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Impact of dosing order of the coagulant and flocculant on sludge dewatering performance during the conditioning process

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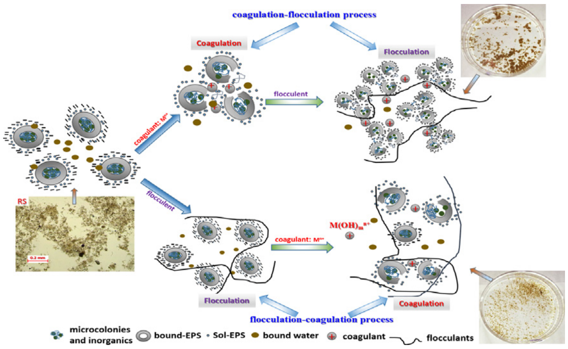
HIGHLIGHTS

- The dosing order of coagulant and flocculant is important for sludge dewatering.
- Coagulant shall be dosed prior to flocculant in sludge conditioning pretreatment.
- Coagulation-flocculation achieves better sludge dewatering performance.
- The mechanism of dewatering performance about different dosing orders is unraveled.

GRAPHICAL ABSTRACT



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ABSTRACT

The combined use of coagulant and flocculant can achieve excellent dewatering performance. In this study, we investigated the impact of dosing order of the coagulant and flocculant on sludge dewatering performance. The results showed that capillary suction time (CST) values during the coagulation-flocculation process decreased 20–25% compared to those during the flocculation-coagulation process using the same doses of additives. Moisture content of the sludge during the coagulation-flocculation process was lower. The dosing order of coagulants and flocculants during the conditioning process was clearly important for sludge dewatering, and the coagulant should be dosed before the flocculant. Furthermore, a mechanism for the different dewatering performance was proposed: larger agglomerated and destabilized colloid particles formed, and more bound water was released into the sludge bulk solution during the coagulation-flocculation process, compared with the flocculation-coagulation process, which resulted in better dewatering performance, as reflected in the CST value and moisture content of the sludge cake. These results enable a better understanding of combined conditioning with coagulants and flocculants on sludge dewatering.

Abbreviations: RS, raw sludge; CST, capillary suction time; PAC, polyaluminum chloride; PAM, cationic polyacrylamide; EPS, extracellular polymeric substance; Bound-EPS, the sum of loosely bound EPS and tightly bound EPS; Sol-EPS, soluble extracellular polymeric substance; PN, proteins; PS, polysaccharides; W_t, the total water; W_b, the bound water; ZP, zeta potential; LVE, linear viscoelastic regime; τ_{max}, the maximum shear stress.

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1. Introduction

Management of wastewater sludge is of tremendous concern to scientists and society, as it comprises 40–50% of operation costs in wastewater treatment plants (WWTPs) (Liu et al., 2016b; Subramanian et al., 2010), disposal routes are severely limited (Al-Rajab et al., 2015; Fisher et al., 2018; Ruiz-Hernando et al., 2013), and it imposes a large environment burden (Edwards et al., 2009). Sludge dewatering is necessary to reduce sludge volume and for disposal (Chen et al., 2001; Raynaud et al., 2012). However, due to high water content bound to microbial cells and sludge flocs, wastewater sludge dewatering efficiency is generally limited (Ruiz-Hernando et al., 2013). Thus, sludge must be conditioned prior to mechanical dewatering to increase dewaterability.

Current research has enhanced sludge dewatering performance using several conditioning processes, including chemical, physical, biological and hybrid conditioning processes (Guan et al., 2017; Liu et al., 2016a; Skinner et al., 2015). These preconditioning processes usually achieve good performance in three ways: improve settleability of the sludge; improve sludge filterability and improve the release of trapped (bound) water (Mowla et al., 2013). Taken together, these improvements change sludge dewaterability and rheological behavior (Feng et al., 2014b).

Coagulation or flocculation of wastewater sludge by dosing of coagulants or flocculants is often used alone or in hybrid conditioning with other processes, such as composite enzymatic and membrane biotechnologies, for full-scale sludge dewatering (Chen et al., 2015; More et al., 2012; Wang et al., 2013). However, sludge jointly conditioned with coagulants and flocculants is rarely reported, and little is known about the application of the hybrid coagulation-flocculation process for sludge dewatering. In fact, the combination of coagulation and flocculation is an efficient and simple method used worldwide for water and WWTPs (Bhatia et al., 2007; Wang et al., 2011; Zouboulis et al., 2009). The hybrid coagulation-flocculation process is popular because of the effective removal of turbidity, microorganisms, and organic matter (Rossini et al., 1999).

We have previously studied the feasibility of sludge jointly conditioned with a coagulant and flocculant and found that it achieved excellent sludge filterability, higher efficiency of water content reduction and avoided adverse effects caused by overdosing to humans and the ecosystem compared with sludge treated individually with a coagulant or flocculant. Nevertheless, this process is poorly understood and much work is needed to optimize the process for further applications, especially for conditioning, such as the stoichiometric relationship between the coagulant and flocculant and the dosing order of the conditioners. It is commonly accepted that the coagulant should be dosed prior to the flocculant during a combined coagulation/flocculation process in water and wastewater treatment (Haydar and Aziz, 2009; Teh et al., 2016). However, it remains unclear whether the dosing order of additives used for the water and wastewater treatment processes will work for the sludge conditioning process (Zheng et al., 2011).

Therefore, to fill the knowledge gap of sludge with combined used of coagulant and flocculant and optimize the combined conditioning process for further applications, this study focused on exploring the effect of dosing order of the coagulant and flocculant on wastewater sludge conditioning (sludge dewatering). We herein investigated sludge dewatering performance in a no-conditioned pretreatment, the coagulation-flocculation process, and the flocculation-coagulation process based on the dose of additives and the dosing order. The mechanisms for differences in dewatering performance between them were also explored.

2. Materials and methods

2.1. Sludge samples and chemicals

Raw sludge (RS) samples were obtained from the discharge of the secondary sedimentation tank in WangXiaoYing Municipal Wastewater Treatment Plant in Hefei, China, which has a capacity of 300,000 m^3/d and uses the oxidation ditch process. The initial solid concentration was 8.35 g/L, which was gently concentrated to 17.60 g/L by setting. The characteristics of the RS are shown in Table 1. The sludge samples were stored at 4 °C until future use (<1 week). Commercial grade polyaluminum chloride (PAC) and cationic polyacrylamide (PAM, molecular weight $\overline{Mn} = 8.0 \times 10^6–15 \times 10^6$) were obtained from Chengdu Aikeda Chemical Technology Co., Ltd. (Chengdu, China). $Fe_2(SO_4)_3$ was purchased from Shanghai Chemical Reagent Company (Shanghai, China) and was of analytical reagent grade.

2.2. Sludge conditioning and dewatering

PAC and $Fe_2(SO_4)_3$ were used as the inorganic coagulants, whereas PAM was the flocculant. Conditioners were added to a 50 mL portion of sludge for each conditioning test. The correlation between the conditioner dosage and capillary suction time (CST) is shown in Fig. S1 to characterize filterability of the sludge samples. To analyze the effect of the combined coagulation and flocculation process for sludge dewatering, two different doses of the inorganic coagulant and the flocculants listed above were selected randomly. Then, a set of tests with different formulations and combinations was conducted. As shown in Table 2, three conditioning modes for sludge were used: no conditioning; the coagulation-flocculation process, the sludge was first rapidly mixed with coagulant, followed by gentle mixing with the flocculant; sludge for the flocculation-coagulation process was gently mixed with the flocculant first, followed by rapidly mixing with the coagulant. Then, these sludge samples were analyzed for dewatering performance and related physicochemical properties.

Dewatering performance was estimated with the CST value and the moisture content of the dewatered cake. The CST value was measured with a CST instrument (Model 319; Trion, London, UK) and each test was performed six times at 25 °C. The sludge samples to assess moisture content were dewatered by the centrifugation method described in Jin et al. (2004) at 500*g* and 1132*g* for 10 min, respectively, and by Buchner funnel filtration (Lo et al., 2001) at 0.05 MPa for different durations (2, 5, and 10 min), all the tests were performed in triplicate.

2.3. Physicochemical characterization of the sludge

2.3.1. Extracellular polymeric substance (EPS) extraction and analysis

Microbial EPS in the sludge was obtained with a modified heat extraction method (Li and Yang, 2007). Briefly, the sludge samples were centrifuged at 5000*g* for 5 min, and the supernatant was collected as soluble EPS. Then, the bound EPSs in the sludge, including loosely bound EPS and tightly bound EPS, were extracted using the method described by Li and Yang (2007). The main components (proteins and polysaccharides) and their concentrations within soluble EPS and bound EPS were determined based on the method described by Li et al. (2016). Polysaccharide (PS) content was measured with the anthrone-based method, and protein (PN) concentrations were determined by the modified Lowry method (Frolund et al., 1996). However, it was still difficult to select a good quantitative and qualitative method to analyze the main EPS compounds (Le et al., 2016; Le and Stuckey, 2016).Therefore, the

Table 1
Characteristics of the raw activated sludge.

pH	6.89 ± 0.10
Total solids (g/L)	17.60 ± 0.10
Volatile suspended solids (VSS, g/g TS)	0.67 ± 0.01
CST (s)	48.9 ± 0.5
Sludge viscosity (mPa·s)	12.23 ± 0.12
Floc size d(50) (μm)	42.38
Zeta potential (mV)	−14.64 ± 0.83