Adaptability of Organic Matter and Solid Content to Fe²⁺/Persulfate and Skeleton Builder Conditioner for Waste Activated Sludge Dewatering

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1 **Adaptability of organic matter and solid content to**
2 **Fe²⁺/persulfate and skeleton builder conditioner for waste**
3 **activated sludge dewatering**

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Abstract

Sludge conditioning is important for improved dewatering, with the sludge characteristics impacting the effect of conditioning. A composite conditioner, Fe^{2+} activated sodium persulfate ($\text{Fe}^{2+}/\text{SPS}$) combined with phosphogypsum (PG), was used to examine its impact on sludges with different organic content or different solid content. Response surface optimization analysis shows that when the best conditioning is achieved, the reduction of the specific resistance to filtration is not sensitive to organic matter content, but the dewatering performance of the sludge is greatly affected by the solid content. The oxidation role of $\text{Fe}^{2+}/\text{SPS}$ and the skeleton builder role of PG, together, affect the conditioning, with oxidation playing a major role in conditioning, especially for greater organic matter content. The organic content also affects the effectiveness of the skeleton builder more than the solid content. Changes in PG significantly impacts the optimal molar ratio and dosage of $\text{Fe}^{2+}/\text{SPS}$. Sludge with greater solid content requires greater $\text{Fe}^{2+}/\text{SPS}$ dosage to provide stronger oxidation to destroy flocs. The composite conditioning decreases the content of extracellular polymeric substances and proteins/polysaccharides with the decrease in protein content being significantly greater than that of polysaccharides, these decreases improve the sludge dewaterability.

Keywords: Sewage sludge; Conditioning; Persulfate oxidation; Skeleton builder; Dewaterability; Extracellular polymeric substances

35 **Abbreviations list**

CS	Conditioned sludge
DS	Dry solid
EPS	Extracellular polymeric substances
LB-EPS	Loosely bound-EPS
OMC	Organic content
PG	Phosphogypsum
PN	Protein
PS	Polysaccharides
RS	Raw sludge
RSM	Response surface methodology
SC	Solid content
SF	$\text{Fe}^{2+}/\text{S}_2\text{O}_8^{2-}$
SPS	Sodium persulfate
SRF	Specific resistance to filtration
TB-EPS	Tightly bound-EPS
WC	Water content

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1 Introduction

With the growth of urban populations and the continuous improvement of municipal service facilities and sewage treatment technology, the amount of sewage sludge produced by urban sewage treatment plants is increasing. The effectiveness of its treatment has become an important issue. Treatment and disposal costs account for about 40–50 % of the total operating costs of sewage treatment plants (Xiao et al. 2017). Sewage treatment plants often use conditioning before mechanical dewatering for improved sludge dewatering performance (Cao et al. 2021, Wu et al. 2020).

Commonly used sludge conditioning methods are physical conditioning (Carrasco and Gao 2019, Liu et al. 2019, Mobaraki et al. 2018, Ramachandra and Devatha 2020), chemical conditioning (Ge et al. 2019, Hu et al. 2020, Wang et al. 2018, Wang et al. 2019, Yu et al. 2019) and biological conditioning (Chen et al. 2015, Huo et al. 2014, Liu et al. 2016a). Advanced oxidation technology has become a subject of research interest in the area of chemical conditioning due to the advantages of low secondary pollution and fast reaction times (Bian et al. 2021, Chen et al. 2021, Chen et al. 2020, Kim et al. 2016, Ni et al. 2019, Wei et al. 2020, Zhang et al. 2020b). Our previous research used Fe^{2+} activated sodium persulfate (SPS) combined with phosphogypsum (PG) for sludge conditioning and found both oxidation and skeleton building effects (Shi et al. 2015). Fe^{2+} /SPS oxidation promoted the rapid generation of column-shaped dihydrated phases of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ from the hemihydrate phases of $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$. Newly generated column-shaped dihydrate phases acted as skeleton builders, thus improving sludge dewatering. There are many studies focus on the chemical conditioner's selection (Badalians Gholikandi et al. 2018, Xiao et al. 2020, Zhang et al. 2019), optimization (He et al. 2020, He et al. 2015, Rumky et al. 2018, Yu et al. 2017) and combination (Guo and Zhou 2020, Guo et al. 2020, Wu et al. 2019a, Wu et al. 2019b), but it is uncertain whether differences in sludge characteristics causes uncertainty in the choice and effectiveness of conditioners.

The characteristics of sludge and the interactions of sludge agents are closely related to the performance of agents (Zhang et al. 2020a). High water content and high

organic matter content are the main factors limiting dewatering of the sludge. Currently, the dosage of sludge conditioning is generally based on sludge volume (per liter) (Lu et al. 2003), sludge dry solids (per g of DS) (Guo et al. 2019a, Liang et al. 2015, Shi et al. 2015) or sludge organic matter content (per g volatile suspended-solid) (Zhen et al. 2012). However, due to the differences in properties of sludge, such as moisture content and organic matter, the same dosage will result in highly variable conditioning effects. Our previous research showed that among the many characteristic indicators of sludge, initial solid content and volatile suspended-solid/total suspended solid were sludge characteristics that most affect the solid content of the dewatered cake with $\text{Fe}^{2+}/\text{S}_2\text{O}_8^{2-}$ -phosphogypsum composite ($\text{Fe}^{2+}/\text{SPS-PG}$) conditioning (Shi et al. 2016). Yu et al. (2017) used sludge dry solid and volatile solid content to optimize the dosage of different organic sludges by Fenton oxidation. The results showed that optimization of oxidation reagent based on volatile solid content is more plausible than that of based on dry solid content for different sewage sludge with different organic matter contents.

Although different method or evaluation have been investigated in sludge conditioning, careful analysis is required to determine how the variability of solid content and volatile suspended-solid/total suspended solid affects optimal dose, oxidative effects and skeleton structure. Therefore, the main aim of this study is to investigate the impact of different solid content and organic content on $\text{Fe}^{2+}/\text{SPS-PG}$ composite conditioning of different sludge types. The specific tasks were to: (i) optimize the dosage $\text{Fe}^{2+}/\text{SPS-PG}$ and determine the dewaterability of each sludge with different solid content and organic content in laboratory optimization experiments. (ii) identify the effectiveness between $\text{Fe}^{2+}/\text{SPS}$ oxidation and PG skeleton builder, so as to determine the use of compound conditioning strategies according to the determined optimal conditions.

2 Materials and methods

2.1 Materials

A waste sewage sludge sample was taken from the Shahu wastewater treatment

plant, Wuhan, China. Large debris such as stones, branches and leaves were removed using a 2 mm sieve. To obtain a good reproducibility, all tests were completed within 3 days and the sludge was stored at 4 °C. The sludge was naturally settled to remove supernatant or was supplemented with a quantitative amount of distilled water to obtain sludge samples with the same organic content but different solid content (denoted as SC). Similarly, if the water content of the sampled sludge samples is kept the same, sludge samples with the same solid content but different organic content (denoted as OMC) can be obtained. The basic characteristics of the sludge are shown in Table 1.

Sodium persulfate (SPS) ($\text{Na}_2\text{S}_2\text{O}_8$, purity >99.9 wt%) and ferrous sulfate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, purity >99.9 wt%) were analytical reagents (Sinopharm company, Shanghai, China). The dissolved Fe^{2+} solutions were prepared from $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ in ultrapure water. Thermally-pretreated PG, used as a skeleton builder, was sieved using a mesh size of 0.08 mm after heating at 150 °C for 2 h (Shi et al. 2015).

2.2 Conditioning procedure

Sludge conditioning experiments were conducted using a programmable jar test apparatus. Sludge (300 mL) was placed in a 500 mL beaker. SPS was added (mg per g of DS) and stirred at 300 rpm for 15 min. Fe^{2+} solution was fed into the slurry and stirred at 150 rpm for 15 min (1/3 of the total amount was added every 5 min). Finally, PG was added and with stirring for 5 min at 150 rpm to complete the conditioning process. Each experiment was carried out three times. A blank control experiment, using raw sludge (RS), was carried out without conditioner.

2.3 Specific resistance to filtration

After conditioning, 100 mL of the conditioned sludge was poured into a 9 cm standard Buchner funnel fitted with pre-wetted qualitative filter paper. A constant vacuum pressure of 80 kPa was then applied until no further filtrate was obtained. Both the filtrate volume and the sludge cake weight were recorded. The moisture content of the filter cake was then determined. Whereafter, the specific resistance to filterability (SRF) was calculated according to Eq. 1.

$$SRF = 2PA^2b/\mu\omega \quad (\text{Eq. 1})$$

P is the filtration pressure (Pa); A is the area of the filter cake (m^2); b (s/m^6) 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)); μ is the viscosity of the filtrate ($\text{Pa}\cdot\text{s}$); ω is the sludge solids concentration (kg/m^3).

The reduction of SRF is expressed by Eq. 2.

$$\text{Reduction of SRF} = \left((SRF_r - SRF_c) / SRF_r \right) \times 100\% \quad (\text{Eq. 2})$$

SRF_r is the specific resistance to filterability of RS (m/kg) and SRF_c is average value of the specific resistance to filterability of the conditioned sludge (CS) (m/kg).

The DS content was measured by evaporation at 105°C for 24 h. Organic matter content was determined using muffle furnace by ignition at 600°C for 3 h. Sludge moisture content, pH and other indicators were determined by the methods defined in "CJ/T221-2005 Sludge Inspection Method for Municipal Sewage Treatment Plant" (China standard for municipal sludge analysis).

2.4 Response surface methodology

A central composite design based on response surface methodology (RSM) was employed to optimize dosages of SPS, Fe^{2+} and PG. Ranges and levels of these three constituents were defined based on the preliminary tests shown in Table 2. The SRF and water content of the filter cakes were considered as the responses. Eighteen runs were required for one set of experiments for each sludge type. The experimental schemes and results are shown in Table S1. For optimization, we firstly analyzed each response to establish the appropriate model using Design Expert 8 software, then searched for a combination of factor levels that simultaneously satisfy the requirements. The goal of the numerical optimization was to obtain the dosage of Fe^{2+} and SPS, setting the target value of the constraint PG dosage and SRF within the range of experimental design.

2.5 Net sludge solids yield

The net sludge solids yield (Y_N) refers to the solid content of the sludge filtered per

unit time and unit filtration area. Generally, when large amounts of skeleton builders are added to the sludge, the solid concentration of the sludge changes, so the filterability is expressed as the theoretical yield Y (Eq. 3). In order to express Y_N , a correction factor f is introduced as per Eq. 4 (Benítez et al. 1994).

$$Y = \left(2P\omega/\mu tSRF\right)^{1/2} \quad (\text{Eq. 3})$$

$$Y_N = f \left(2P\omega/\mu tSRF\right)^{1/2} \quad (\text{Eq. 4})$$

The dose of skeleton builder added (SOL) is defined by Eq. 5.

$$SOL = \left(\frac{\text{mass of skeleton builder added}}{\text{mass of dry solids in the original sludge}}\right) \times 100\% \quad (\text{Eq. 5})$$

Then, f can be expressed as Eq. 6:

$$f = \frac{1}{\left(1 + (SOL/100\%)\right)} \quad (\text{Eq. 6})$$

Finally, the effect of the skeleton builder on the filterability of sludge, η_{SOL} , is defined by Eq. 7.

$$\eta_{SOL} = \left(\frac{((Y_N)_{opt} - (Y_N)_0)}{(Y_N)_{opt}}\right) \times 100\% \quad (\text{Eq. 7})$$

$(Y_N)_{opt}$ is the net yield when conditioning with optimal dosage of Fe^{2+} /SPS-PG; $(Y_N)_0$ is the net yield when conditioning only with Fe^{2+} /SPS.

2.6 Extracellular polymeric substances (EPS) extraction and analysis

A modified heat extraction method was used to extract the slime (S-EPS), the loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) (Li & Yang 2007). Sludge (50 mL) was centrifuged at 4,000 g for 5 min. The supernatant was collected for analysis of S-EPS. The sludge pellet in the tube was then diluted to its original volume of 50 mL with 0.05 wt% sodium chloride (NaCl) solution pre-heated to 70 °C. The sludge sample was then immediately sheared using a vortex mixer for 1 min, followed by centrifugation at 4,000 g for 10 min. The supernatant was then collected for analysis of the LB-EPS. The residual sludge pellet was re-suspended in 0.05 wt% NaCl solution to its original volume of 50 mL and heated to 60 °C in a water bath for 30 min, then centrifuged for 15 min, and the supernatant was collected for analysis of

the TB-EPS. The supernatant of the extracted samples was passed through a 0.45 µm membrane filter to remove suspended particles before analysis. The protein (PN) contents were analyzed using the modified Lowry method with bovine serum albumin solution as the standard (Frølund et al. 1996). The polysaccharide (PS) content was analysed using the anthrone method with glucose as the standard (DuBois et al. 1956, Yu et al. 2017).

3 Results and discussion

3.1 RSM optimization analysis

A quadric surface model was established for the SRF value, water content (WC), and organic matter content of the filter cakes of the different sludges. Variance analysis and regression coefficient significance tests were performed, as shown in Table S2. It can be seen that the models (Table S2) are all significant and have good fit, indicating that the models are appropriate, and predictive analysis can be performed. For example, the quadratic regression model equation for the SRFs of the sludges were established to be:

$$Y_{S1} = 0.11 - 0.058A - 0.18B - 0.071C - 0.03AB + (2.87 \times 10^{-3}AC) + 0.044BC + 0.049A^2 + 0.19B^2 + (7.99 \times 10^{-3}C^2) \quad R^2 = 0.998$$

$$Y_{S2} = 0.06 - (4.63 \times 10^{-3}A) - (7.86 \times 10^{-3}B) - 0.043C + (4.23 \times 10^{-3}AB) + (5.88 \times 10^{-3}AC) + (7.99 \times 10^{-3}BC) + 0.012A^2 + 0.012B^2 + (9.32 \times 10^{-3}C^2) \quad R^2 = 0.998$$

$$Y_{S3} = 0.15 - 0.14A - 0.11B - 0.082C - 0.052AB - (6.30 \times 10^{-3}AC) + 0.030BC + 0.092A^2 + 0.15B^2 + 0.014C^2 \quad R^2 = 0.995$$

$$Y_{S4} = 0.14 - 0.12A - 0.087B - 0.095C + (9.12 \times 10^{-4}AB) + 0.024AC + 0.021BC \\ + 0.11A^2 + 0.11B^2 \\ + (2.54 \times 10^{-3}C^2) \\ = 0.996 \quad R^2$$

$$Y_{S5} \\ = 0.1 - (9.97 \times 10^{-3}A) + (3.06 \times 10^{-3}B) - 0.06C - 0.026AB - (7.87 \times 10^{-3}AC) \\ + (5.68 \times 10^{-3}BC) + 0.014A^2 + (3.81 \times 10^{-3}B^2) \\ + 0.02C^2 \\ = 0.990 \quad R^2$$

$$Y_{S6} \\ = 0.067 + (1.70 \times 10^{-3}A) - 0.023B - 0.057C - (5.75 \times 10^{-3}AB) - 0.015AC \\ + 0.036BC + 0.018A^2 + (6.69 \times 10^{-3}B^2) \\ + 0.034C^2 \\ = 0.995$$

$$Y_{S7} \\ = 0.11 - 0.018A - 0.086B - 0.075C - (1.05 \times 10^{-3}AB) - 0.016AC + 0.041BC \\ + 0.012A^2 + 0.091B^2 \\ - 0.026C^2 \\ = 0.997$$

$$Y_{S8} \\ = 0.14 - 0.013A - 0.14B - 0.048C - (2.91 \times 10^{-4}AB) + (9.10 \times 10^{-5}AC) \\ + 0.02BC + 0.021A^2 + 0.13B^2 \\ - 0.036C^2 \\ = 0.997$$

Where: A , B, C stand for SPS, Fe^{2+} and PG, Respectively.

3.2 Influence of organic matter content on sludge dewaterability

To analyze the difference in the dewatering performance due to OMC, the lowest SRF value was set as the goal, and the dosage of various OMC agents was optimized by RSM. It can be seen from Table 3 that when the best conditioning is achieved (that is, the lowest SRF value), the dosage is variable, but the change of the reduction of SRF is stable above 98 %. This shows that Fe^{2+} /SPS-PG has a stable conditioning effect on different OMC. In addition, it was found that with the increase of organic matter content, the $(Y_N)_{opt}$ value increased and then decreased, with the trend for SRF reversed. When

the organic content is 39.3 %, (Y_N)_{opt} is 1.919, and the sludge filtration performance is the best.

From the perspective of the effectiveness of the skeleton builder, although the η_{SOL} value is variable (0.078–0.187), all sludges reached a stable maximum reduction of SRF. This indicates that the oxidation effect of activated persulfate and the skeleton effect of PG can work together to achieve the best conditioning effect.

The nature of the raw sludge determines the SRF of the conditioned sludge. It can be seen from Fig. 1 that with increasing organic matter content, the SRF values of the raw sludge and conditioned sludge decrease and then increase, but the final reduction of SRF is basically unchanged (Table 3). For the OMC with the same moisture content, on the one hand, adding the same agent does not change the sludge moisture content of the conditioning system (e.g., S_1 – S_4 , S_6). The Fe^{2+} :SPS molar ratio for optimal conditioning of the different sludges is similar and the reaction produces a similar number of $SO_4^{\bullet-}$, so $SO_4^{\bullet-}$ "effective reaction concentration" is equivalent (that is, the relative concentration or dose that causes the equivalent oxidation reaction), free radicals destroy the extracellular polymeric substance within the sludge and release intracellular water (Zhen et al. 2012), resulting in the same reduction of SRF of sludge with organic content of 34.6–43.8 %. This shows that the Fe^{2+} /SPS-PG conditioning system has a stable conditioning effect on different OMC and is suitable for sludge conditioning with low and high organic content.

When the sludge organic matter is the same, the SRF value decreases with the increasing PG dosage (Fig. 2). When the PG dosage exceeds 100 mg/g DS, the change trend of the reduction of SRF of different OMC is stable, which is consistent with the conclusion that Fe^{2+} /SPS-PG conditioning has a wide application range for OMC. However, with increasing organic matter content, the SRF value decreases and then increases. The trend of SRF values of the conditioned sludge is affected by the nature of raw sludge. A higher organic content (organic content >39.3 %) usually contains greater EPS content, which is not conducive to improving the separation of water from the filter cake (Wang et al. 2020). When the molar ratio of Fe^{2+} :SPS is 0.5, the SRF

value for the different OMC is the greatest, and the reduction of SRF varies significantly. This may be because the Fe^{2+} dosage is insufficient and the SPS cannot be activated sufficiently to produce sufficient free radicals, resulting in the sub-optimal destruction of organic components in the sludge.

When the sludge organic matter is the same, the Fe^{2+} :SPS molar ratio is basically unchanged with increasing PG dosage, the η_{SOL} value gradually decreases, and the Y_{N} value gradually increases (Fig. 3). This indicates that the oxidation of $\text{S}_2\text{O}_8^{2-}$ plays a major role in the conditioning system, and the role of PG as a skeleton builder is masked by the oxidation of sulfate radicals. The same PG dosage results in variable changes in η_{SOL} and Y_{N} values for different OMC, indicating that PG has different effects on the conditioning of different OMC. With PG dosage of 100 mg/g DS, the η_{SOL} value is larger than at greater dosage, and the η_{SOL} value of the sludge with organic matter of 34.6 % is the largest, indicating that the low dosage of PG has the greater impact on sludge with low organic matter content. On PG dosage greater than 100 mg/g DS, the η_{SOL} value for different OMC does not change appreciably, which shows that advanced oxidation plays a major role in the conditioning system, and the excessive addition of PG leads to a little impact on the sludge filtration performance.

3.3 Influence of solid content on sludge dewaterability

The RSM optimization experiment results of four different solids contents (SC, S5-S8) conditioning show that the dosages of agents corresponding to the minimum SRF value of different SCs are the same, but the SRF value is different (Table 4). This shows that the SC affects the sludge dewatering performance significantly.

As the SC increases, the $(Y_{\text{N}})_{\text{opt}}$ value increases and then decreases, with the trend of the SRF value being the reverse. These two indicators show that for the SC of 3.8 wt%, the best conditioning is achieved with the maximum η_{SOL} value of 0.147, indicating that for different SC, the 300 mg/g DS PG dosage has the greatest impact on the filterability of the sludge.

As the solid content increases, the SRF value first decreases and then increases, while the trend of the reduction of SRF is the reverse (Fig. 4). For sludge with high SC, a portion of the PG forms a skeleton providing water filtration channels, but a greater dosage of PG causes too much skeleton to be built. The viscosity of the system increases, and the sludge filtration performance deteriorates.

The optimum dosage ratio of Fe^{2+} and SPS for different SCs with different PG doses varies, as does the extent of conditioning (Fig. 5). This shows that the dewatering performance of sludge is closely related to SC and reasonable dosage ratio. When the Fe^{2+} :SPS molar ratio is 0.5, the SRF value for different SC is relatively large, and the SRF value of sludge with low SC is the largest. Low SC means more water content, resulting in the agent concentration being "diluted", thereby reducing the effectiveness of conditioning. If the Fe^{2+} :SPS molar ratio is too small, so that the Fe^{2+} dosage is insufficient, the effective decomposition of SPS is limited as is the production of $\text{SO}_4^{\bullet-}$, weakening the intensity of oxidation of the sludges (Luo et al. 2018, Ni et al. 2019). With PG dosage of 100 mg/g DS and the Fe^{2+} :SPS molar ratio is greater than 0.5, the SRF value gradually decreases with SC decreases, and the oxidation efficiency of $\text{SO}_4^{\bullet-}$ on sludge increases, thereby improving the filtration performance.

To analyse the dynamic relationship between dosage of PG and Fe^{2+} :SPS mol ratio with different solid contents. The dosage of Fe^{2+} and SPS was obtained by numerical optimization, setting the target value of the constraint PG dose and SRF. It can be found that when the SC of sludge is the same, with increasing PG dosage, the Fe^{2+} :SPS molar ratio shows a downward trend. However, for different SC, it shows different trends. When PG is 100 mg/g DS, the Fe^{2+} :SPS molar ratio gradually increases with the increase of SC; when PG is 300 mg/g DS, the Fe^{2+} :SPS molar ratio is basically not affected by the SC. This is because when the dosage of PG is small, the sludge with high SC needs a greater Fe^{2+} :SPS molar ratio to generate more sulfate radicals oxidation to destroy the sludge flocs, and release the bound water to improve the sludge dewatering performance (Zhen et al. 2019). With the PG dosage of 300 mg/g DS, the hydration and skeleton builder effects of PG gradually become obvious during the conditioning process, which balances out the oxidation effect, so the effect of the molar

ratio of Fe^{2+} :SPS becomes stable.

When the SC of the sludge is the same, with increasing PG dosage, the η_{SOL} value gradually decreases and the Y_{N} value gradually increases. With PG dosage of 100 mg/g DS, with increasing SC, the η_{SOL} value gradually decreases, but the Y_{N} value remains basically unchanged. This also shows that low dosage of PG has little effect on the conditioning of the sludge with high SC, and oxidation is dominant. Furthermore, it can be seen that the η_{SOL} values of the variable OMCs is greater than the η_{SOL} values of the variable SCs from (Figs. 3 and 6). This shows that for different OMCs, changes in PG dosage are more likely to cause changes in conditioning effects.

3.4 Changes of EPS characteristic after sludge conditioning

The EPS content in the sludge has an important influence on the sludge dewatering performance. The EPS content and composition change are shown in Fig. 7 after conditioning the different SC sludges using the Fe^{2+} :SPS molar ratio of 0.9 and PG dosage of 300 mg/g DS.

The total amount of EPS and the amount of each form (layer) of EPS are significantly smaller in the conditioned sludge than in the RS indicating that $\text{SO}_4^{\bullet-}$ damages the EPS. The TB-EPS content decreases the most. The oxidative degradation of macromolecular organics into small molecular organics has been found previously to reduce the EPS content and improve filtration performance (Guo et al. 2019b, Liu et al. 2016b, Sari Erkan and Onkal Engin 2020). Further analysis found that the reduction of PN content was significantly greater than that of PS, and the PN/PS of CS was significantly smaller than for RS. This is due to the different chain structure of PN and PS. $\text{SO}_4^{\bullet-}$ preferentially destroys and degrades hydrophobic organics such as PN in EPS, thus causing the reduction of PN to be significantly greater than that of PS, and PN/PS to decrease, as is consistent with the results of Zhen et al. (2019).

With increasing SC, the reduction of PN and PS content increases and then decreases. PN/PS shows the opposite trend. When the SC is 3.8 wt%, the reduction of the EPS and TB-EPS contents are 85.18 % and 89.09 %, respectively. The reduction of

the PN and PS contents are 90.03 % and 70.05 %, respectively and the PN/PS is the smallest at 1.04. This conclusion is the same as Section 3.3, when the sludge SC is 3.8 wt% and the PG dosage is 300 mg/g DS, the SRF reach the minimum value. It is shown that the reduction of EPS, TB-EPS and PN/PS is beneficial to the filtration performance of sludge, (Yu et al. 2021) found that retaining the hydrophobic surface EPS is beneficial to sludge dewaterability. The possible reason for this inconsistency with this result is the PG addition effectively forms a stable and rigid structure and promotes the formation of porous dehydration channels.

4 Conclusions

Fe^{2+} /SPS-PG conditioning was found to be applicable to both high and low organic matter sludges. Organic matter content was found to have little influence on the dewatering of the sludge. The solid content had a significant influence on the effectiveness of the sludge conditioning. Sludge dewaterability was closely related to the solid content and reasonable dosage ratio of the chemical reagent with a trade-off relationship between the dosage of PG and the molar ratio of Fe^{2+} :SPS. Change of PG dosage significantly affected the optimum molar ratio of Fe^{2+} :SPS. Sludge with greater solid content required larger Fe^{2+} :SPS to generate more $\text{SO}_4^{\bullet-}$ to damage the sludge EPS. After chemical conditioning, the content of each type (layer) of EPS of different SC, loosely bound, tightly bound or slime, decreased compared with the RS. The reduction of PN content was significantly higher than that of PS, PN was more easily degraded and oxidized. The decrease of PN/PS changed the hydrophilic/hydrophobic characteristics of EPS and significantly improved sludge dewaterability.

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Consent to Participate

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Consent to Publish

Not applicable

Authors Contributions

Xiaoran Li: Data curation, Writing - original draft preparation, Writing - review & editing.

Yafei Shi: Supervision.

Xi Zhou: Investigation.

Lu Wang: Validation.

Huiqin Zhang: Resources.

Kewu Pi: Conceptualization.

Andrea R. Gerson: Writing - review & editing.

Defu Liu: Project administration.

All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1
Influence of different organic matter content on the optimal response value SRF. RS raw sludge; CS conditioned sludge.

Figure 2

Influence of different organic matter content on sludge dewaterability. PG dosages (mg/g DS) of (a) 100, (b) 200 and (c) 300. (bars refer to SRF and lines refer to reduction of SRF).

Figure 3

The dynamic relationship between dosage of PG (mg/g DS) and $\text{Fe}^{2+}:\text{SPS}$ mol ratio with different organic matter contents.

Figure 4

Influence of different solid contents on the optimal response value SRF. RS $\square$ raw sludge; CS $\square$ conditioned sludge.

Figure 5

Influence of different solid content on the sludge dewaterability for PG doses (mg/g DS) of (a) 100, (b) 200 and (c) 300.

Figure 6

The dynamic relationship between dosage of PG and Fe²⁺:SPS mol ratio with different solid contents.

Figure 7

The changes of EPS content (mg/g DS) before and after sludge conditioning. RS = raw sludge; CS = conditioned sludge. TB = tightly bound; LB = loosely bound; S = slime. PN = protein; PS = polysaccharide.

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