Separation and Purification Technology 144 (2015) 177–185

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Synergy effect of ultrasonication and salt addition on settling behaviors of activated sludge

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ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form 20 February 2015
Accepted 22 February 2015
Available online 28 February 2015

Keywords:
Settling
Ultrasonication
Salt addition
Activated sludge
Reflocculation

ABSTRACT

The batch sedimentation tests were conducted for the excess activated sludge treated by ultrasonication and addition of sodium chloride, and the settling behaviors such as the sedimentation velocity, the sludge volume, and the quality of the supernatant were examined for different values of the load power of ultrasonication, the sonication time, and the sodium chloride concentration. The ultrasonication pretreatment significantly increased the sedimentation velocity in the initial stage of sedimentation, and the effect was dramatically facilitated by the addition of sodium chloride even when the effect was unnoticeable in the pretreatment of the salt addition alone. The effect of ultrasonication was increased with increasing load power and sonication time and found to be evaluated by the specific ultrasonic energy dissipated into a liquid. The increase in the sedimentation velocity brought about by the pretreatment was caused by the increase in the floc size, and the sedimentation velocity was related to the median diameter of flocs, based on the Stokes law considering the effect of both the floc size and floc density. Moreover, the combined pretreatment markedly reduced the sludge volume, as compared to the pretreatments of ultrasonication alone and salt addition alone.

1. Introduction

The activated sludge process is extensively used in the world as the typical biological treatment of both wastewater and industrial effluents. A major issue of the operation of activated sludge systems is the removal of biological solids from the liquid phase followed by dewatering of these biosolids. Although settling is used as the initial step to increase the solids content, poor settleability of activated sludge is often problematic.

In many cases, chemical conditioning prior to solid–liquid separation is used in order to enhance the separation efficiency [1]. Flocculation of activated sludge leads to organic colloids aggregation, thereby improving the ability of sludge to settle [2]. However, the use of chemical flocculants such as salts and polyelectrolytes increases treatment costs and may also cause secondary environmental pollution. Thus, it is necessary to reduce the specific consumption of flocculants as much as possible.

Various physical and chemical pretreatments, in which sludge is disintegrated and microbial cells are destroyed, have been investigated to reduce the biosolids' volume generated from wastewater treatment plants, including ultrasonication [3–5], mechanical disintegration (mills, homogenizers, etc.) [6], thermal hydrolysis [7], ozonation [8], acidification [9], alkaline addition [10], microwave irradiation [11], and their combined treatments [12]. These pretreatments enhance sludge biodegradability prior to anaerobic digestion or recycling in aeration tank. Among them, ultrasonication is a particularly attractive method because it cannot cause secondary environmental pollution as with other mechanical disintegration. However, these pretreatments frequently deteriorate sludge settleability and filterability mainly due to the floc breakage and the release of extracellular polymeric substances (EPS) from cells [13–16].

While ultrasonication has been used for the dispersion or collapse of flocculated particles in the liquid phase, Kakii et al. [17] revealed a really challenging fact that activated sludge disrupted by ultrasonication flocculated once again. This means that the ultrasonic pretreatment appears promising also as a means to improve the solid–liquid separation efficiency of activated sludge. In fact, on the basis of the results of the sedimentation velocity, capillary suction time (CST) and specific cake resistance in filtration, Feng et al. [18,19] indicated that ultrasonication with low specific energy is effective for enhancing sludge settleability and filterability. Vaxelaire et al. [20] reported based on the microscopic observations that numerous filaments of filamentous bacteria were

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http://dx.doi.org/10.1016/j.seppur.2015.02.028
1383-5866/

Nomenclature

C_s	concentration of sodium chloride in sludge (M)
D	fractal dimension for self-similar structure (–)
d_{50}	median diameter of flocs (m)
d_f	floc diameter (m)
E	specific ultrasonic energy dissipated into sludge (J/kg)
g	acceleration of gravity (m/s^2)
H	height of interface plane between sludge and supernatant (m)
H_0	initial height of sludge (m)
H_{300}	interface height after 5 h (300 min) (m)
I	ultrasonic power dissipated into sludge (W)
M	mass of sludge sample (kg)
P	load power (W)
r	correlation coefficient (–)
SV	sludge volume defined as ratio of interface height H to initial height H_0 (–)
SV_{300}	sludge volume defined as ratio of interface height H_{300} after 5 h (300 min) to initial height H_0 (–)
TI	turbidity index defined as the ratio of the turbidity in the supernatant to the concentration of solids in sludge represented by the same unit (mg/L) as the turbidity (–)
t	net ultrasonic exposure time (s)
u_0	sedimentation velocity during hindered settling period (m/s)
θ	sedimentation time (s)
μ	viscosity of supernatant (Pa s)

cut by the ultrasonic pretreatment, leading to a better settling behavior.

Some research has been dedicated to the role of salt addition to the ultrasonicated sludge. Kakii et al. [17] reported that salt addition promoted reflocculation of ultrasonicated sludge. Yin et al. [21] found that ultrasonic pretreatment of activated sludge from petrochemical plant reduced the necessary flocculant dosage by approximately 25–50% because it decreased the specific cake resistance in filtration. Likewise, Hakata et al. [22] reported that the ultrasonic pretreatment with Al^{3+}-based coagulation improved the permeate flux in microfiltration of municipal wastewater treated by an activated sludge-lagoon process. In contrast, Feng et al. [19] demonstrated that sludge suffered from ultrasonication and cationic polymer addition provides no clear advantage over polymeric conditioning alone for improving sludge dewaterability. Dewil et al. [14] reported that the required dosage of flocculant increased proportionally with the level of ultrasonic energy to reach the same dryness as the untreated cake in vacuum filtration. Therefore, it is of particular importance to reveal whether the combined pretreatment of ultrasonication and flocculant addition is effective for the improvement of solid–liquid separation efficiency of sludge.

In the present article, the combined pretreatment of ultrasonication and salt addition is examined in order to improve the solid–liquid separation efficiency. In particular, the paper focuses on the synergy effect of ultrasonication and salt addition on settling behaviors such as the sedimentation velocity, sediment volume, and supernatant quality under various operational conditions of the ultrasonic power, sonication time, and added salt concentration using excess activated sludge produced from municipal sewage treatment works.

2. Materials and methods

2.1. Materials

The excess activated sludge mixed liquor employed in this study was sampled at the Ueda Sewage Treatment Works (Nagoya City, Japan). The solid concentration ranged from 3.6 to 4.9 g/L, the mean value being 4.3 g/L, during the course of our experimental work. The sludge was concentrated at 5.0 g/L by decantation for 20 h in the refrigerator kept at 5 °C to minimize change in its property, and used in the experiments within 4 days. The true density of solids in the activated sludge measured by a pycnometer is 1.45×10^3 kg/m^3 [23]. It is reported that the original activated sludges contain approximately 6–7 kg bound water per kg of dry solid mass [24]. The viscosities of sludge and supernatant were measured by using a capillary viscometer. The concentrations of Na^+ and Cl^- in the sludge were measured by an ion chromatography system (Dionex ICS-1100/2100, Thermo Fisher Scientific Inc., USA). The electric conductivity was measured with a conductivity meter (DS-52, Horiba Ltd., Japan). The zeta potential of particles in the sludge was determined by a particle microelectrophoresis apparatus (Model Mark II, Rank Brothers Ltd., UK). The properties of the activated sludge used in the experiments are listed in Table 1. Sodium chloride was employed as inorganic flocculants.

2.2. Experimental apparatus and technique

The ultrasonic apparatus employed was an ultrasonic homogenizer (UP-200S, Dr. Hielsher GmbH, Germany) equipped with a tip with an operating frequency of 24 kHz and a nominal load power output ranging from 50 to 200 W. After the sludge sample was warmed to room temperature (20 °C), the ultrasonic tip was immersed in the sample of 80 g to a depth of approximately 5 mm above the bottom of a 100-mL beaker. The sample was processed with the tip for different total operating times by pulsed ultrasonic irradiation in which one cycle consisted of both the operating time of 0.5 s and the downtime of 0.5 s in order to avoid the rise in temperature as far as possible. Thus, levels of sonication were varied by changing the load power and sonication time. The ultrasonicated sludge was adjusted to a variety of salt concentrations by the addition of the concentrated solution of sodium chloride. Thereafter, the sludge was conditioned by the rapid mixing at a speed of 150 rpm for 3 min using an agitator (Three-One Motor, BL 600, Shinto Scientific Co., Ltd., Japan) followed by the slow mixing at a speed of 50 rpm for 20 min to allow reflocculation to occur. This agitation condition was determined based on the results obtained for different agitation conditions.

Batch gravity sedimentation experiments were conducted using vertical Plexiglass cylinder with 2.9-cm internal diameter and 20-cm height in order to evaluate the settleability of the treated sludge. The settleability was evaluated by three criteria: the sedimentation velocity, the sludge volume, and the quality of the supernatant. Once the treated sludge of 80 g (corresponding to

Table 1
Properties of activated sludge.

	Activated sludge
pH	6.9
Viscosity (mPa s)	2.62
Na^+ (mg/L)	26
Cl^- (mg/L)	31
Electric conductivity (mS/m)	45.1
Zeta potential (mV)	−26.9