Factors Affecting the Mechanical Deep Dewatering of Sludge from Wastewater Treatment

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Effects of pressure, dewatering time, and sludge cake thickness on the dewatering of wastewater sludge by the hydraulic dehydrator under the condition of adding CaO and $FeSO_4$ were analyzed using the response surface method (RSM). It was found that when the parameters of pressure, dewatering time, and sludge cake thickness were changed, the trends of dewatering papermaking sludge and municipal sludge were similar under the condition of raw sludge with 3% CaO and 3% $FeSO_4$. Specifically, the increase of pressure and dewatering time promotes the dewatering effect of wastewater sludge, and the thinner the sludge cake is, the better the dewatering effect. The water content can be affected by the change of pressure, dewatering time, and sludge cake thickness. In response surface analysis, the model F-value and coefficient of determination (R^2) were 541.43 and 0.9986, respectively, indicating high significance and good correlation. In the model, the change of pressure, dewatering time, and sludge cake thickness affected the water content of paper sludge. Particularly, the increase of pressure and compression time enhanced the dewatering efficiency. The thinner the sludge cake was, the better the dewatering effect of paper sludge was.

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Keywords: Wastewater sludge; Mechanical dewatering; Pressure; Dewatering time; Sludge cake thickness

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INTRODUCTION

With the rapid development of industrialization and modernization, it is inevitable that large numbers of water sources are being used, and the by-product sludge produced by wastewater treatment plants has increased rapidly in recent years (Li *et al.* 2020). This has brought great pressure to human society and the environment (Wang *et al.* 2017). Based on the data released by the National Bureau of Statistics, the annual production of wastewater sludge in China has reached 60 million tons and is expected to reach 90 million tons by 2025 (Bian *et al.* 2021). The composition of wastewater sludge is complex, containing microbial pathogens, proteins, heavy metals, persistent organic matter, and other substances (Cao *et al.* 2021). If not properly treated, it will generate serious impact on human beings and the environment (Sharma *et al.* 2022).

As is well known, the paper industry consumes a lot of water. According to a report released by the Indian Paper Manufacturers Association, the average paper consumption in the world is 57 kg, and it is expected that by 2025, the average paper consumption in India will reach 17 kg (IPMA 2020). According to Latorre *et al.* (2007), every metric ton of paper produced will produce up to 700,000 cubic meters of wastewater. Hubbe *et al.* (2016) describes the various unit operations of a typical pulp and paper mill wastewater treatment plant, as well as the effects of different sludge dewatering and thickening operations and chemical treatment on sludge dewatering. Pulp and paper manufacturing facilities commonly consist of two parts, namely pulping and paper making. Accordingly, the wastewater sludge source can be divided into two parts: one is the pulp residue after the pulping process, in which the raw material is converted into fibers. The other source of sludge content is the wastewater from the papermaking process after being screened by the inclined screen, initial sedimentation, anaerobic process, aeration, secondary sedimentation tank, and other steps. As papermaking sludge contains lignin, cellulose, pathogens, insect eggs, and other components, it is susceptible to rotting, low density, large volume, and so on, making it difficult to treat (Zhang 2019). In addition to cellulose, hemicellulose, and lignin, papermaking sludge also commonly includes fillers, coagulants, and other matter. Considering that, it belongs to the category of an industrial sludge. Compared with the municipal wastewater treatment plant of the same scale, its output is 5 to 10 times that of municipal sludge. As a typical industrial sludge, paper sludge is generally a mixture of activated sludge and deinked sludge or primary sludge. Jiang (2010) determined the contents of cellulose, hemicellulose, protein, and lipid present in chemical pulping sludge to be 25.77%, 5.86%, 1.52%, and 2.74%, whereas in a deinking sludge, those values were 11.99%, 3.92%, 1.78%, and 1.11%, respectively. Among them, cellulose accounted for 20% to 50% of organic matter content in paper sludge. Therefore, in some studies (Zhang *et al.* 2013), cellulase was used to condition paper sludge, thus improving its dewatering effect.

Wastewater sludge is a stable colloidal system, and its moisture distribution has a great influence on the dewatering of wastewater sludge (Deng *et al.* 2011). Within such sludge, bound water (BW) is the water attached to the surface of wastewater sludge flocs. Through Extracellular Polymeric Substances (EPS), a class of polymers that allows particles outside cells to bind together and stick to substrates, they are embedded in the substrate of flocs, where water is difficult to remove in microbial cells. This has become one of the main bottlenecks of wastewater sludge dewatering (Mahmoud *et al.* 2016; Wu *et al.* 2020). The mechanical dewatering method, which physically removes water from wastewater sludge, has been widely used in the dewatering process of wastewater treatment plants. Apart from that, the traditional belt filter press, centrifuge, spiral filter press, plate and frame filter press, and other mechanical dewatering equipment are adopted in the dewatering process of wastewater sludge, and the water content of wastewater sludge usually drops to about 80% (Cao *et al.* 2021). The water content of wastewater sludge can be further reduced to about 65% by adding chemical agents (such as polyaluminum chloride, polyacrylamide, *etc.*) (Li *et al.* 2021). When the solid content of wastewater sludge after dewatering reaches more than 40%, it is said to have reached deep dewatering, and it is a major challenge to move the water content of wastewater sludge into the category of deep dewatering (Hu *et al.* 2021).

Deep dewatering of wastewater sludge has been studied in recent years, when the most widely used way in the wastewater treatment plant is to flocculate modified wastewater sludge through pretreatment, and then mechanical dewatering equipment is selected for dewatering, so as to achieve a deep dewatering effect. Here, it should be noted that commonly used pretreatment methods include electroosmotic dewatering, vacuum preloading, and chemical conditioning (Zhang *et al.* 2022). Rao *et al.* (2022) found through a coupling experiment of electric field and mechanical dewatering that applying electric field to wastewater sludge could open the pores of wastewater sludge and prevent blockage. The effect of mechanical dewatering after electroosmotic dewatering was found to be better than that of mechanical dewatering before electric dewatering. Kim *et al.* (2020) increased mechanical deep dewatering by thermal hydrolysis pretreatment. They discovered that the change of physical and chemical properties of wastewater sludge was related to water dewatering, and factors including thermal hydrolysis degradation of wastewater sludge and formation of refractory organic materials had an important impact on mechanical deep dewatering. The coupling dewatering process of vacuum preloading and mechanical dewatering is effective for the dewatering of wastewater sludge. Guo *et al.* (2022) conducted a coupling experiment between vacuum field and mechanical pressure field. It was hypothesized that mechanical pressure field would provide a high power for water migration; the vacuum field filter cake would offer traction, and materials with different pore results and particle size distribution would affect mechanical dewatering effect. By using additives such as NFC, cationic starch, colloidal silica and cationic polyacrylamide, Barrios *et al.* (2023) studied the addition sequence of the wet end system of papermaking and found that the interaction between the additives is irreversible, and their addition sequence affects the papermaking operation (retention, drainage, and flocculation) and paper properties. Their experimental results show the importance of stirring conditions, and NFC treatment with optimized levels of cationic starch and silica gel as drainage promoting additives can obtain good retention, drainage, moderate fiber flocculation and paper strength.

To investigate the influence of pressure, dewatering time, and sludge cake thickness on the dewatering performance of wastewater sludge, in this paper, deep dewatering of wastewater sludge was conducted to analyze the influence of pressure, dewatering time, and sludge cake thickness on the water content of wastewater sludge before and after conditioning, and the response surface method was adopted to further explore the interaction of pressure, dewatering time, and sludge cake thickness. In addition, the corresponding mathematical model was established to clarify the relationship between the three factors and the deep dewatering performance, reveal their influence on the deep dewatering performance of wastewater sludge, and determine the optimal deep dewatering parameters of wastewater sludge. This was accomplished with optimization experiments, providing reference and guidance for the experimental conditions of mechanical deep dewatering and engineering applications, which is of great significance for reducing wastewater sludge dewatering.

MATERIALS AND METHODS

Sludge Sample

The municipal sludge samples were taken from the raw sludge of a wastewater treatment plant in Dongguan. After being pre-compressed and dehydrated by a centrifugal dewatering machine, the municipal sludge samples with water content of 81.3% were collected. Paper sludge samples were obtained from a paper factory in Jiangmen City and the water content of the original sludge was 76.3% after pre-dewatering by belt dewatering machine and stored at 4 ℃ for no more than 3 days. In addition, water content, pH, and zeta potential were evaluated. In addition, X-ray fluorescence tests were carried out in order to estimate the contents of minerals likely to be present in the papermaking sludge and municipal sludge.

Experimental Equipment

The commonly used mechanical dewatering equipment, such as belt dehydrators and filters, removes water from wastewater sludge with the help of shear stress generated by the winding of press rolls and press cloth. It is characterized by thin sludge cake thickness, short dewatering time, and low pressure. The plate and frame dehydrator is used to send wastewater sludge into the filter chamber through high pressure pumps, and the water of wastewater sludge is separated from the filter cloth through the pressure difference. In terms of the characteristics, that kind of method is featured with high pressure, large sludge cake thickness, and long dewatering time.

As for mechanical dewatering equipment, a sludge hydraulic dewatering machine made by the authors' laboratory was used to study the deep dewatering of municipal sludge and papermaking sludge, and its structure is shown in Fig. 1. The equipment is composed of the display and control system (1), filter press system (2), hydraulic system (6), hydraulic cylinder (3), position sensor (4), *etc*. Among them, the press filtration system consists of an upper outlet (7), an upper filter screen (8), an upper gland (9), a sludge chamber (10), a lower filter screen (11), and a lower outlet (12). Regarding the filter screen, plate and frame filter press polyester filter cloth 630 is adopted, and it has the characteristics of acid resistance, weak alkali resistance, wear resistance, corrosion resistance, good recovery, low electrical conductivity, and so on.

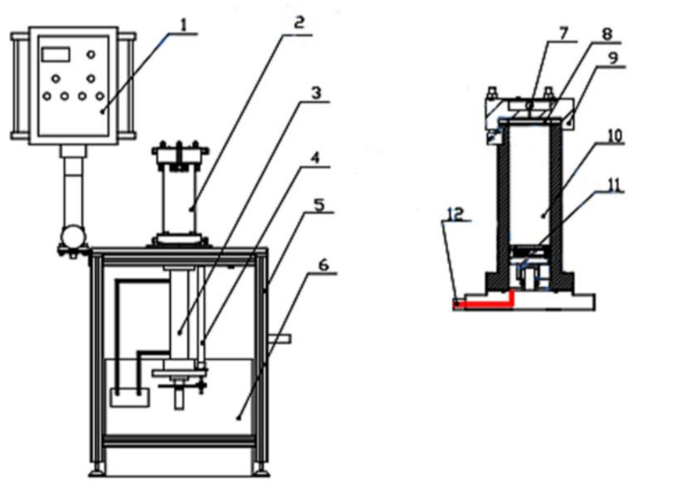


Fig. 1. Hydraulic sludge dewatering device

Experimental Methods

The sludge samples were taken, weighed to 120 g, and placed in the sludge chamber of the hydraulic dehydrator. The initial sludge cake thickness of the municipal sludge was

15.5 mm, and the thickness of the papermaking sludge was 19 mm. The hydraulic dehydrator was started for dewatering. During the dewatering process, the sludge discharged water with the increase of pressure. The pressure of 1.5 MPa was used as the initial value, and the maximum pressure was set at 5.5 MPa. The dewatering time was 5 min as the initial value and 30 min as the final value. The sludge cake thickness is taken as the higher value of the change of sludge based on the limit value of pressure and dewatering time. Furthermore, the influence of mechanical dewatering parameters on the dewatering of sludge under different pressure, dewatering time, and sludge cake thickness was evaluated based on the water removed by dewatering equipment and the moisture content measured by sludge cake.

Analysis Method

An electronic digital weighing scale was used to measure the mass of sludge cake and the mass of water. The moisture content of sludge cake was measured by drying water in a drying oven set at 105 °C. Origin2021 (OriginLab) software was utilized to process the collected experimental data and make the graphs. Design Expert8.0.6 (Stat-Ease) software was employed to design experiments and optimize and verify the influence of mechanical dewatering factors.

RESULTS AND DISCUSSION

Results of tests on the initial sludge samples are shown in Table 1.

Table 1. Basic Properties of Sewage Sludge Samples

Sample	Moisture Content (%)	pH	Zeta Potential (mV)	Oxide Content (%)						
Paper sludge	76.32	7.26	-17.4	CaO	Al_2O_3	Fe_2O_3	SiO_2	SO_3	P_2O_5	MgO
				27.49	10.29	4.43	3.83	3.12	1.45	1.25
Municipal sludge	81.34	8.50	-24.1	Al_2O_3	SiO_2	P_2O_5	Fe_2O_3	SO_3	CaO	K_2O
				22.22	17.75	6.27	4.97	2.11	1.76	1.30

In the detection of the basic properties of paper sludge and municipal sludge, the pH of paper sludge is acidic, the municipal sludge is alkaline, and the Zeta potential detection is negative on the surface. The composition of CaO and Al_2O_3 in paper sludge accounted for the largest proportion, and the composition of Al_2O_3 and SiO_2 in municipal sludge accounted for the largest proportion. The results are consistent with the presence of calcium carbonate particles in paper mill sludge, while there appears to be a large amount of clay in urban sludge samples.

Effect of Pressure Change on Dewatering of Wastewater Sludge

Figure 2 shows the effect of pressure changes on the dehydrated water amount of wastewater sludge and the moisture content of sludge cake.

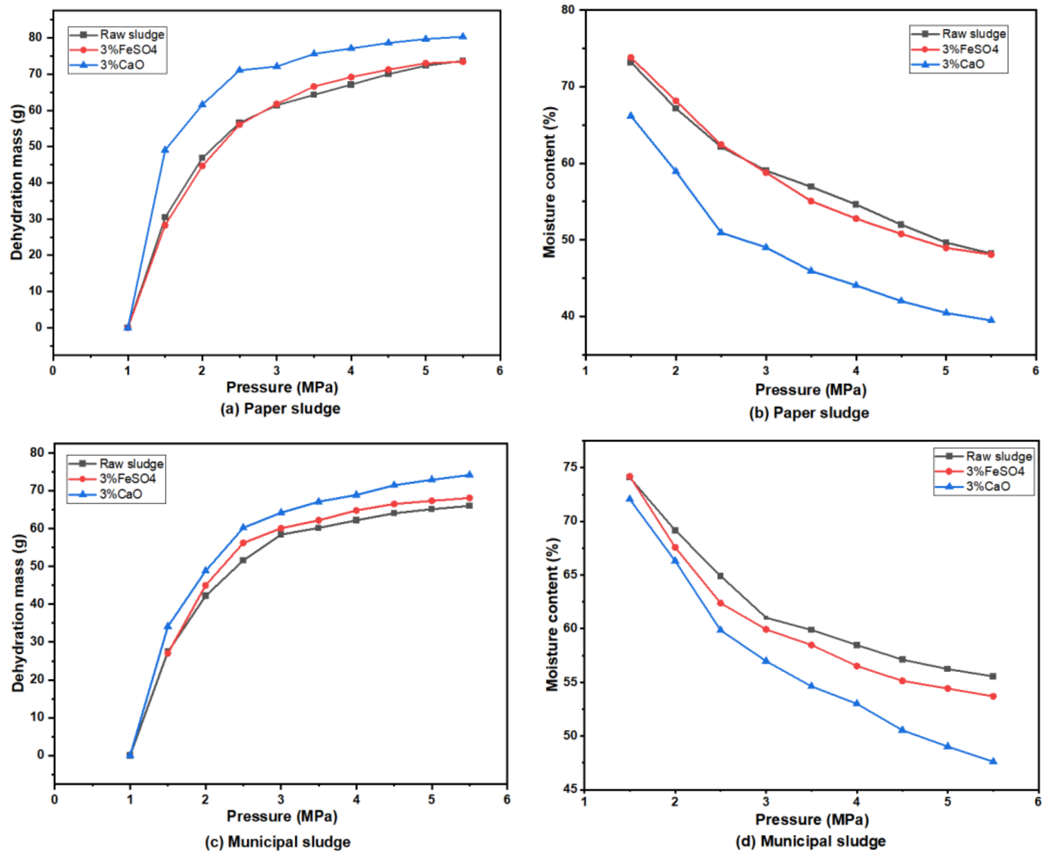


Fig. 2. Effect of pressure change on sewage sludge dewatering

The influence of pressure change on the dewatering of wastewater sludge was observed. Under different pressure conditions, the quality of water removed from wastewater sludge was closely related to the water content. Figures 2(a) and 2(c) show the variation curves of paper sludge dewatering and municipal sludge dewatering with pressure. It can be seen that with the increase of pressure, the dewatering rate of paper sludge and municipal sludge changed from slow to more rapid and tended to be stable at longer durations. Figures 2(b) and 2(d) present the curves concerning water content of papermaking sludge and municipal sludge changing with pressure. The charts display that the water content of papermaking sludge and municipal sludge decreased to different degrees under the conditions of raw sludge, 3% CaO and 3% $FeSO_4$; the decreasing trend was first fast and then slow and tended to become stable because with the increase of the wastewater sludge pressure; then the free water part was rapidly discharged. When the water had been discharged to a certain extent, the dewatering effect of the pressure change on the wastewater sludge began to decline, and finally reached a stable level. The water content showed a rapid decrease and then tended to be stable.

From the change in water content of paper sludge and municipal sludge with pressure, it can be seen that the water content of paper sludge under the condition of adding 3% CaO was the lowest, but that of paper sludge under the condition of raw mud dropped to about 50%, because the paper sludge itself contains a lot of cellulose, hemicellulose, filler, and other substances, which form the skeleton construction in the process of pressure, thus being conducive to the release of water. It is worth noting that the variation curves concerning dewatering and water content of paper sludge and municipal sludge under the condition of raw sludge, 3% CaO and 3% $FeSO_4$ were similar, indicating that the change of pressure in the process of mechanical dewatering affected the water content of wastewater sludge.

Effect of Dewatering Time on Dewatering of Wastewater Sludge

The effect of dewatering time on the dehydrated water amount of wastewater sludge and the moisture content of sludge cake is shown in Fig. 3.

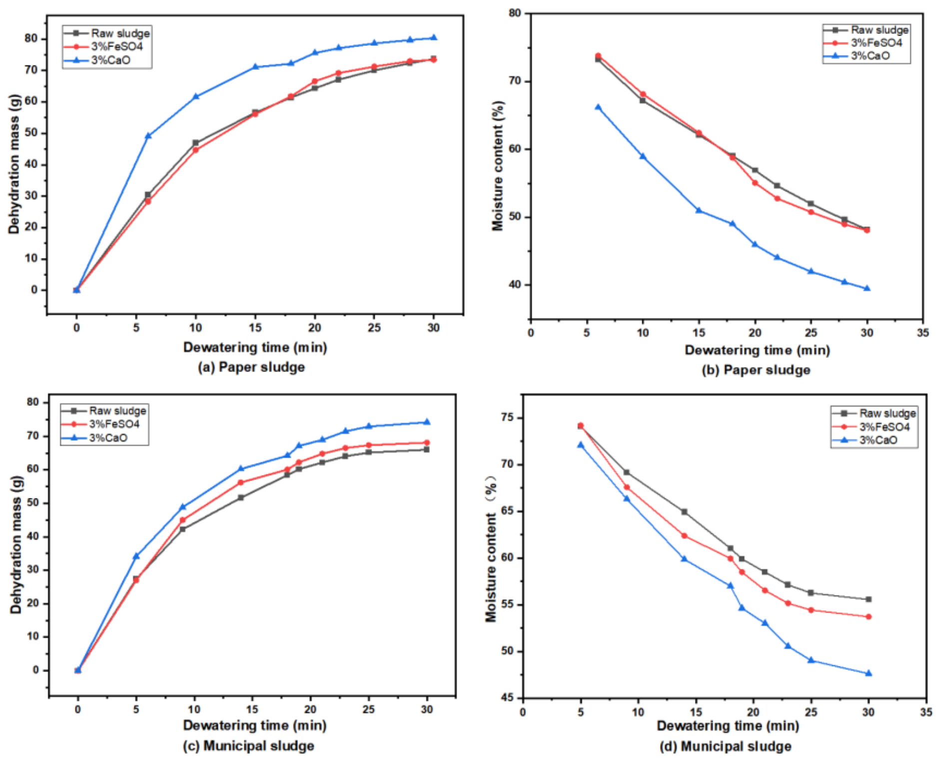


Fig. 3. Effect of dewatering time variation on sewage sludge dewatering

In the experiment, the dewatering amount and water content of wastewater sludge under compression were adjusted to reflect the influence of dewatering time. The moisture content of wastewater sludge under the condition of raw sludge, 3% CaO, and 3% $FeSO_4$ was similar with the dewatering time. Figures 3(a) and 3(c) show the variation curves of paper sludge and municipal sludge dewatering quantity with dewatering time. It can be observed that the quantity of water released from paper sludge and municipal sludge changed first quickly and then slowly, and finally became stable. Figures (b) and (d) display the variation curves about water content of papermaking sludge and municipal sludge with dewatering time. It can be observed that the change of water content showed a declining trend. It was first fast and then slow because under constant pressure of wastewater sludge, with the increase of dewatering time, dehydration speed is from fast to slow. In this case, continuing to increase the dewatering time of wastewater sludge dewatering did not have a further significant effect, and a stable condition gradually became established.

The dewatering effects of adding raw mud, 3% CaO, and 3% $FeSO_4$ to papermaking sludge were higher than that of municipal sludge. Makinen *et al.* (2013) studied the effects of recovered fibers and fine components on the dewatering performance of the sludge, and the results showed that the dewatering ability of the cellulose in the sludge became worse after extraction, indicating that the fiber in the papermaking sludge could improve the compressibility of the sludge. During the process of paper sludge and municipal sludge affected by the change of dewatering time, the curves of dewatering water and moisture content of raw sludge with 3% CaO and 3% $FeSO_4$ under the conditions of compression time were close to each other, suggesting that dewatering time is one of the principal factors affecting the moisture content of wastewater sludge in the process of mechanical dewatering.

Effect of Sludge Cake Thickness Change on Dewatering of Wastewater Sludge

The effect of sludge cake thickness on sludge dewatering and sludge cake moisture content is shown in Fig. 4.

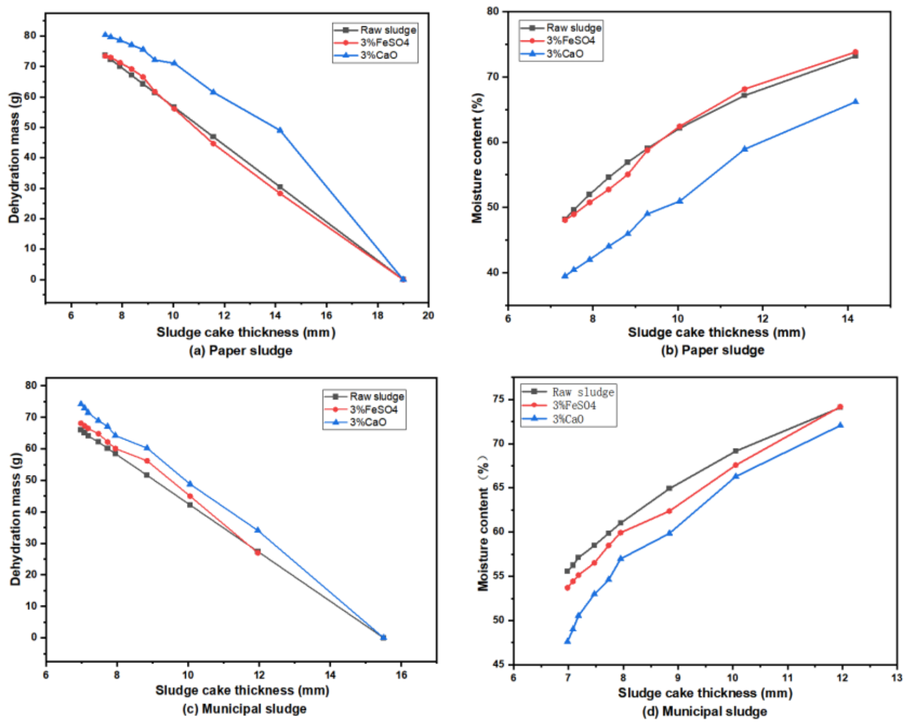


Fig. 4. Effect of thickness change of sludge cake thickness on dewatering of sewage sludge

Figures 4(a) and 4(c) show the variation curves of paper sludge and municipal sludge dewatering as a function of sludge cake thickness. It can be seen that the thinner the sludge cake, the higher was the dewatering. Figures 4(b) and 4(d) display the variation curves of paper sludge and municipal sludge moisture content with sludge cake thickness. As sludge cake thickness increased, the moisture content also increased rapidly. This is consistent with a mechanism whereby the thin sludge cake is conducive to the dewatering of wastewater sludge, and the thicker the sludge cake is, the thicker the barrier layer is formed, which is not conducive to dewatering. The moisture content of the papermaking sludge was lower than that of municipal sludge because the cellulosic fibers provided a skeleton function in dewatering, forming the dewatering channels, so that water can be better discharged. The dewatering and water content of papermaking sludge and municipal sludge showed similar curve trends with the change of sludge cake thickness, both of which displayed that the dewatering volume decreased and the water content increased with the increase of sludge cake thickness, revealing that sludge cake thickness had a great change on the water content in the process of mechanical dewatering, and the greater the sludge cake thickness, the slower and less complete was the dewatering process.

EXPERIMENT OPTIMIZATION

The effect of mechanical dewatering on paper sludge and municipal sludge was analyzed. The moisture content of raw sludge and municipal sludge was similar to that of raw sludge with 3% CaO and 3% $FeSO_4$. Therefore, paper sludge was selected as the evaluation index.

Optimization of Experimental Design

Design Expert software was used for experimental design. According to Box-Behnken design principle, moisture content was taken as the response value, and pressure, dewatering time and sludge cake thickness were selected as independent variables A, B and C, respectively, to analyze their influence on moisture content. The optimized experimental design and results are shown in Table 2.

Table 2. Design and Results of Box-Behnken Experiment

Number	Factor A	Factor B	Factor C	Response Value
	Pressure (MPa)	Dewatering Time (min)	Sludge cake Thickness (mm)	Moisture Content (%)
1	3.50	5.00	20.00	68.81
2	3.50	30.00	5.00	51.01
3	1.50	5.00	12.50	71.51
4	5.50	30.00	12.50	53.84
5	1.50	17.50	5.00	59.94
6	3.50	30.00	20.00	60.37
7	3.50	5.00	5.00	59.26
8	1.50	17.50	20.00	69.41
9	5.50	17.50	5.00	51.73
10	1.50	30.0	12.50	62.85
11	3.50	17.50	1250	61.04
12	3.50	17.50	12.50	60.94
13	3.50	17.50	12.50	61.20
14	.50	17.50	12.50	61.82
15	5.50	5.00	12.50	62.85
16	3.50	17.50	12.50	61.39
17	5.50	17.50	20.00	60.37

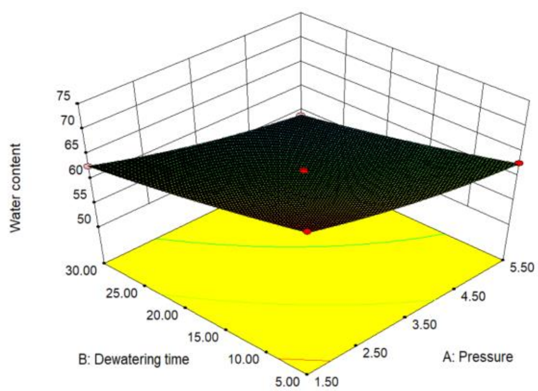
Analysis of Experimental Significance

The regression coefficient significance analysis results concerning the quadratic simulation equation of the optimization experiment with water content as the response value are shown in Table 3. From single factor analysis, A, B, and C had a significant linear relationship with moisture content, while C^2 had a significant curved surface effect on water content.

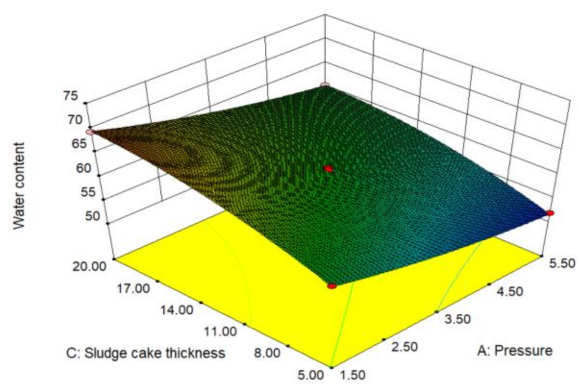
Table 3. Significance Analysis of Regression Coefficient of Water Content Quadratic Simulation Equation

Factor	Parameter Estimation	Degree of Freedom	Standard Error	F-value	Prob (P)＞F
Intercept	43.51	1	0.063		
A-Pressure	-2.48	1	0.05	1512.63	＜0.0001
B-Dewatering time	-1.68	1	0.05	1464.51	＜0.0001
C-sludge cake thickness	0.73	1	0.05	1700.03	＜0.0001
AB	-0.45	1	0.71	0.03	0.5986
AC	0.04	1	0.71	1.71	0.2324
BC	0.18	1	0.71	0.09	0.7734
A^2	1.27	1	0.069	41.14	0.0004
B^2	0.70	1	0.069	10.12	0.0154
C^2	0.056	1	0.069	152.07	＜0.0001

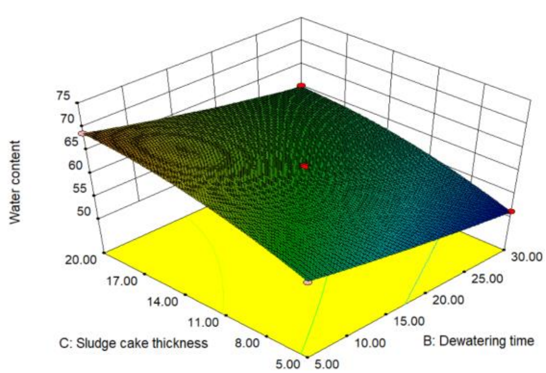
Response surface graphs generated by the interaction among independent variable factors, namely pressure, dewatering time, and sludge cake thickness are displayed in Fig. 5.



(a) Pressure-Dewatering time response surface



(b) Pressure-Sludge cake thickness response surface



(c) Dewatering time-sludge cake thickness response surface

Fig. 5. Moisture content response diagram

The interaction effect diagrams of mechanical dewatering pressure, dewatering time, and sludge cake thickness on water content of papermaking sludge are shown in Fig. 5. Figure 5(a) represents the influence of pressure and dewatering time on water content, whereas Fig. 5(b) displays the influence of pressure and sludge cake thickness on water content. It can be observed that water content of papermaking sludge decreased with the decrease of sludge cake thickness and the increase of pressure, implying that water content is positively correlated with the influence of sludge cake thickness and negatively associated with the influence of pressure. Figure 5(c) shows the influence of dewatering time and sludge cake thickness on water content. It can be observed that water content of papermaking sludge decreased with the decrease of sludge cake thickness and the increase of dewatering time, manifesting that water content was positively related to sludge cake thickness and negatively connected with dewatering time. Thus, the water content of paper sludge varied dramatically under different parameters of pressure, dewatering time, and sludge cake thickness, which makes a vital influence on the dewatering effect of paper sludge.

When the parameters of pressure, dewatering time, and sludge cake thickness change in the process of mechanical dewatering, the water content of wastewater sludge changes with each other. When the pressure, dewatering time and sludge cake thickness adjust to each other, wastewater sludge can flexibly meet the corresponding water requirements. In practice, according to the cost, specific requirements and other conditions, pressure, dewatering time, and sludge cake thickness can complement each other. Compared with the traditional plate and frame type dewatering or belt type dewatering modes, this method has obvious advantages.

Optimization Scheme

The results demonstrate that pressure, dewatering time, and sludge cake thickness have important effects on the dewatering effect of papermaking sludge. The water content is now set to the range 51.0% to 71.5%. The software was employed to calculate the parameter scheme of pressure, dewatering time, and sludge cake thickness. Then, it provided 43 groups of optimization schemes, and 5 groups of experimental conditions were randomly selected for verification and comparison. The results are shown in Table 4.

Table 4. Optimization Scheme and Experimental Results

Number	Pressure (MPa)	Dewatering Time (min)	Sludge Cake Thickness (mm)	Moisture Content (%)	
				Projection	Actual
1	5.50	30.00	5.00	50.99	51.23
2	5.50	30.00	12.5	54.02	53.49
3	5.50	17.50	5.00	51.58	51.83
4	3.50	30.00	12.50	53.92	54.20
5	5.50	17.50	12.50	54.88	54.76

As can be seen from Table 3, the predicted water content of sludge cake in 5 randomly selected dewatering schemes was 50.99%, 54.02%, 51.58%, 53.92%, and

54.88%, respectively. The actual values of pressure, dewatering time and sludge cake thickness set according to the dewatering plan were 51.2%, 53.9%, 51.8%, 54.2% and 54.8%. It can be seen from the experimental results that the actual value of sludge cake moisture content was close to the predicted value, indicating that pressure, dewatering time, and sludge cake thickness had significant effects on the water content in the mechanical dewatering process. During the actual production process, the comparison of different schemes can be comprehensively considered by analyzing pressure, dewatering time, energy consumption of sludge cake thickness during the process of dewatering, productivity, and other factors.

CONCLUSION

The changes of pressure, dewatering time, and sludge cake thickness parameters are adjustable in mechanical dewatering, and the change trend concerning the change curve of water content of wastewater sludge under different conditions is similar when changing its parameters. Specifically, the increase of pressure and dewatering time improves the dewatering effect, and a thin sludge cake has a positive effect on mechanical dewatering. The results indicated that the change of pressure, dewatering time, and sludge cake thickness had great correlation with the water content of sludge mechanical dewatering. In mechanical deep dewatering, for different types of wastewater sludge, the parameters of adjusting pressure, dewatering time, and sludge cake thickness exhibited similar trends to the dewatering effect. The difference is that under the same mechanical dewatering and conditioning conditions, the water content of paper sludge is lower than that of municipal sludge. The reason is that paper sludge contains cellulose, hemicellulose, filler, and other materials that can form skeleton construction in mechanical dewatering.

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