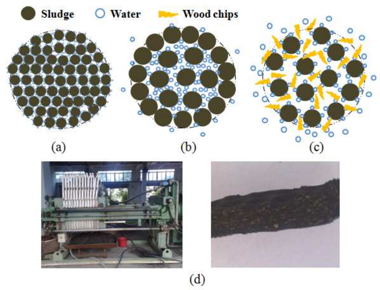
RSC Advances

Graphical Abstract



Schematic mechanism of the effect of adding wood chips on sludge dewatering: (a) sludge without conditioning; (b) sludge with chemical conditioning; (c) sludge with chemical and physical conditioning; and (d) a physical image of a dewatered sludge cake with wood chip conditioning

Effectiveness and mechanisms of the combined use of wood chips and chemical coagulation to condition the sewage sludge was investigated.

Revised manuscript for ***RSC Advances*** as ***Communication***
Date: 2014-05-22

Effect of adding wood chips on sewage sludge dewatering in a pilot-scale plate-and-frame filter press process

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ABSTRACT:

The addition of wood chips combined with cationic polyacrylamide (CPAM) and polymeric aluminium chlorides (PACl) to sewage sludge were investigated to enhance the dewatering in a pilot-scale plate-and-frame filter press. The results indicated that the chemical coagulation significantly affected the moisture content (MC) and specific resistance to filtration (SRF) of the sludge in bench-scale tests. The lowest MC and SRF were 87.93% and 0.31×10^{11} m kg^{-1}, respectively, for CPAM and PACl dosages of 0.04% and 4%, respectively. However, when the wood chips were combined with chemical coagulation conditioning, minimal improvements were noted in the sludge dewatering ability compared to the coagulation conditioning alone. Moreover, the addition of wood chips was effective for the subsequent plate-and-frame filter press dewatering process. The wood chips acted as skeleton builders during this high-pressure dewatering (1.0 MPa). The lowest MC was 50.3% when the dosages of CPAM, PACl and wood chips were 0.05%, 4% and 100%, respectively. Furthermore, a wood chip dosage of 100% increased the high heat value (HV) and low HV of the products by 20% and 150%, respectively, compared to the control. Several subsequent disposal options, such as landfilling, incineration and bio-composting the products, are proposed as a result of the low MC and high low HV of the products.

Keywords: sludge dewatering; physical and chemical conditioning; wood chips; sludge disposal

1. Introduction

Wastewater treatment processes produce a large amount of sludge that commonly contains over 90% water. The volume of the sludge must be reduced before disposal to decrease the costs of transportation and handling[1]. However, sewage sludge is typically poorly dewatered during mechanical dewatering processes because of the existence of colloidal materials and extracellular polymeric substances (EPSs). These materials strongly bind water molecules to the solid surfaces or capture water inside the cells or flocs[2, 3].

The sludge dewatering ability can be enhanced by sludge conditioning[4]. Chemical conditioning prior to the mechanical dewatering process is necessary to improve the sludge dewatering ability. Chemical conditioning can force the sludge particles to flocculate into larger particles or flocs[5]. Chemical conditioning is advantageous because it increases the liquid extraction, solids concentration, throughput and energy efficiency of the downstream process equipment[6]. However, chemical conditioning has difficulties improving the sludge cake solids content at higher pressures, such as the pressures experienced in belt filter presses and plate-frame pressure filtration processes[7, 8]. The sludge is highly compressible during the dewatering compression stage. The high compressibility of sludge causes sludge cake particles to be deformed at high pressures following the cake growth. This deformation closes cake voids and reduces the sludge filterability[9]. Therefore, physical conditioners, which are often known as skeleton builders or filter aids based on their role in sludge dewatering, are commonly used to reduce the compressibility of the sludge and improve the mechanical strength and the permeability of the sludge during compression. These physical conditioners can form a permeable and more rigid lattice structure to maintain porosity at high pressures during the mechanical dewatering[1, 10].

Based on the literature review, the most used physical conditioners are lime, coal fly ash, gypsum and cement kiln dust[11-15]. These conditioners would significantly reduce the organic content and high heat value (HV) of the dewatered sludge. Additionally, the addition of these conditioners would decrease the options available for the sludge disposal, such as incineration and bio-composting. Unlike inorganic physical conditioners, organic conditioners have two advantages, namely, their lower ash content and higher HV. Lin et al.[16] proposed to select wood chips and wheat dregs as physical conditioners to increase the organic contents and high HVs of the sludge. However, the dosage of the wood chips was as high as 300%, which significantly increased the sludge solids yield. Therefore, this product might not be suitable for landfilling. Additionally, the moisture content (MC) of the dewatered sludge was only 74-90% at a pressure of 80 kPa during the conditioning process. High MCs result in reduced low HVs. Thus, in their study, the dewatered sludge did not self-sustain burning during incineration.

To decrease the dosage of organic physical conditioners and the MC value of the dewatered sludge simultaneously, we analysed the effect of adding wood chips on the sludge dewatering performance in a pilot-scale plate-and-frame filter press with high pressure (1.0 MPa). Furthermore, the mechanism of the effects of the addition of conditioned wood chips was investigated. Finally, the disposal options for the products were analysed.

2. Materials and methods

2.1 Materials

2.1.1 Sludge

Gravity concentrated sewage sludge was gathered from a municipal wastewater treatment plant (WWTP) in Guangdong Province, China. The MC of the raw sludge was approximately 98%; the VSS contents ranged from 50% to 52%; and the pH values were between 6.8 and 7.5.

2.1.2 Conditioning reagents

Polymeric aluminium chloride (PACl) and cationic polyacrylamide (CPAM) were selected as the chemical conditioners. The raw wood chips were used as the physical conditioners. The wood chips were obtained from the Foshan City Forestry Bureau, Guangdong Province, China. The MC of the wood chips was 10-12% and the particle sizes ranged from 10 to 60 orders.

2.2 Bench-scale sludge dewatering conditioning tests

To determine the optimal dosage of the reagents, bench-scale sludge conditioning studies were performed in six paddle stirrers (Phipps & Bird). The raw sludge and required dosages of the reagents were added to the jars and rapidly mixed at 200 rpm for 1 min. This rapid mixing process was followed by a tapered flocculation at 60 rpm for 10 min. Then, the conditioned sludge was removed to perform the dewatering analyses.

2.3 Pilot-scale plate-and-frame filter press sludge dewatering process

As seen in Fig. 1, the pilot-scale dewatering process was divided into two parts. The first part was the sludge conditioning process, which was performed in a tank with a working volume of 1.0 m^3. The dosages of the conditioners at the pilot scale were determined by the results of the bench-scale tests. The second part was the sludge-enhanced dewatering process, which was conducted in a plate-and-frame filter press with a working capacity of 1.0 m^3. The raw sludge was transferred from a gravity thickener to the conditioning tank.

Chemical reagents were added, and the tank was rapidly mixed for 1 min at 60 rpm. Wood chips were added, and the tank was rapidly mixed for 1 min. The reactors were then slowly mixed for 20 min at 20 rpm. After conditioning, the sludge was transferred to the filter press with a screw pump. The pressure gradually increased from 0 to 1.0 MPa over 30 min. The sludge was then pressed at 1.0 MPa for another 1-2 h. After this dewatering, the pressure was released, and the products were removed for further analyses.

Fig. 1

2.4 Assessment of the sludge dewatering performance

The most common sludge dewatering performance index is the MC of the dewatered sludge. In addition, the sludge dewatering ability is often characterised by the specific resistance to filtration (SRF, m kg^{-1}), which is associated with the slope of the plot of t/V versus V (Eq. (1), as used by Novak et al.[17]). Eq. (1) is a simplified form derived from the conventional filtration theory based on Darcy's law.

$$\frac{t}{V} = \frac{\mu SRFw}{2PA^2}V + \frac{\mu R_m}{PA} \quad (1)$$

where t is the filtration time (s), V is the filtrate volume at time t (m^3), μ is the viscosity of the filtrate, w is the mass of cake solids deposited per unit volume of filtrate (kg m^{-3}), P is the compression pressure (N m^{-2}), A is the filtration cross-sectional area (m^2) and R_m is the resistance associated with the filter medium (m^{-1}). If α is the slope of the linear plot, SRF can be determined using Eq. (2).

$$SRF = \frac{2PA^2\alpha}{\mu w} \quad (2)$$

The ultimate analysis was performed in an elemental analyser (multi EA® 5000, Jena, Germany). The relationship between the observed high HV (MJ kg^{-1}) and the C, H, O and N contents of the sludge can be estimated through Eq. (3)[18], and the low HV can be derived from the high HV on a dry basis and the cake MC, as shown in Eq. (4)[16]:

$$\text{High HV} = (33.5[C] + 142.3[H] - 15.4[O] - 14.5[N]) \times 10^{-2} \quad (3)$$

$$\text{Low HV} = \text{High HV} \times (1 - MC) \quad (4)$$

2.5 Analytical methods

The MC of the sludge was measured by a moisture detector (SFY-20, China). The pH value was detected by a pH meter (PHSJ-4F, China). The VSS was determined by the following steps: (1) filtering the mixed liquor to obtain the solids, (2) drying the samples at 105°C for 24 h and subsequently weighing the dried sample, (3) burning the sample at 600°C for 1 h and (4) weighing the ash content and calculating the MLVSS. All samples were analysed in triplicate.

3. Results and discussion

3.1 Effect of conditioning by chemical coagulation on the sludge dewatering ability in bench tests

The effect of CPAM and PACl conditionings on the MC and SRF of the sludge is presented in Fig. 2 (a-d). The PACl dosage exhibited a large effect on the MC of the dewatered sludge. The MC decreased with increasing dosages of PACl. The lowest MC was 87.93% when the CPAM and PACl dosages were 0.04% and 4%, respectively. The dosage of CPAM had only a slight effect on the MC of the dewatered sludge; the MC slightly reduced with increasing dosages of CPAM. The SRF markedly decreased from 11.29×10^{11} m kg^{-1} to 0.40×10^{11} m kg^{-1} when PACl was present in all four groups. The optimum dosages of PACl were between 3% and 4% in all experiments. However, the content of CPAM (from 0.05% to 0.4%) displayed a minimal effect on the SRF. Similar results were found by a study by Niu[19] in which PACl improved the dewatering ability of sludge because of the rapid aggregation of sludge particles induced by charge neutralisation and bridging. This expansion of particles was followed by floc densification that was caused by double-electric-layer compression. Fig. 2 (e) illustrates the effect of pH on the combination of conditioning. The SRF changed only slightly (from 0.34×10^{11} to 0.50×10^{11} m kg^{-1}) when the pH increased from 5.0 to 9.0. The MC decreased slightly from 91.3% to 88.4%. The functions and species of Al were different in different pH conditions[20]. When the pH increases, the primary form of Al may be $Al(OH)_3$ and $Al(OH)_4^+$. These species would adsorb and bridge with the sludge floc and thereby prevent destabilisation. Overall, PACl improved the dewatering ability of the sludge. As a flocculent, CPAM displayed minor effects on the dewatering ability of the sludge. Additionally, pH hardly influenced the combination of PACl and CPAM conditioning.

3.2 Effect of wood chips on the sludge dewatering ability in the bench tests

As shown in Fig. 2 (f), different dosages of wood chips (from 0 to 100%) were added to the conditioning system. The wood chips improved the MC of the dewatered sludge only slightly (from 88.45% to 91.28%) in the four trials. Additionally, no obvious change was detected in the SRF (ranging from 0.3 to 0.4×10^{11} m kg^{-1}). The results were different from those of Lin[16], who reported that the wood chip dosage (0, 90, 100, 200 and 300%) could affect the sludge dewatering, and the sludge cake MCs were 88.6, 85.3, 80.4, 77.2 and 74.8%, respectively. The reason for this difference in results might be the different operation pressures in the two studies. The pressure was 30 kPa in the SRF tests in our studies; however, Lin's vacuum filtration tests were conducted at 80 kPa. The pressure did not influence the dewatering ability of the sludge but affected the removal efficiency of the MC. Although the addition of wood chips did not improve the dewatering ability in the SRF tests, the effect of the addition of wood chips became significant with increasing pressure. Therefore, the effect of high-pressure conditions (1.0 MPa) in the plate-and-frame filter press was investigated.

Fig. 2

3.3 Effect of combining coagulation and adding wood chips in the pilot-scale filter

press

The laboratory experimental results indicated that the sludge did not require pH adjustment. To reduce the cost of the agents used, the CPAM dosage was selected as 0.05% in the pilot-scale plate-and-frame filter press. As the dosage of PACl greatly influenced the sludge dewatering ability, an investigation at the pilot scale was required. The dosages of PACl and wood chips were varied from 1 to 4% and from 0 to 100%, respectively, to optimise the performance of the sludge dewatering.

The MC of the dewatered sludge decreased with increasing the dosages of wood chips in Group 1 in Table 1. When the dosage of wood chips was greater than 80%, the MC of the dewatered sludge dropped below 60%. Additionally, increasing the dosage of PACl (from 1% to 4%) also decreased the MC of the dewatered sludge (from 68.3% to 50.3%) in Group 2, and an identical tendency was observed in Group 3. The lowest MC (50.3%) was achieved with the additions of 0.05% CPAM, 4% PACl and 100% wood chips. In our bench-scale results, the addition of wood chips did not noticeably improve the MC at a pressure of 30 kPa. In Lin et al.[16], the lowest MC was 74.8%, and this MC was achieved with a vacuum pressure of 80 kPa and the addition of 300% wood chips. Therefore, increasing the conditioning pressure could enhance the function of the wood chips. The wood chips served as skeleton builders at high pressures. This function was similar to other physical conditioners, such as lime, coal fly ash, gypsum and cement kiln dust[11-15]. The difference between the wood chips and other physical conditioners was that the former increased the VSS of product. As shown in Table 1, the value of VSS increased from 50.2% to 72.5% with an increase in the dose from 0 to 100% in Group 1. However, the addition of PACl had only a slight effect on the VSS in Groups 2 and 3 because of the small amount added.

3.4 Mechanism of adding wood chips in the pilot-scale plate-and-frame filter press

Based on our experimental results, a schematic model covering the addition of wood chips on the sludge dewatering in a pilot-scale plate-and-frame filter press is presented in Fig. 3. The sludge with no conditioners obtained the highest MC. The free water, interstitial water and capillary water adhered tightly to the sludge cells. Bridging occurred when CPAM and PACl were added. The sludge became larger and denser, and the free water and partial interstitial water were released. However, the sludge was highly compressible, and the formation of a compact cake blocked the water from leaking out. The formation of this cake explains the still high MC at high pressures. The compressibility of the sludge decreased when a sufficient amount of wood chips was added to the sludge. The wood chips formed a permeable and more rigid lattice structure, which remained porous at 1.0 MPa. Thus, the water discharged through these channels, and a low MC was achieved. Although the addition of wood chips could not improve the sludge dewatering ability in the SRF tests, an appropriate amount of wood chips acted as skeleton builders in the sludge; this skeletal system significantly improved the sludge dewatering efficiency in a pilot-scale plate-and-frame filter press at high pressures.

Table 1

Fig. 3

3.5 Evaluations of the HVs of the dewatered sludge

Increasing the dosage of wood chips increased the percentages of [C], [H] and [O]. This change in the material characteristics increased the high HV of the dewatered sludge from 13.45 MJ kg^{-1} to the maximum of 16.36 MJ kg^{-1} in Group 1 in Table 2. The low HV increased by 150% compared to the control because of the high dewatering efficiency. As seen in Groups 2 and 3, the PACl addition changed the high HV of the sludge only slightly; however, the addition of PACl increased the low HV of the sludge because of the decreased MC.

Table 2

Organic physical conditioners increased the high HV of the sludge. However, conditioning with inorganic conditioners reduced the percentages of [C], [H] and [O] and therefore decreased the high HV. Table 3 presents the effect of different conditioning methods on the high HV of the sludge. Deneux-Mustin et al. [11] used 35% ferric chloride and lime as physical conditioners. These physical conditioners theoretically decreased the high HV of sludge by 25.9%. Benítez et al. [14] added 150% fly ash as a physical conditioner; the fly ash theoretically decreased the high HV by 60%. A combination of Fenton's reagent, lime and ordinary Portland cement was used as conditioners for sludge deep dewatering in a report by Liu et al [21]. Although the final MC of sludge reached 50%, nearly 30% lime and 50% ordinary Portland cement were added to the sludge to provide the inorganic skeleton. Additionally, the Fenton's reagent also carbonised a mass of organic matter. Therefore, that method also significantly reduced the high HV of the sludge. Unlike these studies, Lin et al.[16] reported that organic physical conditioners (300% wood chips and wheat dregs) increased the high HV of the sludge by 28.4%. However, the low HV of the sludge did not increase significantly. The low HV depends on not only the elemental content but also the MC of the sludge. As discussed above, the high MC occurred because of the low dewatering efficiency under low pressures. Thus, our pilot-scale work provided a great improvement by significantly reducing the MCs of the through the addition of wood chips at high pressures. Therefore, it can be concluded that conditioning with wood chips at a high pressure (1.0 MPa) produced a sludge cake with high values for both the high HV and low HV.

Table 3

3.6 Subsequent sludge disposal options

To achieve a more informed and sustainable sludge management process, the processes of landfilling, incineration, and recycling for brick and cement manufacturing and fertiliser for urban greening are proposed for sludge disposal[22-24]. Fig. 4 summarises the possible sludge disposal processes in current studies.

The shear strength of the sludge is often estimated from the MC. The vane shear and compressive strength, which are important indexes for municipal solid waste landfills, increase with decreasing MCs [25]. The sludge with an MC below 60% is allowed to be landfilled in China (GB/T 23458-2009). In this study, landfilling is a potential disposal route for the product because the MC for the sludge was under 60%.

With regard to sludge composting, Huet et al.[26] found that the MC greatly affected the initial bulk density, free air space (FAS), air permeability and thermal conductivity during aerobic composting. Trémier et al.[27] also reported that increasing the MC up to an optimum level (55%) improved the biodegradation of the organic matter. Beyond this optimum MC value, water negatively affected aeration and the microbial O_2 supply. Given this optimum value, wood chips at the provided dosage of 80-100% conditioning in our studies could meet the requirements of composting.

The MC is a critical factor in incineration. Lin et al.[28] conducted experiments on the co-incineration of sewage sludge with municipal solid waste in a grate furnace incinerator. The results indicated that semi-dried sludge with lower MCs and higher low HVs were more appropriate for co-incineration with MSW. Thus, MC is a key factor in sludge incineration. In China, the sludge with MCs below 50% or low HVs above 5 MJ kg^{-1} are allowed in self-sustain burning; the sludge with MCs below 80% or low HVs above 3.5 MJ kg^{-1} are allowed in fuel burning (CJ/T 290-2008). In our results, the low HV of the sludge products ranged from 4.4 to 8.0 MJ kg^{-1}, which satisfied these requirements. Chang[29] also reported that that the co-combustion of sludge and wood chips not only handles the fast growing sludge stream but also yields a saving in the fuel cost and treatment fees of sludge and ashes.

In conclusion, the MC or solid contents of the dewatered sludge determines the subsequent disposal options. After chemical coagulation and the addition of wood chips, the sludge achieved a relatively low MC and high HV. The low MC allows the products to be transported and landfilled, and the high HV allows the products to be incinerated and composted.

Fig. 4

4. Conclusion

1. Chemical coagulation significantly influenced the MC and SRF of the sludge. The lowest MC and SRF were 87.93% and 0.31×10^{11} m kg^{-1}, respectively, when the dosage of CPAM and PACl were 0.04% and 4%, respectively.

2. The addition of wood chips combined with chemical coagulation conditioning improved the sludge dewatering ability only slightly compared with the coagulation conditioning alone. However, the addition of wood chips was effective in the plate-and-frame filter press dewatering process because the wood chips act as skeleton builders at the high pressures (1.0 MPa) experienced in the dewatering process. The lowest MC reached 50.3% when the CPAM, PACl and wood chip dosages were 0.05%, 4% and 100%, respectively.

3. The conditioning with wood chips increased the high HV and low HV of the dewatered sludge by a maximum of 20% and 150%, respectively.

4. Several disposals options, such as landfilling, incineration and bio-composting, are proposed because of the low MC and high HVs of the products.

Acknowledgement

This research was support by National Natural Science Foundation of China (51038003), the Funds for Creative Research Groups of China (51121062), Industry-University-Research Collaboration Project of Guangdong Province & Chinese Ministry of Education (2012B091000029), Key Breakthrough Project of

Guangdong & Hong Kong (2012BZ100021) and Industry-University-Research Collaboration Project of Chancheng District (2012107101169).

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Figure captions

Fig. 1 Schematic diagram of the pilot-scale sludge dewatering process

Fig. 2 Effect of combined conditioning on the MC and SRF of the dewatered sludge (a, b, c and d: effect of CPAM and PACl dosages on the MC and SRF; e: effect of pH on the MC and SRF during CPAM and PACl conditioning; and f: effect of adding wood chips on the MC and SRF)

Fig. 3 Schematic mechanism of the effect of adding wood chips on sludge dewatering: (a) sludge without conditioning; (b) sludge with chemical conditioning; (c) sludge with chemical and physical conditioning; and (d) a physical image of a dewatered sludge cake with wood chip conditioning

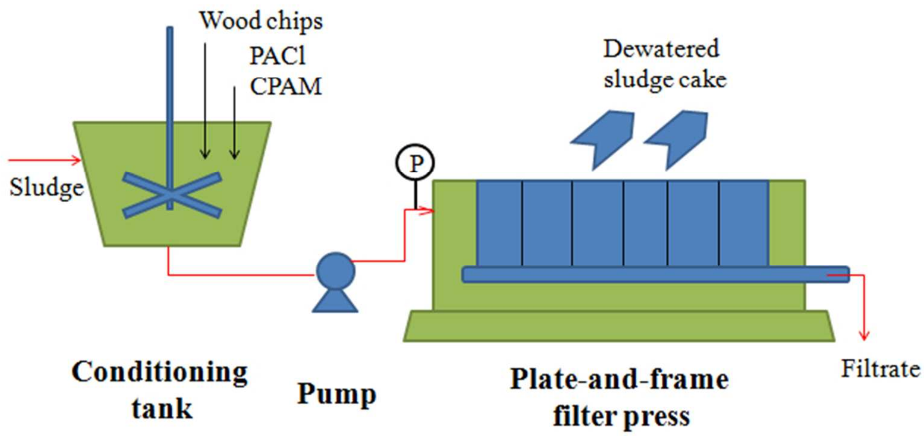
Fig. 4 Schematic diagram of sludge disposal options

Table captions

Table 1 Effect of the dose of the conditioners on the MC and VSS of dewatered sludge

Table 2 Effect of the conditioner dosage on the HV of the dewatered sludge

Table 3 Comparative studies of the effect of the conditioners on the high HV of the dewatered sludge



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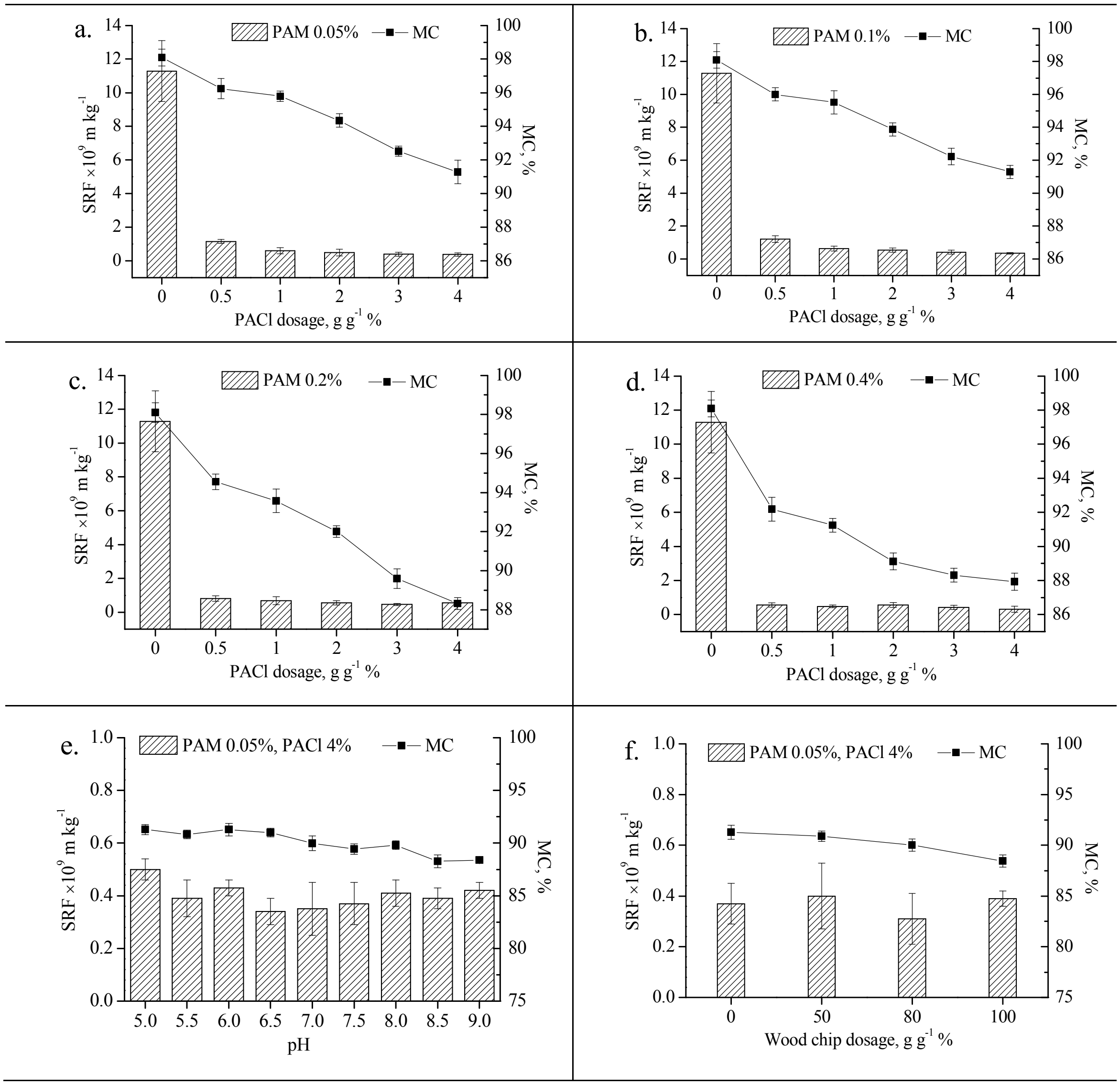

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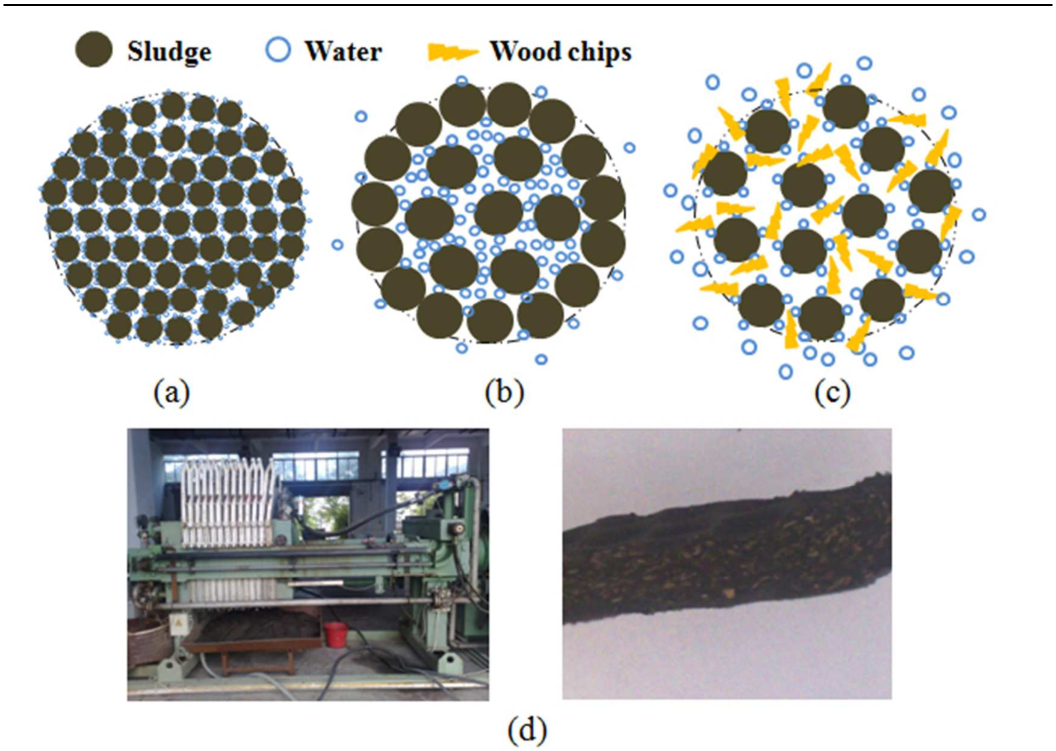

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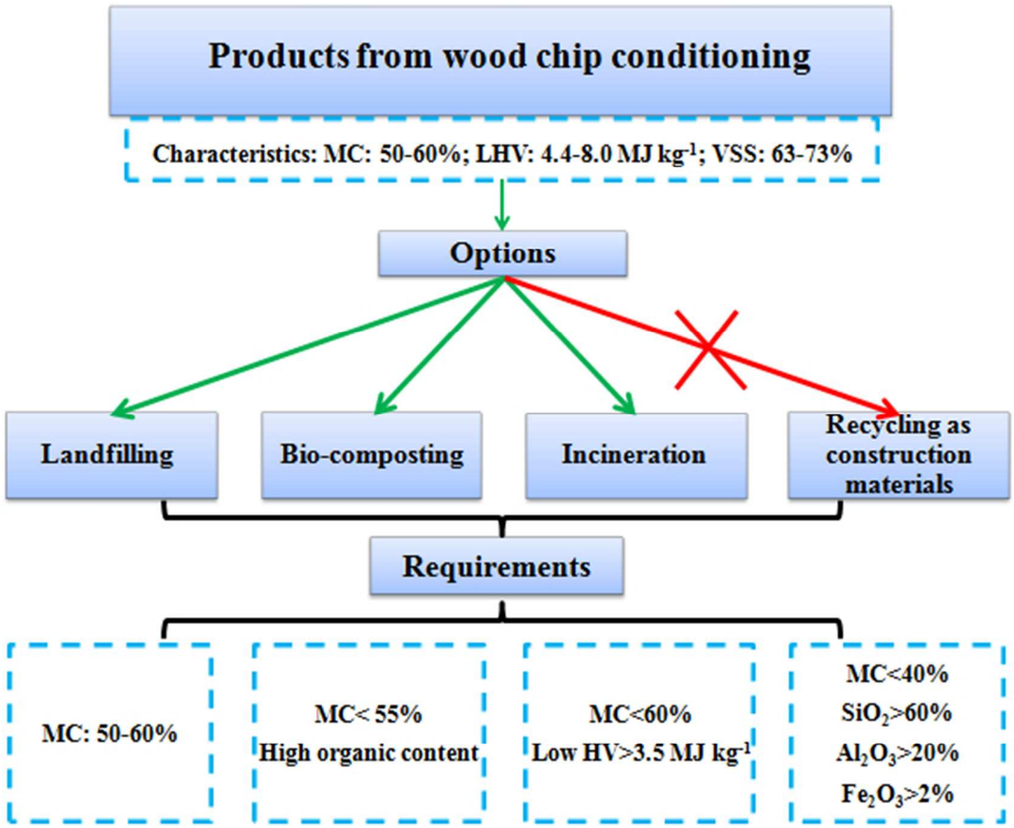

420

421 **Fig. 4 Schematic diagram of sludge disposal options**

422

Table 1 Effect of the dose of the conditioners on the MC and VSS of dewatered sludge

	Reagents dosage, %			Dewatered sludge properties	
	CPAM	PACl	Wood chips	MC, %	VSS, %
Group 1	0.05	4	0	76.1	50.2
	0.05	4	50	70.4	63.6
	0.05	4	80	55.4	65.1
	0.05	4	100	50.3	72.5
Group 2	0.05	4	100	50.3	72.5
	0.05	2	100	53.3	75.7
	0.05	1.5	100	55.2	73.1
	0.05	1	100	68.3	73.1
Group 3	0.05	4	80	55.4	65.1
	0.05	3	80	56.0	68.1
	0.05	2	80	66.4	66.9
	0.05	1	80	71.1	67

Table 2 Effect of the conditioner dosage on the HV of the dewatered sludge

	Reagents dosage, %			Dewatered sludge					
				Elemental analysis, %				Theoretical HV, MJ kg^{-1}	
	CPAM	PACl	Wood chip	C	H	N	O	High	Low
Group 1	0.05	4	0	31.7	5.3	6.4	24.6	13.45	3.21
	0.05	4	50	37.4	5.4	4.3	29.9	14.94	4.42
	0.05	4	80	39.2	5.7	3.6	31.6	15.85	7.07
	0.05	4	100	40.2	5.7	3.3	32.5	16.15	8.03
Group 2	0.05	4	100	40.2	5.7	3.3	32.5	16.15	8.03
	0.05	2	100	40.5	5.8	3.4	32.8	16.29	7.61
	0.05	1.5	100	40.6	5.8	3.4	32.8	16.32	7.64
	0.05	1	100	40.7	5.8	3.4	32.9	16.36	4.73
Group 3	0.05	4	80	39.2	5.7	3.6	31.6	15.85	7.07
	0.05	3	80	39.4	5.7	3.7	31.8	15.92	7.00
	0.05	2	80	39.6	5.8	3.7	31.9	16.00	5.38
	0.05	1	80	39.8	5.8	3.8	32.1	16.08	5.1

430 **Table 3 Comparative studies of the effect of the conditioners on the high HV of**

431 **the dewatered sludge**

	Dewatering conditioners	**High heat value change rate, %**
Deneux-Mustin [11]	35% Ferric chloride + lime	-25.9
Benítez [14]	Polymer + 150% fly ash	-60.0
Liu [21]	Fenton + 30% lime + 50% ordinary Portland cement	-44.4
Lin [16]	Alum/$FeCl_3$ + 300% wood chips/wheat dregs	28.4
Our study	CPAM + PACl + 100% wood chips	20.1

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