Effect of Soy Protein-Based Flocculant on Flocculation and Filtration of Diatomite and Kaolin Suspensions

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ABSTRACT

The effect of ethylated soy protein-based bioflocculant (EtSP) as a filter aid reagent was investigated. The efficiency of EtSP as a filter aid was evaluated in terms of the specific cake resistance, α, and was compared with chitosan and polyaluminum chloride (PAC). Diatomite and kaolin were used as model particles. Total filtration resistance, R, decreased with increasing flocculant dosage (wt.%, flocculant/particle) and was almost constant in the range of 1 wt.% or more for both particles. The α value was significantly decreased from 1.01×10^{11} to 9.01×10^{10} m/kg for diatomite and from 5.11×10^{10} to 5.20×10^{9} m/kg for kaolin by the addition of EtSP in the case of 1.0 wt.%. The α value for cakes formed by EtSP was much smaller than that formed by chitosan and PAC. In the case of diatomite, in the dose range of 0.5-1.0 wt.%, the α value for cakes formed by EtSP and chitosan was almost the same. However, at the excess dose of 2.0 wt.% over, the α value formed by chitosan abruptly increased. In the case of kaolin, in the dose range of 1.0-2.0 wt.%, the α values of chitosan and PAC were mostly the same, however, these values were larger ca. nine times than that of EtSP.

Keywords: flocculation filtration, filter-aid flocculant, soy protein, biodegradable flocculant, specific cake resistance, ethylated protein

HIGHLIGHTS

The proposed filtration model was verified by experimental results.

Evaluation of the efficiency of EtSP as a filter aid by the specific cake resistance, α.

The α value by EtSP was much smaller than that by PAC at proper dosages.

INTRODUCTION

Removal of suspended solids by filtration plays an important role in wastewater treatment (Nishi *et al*. 2012), tap water production (Zouboulis & Katsoyiannis 2002; Fiksdal & Leiknes 2006; Jeong & Vigneswaran 2013), and downstream processes (Khouni *et al*., 2020) in various industries. Sometimes, during the filtration process, small particles penetrate deeply into the filter media and cause premature turbidity breakthrough. This requires more frequent backwashing of the filter and the use of large volumes of backwash water to be able to remove the particles that have penetrated deeply into the filter media. To avoid the clogging of filter media with small particles, the use of filter aid is one of the most effective methods. When a flocculant is used as a filter aid, the size of particles can be increased by interparticle bridging.

Indeed, the use of filter aids has demonstrated multi-benefits, namely, an improvement of filtrate quality, ~~a~~ resistance to early breakthrough, and a reduction in the magnitude and duration of the filter ripening sequence. It has been reported that the addition of polyelectrolytes as a filter aid could drastically improve filtration performance of suspended solids in the effluent stream from recirculating aquaculture systems (Ebeling *et al*. 2003; Sharrer *et al*. 2009; Guerdat *et al*. 2013). In other industrial fields, flocculants/filter aids have been used in the dewatering of digested sewage sludge (Qi *et al*. 2011) and ultrafine coal (Tao *et al*. 2000), and pre-treatment to reverse osmosis desalination (Johir *et al*. 2009). Polyelectrolytes were also used as a membrane performance enhancer to prevent membrane fouling in a membrane bioreactor process (Yoon *et al*. 2005; Wu *et al*. 2006; Ji *et al*. 2008).

On the other hand, the harmfulness of conventional flocculants has been pointed out by many researchers. Synthesized high-molecular-weight polymers, such as polyacrylamide, are proved to be toxic especially to aquatic organisms (Dearfield *et al*. 1988; Hasegawa *et al*. 1990; Bolto & Gregory 2007), while others, such as aluminum compounds are known to negatively impact plant growth (Jones & Kochian 1995; Balcelo' & Poschenrieder 2002). Therefore, effective and eco-friendly bioflocculants, that are easily biodegraded and produce no secondary pollution, have been a topic of intense research and have gained much wider attention in recent years. However, for practical applications, high production costs have been a major problem in bioflocculant production by using microorganisms due to the relatively expensive conventional substrates such as glucose, fructose, sucrose, and so on (Fujita *et al*. 2000; Shih *et al*. 2001; Deng *et al*. 2003; He *et al*. 2004).

Based on the strong demand for safe, eco-friendly, and low-cost bioflocculants, we investigated the use of general proteins, such as chicken egg white albumin, cow's milk casein, and soy protein as raw materials for bioflocculant. We have reported that bioflocculants prepared by methyl esterification of proteins exhibited much higher flocculation performance for diatomite, kaolin, and kanto loam suspensions than polyaluminum chloride (PAC) and chitosan (Seki *et al*. 2003, 2004, 2009, 2010; Liu *et al*. 2012). However, methanol is toxic and hazardous to human health. So, we considered that the use of ethanol for esterification is more suitable for the safety of human health, the manufacturing field, and the environment than the use of methanol (Seki *et al*. 2009).

In the previous study (Seki *et al*. 2009), we demonstrated that the ethylated egg albumin was a high-performance bioflocculant in comparison with flocculation by PAC by using diatomite suspension. As described in the above paragraph, it has been necessary to be biodegradable and eco-friendly for filter aid reagent or flocculant. In addition, in our previous study (Seki *et al*. 2010; Liu *et al*, 2012), soy protein was also an alternative potential protein-based bioflocculant as same as egg albumin.

Therefore, in this study, ethylated soy protein (EtSP) was applied to the flocculation filtration of diatomite and kaolin suspension. Diatomite and kaolin particles were selected as typical model substances for soil particles and clay particles in common soil. The gravity filtration experiments were carried out by using EtSP, chitosan, and polyaluminum chloride (PAC) as flocculants or filter aids. The effect of EtSP on the flocculation filtration of diatomite and kaolin suspensions was compared with chitosan and PAC in terms of specific cake resistance as a filter aid performance indicator.

MATERIALS AND METHODS

Materials

Protein powder (soybean, ca. 90 %), ethyl alcohol (99.5 %), ammonia solution (25 %), HCl solution (36 %), NaOH (97 %), and $NaHCO_3$ (99.5 %) were purchased from Wako Pure Chemical Industries, Japan. Protein powder was of practical grade and other chemicals were of reagent grade, respectively. Polyaluminum chloride (PAC) solution (10.2 ± 0.2 wt.% as Al_2O_3) was purchased from Taki Chemical Co., Japan. Chitosan which has an average molecular weight of about 1000 kDa was purchased from Hokkaido Soda, Japan. The chitosan powder was dissolved in the same weight of acetic acid and diluted to 5.0 kg/m^3 with distilled water. They were used without further purification.

Diatomite (diatomaceous earth) and kaolin were purchased from Kanto Chemical Co. Inc., Japan, and Wako Pure Chemical Industries. Ltd., Japan, respectively. According to the data from the supplier, diatomite was composed of about 90% SiO_2 and kaolin was composed of about 45% SiO_2 and 40% Al_2O_3. Both powders were dried at 80°C for 24 h and stored in a desiccator. The size distribution of particles was measured using a laser diffraction particle size distribution analyzer (LA-300, Horiba Ltd., Japan). The median diameter and mode diameter of diatomite were 11.1 and 16.2 μm, respectively. The density of diatomite measured by a pycnometer was 2510 kg/m^3. In the same manner, the median diameter and mode diameter of kaolin were 2.7 and 2.8 μm, respectively.

The density of kaolin was 2960 kg/m^3.

Preparation of bioflocculant (EtSP)

Soy protein was ethylated according to the method reported by Fraenkel-Conrat and Olcott (1945). Soy protein powder (20 g) was dissolved in 0.001 M NaOH (1.0 L) and then precipitated by the addition of 0.1 M HCl solution at about pH 4.5. The soy protein was separated from the aqueous phase by filtration and was washed twice with ethyl alcohol. It was suspended in 1.0 L of ethyl alcohol containing HCl (0.1 M) and was stirred for 48 h at room temperature. After neutralization with ammonia solution, the ethylated soy protein (EtSP) was separated by centrifugation at 3000 rpm for 10 min and was air-dried at room temperature with occasional grinding for 1 day. The dried EtSP was pulverized in a high-speed mixer and was stored in a desiccator. The dry powder of EtSP was dissolved in 5% ethanol solution under ultrasonication (20 kHz, 30 W, 2 min) before use. The degree of esterification of soy proteins by ethanol was determined from the change in the number of carboxylic groups before and after esterification. The number of carboxylic groups was determined by potentiometric titration. The procedure was mostly the same method of previous studies. The detail information is referred to in the previous study (Seki et al., 2003). The degree of esterification of EtSP in the present study was ca. 90 %. The electrostatic properties of EtSP were mostly the same as those of MeSP (methylated soy protein) used in the previous study. The detail information would be referred to in the literature (Liu *et al*. 2012).

Filtration experiments

A Schematic diagram of the experimental setup is shown in Figure. 1. Gravity filtration experiments were performed in a clear acrylic cylindrical tube with an inner diameter of 32 mm and a height of 250 mm. A filter holder was attached to one end of the tube. The outlet diameter of the filter holder was 50 mm and the effective filtration area was 8.0×10^{-4} m^2 (hereafter this setup will be referred to as "filtration apparatus"). To ensure a clear filtrate in all experiments, a filter paper which consists of 99% α-cellulose and has a cut-off size of 5 μm (Qualitative filter paper No. 2, ADVANTEC MFS, INC., Japan) was used as the filter medium. The filtration apparatus was placed above an electronic balance and the filtrate was collected in a 300 mL plastic beaker placed on the electronic balance. The filtrate outlet of the filtration apparatus was closed with a silicone rubber stopper until the

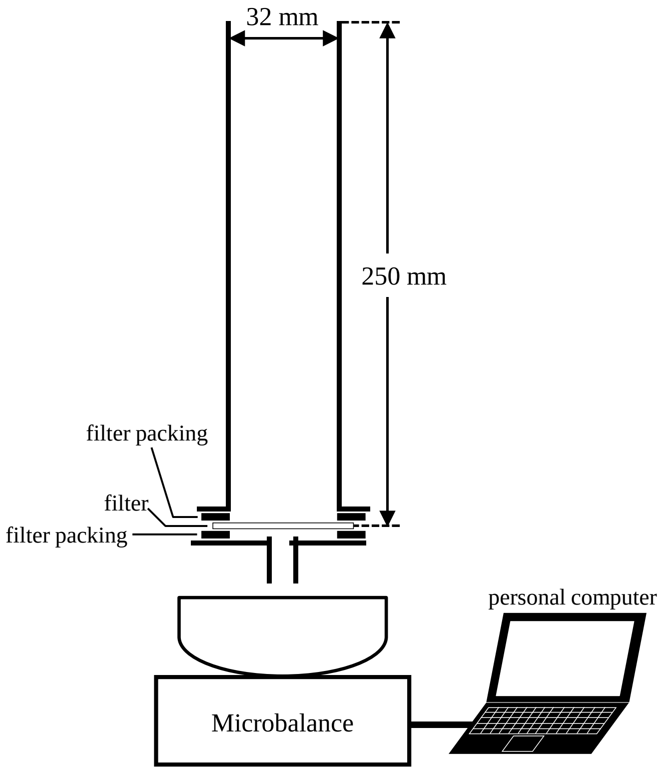

Figure 1 Schematic drawing of the experimental setup for flocculation filtration system.

filtration was started.

Diatomite or kaolin suspensions were prepared by dispersing dry powder in distilled water in a 300 mL glass beaker. The pH of the suspension was adjusted to 7.0 ± 0.2 with the addition of 0.1 mL of 0.01 M $NaHCO_3$ solution. The suspension was stirred with a propeller stirrer for more than 12 h to establish the equilibrium state. A certain amount of flocculant solution was added to the suspension. The total volume of the suspension at this point was 150 mL. It was stirred rapidly at 150 rpm for 13 min, followed by slow stirring at 50 rpm for 2 min with a jar tester.

The suspension was poured into the filtration apparatus and settled for 30 min to ensure the formation of the cake layer. The flocs formed by EtSP settled on the filter medium within 5 min, and a clear liquid upper phase was obtained. After the settling, the silicone rubber stopper was removed and the clear liquid was filtered through the cake layer. The weight of filtrate collected in the beaker was recorded every 5 seconds by using a personal computer. After each experiment, the total weight of filtrate was measured to obtain the density of the filtrate. Based on the density of water, the weight of filtrate at each time point was converted into the volume of the filtrate. In the case of the control experiment without flocculant, the suspension was settled for about 24 h to ensure the formation of the cake layer. A filtration experiment without suspended solids or with distilled water was also conducted to determine the filter medium resistance. The experiments were repeated at least three times, and the average values were used for data analysis.

THEORETICAL

Proposed filtration model for estimation of specific cake resistance, α

According to Darcy's law, a general equation for a filtration process is expressed as:

$$\frac{dV}{dt} = \frac{A\Delta P}{\mu R} \tag{1}$$

where A is the filtration area, ΔP is the pressure drop across the filter, R is the total filtration resistance, t is the filtration time, V is the filtrate volume at t, μ is the viscosity of the fluid, respectively. In the case of batch-type gravity filtration, the pressure drop across the filter is given as:

$$\Delta P = \rho g(h_0 - V / S) \tag{2}$$

where, S is the cross-sectional area of the filtration apparatus, h_0 is the initial height of the suspension, ρ is the density of suspension, and g is the gravitational acceleration, respectively. The total filtration resistance (R) is the sum of the cake resistance (R_c) and the filter medium resistance (R_m). Thus, Equation (1) is written as:

$$\frac{dV}{dt} = \frac{A\rho g(h_0 - V/S)}{\mu R} = \frac{A\rho g(h_0 - V/S)}{\mu(R_c + R_m)} \tag{3}$$

The filter medium resistance is usually considered to be a constant for a given medium. As for the cake resistance in our study, the diatomite particles were settled on the filter medium before the filtration, and the mass of the cake was constant through the filtration process. By assuming that the cake is incompressible, the cake resistance can also be considered to be constant for each run of the filtration experiments. Thus, by integrating Equation (3) assuming that R_c and R_m are constant, the following equation is obtained:

$$\begin{aligned} \frac{\rho g A}{\mu S} t &= (R_c + R_m)\ln\left(\frac{h_0 S}{h_0 S - V}\right) \\ &= (R_c + R_m)\ln\left(\frac{V_T}{V_T - V}\right) \end{aligned} \tag{4}$$

where V_T is the total volume of the diatomite suspension (150 mL). According to Equation (4), the plot of the $\rho gAt/\mu S$ vs. $\ln[(V_T/(V_T - V)]$ gives a straight line through the origin, and the total filtration resistance ($R = R_c + R_m$) can be obtained from the slope value of the line. The cake resistance (R_c) was obtained by subtracting the filter medium resistance from the total filtration resistance. The cake resistance can be expressed by the following equation assuming that the cake is incompressible:

$$R_c = R - R_m = \frac{\alpha C V_T}{A} \tag{5}$$

where, α is the specific cake resistance and C is the solids concentration in the suspension, respectively. Consequently, the specific cake resistance can be obtained from Equation (5).

RESULTS AND DISCUSSION

Determination of specific cake resistance

The filter medium resistance (R_m) was determined from the flow rate of distilled water through the filter medium. In the case of the filtration of distilled water, the cake resistance can be set to zero. Thus, the slope of the line obtained from the plot of Equation (4) gives the value of R_m. The value of R_m was found to be 7.55×10^8 m^{-1} for the filter paper used in this study. The plot of Equation (4) showed a good linear relationship with a correlation factor of 0.997 (data were not shown).

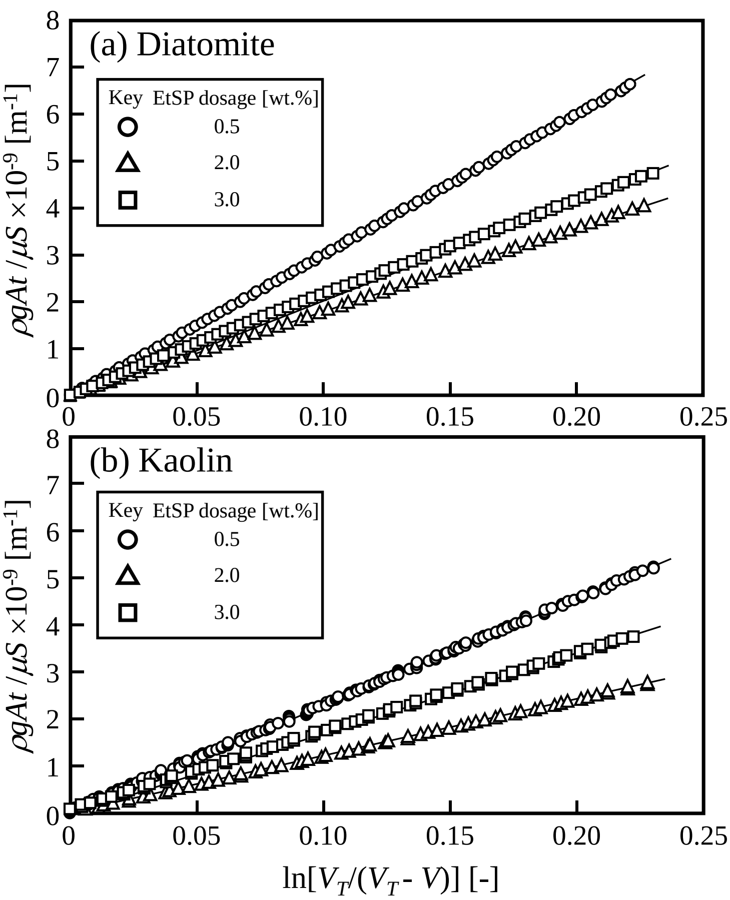

Figure 2 Determination of total filtration resistance, R, by fitting of the data to Equation (4) for (a) diatomite and (b) kaolin. The concentration of the particles was 20 kg/m^3. The value of the slope for the regression line (straight line) of the data corresponds to the total filtration resistance.

The linear equation represented by Equation (4) was applied to the experimental data to determine the total filtration resistance. The typical results were presented in Figure 2. The data used in Figure 2 were obtained from the gravity filtration experiments conducted at a diatomite concentration of 5.0 kg/m^3. The dosages of EtSP were 0.5 - 3.0 wt.% of diatomite and kaolin. The unit of wt.% corresponds to the percentage of the mass of flocculant added per unit mass of particles. The results showed good linear relationships with correlation coefficients greater than 0.995, thus, the total filtration resistance could be obtained from the slope of each line.

Effect of suspended particle concentration

Figure 3 shows the effect of the suspended particle concentration on the total filtration resistance at different dosages of EtSP. The dosage was expressed as the percentage of EtSP relative to particles on a dry weight basis. The total filtration resistance at the suspended particle

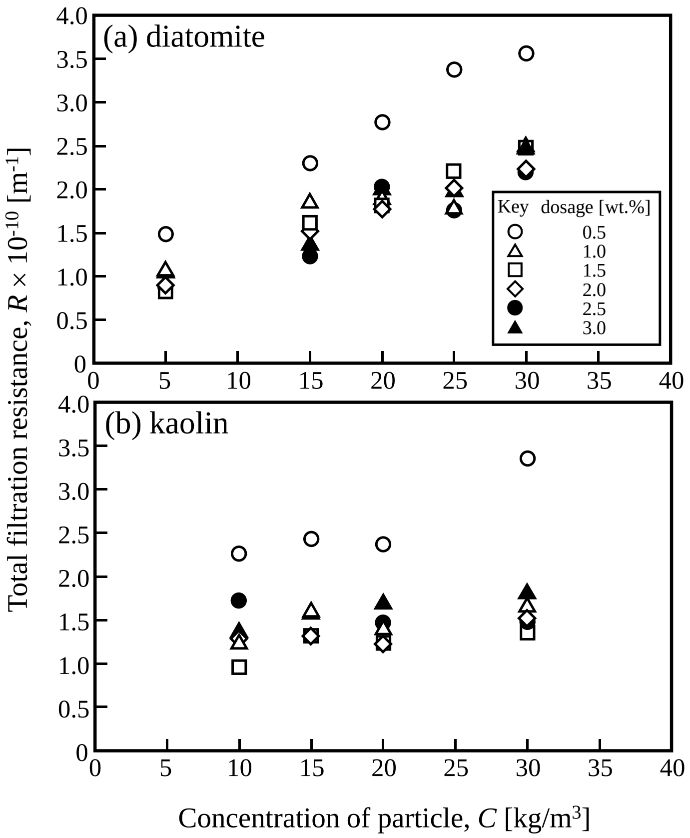

Figure 3 Effect of particle concentration on the total filtration resistance, R, at different EtSP dosages for (a) diatomite and (b) kaolin. The symbol in Figure 3b is same as Figure 3a.

concentration of 0 kg/m^3 corresponds to the filter medium resistance, R_m (7.55×10^8 m^{-1}). The filter medium resistance was much smaller than the total filtration resistance in the presence of diatomite or kaolin. The total filtration resistance increased proportionally with the increase in the diatomite concentration. Assuming that the cake is incompressible, the thickness of the cake increases proportionally with the mass of diatomite settled on the filter medium. Thus, it is considered reasonable that the cake resistance increased proportionally with diatomite concentration. In the case of diatomite, the total filtration resistance increased proportionally with the increase in the diatomite concentration or the mass of diatomite. In this study, almost all of the suspended particles are settled on the filter before the filtration. So, when the cake is incompressible, the thickness of the cake should proportionally increase with the mass of the suspended particle or the mass of sediment on the filter. Thus, it is considered reasonable that the total filtration resistance proportionally increases with the concentration of suspended particles. On the other hand, in the case of kaolin, expect for 0.5 wt.%, the value of R became almost constant at the higher dosage (1.0-3.0

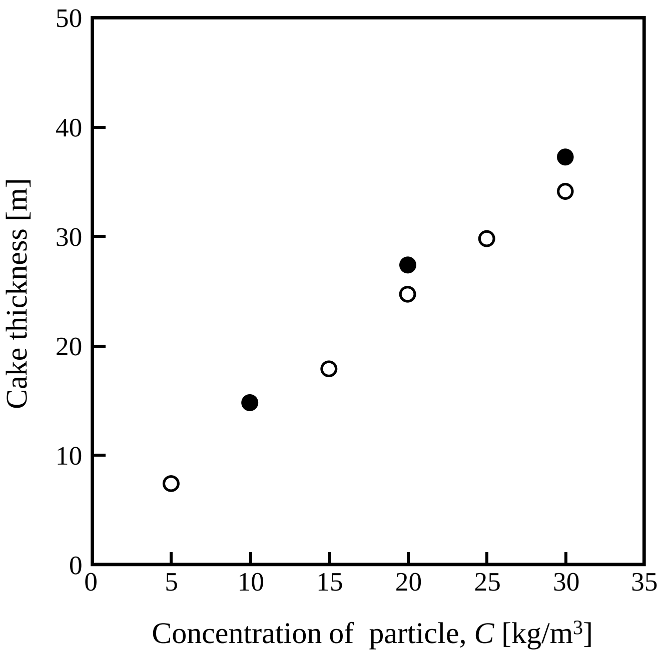

Figure 4 Effect of particle concentration, C, on the cake thickness for diatomite (open circle) and kaolin (solid circle). Dosage of EtSP was 1.5 wt.% of both the particles.

wt.%).

Figure 4 shows the cake thickness as a function of particle concentration. The EtSP dosage was 1.5 wt.% of each particle. The cake thickness increased proportionally with particle concentration. Judging from the results, the cakes of both particle floc formed by EtSP were considered to be incompressible.

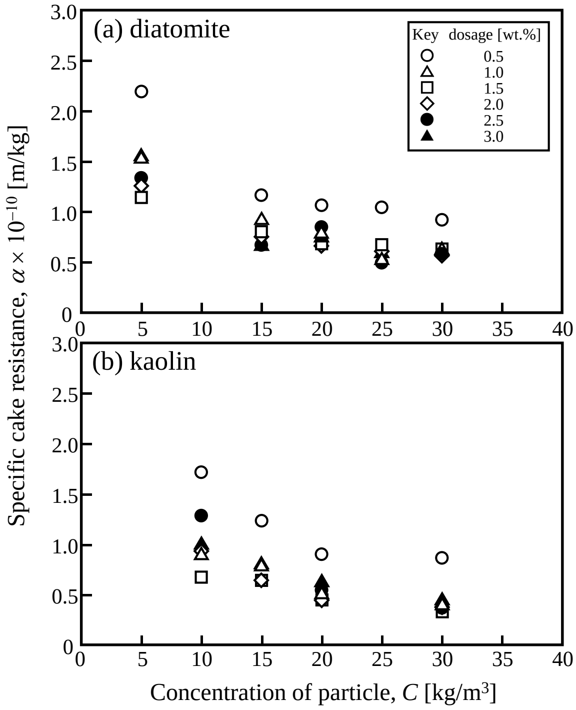

Figure 5 Effect of diatomite concentration on the specific cake resistance, α, at different EtSP dosages for (a) diatomite and (b) kaolin. The symbol in Figure 5b is same as Figure 5a.

Figure 5 shows the effect of suspended particle concentration on the specific cake resistance, α, at different EtSP dosages. The specific cake resistance was determined from Equation (5). As expected the α value deceased as the void volume in the cake was larger. In the absence of EtSP, the specific cake resistances were almost constant at the particle concentrations of 5.0 – 30.0 kg/m^3. The average value of specific cake resistances of diatomite and kaolin were 1.03×10^{11} and 4.05×10^{10} m/kg, respectively. At the same dosage of EtSP, the specific cake resistances were almost constant at the particle concentration higher than 15 kg/m^3 for diatomite and kaolin, respectively. The specific cake resistances of diatomite and kaolin at 15 kg/m^3 were significantly reduced from 1.03×10^{11} to 0.12×10^{11} m/kg and from 4.05×10^{10} to 0.79×10^{10} m/kg by the addition of 1.0 wt.% of EtSP, respectively. In other words, according to Equation (3), the filtration rate was increased about ten times for diatomite and about five times for kaolin by the addition of EtSP.

Effect of flocculant dosage

Figure 6 shows the effect of EtSP dosage on the specific cake resistance at different particle concentrations. The specific cake resistance of both particles was significantly decreased by the addition of 0.5 wt.% of EtSP. At the same particle concentration, the specific cake resistances were almost constant at the EtSP dosages of 1.0–2.5 wt.%. The specific cake resistances at 15–30 kg/m^3 were almost the same at the EtSP dosages of 0.5–2.0 wt.% for both particles.

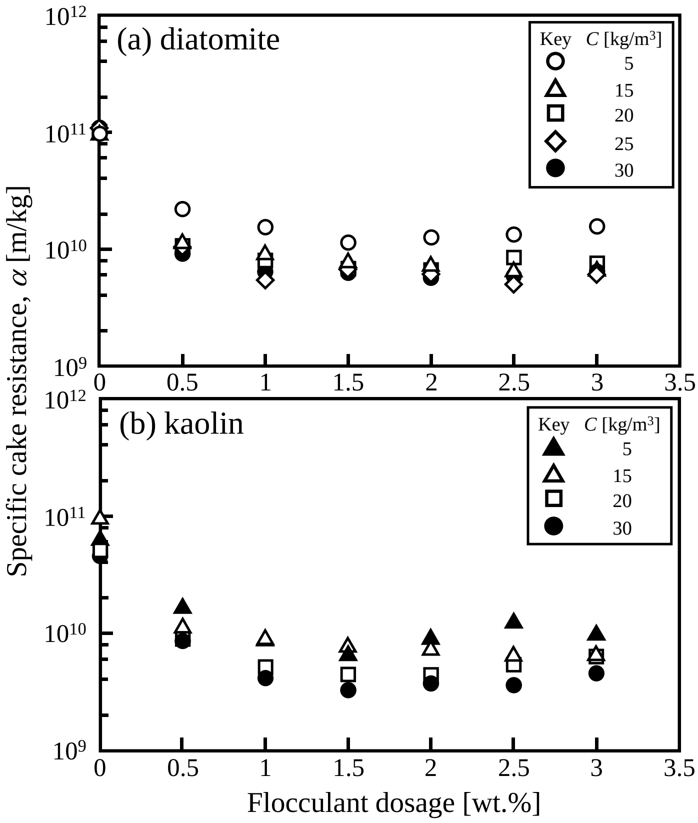

Figure 6 Influences of EtSP dosage and particle concentration, C, on the specific cake resistance, α, for (a) diatomite and (b) kaolin.

In visual observation, large flocs were formed in the flocculation process by adding EtSP before the filtration process. EtSP should be considered as macromolecular and polyvalent flocculant. These flocculants are known to bridge between particles by chemical binding forces and to form large flocs having high settling velocities. Ruehrwein and Ward (1952) first proposed the basic principle of bridging flocculation in 1952, presenting a model in which a single polymer chain was bridging between two or more particles. Some more vigorous studies about bridging flocculation have been developed (Smellie and La Mer, 1958; Healy and La Mer, 1964; La Mer, 1966; Fleer and Lyklema, 1974; Gregory, 1988; Biggs *et al*. 2000; Nyström *et al*. 2003). The flocculation mechanism in the present study could be bridging flocculation.

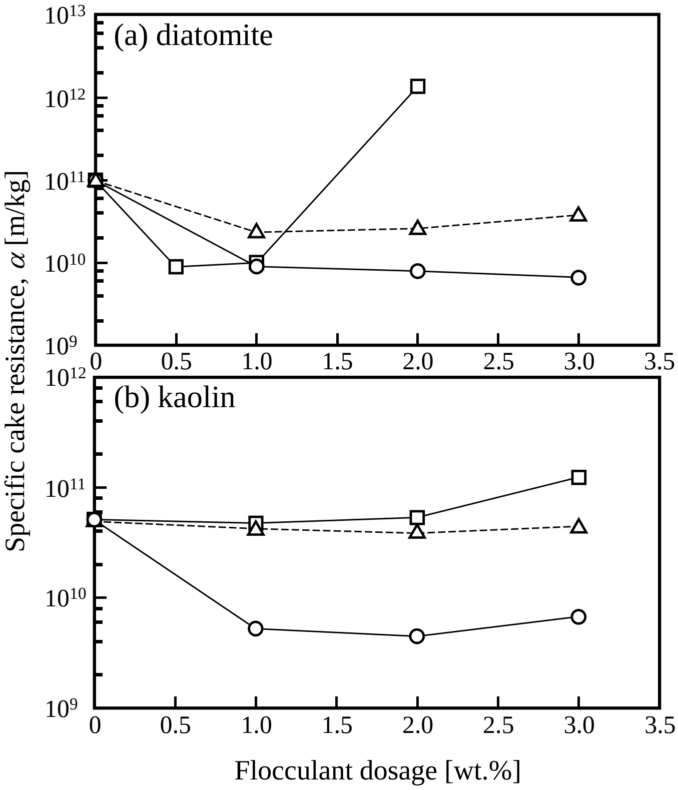

Figure 7 Comparison of the specific cake resistances, α, of (a) diatomite and (b) kaolin flocs formed by EtSP (circle), chitosan (square) and PAC (triangle) as a function of flocculant dosage. The particle concentration is 20 g/L.

Comparison of the efficiency of EtSP with chitosan and PAC

In Figure 7, the specific resistances of cakes formed by EtSP, chitosan, and PAC are compared as a function of flocculant dosage. In the case of PAC, no significant improvement in the specific cake resistance was observed for both particles. The average of the specific cake resistances of diatom and kaolin at the dosages of 1.0–3.0 wt.% were 7.87×10^{10} and 5.45×10^{9} m/kg, respectively. The specific resistances of cakes formed by EtSP were almost lower than those formed by chitosan and PAC for diatomite and kaolin. As seen in Figure 7a, the abrupt increase in α of diatomite adding chitosan at 2.0 kg/m^3 might be caused by becoming viscous in the suspension. As a result, EtSP is found the be the most effective flocculant in comparison with chitosan and PAC in the present experimental range.

Wei *et al*. (2018) summarized the dewatering performance of practical sludge by using several kinds of flocculants, thus, inorganic salt, organic synthetic polymeric, natural polymeric, and so on. Specific resistance to filtration (SRF) was employed to evaluate optimum conditions in each dewatering process. The magnitude of these values was mostly ranged in 10^{12} – 10^{13} m/kg, which were somewhat larger value than the values shown in the present study although simple comparison might be inadequate because the objective suspension is not the same one.

In most studies on bioflocculants, especially extracellular or intracellular produced substances, flocculation ability was estimated by clarification of turbidity (Fujita *et al*. 2000; Shih *et al*. 2001; Krentz *et al*. 2006; Chen *et al*. 2011). Some investigators have reported dewatering performances of bioflocculants by using practical sludge. A few studies have dealt with evaluating biodegradable flocculants' ability as a filter aids by the specific resistance as the evaluation parameter. Mohtar *et al*. (2019) recently reported flocculation kinetics and dewatering by using a bioflocculant, which is quaternized cellulose derived from oil palm empty fruit bunches (q-EFBC) and evaluated the specific resistance to filtration (SRF) with kaolin suspension. They reported that the optimum dosage was 62.5 mg/L and the value of SRF was 1.49 $\times 10^{10}$ kg/m, which corresponded to ca. 34 % of SRF at the blank. The dosage could be translated 4.4 wt.% according to their experimental conditions. The degree of decrease in the specific cake resistance by adding flocculant in the present study is larger and the optimum dosage in the present study is lower than their values, however, the comparison might be difficult because Mohtar *el at*. (2019) used kaolin as a model suspension and the difference in particles and each experimental condition should affect the value of the specific resistance.

CONCLUSION

The effect of soy protein-based bioflocculant, EtSP, on the flocculation filtration of diatomite and kaolin suspensions was examined. Both particles were flocculated and settled on the filter medium to form the cake layer. Then the clear liquid phase was filtered through the cake layer of flocculated diatomite and kaolin particles.

The experimental data followed the modified Darcy's equation very well. The total filtration resistance, the filter medium resistance, and specific cake resistance were obtained from the data analysis. The cake thickness and the cake resistance of both particle flocs formed by EtSP increased proportionally with the increase of diatomite. Thus, the cake of diatomite and kaolin flocs formed by EtSP was considered to be incompressible. In the absence of flocculant, the specific cake resistance of diatomite and kaolin were 1.01×10^{11} m/kg and 5.11×10^{10} m/kg, respectively. The specific cake resistance significantly reduced to ca. 8.9×10^{9} m/kg and 6.6×10^{9} m/kg for diatomite and kaolin by the addition of 1.0 wt.% of EtSP.

The performance of EtSP as the filter aid was compared with a well-known bioflocculant chitosan and a widely used commercial flocculant, polyaluminum chloride (PAC) in terms of the specific cake resistance. The specific resistances of cakes formed by EtSP and chitosan were much lower than those formed by PAC. In the case of diatomite, the specific resistances of cakes formed by EtSP were almost the same as those formed by chitosan at the dosages of 1.0–2.0

wt.%. However, at the dosages of 2.5 and 3.0 wt.%, the specific resistances of cakes formed by EtSP were lower than those formed by chitosan. In the case of kaolin, the specific cake resistance was mostly lower than those formed by chitosan and PAC in the dosage range of 1.0-3.0 wt.%.

From a practical point of view, the scale-up of this process should be important. In scale up, especially the mixing and the agitation parameters would play an important role in the flocculation process before the filter process. In a further study, it would be necessary to reveal the influences of the stirring and the mixing on the filtration efficiency and the specific cake resistance in the flocculation filtration process.

In further study we will conduct flocculation and filtration experiments with a real wastewater by using EtSP.

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NOMENCLATURE

A	= filtration area	[m^2]
V	= filtrate volume	[m^3]
t	= time	[min]
ΔP	= pressure drop across filter	[Pa]
R	= total filtrate resistance	[m^{-1}]
R_c	= cake resistance	[m^{-1}]
R_m	= medium resistance	[m^{-1}]
S	= cross sectional area of filtration apparatus	[m^2]
h_0	= initial height of suspension	[m]
g	= gravitational acceleration	[m/min^2]
V_T	= total volume of suspension	[m^3]
C	= solid concentration in suspension	[kg/m^3]
α	= specific cake resistance	[m/kg]
μ	= viscosity of the fluid	[kg/(m s)]
ρ	= density of suspension	[kg/m^3]

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Figure captions

Figure 1 Schematic drawing of the experimental setup for flocculation filtration system.

Figure 2 Determination of total filtration resistance, *R*, by fitting of the data to Equation (4) for (a) diatomite and (b) kaolin. The concentration of the particles was 20 kg/m^3. The value of the slope for the regression line (straight line) of the data corresponds to the total filtration resistance.

Figure 3 Effect of particle concentration on the total filtration resistance, *R*, at different EtSP dosages for (a) diatomite and (b) kaolin. The symbol in Figure 3b is same as Figure 3a.

Figure 4 Effect of particle concentration, *C*, on the cake thickness for diatomite (open circle) and kaolin (solid circle). Dosage of EtSP was 1.5 wt.% of both the particles.

Figure 5 Effect of diatomite concentration on the specific cake resistance, α, at different EtSP dosages for (a) diatomite and (b) kaolin. The symbol in Figure 5b is same as Figure 5a.

Figure 6 Influences of EtSP dosage and particle concentration, *C*, on the specific cake resistance, α, for (a) diatomite and (b) kaolin.

Figure 7 Comparison of the specific cake resistances, α, of (a) diatomite and (b) kaolin flocs formed by EtSP (circle), chitosan (square) and PAC (triangle) as a function of flocculant dosage. The particle concentration is 20 g/L.