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ORIGINAL PAPER

Principal component analysis on sewage sludge characteristics and its implication to dewatering performance with Fe^{2+}/persulfate-skeleton builder conditioning

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Abstract Sludge samples taken from different sources and times may have different characteristics that could affect dewatering performance. In this study, 20 sludge samples from five wastewater treatment plants and different seasons in 1 year were characterized. Pearson correlation analysis indicated that solid content (SC), total suspended solid (TSS), polysaccharides and proteins contents had positive correlations with the capillary suction time (CST), whereas volatile suspended–solid/total suspended solid (VSS/TSS) exhibited negative correlations with CST. Moreover, no correlations between CST and specific resistance to filtration were found among these different sludge samples. The principal component analysis confirmed that only two group variables could represent most of the sludge characteristic parameters. The first set of variables represents the particulate nature of the biotic factors (SC, VSS/TSS, SCOD, TSS, polysaccharides and proteins), and the second set is the pH. CST could not be a reasonable indicator of dewaterability in sludge deep dewatering by $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum composite conditioning. Furthermore, the results of diaphragm filter press dewatering showed that initial SC and VSS/TSS were the most dominant sludge characteristics affecting the solid content of dewatered cake ($R_p = 0.610$, $p = 0.016$; $R_p = -0.838$, $p = 0.000$, respectively) with $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum composite conditioning. Results from this study suggest that dewatering performance is predictable by sludge characteristics parameters for $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum conditioning.

Keywords Sewage sludge · Sludge characteristics · Sludge dewatering · Persulfate · Principal component analysis

Abbreviations

CST	Capillary suction time
DE	Dewatering efficiency
DS	Dry solid
EPS	Extracellular polymeric substances
LZ	Longwangzui WWTP
PCA	Principal component analysis
PN	Proteins
PS	Polysaccharides
SC	Solid content
SCOD	Soluble chemical oxygen demand
SL	Sand Lake WWTP
S-P	$Fe^{2+}/S_2O_8^{2-}$-phosphogypsum
SPS	Sodium persulfate
SRF	Specific resistance to filtration
ST	Sanjintan WWTP
TL	Tangxun Lake WWTP
TSS	Total suspended solids
VSS	Volatile suspended solids
WWTP	Waste water treatment plant
ZK	Zhuankou WWTP

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Introduction

Sewage sludge is a by-product of wastewater treatment plants (WWTPs). Its handling/disposal represents ~50 % of total wastewater treatment operating costs, and poor dewatering efficiency is the bottleneck of all sludge disposal systems (García Becerra et al. 2010; He et al. 2015). Due to high compressibility and gel-like water retention capacity of the sludge that could be hardly removed water by simple mechanical compression, chemical conditioning is commonly incorporated firstly to improve its dewaterability ahead of mechanical compression (Mowla et al. 2013).

Selection of chemical conditioners is greatly dependent on sludge properties, such as sludge chemical compositions [extracellular polymeric substances (Jin et al. 2003; Mikkelsen and Keiding 2002)], physical properties [fractal dimensions (Vahedi and Gorczyca 2011), porosity (Thapa et al. 2009), osmotic pressure (Jin et al. 2003)] and rheological parameters [e.g., yield stress (Marinetti et al. 2010) and shear sensitivity (Dentel and Dursun 2009)]. Over the past decade, some sludge characteristics have been found to correlate with the sludge dewaterability. More recently, Skinner et al. (2015) proposed a model of filtration using sludge properties as inputs for quantification and comparison of dewaterability as the permeability and compressibility of sludge. In addition, moisture distribution ["free," "interstitial," "surface" or "bound" water (Lee 1996; Vesilind 1994)] is commonly accepted as the crucial factor influencing in dewatering performance. However, the water distribution concept alone is not sufficient to elucidate the dewaterability because some characterization methods of water distribution are not able to provide quantitative results and also relatively difficult to implement (Deng et al. 2011; Vaxelaire and Cezac 2004). Because the sludge properties vary with both production time and locations, it is insufficient to explain why difficulties to predict dewatering performance use water distribution. Therefore, it is essential for in-depth understanding on the correlations between sludge dewaterability and the main physicochemical characteristics of sludge conditioning and deep dewatering.

In recent years, Fenton and Fenton-like processes, as one group of advanced oxidation processes, have been widely investigated and proved to be an efficient chemical conditioning for sludge (He et al. 2015; Lu et al. 2003; Mo et al. 2015; Zhou et al. 2015). We have previously utilized $Fe^{2+}/S_2O_8^{2-}$ and/or phosphogypsum as sludge conditioner to efficiently breakdown sludge flocs, and further from skeleton structures for significantly improving the dewaterability, 45.7 wt% cake moisture content and 91.7 % dewatering efficiency had been successfully achieved (Shi et al. 2015a, b). Nevertheless, how sludge properties affecting dewaterability need to be fully characterized in order to achieve deep dewatering, especially sludge characteristics that vary with different sources.

The objective of this research was to provide a comprehensive study on the effects of dewaterability concerning various characteristics of different sludge sources and production times on the basis of $Fe^{2+}/S_2O_8^{2-}$-skeleton builder conditioning. The sludge characteristics including solid content (SC), pH, total suspended solid/volatile suspended solid (TSS/VSS), TSS, soluble chemical oxygen demand (SCOD), polysaccharides and proteins were analyzed with Pearson correlation and principal component analysis (PCA). Principal factors associated with sludge characteristics and dewatering performance in the diaphragm filter press dewatering process were also proposed. This study proposed the dominant sludge characteristics that were able to evaluate the potential sludge dewaterability with $Fe^{2+}/S_2O_8^{2-}$-skeleton builder conditioning.

Materials and methods

Sample collection and preparation

Sludge samples were collected from five WWTPs in Wuhan, China, during a 1-year period, in April (named as I thereafter), August (named as II thereafter), November (named as III thereafter) and December (named as IV thereafter) in 2012–2013, as shown in Table S1. These five WWTPs, including Longwangzui (LZ), Sand Lake (SL), Sanjintan (ST), Tangxun Lake (TL) and Zhuankou (ZK), were chosen based on their geographic locations and the types of sewage treatment processes. The sample from LZ was mixed sludge with thickening process, while the samples from another four WWTPs were excess waste activated sludge without thickening process. All samples were stored at 4 °C, and all the tests of each batch were completed within 3 days.

Physicochemical analysis

Solid content (SC), pH, total suspended solid/volatile suspended solid (TSS/VSS) and soluble chemical oxygen demand (SCOD) were measured according to CJ/T 221-2005 (China standard for municipal sludge analysis).

Proteins (PN) and polysaccharides (PS) are two major constituents of EPS. The supernatant was filtered using a 0.45-μm pore size membrane filter (hydrophilic polyethersulfone) for the determination of PN and PS. PN was analyzed by the modified Lowry method, using bovine serum albumin as the standard (Frølund et al. 1996).

PS was determined by the Anthrone method, using glucose as the standard (DuBois et al. 1956).

The SRF was calculated using the following formula (Eq. 1).

$$\mathrm{SRF} = \frac{2PA^2b}{\mu w} \quad (1)$$

where A is the area of the filter cake (m^2), P is the filtration pressure (N/m^2), b is the slope of the plot of time over filtrate volume against filtrate volume (s/m), b is the slope determined from the t/V versus V plot, (V is the volume of filtrate, m^3; and t is the filtration time, s, V as the X axis, t/V as the Y axis) (s/m^6). μ is the viscosity of filtrate (Ns/m^2), and w is the sludge solids concentration (kg/m^3).

The CST was measured using a 304 M CST instrument (Triton, UK). Slurry is poured into the 10-mm-diameter tube resting on a piece of filter paper. The filtrate is extracted by capillary suction, and a cake is formed at the bottom of the tube. By measuring the distance of the filtrate that is required to travel along the paper as a function of time, the cake resistance can be determined.

$Fe^{2+}/S_2O_8^{2-}$-phosphogypsum composite conditioner

Fe^{2+}-activated sodium persulfate (SPS) combined with pretreated phosphogypsum (referred as S-P composite conditioner) greatly enhanced sludge dewaterability (Shi et al. 2015a). The S-P conditioner including 100 mg SPS/g DS (dry solid), 23.5 mg Fe^{2+}/g DS and 300 mg pretreated–treated phosphogypsum/g DS. The Fe^{2+} solutions (40 wt%) were prepared from $FeSO_4 \cdot 7H_2O$ and distilled water. Raw phosphogypsum was collected from a phosphate fertilizer manufacturer in Guangxi, China. Hemihydrate ($CaSO_4 \cdot 0.5H_2O$) and a small amount of quartz were the main mineral phases in the pretreated phosphogypsum. It was pretreated at 150 °C for 2 h and then sieved using a 0.08 mm in size before used as the skeleton builder.

Diaphragm filter pressing test

Dewatering tests were performed using a laboratory-scale diaphragm filter press with six diaphragm plates (250 mm × 250 mm plates, 10 mm depression). The schematic is shown in Fig. 1. The S-P composite conditioning was conducted as follows: First, SPS was added at a dose of 100 mg/g dry solid (DS) to a known amount of sludge in the conditioning tank and stirred at 300 rpm for 10 min. Afterward, Fe^{2+} was sequentially fed at 23.5 mg/g DS and stirred at 100 rpm for 15 min. Finally, 300 mg thermal-treated phosphogypsum/g DS was added and kept stirring for 5 min at 100 rpm to complete the conditioning process. CST and SRF of the conditioned sludge were tested to evaluate the filterability. Dewatering tests were conducted using the following procedure: The conditioned sludge was pumped into a sealed storage tank, in which the internal pressure was controlled by air pressure to feed the sludge to the diaphragm filter press. Then, the pressure was gradually increased to 0.8 MPa until the discharge rate decreased, and the filtrate was collected and weighed. Last, all diaphragm plates were injected with compressed air at 1.2 MPa for about 15 min to squeeze the diaphragm plates for additional dewatering. After the pressure was released, the solid cakes inside each chamber were removed from the filter cloth and weighed. The solid content of the dewatered cake was determined after being dried at 105 °C for 24 h, and the dewatering efficiency (DE) was calculated according to Eq. 2.

$$\mathrm{DE}(\%) = \frac{M_{\text{filtrate}} - M_{\text{conditioners}}}{M_{\text{cs}}} \times 100 \quad (2)$$

where M_{filtrate} is the total mass of the filtrate (kg); $M_{\text{conditioners}}$ is the water mass in the conditioners (kg); and M_{cs} is the total mass of water in the conditioned sludge before dewatering (kg).

Statistical analysis

Statistical analysis using univariate linear correlation was performed to evaluate the dominant factors. The Pearson's correlation coefficient (Rp) was used to evaluate linear correlations between two parameters. The Rp is always between −1 and +1, where −1 denotes a perfect negative correlation, +1 presents a perfect positive correlation and 0 indicates the absence of a relationship. Correlations were considered statistically significant at a 95 % confidence interval ($p < 0.05$).

Principal components analysis (PCA) was conducted to determine the relationship among the sludge characteristic parameters (SC, pH, TSS/VSS, SCOD, PN, PS). This analytical method can extract the important information from a number of possibly correlated variables and represent them as a set of new uncorrelated and fewer variables, called principal components. It has been successfully applied to wastewater applications for monitoring and diagnostics of wastewater treatment processes (Tomita et al. 2002). Because the variables (SC, pH, TSS/VSS, SCOD, PN, PS) had different variances and units of measurements in this study, all data were normalized and scaled to equal unit variance (mean value of 0 and standard deviation of 1) prior to PCA. The components of the PCA were rotated by the varimax rotation. With this approach, the number of variables is reduced to a few axes (principal components) that represent more variance than randomly regressed variables. The statistical analysis above was all processed using the SPSS software (SPSS Inc., Chicago, USA).

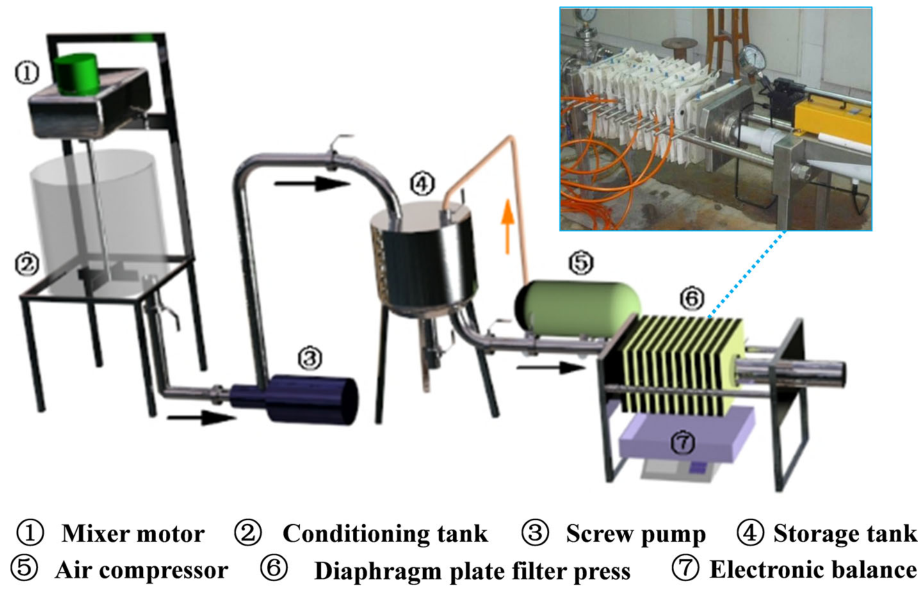

Fig. 1 Experimental setup for diaphragm filter dewatering in the laboratory scale

Results and discussion

Sludge characteristic parameters

Variations in sludge characteristics parameters

A comprehensive comparison among the sludge characteristics from different WWTPs in four consecutive quarters is shown in Fig. 2. It distinctly indicated that samples from LZ and SL had higher solid content values (2.1–8.3 wt%), whereas others exhibited lower solid content values, especially those from TL and ZK (0.6–1.7 wt%) (Fig. 2a). In spite of the differences in wastewater treatment processes and the sludge types, TSS and solid content had a similar tendency (Fig. 2d). The pHs had insignificant variations, from 6.4 to 7.0, in all samples (Fig. 2b). In addition, it is clear that VSS/TSS values are narrowly distributed in LZ, SL and ST WWTPs, when compared to SCOD values that had a greater dispersion (Fig. 2c, e). Note that the VSS/TSS values in winter are higher than those of other seasons. Besides the variation in the biological treatment process and sludge storage duration, sediment was brought into WWTPs because of the deficient pipeline may also contribute to these differences.

The variations of PS and PN contents are similar to that of solid content (Fig. 2f, g). Most notably, there is no good correlation between the CST and SRF (Fig. 2h, i), which are in conflict with the common sense that a longer CST is along with a higher SRF. The CST values of the samples with lower solid content values were essentially similar. However, SRF was affected by several factors compared with solid content. Indeed, the CST tests provide a more accurate indication of filterability when the solid content values exceed 5 wt% as suggested by Lee and Hsu (1994). Therefore, CST as a sludge dewaterability indicator becomes less reasonable for the excess activated sludge of extremely higher water content of >99 wt% without thickening treatment, such as the raw sludge samples from TL and ZK with lower solid content.

Correlations between sludge characteristic parameters

To facilitate statistical analysis, pearson's correlation coefficients (R_p) were calculated by statistically pairing the values of sludge properties. The results are summarized in Table 1.

Results of statistical analyses indicate that there are no good correlations between pH and the other characteristic parameters. The positive correlations between SC and TSS, SCOD, PS, PN ($R_p = 0.966$, $p = 0.000$; $R_p = 0.700$, $p = 0.001$; $R_p = 0.718$, $p = 0.001$; $R_p = 0.835$, $p = 0.000$, respectively) and a negative correlation between SC and VSS/TSS ($R_p = -0.819$, $p = 0.000$) were found. This suggests that the sewage treatment processes influence sludge composition, as well as SC.

For dewaterability, the CST was found to be positively correlated with the initial SC, TSS, PS and PN ($R_p = 0.738$, $p = 0.000$; $R_p = 0.689$, $p = 0.002$; $R_p = 0.511$, $p = 0.030$; $R_p = 0.559$, $p = 0.016$, respectively) and negatively correlated with initial VSS/TSS ($R_p = -0.576$, $p = 0.012$). The SRF was negatively correlated with the initial SC and TSS ($R_p = -0.476$, $p = 0.046$; $R_p = -0.559$, $p = 0.016$, respectively) and not correlated with the initial VSS/TSS, PS and PN.

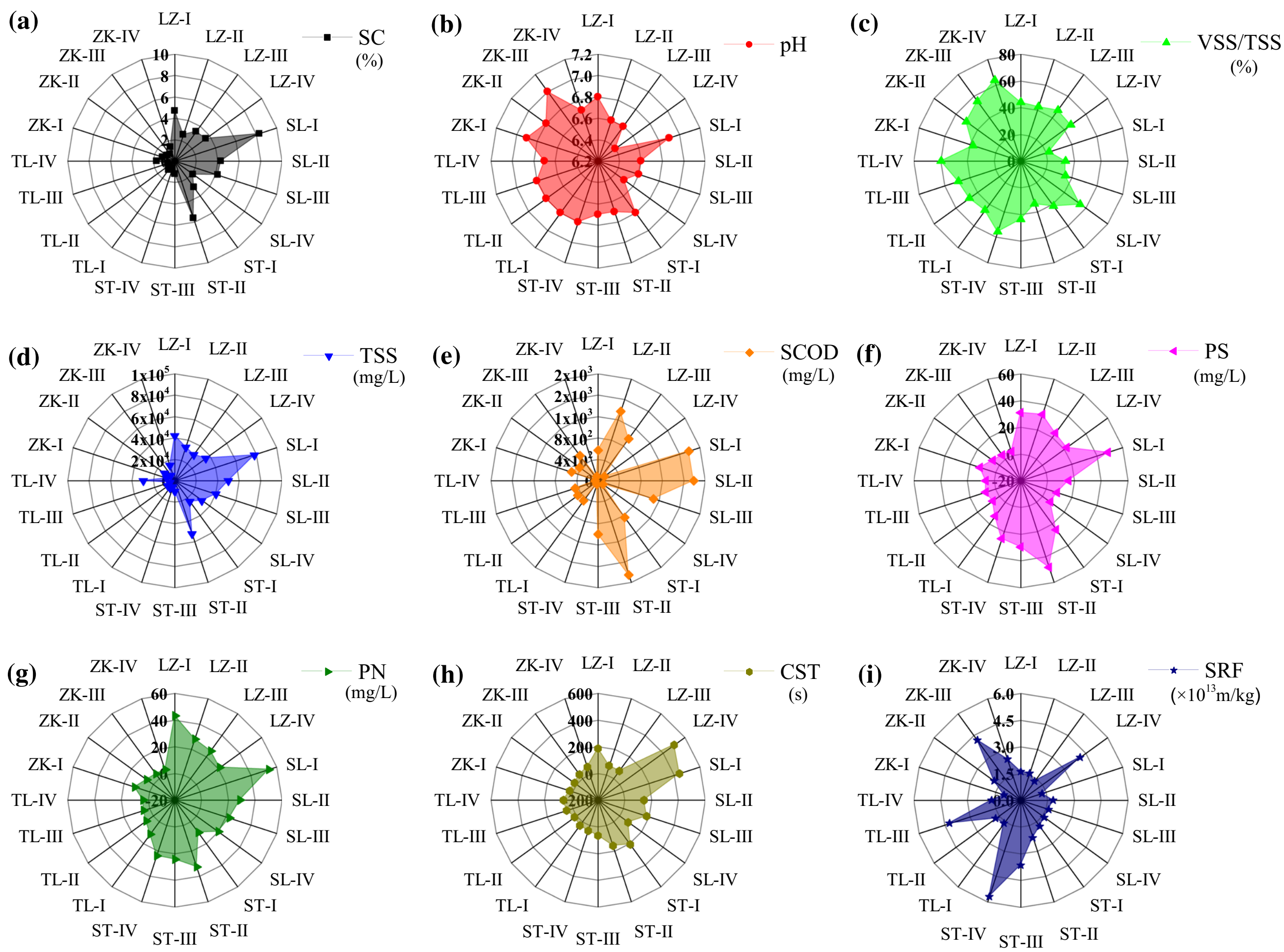

Fig. 2 Radar charts comparing the 20 sludge samples collected from five WWTPs (LZ, SL, ST, TL and ZK) in four quarters (I, II, III and IV) with regard to their basic sludge characteristics: **a** SC, **b** pH, **c** VSS/TSS, **d** TSS, **e** SCOD, **f** PS, **g** PN, **h** CST and **i** SRF

Although CST and SRF are two common parameters for estimating the filterability of sludge and are essential to determine the optimal conditioner doses, it was found that CST was not linearly correlated with SRF in this study. There are three plausible explanations for this result. First, CST value usually only correlate well with SRF for a specific suspended solid content, but not for biological sludge containing organic matter, such as flocs (Scholz 2005). Second, CST measurement is highly sensitive to properties such as SC and TSS, while SRF was found to be insensitive to some properties, such as biological activity, particles compressibility and temperature (Sawalha and Scholz 2010). The variation of the characteristics among different plants and times results in the inconsistent trend. Third, a more plausible explanation is that the interrelationships appeared to be multivariate and nondeterministic, depending on filterability, TSS and temperature (Sawalha and Scholz 2010). Consequently, identification of the primary factors that relate to dewatering performance becomes necessary.

Principal component analysis

Statistical method PCA could effectively reduce the multidimensional space into fewer components, while keeping the variability of the data set. PCA is utilized to group samples according to the sludge characteristics. In this study, the first principal component (PC1) was responsible for 66.49 % of the total variance in the data sets (Supplementary material Table S2), and the second principal component (PC2) was responsible for another 16.90 %; thus, those two PCs accounted for 83.39 % of the total variability.

The influence of each measured variable is given by its loading according to its score, which allowed a decision on the importance of the variables with regard to the

Table 1 Pearson correlation analysis of the characteristics parameters of various raw sludge samples

	SC	pH	VSS/TSS	TSS	SCOD	PS	PN	CST	SRF
SC									
*R*p	1								
Sig. (two-tailed)									
pH									
*R*p	−0.105	1							
Sig. (two-tailed)	0.678								
VSS/TSS									
*R*p	−0.819**	0.003	1						
Sig. (two-tailed)	0.000	0.990							
TSS									
*R*p	0.966**	−0.221	−0.757**	1					
Sig. (two-tailed)	0.000	0.378	0.000						
SCOD									
*R*p	0.700**	0.050	−0.876**	0.668**	1				
Sig. (two-tailed)	0.001	0.843	0.000	0.002					
PS									
*R*p	0.718**	0.020	−0.686**	0.631**	0.652**	1			
Sig. (two-tailed)	0.001	0.938	0.002	0.005	0.003				
PN									
*R*p	0.835**	−0.099	−0.738**	0.796**	0.627**	0.827**	1		
Sig. (two-tailed)	0.000	0.695	0.000	0.000	0.005	0.000			
CST									
*R*p	0.738**	−0.262	−0.576*	0.689**	0.270	0.511*	0.559*	1	
Sig. (two-tailed)	0.000	0.293	0.012	0.002	0.278	0.030	0.016		
SRF									
*R*p	−0.476*	0.156	0.362	−0.559*	−0.396	−0.102	−0.256	−0.074	1
Sig. (two-tailed)	0.046	0.537	0.140	0.016	0.103	0.686	0.305	0.771	

* Correlation is significant at the 0.05 level (two-tailed)

** Correlation is significant at the 0.01 level (two-tailed)

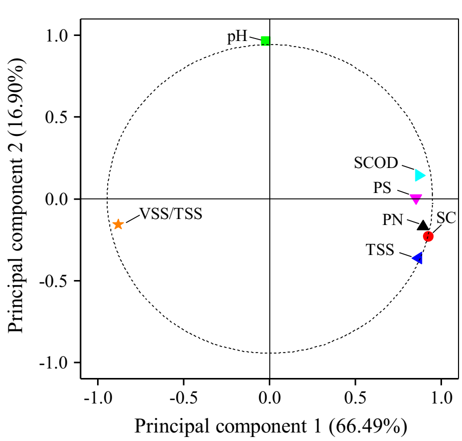

Fig. 3 Scatter plots of the first two principal component vectors for seven parameters of sludge property (principal component 1 vs. principal component 2)

differences observed among the parameters. Figure 3 shows that all the initial variables could be well explained by the first two PCs since all points were found very close to the unit circle. All the seven parameters are classified into two groups. SC, SCOD, TSS, PN, PS and VSS/TSS were situated in the boundary of the graph with higher scores in PC1 and could be interpreted as "biotic factor." The variable with a higher influence on PC2 is pH, which affected the adsorption and ionization equilibrium of the dispersed sludge particles. In general, it is considered that variables near each other are positively correlated, while those on the opposite sides of the origin are negatively correlated in the loading plots. SC, SCOD, TSS, PN and PS were plotted in similar positions, whereas VSS/TSS was plotted on opposite sides of the origin. Therefore, VSS/TSS was found to be negatively correlated with SC, and SC was positively correlated with SCOD, TSS, PN and PS.

Considering the sludge liquid/solid phase, the primary properties of the liquid phase which influence sludge suspension property are pH and soluble organic content (e.g., PN and PS). The primary properties of the solid phase which influence sludge suspension property are the SC and flocculent nature of the solid. Therefore, the SC and VSS/TSS are considered as the most important two parameters in influencing sludge dewaterability.

Correlation between sludge dewatering performance and the characteristics parameters

Dewatering performance

The dewatering performance from the diaphragm filter press tests is illustrated in Fig. 4. Each parameter is represented as a special pattern in a radar chart using responses of various types of sludge. The pH, CST and VSS/TSS values of raw sludge and conditioned sludge clearly showed different patterns (Fig. 4a–c), and those values of conditioned sludge were decreased from 6.4–7.0, 15.4–502.4 s and 22.3–63.5 wt% to 4.5–5.8, 11.6–111.9 s and 21.9–61.9 wt%, respectively. Different initial SC results in a large difference in water volume at the same amount of dry solid and therefore a large variation in pH at a fixed S-P dosage for conditioning when using “mg/g dry solid” as the dosage unit of conditioners.

In spite of the fact that CST value was directly affected by sludge solid concentration, CST reduction correlated strongly with the initial SC. Less than 55 % of the CST reduction took place when solid content ranged from 0.6 to 2.1 wt%, yet the 65–85 % of CST reduction took place with solid content in the range of 2.6–8.3 wt%. The value of VSS/TSS of the dewatered cake was slightly lower than the conditioned sludge. Dewatering efficiency (DE) was generally as high as 80 %, and the SC values of the dewatered cake were higher than 40.0 wt% when the initial SC was above 3.0 wt% (Fig. 4d). DE and SC of the dewatered cake in summer were generally higher than those of other seasons for a given WWTP. The reason for this was probably due to the higher VSS/TSS content and lower environmental temperature in winter that could affect the $Fe^{2+}/S_2O_8^{2-}$ reaction during sludge conditioning.

Correlation of dewatering performance parameters

The results of the Pearson’s correlation of the major determining factors and dewatering performance are summarized in Table 2. The VSS/TSS of the dewatered cake was found to be positively correlated with the initial VSS/TSS ($R_p = 0.899$, $p = 0.000$), while that was negatively correlated with the initial SC ($R_p = -0.610$, $p = 0.016$). However, the SC of the dewatered cake was positively correlated with the initial SC ($R_p = 0.610$, $p = 0.016$) and negatively correlated with the initial VSS/TSS ($R_p = -0.862$, $p = 0.000$). Additionally, there was no good negative correlation between CST or SRF of conditioned sludge and SC of dewatered cake. However, SRF of conditioned sludge was found to be negatively correlated

Fig. 4 Radar chart patterns for 20 sludge samples collected from five WWTPs (LZ, SL, ST, TL and ZK) in four quarters (I, II, III and IV) with different parameters in S-P composite conditioning: **a** pH, **b** CST, **c** VSS/TSS, **d** solid content (SC) of dewatered cake and dewatering efficiency (DE)

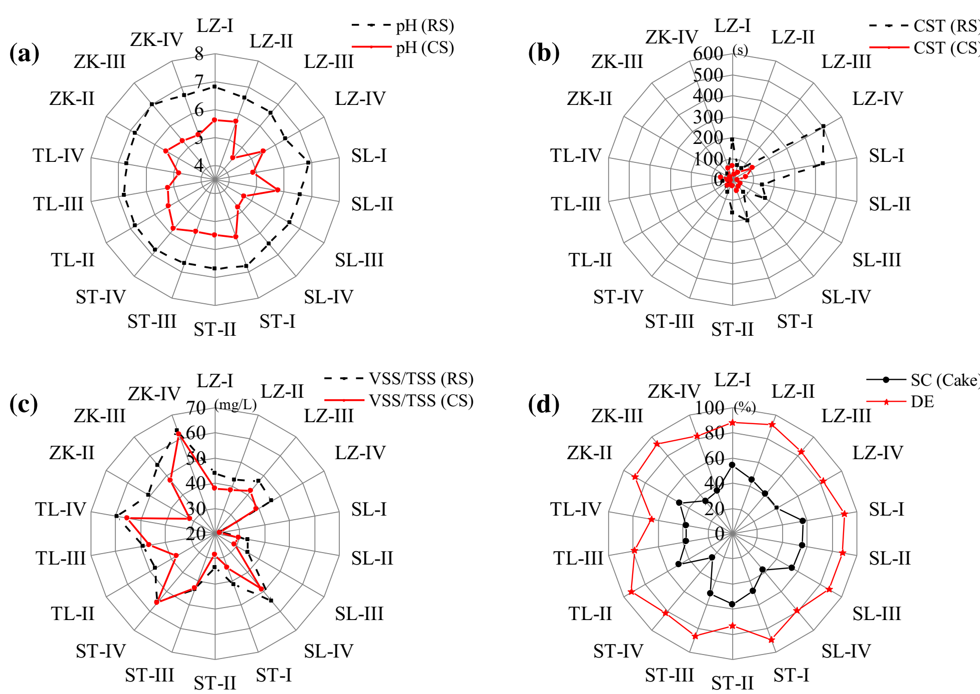

Table 2 Pearson correlation analysis of sludge characteristics and dewatering performance indicators

	CST (RS)	SRF (RS)	SC (RS)	VSS/TSS (RS)	CST (CS)	SRF (CS)	pH (filtrate)	VSS/TSS (cake)	SC (cake)	DE
CST (RS)										
*R*p	1									
Sig. (two-tailed)										
SRF (RS)										
*R*p	0.145	1								
Sig. (two-tailed)	0.606									
SC (RS)										
*R*p	0.574*	−0.396	1							
Sig. (two-tailed)	0.025	0.144								
VSS/TSS (RS)										
*R*p	−0.346	0.252	−0.731**	1						
Sig. (two-tailed)	0.206	0.364	0.002							
CST (CS)										
*R*p	0.818**	0.157	0.314	0.161	1					
Sig. (two-tailed)	0.000	0.576	0.255	0.567						
SRF (CS)										
*R*p	−0.091	0.112	−0.304	0.426	0.269	1				
Sig. (two-tailed)	0.746	0.692	0.271	0.113	0.332					
pH (Filtrate)										
*R*p	−0.020	0.410	−0.218	0.013	−0.159	−0.116	1			
Sig. (two-tailed)	0.944	0.129	0.435	0.964	0.571	0.681				
VSS/TSS (Cake)										
*R*p	−0.298	0.384	−0.610*	0.899**	0.234	0.566*	0.028	1		
Sig. (two-tailed)	0.280	0.157	0.016	0.000	0.401	0.028	0.920			
SC (Cake)										
*R*p	0.188	−0.568*	0.610*	−0.838**	−0.224	−0.265	−0.084	−0.862**	1	
Sig. (two-tailed)	0.502	0.027	0.016	0.000	0.422	0.341	0.766	0.000		
DE										
*R*p	−0.089	−0.003	−0.164	−0.263	−0.405	−0.541*	0.148	−0.367	0.210	1
Sig. (two-tailed)	0.752	0.993	0.559	0.344	0.135	0.037	0.599	0.178	0.453	

RS raw sludge, *CS* conditioned sludge

* Correlation is significant at the 0.05 level (two-tailed)

** Correlation is significant at the 0.01 level (two-tailed)

with DE ($R_p = -0.541$, $p = 0.037$). This result demonstrated that CST could not be a reasonable indicator for predicting SC of dewatered cake in deep dewatering by $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum composite conditioning, while SRF may serve as a useful means for assessing the DE.

Compared with other factors, SC and VSS/TSS are the most important factors for dewatering performance, and the relationship between the SC of dewatered cake and the initial SC and VSS/TSS is shown in Fig. 5.

Figure 5 shows a high level of confidence as to the achievable SC of the dewatered cake compared to the initial SC and VSS/TSS. The relationship between the parameters is obvious, which has a strong relationship between the SC of the dewatered cake and the initial SC, as well as the initial VSS/TSS. It is consistent with Skinner's (2015) findings which showed that VSS/TSS parameter was a strong indicator of sewage sludge dewatering performance. The amount of VSS/TSS, on the one hand, directly affects the flocs composition and compressibility; on the other hand, in terms of EPS type and content account, VSS/TSS reflects a dominance of the volatile components in sludge during $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum conditioning (Shi et al. 2015b). Moreover, higher initial SC also means less water, which would therefore result in an increase in the activation reaction rate due to

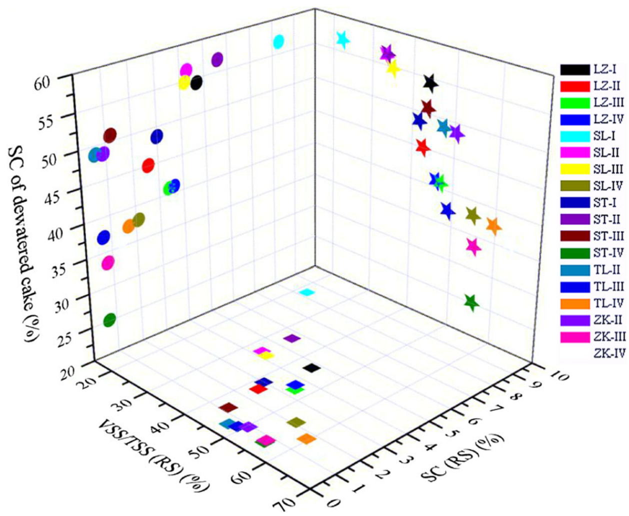

Fig. 5 Relationship among the solid content (SC) of dewatered cake, the initial SC and VSS/TSS from the diaphragm filter press tests

the conditioning system containing high concentrations of the reactants at a fixed S-P dosage.

Although a high SC of the dewatered cake is the comprehensive result of multiple factors such as SC, VSS/TSS and dewatering process, high SC and low VSS/TSS were beneficial for obtain a high SC of the dewatered cake with $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum composite conditioning. Overall, the VSS/TSS and SC are the two dominating properties for the $Fe^{2+}/S_2O_8^{2-}$-phosphogypsum conditioning. Hence, it is easier to obtain a high solid content dewatered cake when its initial VSS/TSS was lower than 50.0 wt% and initial SC was higher than 3.0 wt%. It should be noted that there is no agreed standard unit for dosages of various chemical conditioners, and different units were used for sludge conditioning, such as "mg/L" (Lu et al. 2003; Wang et al. 2009), "mg/g dry solid" (He et al. 2015; Liu et al. 2012; Mo et al. 2015), "*v*/*v*" (Zhang et al. 2015) and "mmol/g VSS" (Zhen et al. 2012). In view of the importance of SC and VSS/TSS in sludge conditioning, an integrated dosage optimization method which based on the SC and VSS/TSS should be further considered for sludge conditioning.

Conclusion

Twenty sludge samples from five wastewater treatment plants over four consecutive quarters were characterized for their physicochemical properties. This paper developed the relationships between sludge characteristics parameters and dewatering performances and provided valuable information for S-P composite conditioning.

Pearson correlation analyses indicated that positive correlations existed among the initial SC and TSS, PS and PN, while negative correlations exhibited between initial SC and VSS/TSS. This suggests that the sewage treatment processes influence sludge composition. Meanwhile, the initial SC values were correlated positively with CST and negatively with SRF. The variation of the characteristics among different plants and times results in the inconsistent trend. CST could not be a reasonable indicator of dewaterability for the excess activated sludge of extremely higher water content in deep dewatering by S-P composite conditioning.

Initial VSS/TSS and SC are the two dominant properties with regard to the S-P composite conditioning. A high initial SC (>3 wt%) and low initial VSS/TSS (<50 wt%) is conducive to obtain a high solid content (>40 wt%) of the dewatered cake in the diaphragm filter press dewatering.

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