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Ultrahigh-pressure expression of activated sludge assisted with self-flocculation caused by ultrasonication

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ABSTRACT

The flocculant-free mechanical deliquoring method has been proposed for obtaining the compressed cake with an extremely low moisture content in expression of municipal excess activated sludge. The method is comprised of the mild ultrasonic pretreatment followed by ultrahigh-pressure expression. The floc breakage induced by ultrasonication greatly facilitated the removal of bound water during ultrahigh-pressure expression. Moreover, the cell disruption caused by ultrasonication induced self-flocculation of the sludge with the aid of the intracellular materials released from within the cells, preventing the souring of dewaterability. The moisture content of the compressed cake produced by expression of ultrasonicated sludge was dramatically reduced to as low as 38.0 wt% at the ultrahigh-pressure of 50 MPa, which exhibited the value much lower than that obtained for untreated sludge, due to the removal of bound water. Analysis of kinetics of ultrahigh-pressure expression for ultrasonicated and untreated sludge showed that the primary consolidation was followed by a three-stage creep phenomenon with different values of the creep constant. The primary consolidation based on the Terzaghi spring analogy accounted for the major portion of moisture removal in this method, and the effect increased with increasing pressure.

1. Introduction

The activated sludge processes have been extensively used in the world as a typical biological treatment of wastewater and industrial effluents. The ever-increasing quantities of excess sludge are a crucial problem from the viewpoint of increased transport costs, a serious shortage of the remaining landfill capacity, and more severe environmental regulations. Therefore, it is essential to reduce the volume of sludge produced as much as possible. Mechanical deliquoring of excess sludge is widely employed as an energy-saving deliquoring method compared with the succeeding thermal drying and incineration. Thus, it is considered most desirable to remove the maximum feasible amount of liquid by mechanical pressing.

Considerable research has been so far conducted on mechanical expression of excess sludge (Kawasaki et al., 1990, 1991; Kang et al., 1990a, 1990b; Matsuda et al., 1994; La Heij et al., 1996a, 1996b; Christensen and Keiding, 2007; Sakohara et al., 2007; Citeau et al., 2011; Anlauf, 2014; Christensen et al., 2015). However, in expression of highly compressible cakes, unexpectedly, elevating pressure frequently failed to sufficiently decrease the cake moisture content due to the formation of highly resistant skin layer close to the filter medium developed during filtration (Tiller and Horng, 1983; Tiller and Yeh, 1987). Moreover, it is quite

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Nomenclature

A	ratio of primary consolidation to overall consolidation
B	creep constant
C_e	modified consolidation coefficient (m^2/s)
d_s	specific surface area size of flocs (m)
e	local void ratio of cake
i	number of drainage surfaces
L	cake thickness (m)
L_1	cake thickness at $\theta_c = 0$ (m)
L_∞	cake thickness at $\theta_c = \infty$ (m)
P	load power of ultrasonic homogenizer (W)
p_e	expression pressure (Pa)
p_s	local solid compressive pressure (Pa)
R_e	final moisture content of compressed cake on mass basis (wt%)
t	net ultrasonic exposure time (s)
U_c	average consolidation ratio

Greek letters

α	local specific flow resistance of cake (m/kg)
η	creep constant (s^{-1})
μ	liquid viscosity (Pa s)
θ_c	consolidation time (s)
ρ_s	true density of solids (kg/m^3)
ω_0	total solid volume per unit cross-sectional area (m^3/m^2)

difficult to substantially reduce the moisture content of compressed cake by mechanical expression because of the existence of the liquid contained within the microorganism cells and the immobile liquid strongly associated with the floc referred to as bound water (Matsuda et al., 1992). Kawasaki et al. (1996) examined the role of bound water on the expression behaviors of excess activated sludge preconditioned by the freezing-and-thawing method. However, it remains to be clarified whether the bound water is able to be squeezed out of the cake with the use of ultrahigh pressure in expression.

In the previous work (Iritani et al., 2014a), an innovative deliquoring method conducted by ultrahigh-pressure expression assisted with reversible flocculation was proposed in order to obtain the compressed cake with an extremely low moisture content at a high rate of deliquoring. In the method, low-pressure filtration of the sludge preconditioned through the use of flocculant was followed by ultrahigh-pressure expression of the particulates re-dispersed by water permeation through the filter cake. As a result, the moisture content of the compressed cake was substantially reduced, and then the kinetics of ultrahigh-pressure expression was examined based on the model. Subsequently, the influence of the type of flocculants on ultrahigh-pressure expression behaviors was revealed by use of an inorganic flocculant, polyaluminum chloride (PACl), and an organic cationic polymer flocculant, Kurifix provided by Kurita Water Ind. (Iritani et al., 2014b). It was reported that the increase in the expression pressure decreased the ultimate cake moisture content more pronouncedly in the case of PACl compared to Kurifix. However, whatever the case may be, it would be desirable to limit the use of flocculants and it would be best if any flocculants are not used.

There exist several physical and chemical pretreatments such as ultrasonication (Yin et al., 2004; Laurent et al., 2009; Mohammadi et al., 2011), mechanical disintegration (Kopp et al., 1997), acidification (Chen et al., 2007), alkaline addition (Rajan et al., 1989), etc. to destroy microbial cells and to reduce the biosolids' volume. Although activated sludge was disrupted by ultrasonication, disrupted flocs flocculated within a relatively short time once again (Kakii et al., 1994). Eventually, the gentle ultrasonication pretreatment significantly increased the floc size, thereby resulting in the increased settling velocity (Iritani et al., 2015). Previous studies suggested that not only sludge settleability but also filterability was improved by ultrasonication with low specific energy (Feng et al., 2009a,b).

In the present article, ultrahigh-pressure expression assisted with self-flocculation of the sludge induced by cell disruption resulting from ultrasonication is examined as a promising method of flocculant-free mechanical deliquoring processes for obtaining the compressed cake with an extremely low moisture content. The moisture content of compressed cake obtained from activated sludge was measured by varying the expression pressure, the load power of ultrasonication, and the net ultrasonic exposure time, and the availability of the method is examined. In addition, the expression kinetics is analyzed by use of the modified Terzaghi model in series with the multi-stage creep model.

2. Experimental

2.1. *Materials*

The experiments were carried out employing the excess activated sludge mixed liquor sampled from the Ueda Sewage Treatment Works (Nagoya City, Japan). The sludge collected fell within the range of solid concentrations from 3 to 5 g/L, varying quite a bit depending on the date of sampling. The sludge was concentrated up to 5.0 g/L by decantation for approximately 20 h in the refrigerator stored at 5 °C to minimize change in its property and immediately used in the experiments after it was left out to reach to the room temperature (23 ± 3 °C). The true density of solids measured by a pycnometer is 1.45×10^3 kg/m^3.

2.2. *Experimental apparatus and technique*

The pretreatment of sludge was conducted using 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 40 to 200 W. The ultrasonic tip was immersed in the sludge of 80 g to a depth of approximately 5 mm above the bottom of a 100-mL beaker. The sludge was processed with the tip for different total operating times by pulsed ultrasonication in which one cycle comprised of both the operating time of 0.5 s and the down time of 0.5 s conducted to avoid the temperature rise caused by ultrasonication as far as possible (Iritani et al., 2014c, 2015). The ultrasonication levels were varied by changing the load power and sonication time. After ultrasonication, the sludge was gently stirred at a speed of 50 rpm for 20 min using an agitator (Three-One Motor BL600, Shinto Scientific Co., Ltd., Japan) with a four-bladed propeller to promote reflocculation.

The size distribution of flocs in the sludge pretreated under various conditions was measured using a laser diffraction