Therefore, alum can also undergo flocculation to form a large and loose pack of sludge, which is easily attracted to anode.[20]

SUMMARY AND CONCLUSIONS

Salt is found beneficial to electro-osmosis dewatering. At voltage intensity of 2 and 6 V/cm, the salinity effect on stationary electro-osmosis dewatering is not significant. It is evident at a voltage intensity of 4 V/cm. It was found that increasing the salinity from 5,000 to 10,000 ppm can increase the sludge solid content about 2–3%. As expected, the rate of water removal increases with the voltage intensity. Because of the release of chlorine gas, the sludge pH increases while EOD proceeds. This increase in pH causes the zeta potential to increase which in turn increases the rate of water removal. Consequently an S-shaped dewatering curve was found.

With chemical addition, the efficiency of electro-osmosis dewatering can be enhanced. The performance of chemicals is evident at low salinity.

The performance of organic polyelectrolytes is better than inorganic chemicals in improving the electro-osmosis dewatering, probably due to the change of the surface properties of the sludge particles.

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