

Enhancement of dewatering performance of digested paper mill sludge by chemical pretreatment

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Abstract. The wide application of anaerobic digestion (AD) for waste sludge results in a huge amount of digested sludge, while the appropriate reuse of digested sludge depends on effective solid-liquid separation. Thus, chemical (acid/alkali) pretreatment effects on dewaterability of digested paper mill sludge (DPMS) for better downstream reuse based on enhanced solid-liquid separation were investigated in this research. The dewatering properties of paper mill sludge (PMS) were also investigated to elucidate the impact of AD on sludge dewaterability. The results indicated that a higher DPMS dewaterability was noted with acid pretreatment (pH5). A 41.37% moisture content and 74.41% dewatering efficiency were determined for DPMS after acid (pH5) pretreatment within 25 min. In addition, a 7.13 mg•g⁻¹ VSS of extracellular polymeric substances (EPS) and 101.50 μm of average particle size were observed. It was also observed that both EPS concentrations and particle sizes were key parameters influencing DPMS dewaterability. Lower EPS concentrations with larger average particle sizes contributed to enhanced sludge dewaterability. Moreover, dewaterability of PMS was higher than that of DPMS, which illustrated that AD would decrease the sludge dewaterability.

1. Introduction

As a solid by-product of the papermaking industry, paper mill sludge (PMS) is continuously produced by wastewater treatment, and originates from pulping and paper-making processes. It is reported that nearly 400 million tons of paper production around the world annually will produce approximately 18 million dry PMS [1]. The majority of them have been directly delivered to landfills or discarded carelessly. Otherwise, PMS is a type of significant biosolid waste containing plenty of organic components. Thus, biological treatments of PMS, such as composting and anaerobic digestion, are popular. Anaerobic digestion has been, and continues to be, widely applied in the stabilization process of sludge management, providing effective pathogen destruction, reduction of volatile solids (VS) and odor potential and an energy source in the form of biogas [2]. Anaerobic digestion of PMS for methane production has been reported in China, which indicates the potential benefits in the resource utilization of this industrial organic waste as well as in the solving of energy shortage problems [3].

However, as a result of the wide application and utilization of the anaerobic digestion (AD) of PMS, digested paper mill sludge (DPMS) presents another disposal problem with its high moisture content. It contains plenty of secondary fiber fines with a lower total solid (TS) content (generally less than 8%) [4]. Discharging DPMS to sewage sludge plants causes excessively high organics loads for the



wastewater treatment process. Application of raw DPMS as a liquid fertilizer in agriculture or horticulture is also unfeasible due to the low fertility and possible pathogens. Proper reuse of DPMS is always based on efficient solid-liquid separation. Otherwise, the dewaterability of sewage sludge has been focused on for a long time, instead of paying much attention to the dewaterability of anaerobic digesterate [2, 5, 6, 7]. On the other hand, based on the few current results for the dewaterability of anaerobic digesterate, different results about the impact of anaerobic digestion on sludge dewaterability have been reported, owing to various sludge. Some indicated that anaerobic digestion generally impeded sludge dewaterability, while the other reported that sludge dewaterability was enhanced after anaerobic digestion [2, 5, 8]. According to authors' knowledge, no related report on DPMS dewaterability is available.

To determine sludge dewaterability, moisture content and dewatering efficiency are used as common indexes. Besides, extracellular polymeric substance (EPS) is regarded as one of the most important factors that influence the dewatering characteristics of sludge [9, 10]. As metabolic products accumulate on the bacterial cell surface, EPS consists of organic polymers, proteins, polysaccharides and DNA, which are highly hydrated and may contain up to 99% water by weight, thereby retaining a high level of water in the sludge [11, 12]. Due to its physico-chemical properties, EPS is thought to have considerable impact not only on the charge of sludge surface, bioflocculation process, settling and dewatering [13], but also serves as the protective cover for cells against the harsh external environment or as the carbon and energy reserves during starvation [14].

On the other hand, sludge dewaterability is related to its composition and structure. Various pretreatments have been applied to enhance sludge dewaterability, including the common chemical pretreatments. The influence of acid pretreatment on sludge dewaterability, EPS concentrations and settling performance of activated sludge has been investigated, and the results suggested that the moisture contents of dewatered sludge varied with pH values, and the optimum pH value for filtration dewatering was 2.5 [15]. He et al. [16] observed that there were no comprehensive changes in the sludge dewatering efficiency when acid pretreatment was applied, but the moisture content of dewatered sludge decreased evidently. This phenomenon indicated that the degree of dehydration improved. However, no research has reported on the effect of acid/alkali pretreatment on DPMS dewaterability.

The objective of this study was to evaluate the dewaterability of DPMS by pretreatment with acid or alkali at different pH values. Moisture contents, dewatering efficiencies and EPS concentrations were analyzed in the dewatering process. It is proposed to provide a feasible reuse method for anaerobic digesterate via enhanced solid-liquid separation for downstream application.

2. Materials and methods

2.1. Preparation of sludge

PMS was collected directly from the secondary clarifiers (normally settling tanks) of the Guangzhou Pulp & Paper Plant, China. There are two processes in this plant: one is bleaching chemi-thermo-mechanical pulp (BCTMP) made from Masson pine; the other is papermaking from waste paper after de-inking. Waste water arises from three sections – pulping, papermaking and de-inking – and is usually dewatered to 60% - 70% moisture content at the end of wastewater treatment. In order to get the optimal C/N ratio, monosodium glutamate waste liquor was applied, which was collected from Ao-Sang Monosodium Glutamate Factory (Guangzhou, China).

DPMS was obtained from anaerobic digestion of PMS at $(37 \pm 1)^\circ\text{C}$, TS of 10% for 40 days, inoculating with 10% seed sludge (based on TS) that was obtained from the sewage tank (near Building 4 in the South China Agricultural University, Guangzhou, China) and was acclimatized with PMS step by step in the laboratory for 3 months. The anaerobic digesterate was settled for 24 hours. The clear supernatant was removed to obtain the tested sludge. The tested sludge was stored in the refrigerator (0 - 4°C) prior to the experiment.

The target sludge of PMS was characterized as pH 7.63, TS 35.68%, VS 40.74% (based on TS), and EPS concentration 19.34 mg•g⁻¹ VSS. The tested sludge of DPMS was characterized as pH 8.00, TS 24.96%, VS 27.54% (based on TS), and EPS concentration 28.62 mg•g⁻¹ VSS.

2.2. Experimental procedure

2.2.1. A subsection. Pretreatment: A series of bench-scale experiments were conducted in 500 mL beakers loaded with 250 mL tested sludge. 20% (w/v) NaOH solution and 20% (v/v) HCl solution were added until the final pH value of each beaker reached 5, 7, 9 and 11, respectively. The tested sludge was continuously stirred slowly for 5 min while adding chemicals, till the target pH value was obtained. Then, the mixture was allowed to react for 20 min. As for the control treatment, no chemicals were applied. All experiments were carried out at room temperature.

2.2.2. Suction filtration test. Suction filtration was conducted in a Buchner funnel with a quantitative filter paper under a 0.04 MPa vacuum. 20 mL sludge was poured into the Buchner funnel to filter for 40 min. The moisture content of dewatered sludge was determined according to the Standard Methods [17]. Dewatering efficiency was determined according to the following equation:

$$\text{Dewatering efficiency} = \frac{Q_r - Q_c}{Q_r} \times 100(\%)$$

where Q_r is the weight of the water in sludge before dewatering and Q_c is the weight of the water in sludge after dewatering.

2.2.3. Settling test. 100 mL tested sludge was poured into a measuring cylinder and kept subsiding for 90 min to investigate the sludge settling performance. The volume of settled sludge was recorded once every 10 min.

2.3. Analytical methods

TS, VS, volatile suspended solids (VSS), moisture content and pH were determined according to the Standard Methods [17]. Particle size was determined by the screen method. Tested sludge was screened step by step with tap water on a sieve with a diameter of 1.25, 0.9, 0.8, 0.63, 0.45 and 0.2mm, respectively. The sludge that remained on each sieve was collected and dried at 105°C for 24 h. The weight percentage of particles for each size was equal to the sludge weight on each sieve divided by the total sludge weight, based on dry mass. Proteins were analyzed using the ultraviolet absorption spectrum method with bovine serum albumin as the standard, polysaccharides were measured according to the anthrone-H₂SO₄ method, and DNA analysis was carried out using the ultraviolet absorption spectrum method [18]. As the main components of EPS were proteins, polysaccharides and DNA, a EPS concentration could be determined by the sum of its components' concentrations. In order to know the configurations of tested sludge with different pretreatments, a scanning electron microscope (SEM) (XL30, FEI, USA) was applied for sludge samples.

EPS was extracted based on formaldehyde-NaOH method. Firstly, 50 mL sludge was centrifuged at 6000G for 5 min. Then, sludge pellets were resuspended and diluted to the original volume by adding buffer solution (2 mmol/L Na₃PO₄, 4 mmol/L NaH₂PO₄ and 1 mmol/L KCl, pH=7), followed by adding 0.3 ml formaldehyde solution and stirring for 30 min. Afterwards, 50 mL NaOH solution (0.04 mol/L) was added to the sludge and the mixture was agitated at 300 r/min for 1 h, then centrifuged at 6000G for 10 min. The supernatant filtered with 0.2 μm microfiltration membrane was used to test the concentrations of proteins, polysaccharides and DNA.

3. Results and discussion

3.1. Moisture content and dewatering efficiency

As presented in table 1, the lowest moisture content of 41.37% was obtained in the pretreated DPMS (pH 5), while the highest moisture content of 46.59% was obtained in the original DPMS (pH 8). The moisture content in the dewatered sludge dropped down by 11.2% when HCl pretreatment with pH 5 was applied. The moisture contents of the pretreated DPMS (pH 7), pretreated DPMS (pH 9) and pretreated DPMS (pH 11) were 41.66%, 44.65% and 44.45%, respectively, all of which were lower than those of the original DPMS (pH 8). The results of moisture contents indicated that pretreatment with HCl (pH 5) provided a better condition for DPMS to obtain a higher dewaterability.

Besides, the highest dewatering efficiency of 76.04% was obtained in the pretreated DPMS (pH 7), the second highest of 74.41% was obtained in the pretreated DPMS (pH 5), and both of them were higher than that which was obtained in the original DPMS (pH 8). The dewatering efficiencies of the pretreated DPMS (pH 9) and the pretreated DPMS (pH 11) were 72.34% and 65.71%, respectively. The results indicated that acid pretreatment with pH 5 and pH 7 showed a higher dewatering efficiency than alkali pretreatment with pH 9 and pH 11. Also, the lowest dewatering efficiency was noted in the treatment with pH 11.

In this test, the moisture contents of dewatered sludge for different treatments ranked in the order of pretreated DPMS (pH 5) < pretreated DPMS (pH 7) < pretreated DPMS (pH 11) $\approx$ pretreated DPMS (pH 9) < original DPMS (pH 8). Meanwhile, the dewatering efficiency observed in each treatment followed the order of pretreated DPMS (pH 7) > pretreated DPMS (pH 5) > pretreated DPMS (pH 9) > original DPMS (pH 8) > pretreated DPMS (pH 11). It could be inferred that a strong alkaline environment is not favorable to enhance DPMS dewaterability, while a neutral or weakly acidic condition behaves in the opposite way. The possible main reason is that the sludge surface is negatively charged, and the acid changes its surface properties by neutralizing the negative charges and compressing the double electrode layer, resulting in more flocculation of flocs, which probably favors the dewatering process. What's more, it was reported that the hydrophobic fraction of carboxyl and other polar groups was enhanced with the decrease of pH value, which reduced their adsorption ability for water molecules, resulting in a transformation of water distribution in sludge [19]. Based on those results, the higher content of bound water in sludge reduced the mechanical dewatering ability. An excess of alkali could possibly increase the negative charges of sludge particles, and then disperse the sludge flocs, resulting in a worse dewaterability. Overall, taking the moisture content of dewatered sludge and dewatering efficiency into consideration, pretreatment with pH 5 was optimal to enhance the DPMS dewaterability compared to other acid/alkali pretreatments.

Table 1. Moisture contents of dewatered sludge and dewatering efficiencies of DPMS.

	Original DPMS (pH8)	Pretreated DPMS (pH5)	Pretreated DPMS (pH7)	Pretreated DPMS (pH9)	Pretreated DPMS (pH11)
Moisture Content (%)	46.59 $\pm$ 0.37	41.37 $\pm$ 0.34	41.66 $\pm$ 0.57	44.65 $\pm$ 0.27	44.45 $\pm$ 0.17
Dewatering Efficiency (%)	69.28 $\pm$ 0.24	74.41 $\pm$ 0.21	76.04 $\pm$ 0.33	72.16 $\pm$ 0.09	65.71 $\pm$ 0.13

DPMS: Digested paper mill sludge

3.2. EPS concentrations and compositions

According to figure 1, the lowest EPS concentration of 7.13 mg•g⁻¹ was noted in the pretreated DPMS (pH 5), while the highest of 54.82 mg•g⁻¹ was obtained in the pretreated DPMS (pH 11). EPS concentrations in the original PMS (pH 8), original DPMS (pH 8), pretreated DPMS (pH 7) and pretreated DPMS (pH 9) were 19.34 mg•g⁻¹, 28.62 mg•g⁻¹, 18.10 mg•g⁻¹ and 37.20 mg•g⁻¹, respectively. Therefore, the EPS concentrations in the reactors with different pretreatments followed the trend of

pretreated DPMS (pH 5) < pretreated DPMS (pH 7) < original PMS (pH 8) < original DPMS (pH 8) < pretreated DPMS (pH 9) < pretreated DPMS (pH 11). It was clearly observed that EPS concentrations increased with the increase of pH values in reactors. Additionally, it was found that the main component of EPS in each treatment was proteins, amounting to 60-85%, no matter whether pretreatments were applied or not. The concentration of polysaccharides was the second most in the sludge before pretreatments. However, the concentration of DNA increased to be the second most component in sludge after pretreatments, amounting to 11-14%, which was followed by polysaccharides, amounting to 2-5%. Generally, a high concentration of DNA in EPS could be an alarming indication that the cells were lysed in the harsh extraction process [13]. However, it could be considered that the extraction process for EPS was effective in this study because the percentage of DNA concentration was less than 15% [12]. With regard to reducing the polysaccharide concentration after acid/alkali pretreatments, it was possibly due to the disintegration of polysaccharides, which caused less extracted polysaccharides.

An excess of alkali possibly led to the dissolution of proteins and polysaccharides, and then the EPS solubility increased. Thus, abundant EPS were released from the cellular surface [12]. In this study, the EPS concentration of DPMS was higher than that of PMS. One possible reason might be related to the fact that the pH value of PMS increased after anaerobic digestion [3, 4], and then the solubility of EPS increased.

As shown in figure 2, less EPS was extracted, and a lower moisture content was noted. Meanwhile, the dewatering efficiency decreased with the increase of EPS concentration. Therefore, the correlation between dewaterability of pretreated DPMS, evaluation with moisture content and dewatering efficiency, and EPS concentration are presented (see figure 2). Based on this fact, it could be inferred that an increase of EPS concentration would reduce DPMS dewaterability. This is possibly due to the highly hydrated nature of EPS that retains water within the sludge matrix, which counteracted the formation of flocculation [9]. Meanwhile, acid pretreatment removed some EPS from the sludge surface, and then a majority of bound water was released. Consequently, the proportion of free water that could be removed by mechanical force increased, making pretreated DPMS easy to pack the sludge aggregates and reduce the moisture content of dewatered sludge [16]. Therefore, it can be concluded that EPS was important for DPMS dewaterability, and acid pretreatment could remove EPS, resulting in an enhanced degree of DPMS dehydration. Otherwise, as the main component of EPS, proteins were reported to likely play a significant role in its properties [20]. Further research on the influence of EPS components on DPMS dewaterability could be carried out in the future.

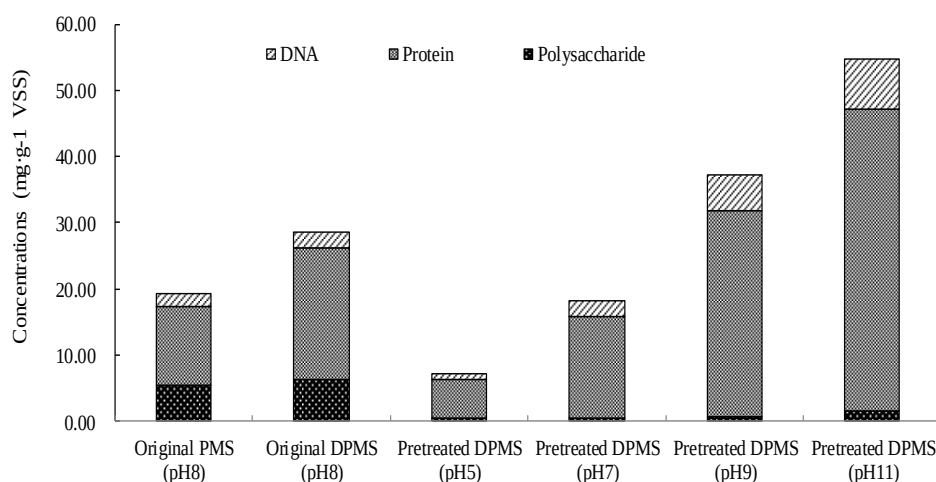


Figure 1. EPS concentrations and components for various sludge.

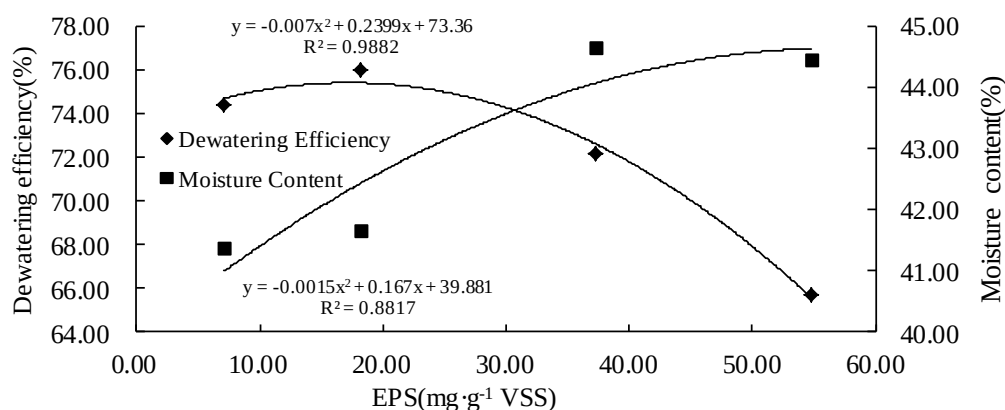


Figure 2. Correlation between EPS concentrations and dewaterabilities of pretreated DPMS.

3.3. Settling performance

As shown in figure 3, the settled sludge volume of the original PMS (pH 8) was lower than that of the original DPMS (pH 8), which indicated that the sludge dewaterability was reduced after anaerobic digestion. The settled sludge volumes of the pretreated DPMS (pH 5) and pretreated DPMS (pH 9) were significantly lower than those of the original DPMS (pH 8). This illustrated that acid or alkali pretreatment was helpful to enhance sludge settling performance.

The settling performances of different treatments ranked in the order of original PMS (pH 8) > pretreated DPMS (pH 5) > pretreated DPMS (pH 9) > original DPMS (pH 8) $\approx$ pretreated DPMS (pH 7) = pretreated DPMS (pH 11). Meanwhile, the sedimentation curves in Figure 3 also demonstrated that pretreated DPMS (pH 5) achieved the best settling performance among the four treatments with different pH values. This result is in accordance with the sludge dewaterability. Additionally, this result indicated that the settling performance of DPMS could be affected by pH values. Weakly acidic or alkaline conditions (pH 5 and pH 9) could enhance the sludge settling ability, while a strong alkaline environment (pH 11) would be negative for settling. Combined with EPS concentrations of pretreated DPMS (see section 3.2) and conclusions obtained by Liao et al. [12], the poor settling performance in strong alkaline conditions was possibly caused by the high concentration of EPS, which hindered further connections among the cells owing to the steric effect, and the increased diversity of density between sludge flocculation and water due to a close-grained hydrogel formation by EPS [9].

Regarding the settled volume of original PMS (pH 8), it was lower on average than that of the original DPMS. Since sludge dewaterability was consistent with its settling performance, and the settling performance was related to EPS concentrations [21, 22], taking the EPS concentrations and settling performances into consideration (figure 1 and figure 3), it can be inferred that anaerobic digestion reduced PMS dewaterability. This result was in line with the earlier results [2, 8].

By the way, the trial with pretreated DPMS (pH3) had been designed in this study to test DPMS dewaterability in a strong acidic environment. Otherwise, an extremely intense reaction happened in the pretreatment reactor so that further tests could not continue. This phenomenon was caused by too much H^+ , which led to the failure of the reaction.

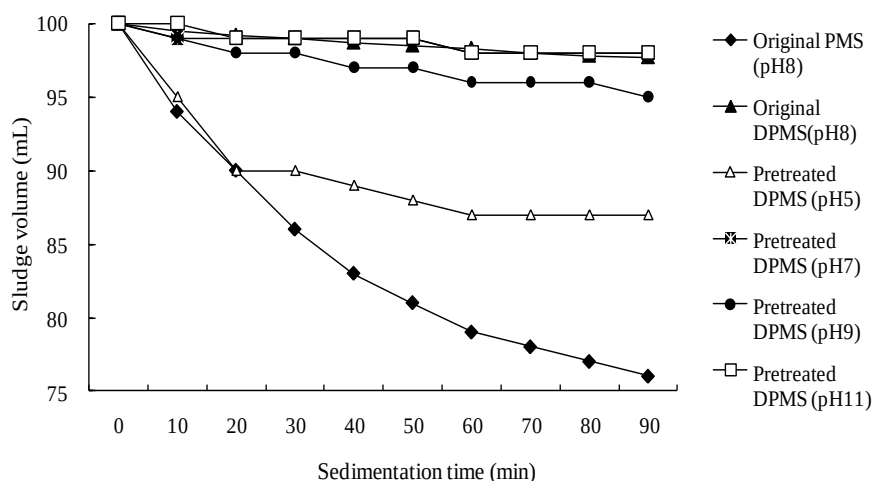


Figure 3. Settling performances of raw sludge and pretreated sludge.

3.4. Particle size distribution in sludge

Table 2 shows the observed differences in particle size distribution, and the differences are displayed by weight percentage of sludge particle size. Most of the particles presented had diameters of less than 180 μm (figure 4). However, for the particle size range above 1650 μm , the weight percentage in the original DPMS (pH8) was approximately 10% higher than those in the other acid/alkali pretreatments. Besides, it was noticed that when the particle size became small (<180 μm), the weight percentage of this size increased with the increase of the pH value. Moreover, the largest mean particle size of 121.82 μm was obtained in the original PMS (pH 8), and the smallest mean particle size of 99.15 μm was observed in the pretreated DPMS (pH 11).

With regard to the treatments after acid/alkaline pretreatment, it was observed that the pretreated DPMS (pH 11) with the smallest mean particle size of 99.15 μm had the worst dewaterability, as evaluated by a high moisture content and the lowest dewatering efficiency. In contrast, the pretreated DPMS (pH 5) with the largest mean particle size of 101.50 μm had the best dewaterability, as evaluated by the lowest moisture content and a high dewatering efficiency (tables 1-2, figures 1-3).

Therefore, a correlation between the dewaterability of pretreated DPMS and the mean particle size is presented in Figure 4. It indicates that the increased mean particle size in DPMS could obtain a better dewaterability, which confirms the earlier conclusion that sludge with a smaller mean particle size has worse dewaterability [10]. Thus, from the point of the mean particle size, it was proven again that AD would reduce the PMS dewaterability by decreasing the particle size in sludge.

Besides, Karr and Keinath [23] fractionated the sludge into various size ranges and found that its filterability reduced with the decrease of particle size. Meanwhile, some authors have also reported that sludge particle size could markedly influence sludge dewaterability [5, 24]. The sludge in an acidic environment was difficult to shear into smaller particles, while the sludge in an alkaline environment was gelatinous and could be cutted into small particles [23, 25]. As a result, the treatment of pH 5 with the largest mean particle size of 101.50 μm showed the best dewaterability (figures 1-4).

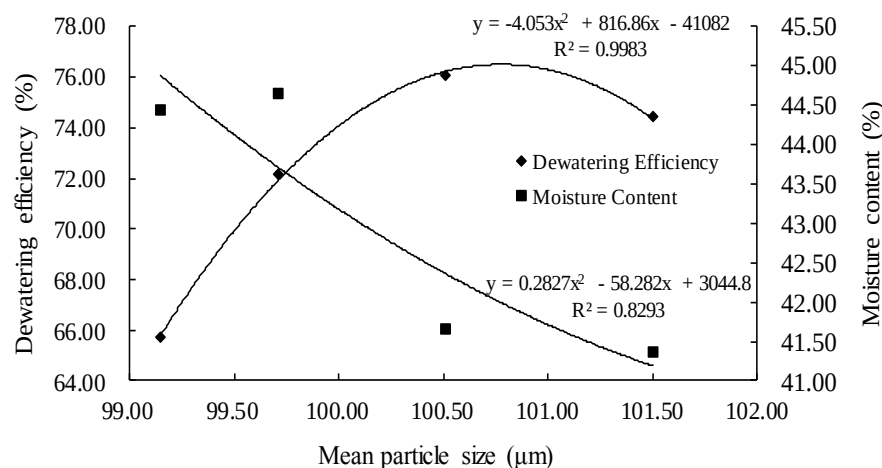
Therefore, these above results show that acid/alkali pretreatments under different pH values were able to change the particle size distribution in DPMS, which means that pH values had a considerable impact on DPMS dewaterability. Moreover, there was a significant inverse correlation between the dewaterability and the percentage of small particle size. In a word, acid pretreatment with pH 5 for DPMS was optimal to enhance its dewaterability.

Table 2. Particle size distribution in sludge measured by weight percentage (%).

Treatment	Particle size (μm)						Mean particle size (μm)
	>1650	830~1650	380~830	250~380	180~250	<180	
Original PMS ^{a)}	25.34	3.23	19.88	11.39	0.18	39.98	121.82
Original DPMS ^{b)} (pH8)	14.93	2.59	15.78	12.04	0.85	53.81	110.38
Pretreated DPMS (pH5)	6.13	3.3	10.24	10	0.96	69.37	101.50
Pretreated DPMS (pH7)	2.83	3.43	13.35	4.8	4.27	71.32	100.51
Pretreated DPMS (pH9)	3.64	5.84	10.02	3.95	3.38	73.17	99.71
Pretreated DPMS (pH11)	3.34	5.96	10.41	3.08	2.74	74.48	99.15

a) PMS: Paper mill sludge

b) DPMS: Digestd paper mill sludge

**Figure 4.** Correlation between mean particle sizes and dewatering efficiencies of pretreated DPMS.

3.5. Flocs structure

As shown in figure 5, flocs in the original DPMS (pH 8) had much more swelling than those in the original PMS (pH 8). Also, the fine particles in the original DPMS (pH 8) were more than those in the original PMS (pH 8). Likewise, the weight percentages of particles less than $180\mu\text{m}$ in the original PMS (pH 8) and original DPMS (pH 8) were 39.98% and 53.81%, respectively. This result demonstrated that the flocs structure of PMS was disrupted by anaerobic digestion, which resulted in a smaller particle size in DPMS and leading to a poor dewaterability [4]. Meanwhile, SEM images of the original and pretreated DPMS clarified that the flocs structure was further dispersed after pretreating by acid/alkali, which was in line with the previous report that pretreatment contributed to the rearranging/breaking of some chemical bonds [26]. Furthermore, considering the sludge flocs after acid/alkaline pretreatment, alkaline pretreatment was found to cause DPMS swelling and loosening, while acid pretreatment produced more particles with bigger size in DPMS. However, pretreated DPMS (pH 7) and pretreated DPMS (pH 9) had a similar flocs structure. Therefore, based on the flocs

structure, the fact that pretreated DPMS (pH5) had the best dewaterability while pretreated DPMS (pH11) had the worst was reasonable.

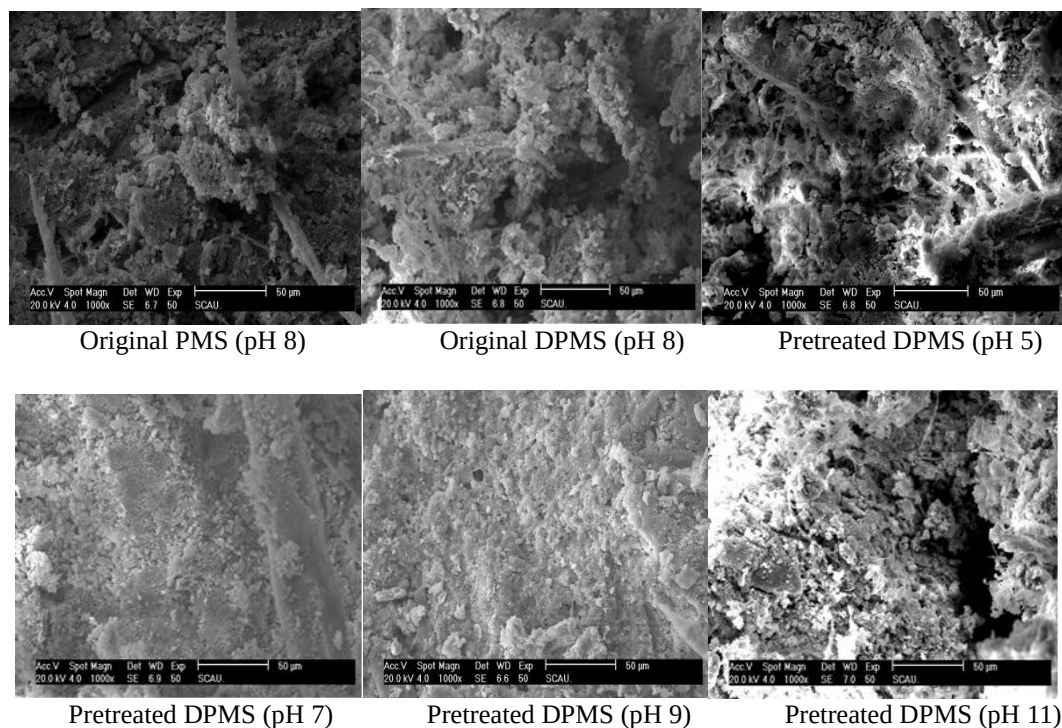


Figure 5. Microphotographs of sludge before and after pretreatment at 30 bar (1000 ×).

4. Conclusions

DPMS pretreated at pH 5 achieved the best dewaterability compared to other pretreated trials. It can be concluded that a weak acidic environment could enhance DPMS dewaterability, while a strong alkaline environment was detrimental to it. Compared to PMS, DPMS demonstrated poorer dewaterability because of the floc structure dispersion and finer particle formation in AD.

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References

- [1] Torsten M and Elizabeth A E 2014 Anaerobic digestion of pulp and paper mill wastewater and sludge *Water Research* **65** pp 321-49
- [2] Ayol A 2005 Enzymatic treatment effects on dewaterability of anaerobically digested biosolids-I: performance evaluations *Process Biochemistry* **40**(6) pp 2427-34
- [3] Lin Y Q, Wang D H and Xiao M Q 2011 Mesophilic batch anaerobic co-digestion of pulp & paper sludge and monosodium glutamate waste liquor for methane production in a bench-scale digester *Bioresource Technology* **102**(4) pp 3673-78
- [4] Lin Y Q, Wang D H, Wu S Q and Wang C M 2009 Alkali pretreatment enhances biogas production in the anaerobic digestion of pulp and paper sludge *Journal of Hazardous Materials* **170**(1) pp 366-73

- [5] Lawler D F, Chung Y J, Hwang S J and Hull B A 1986 Anaerobic digestion: effects on particle size and dewaterability *Journal of Water Pollutant Control Federal* **58**(12) pp 1107-17
- [6] Bala S S, Yan S, Tyagi R D and Surampalli R Y 2010 Extracellular polymeric substances (EPS) producing bacterial strains of municipal wastewater sludge: Isolation, molecular identification, EPS characterization and performance for sludge settling and dewatering *Water Research* **44**(7) pp 2253-66
- [7] Molla A H and Fakhru'-Razi A 2012 Mycoremediation-a prospective environmental friendly technique of bioseparation and dewatering of domestic wastewater sludge *Environmental Science and Pollutant Research* **19**(5) pp 1612-19
- [8] Novak J T, Sadler M E and Murthy S N 2003 Mechanisms of floc destruction during anaerobic and aerobic digestion and the effect on conditioning and dewatering of biosolids *Water Research* **37**(13) pp 3136-44
- [9] Neyens E and Baeyens J 2003 A review of thermal sludge pre-treatment processes to improve dewaterability *Journal of Fermentation Bioengineering* **98** pp 51-67
- [10] Pei H Y, Hu W R, Li J and Chen L 2007 Dewaterability and particle size distribution of activated and digestion sludge *Environmental Science - China* **28**(10) pp 236-2241
- [11] Costerton J W, Irvin R T and Cheng K J 1981 The bacterial glycocalyx in nature and disease *Annual Reviews of Microbiology* **35** pp 299-324
- [12] Liao B Q, Allen D G, Droppo I G, Leppard G G and Liss S N 2001 Surface properties of sludge and their role in bioflocculation and settleability *Water Research* **35**(2) pp 339-50
- [13] Liu H and Fang H H P 2002 Extraction of extracellular polymeric substances (EPS) of sludge. *Journal of Biotechnology* **95**(3) pp 249-56
- [14] Frølund B, Palmgren R, Keiding K and Nielsen P H 1996 Extraction of extracellular polymers from activated sludge using a cation exchange resin *Water Research* **30**(8) pp 1749-58
- [15] Chen Y G, Yang H Z and Gu G W 2001 Effect of acid and surfactant treatment on activated sludge dewatering and settling *Water Res.* **35**(11) pp 2615-20
- [16] He W Y, Yang H Z and Gu G W 2006 Acid treatment of waste activated sludge for better dewaterability *Environmental Pollution & Control* **28**(9) pp 680-83
- [17] APHA (American Public Health Association) 2005 *Standard Methods for the Examination of Water and Wastewater (21th ed.)* Washington, DC, USA
- [18] Wang J T and Fang J 2010 Biochemistry experiments *Science and Technology Press in Huazhong University Wuhan, China*
- [19] Yuan Y and Yang Z H 2003 Study on effect of surfactant and acid treatment on sludge dewaterability (in Chinese) *Sichuan Environment* **22**(5) pp 22, 1-8
- [20] Shao L M, He P P, Yu G H and He P J 2009 Effect of proteinss, polysaccharidess, and particle sizes on sludge dewaterability *Journal of Environmental Science* **21** pp 83-88
- [21] Forster C F 1971 Activated sludge surfaces in relation to the sludge volume index *Water Research* **5**(11) pp 861-870
- [22] Urbain V, Block J C and Manem J 1993 Bioflocculation in activated sludge: An analytic approach *Water Research* **27**(5) pp 829-38
- [23] Karr P R and Keinath T M 1978 Influence of particle size on sludge dewaterability *Journal of Water Pollutant Control Federal* **50** pp 1911-30
- [24] Houghton J I and Stephenson T 2002 Effect of influent organic content on digested sludge extracellular polymer content and dewaterability *Water Research* **36**(14) pp 3620-28
- [25] Novak J T, Goodman G L, Pariroo A and Huang J 1988 The blinding of sludge during filtration *Journal of Water Pollutant Control Federal* **60** pp 206-14
- [26] Seehra M S, Akkineni L P and Yalamanchi M 2012 Structural characteristics of nanoparticles produced by hydrothermal pretreatment of cellulose and their applications for electrochemical hydrogen generation *International Journal of Hydrogen Energy* **37** pp 9514-23