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Centrifugal Reduction Treatment Process for High-Water-Content Sludge in Oilfield

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ABSTRACT

To ensure that injection water quality reaches the standard, oil field sewage stations adopt a continuous sludge dredging process to reduce the content of suspended solids and sand. A large amount of high-water-content oily sludge is produced, which results in increased costs of transportation and subsequent harmless treatment. Therefore, a sludge reduction treatment is necessary. A set of centrifugal reduction processes for oily sludge was designed in this study, with the horizontal screw centrifuge as the key piece of equipment. In the laboratory, CPAM flocculant was screened. In the field test, the effects of four factors rotational speed, differential speed, the feeding quantity of sludge, and flocculant dosage on the reduction effect were determined. The results show that when the rotational speed is higher, the differential speed is lower, and the feeding quantity of sludge remains lower, and the flocculant dosage remains higher, after treatment, the water content of the sludge is lower and the solid content of the sludge is higher. The optimal parameters of the centrifugal reduction process were determined using an orthogonal experimental design as follows: rotational speed 2,607 rpm, differential speed 8 rpm, the feeding quantity of sludge 7 m^3/h, and flocculant dosage 100 g/m^3. After treatment, the average water content of the sludge decreased from 92.75% to 56.57%, and the average solid content of the sludge increased from 2.30% to 36.72%. The split ratio of the water-outlet and sludge-outlet was in the range of 8.71:1 to 12.57:1, and the corresponding sludge reduction ratio was 89.70% to 92.63%, confirming successful sludge reduction.

INTRODUCTION

With the popularization of polymer flooding technology in oilfields, the suspended solids and sand contents in oilfields producing water have increased, placing an enormous amount of pressure on the sewage treatment system, causing substandard injection water quality and formation pollution. This has negatively influenced the oilfield development efficiency. These problems are effectively alleviated by the continuous sludge dredging process in the sewage treatment system, and shortening the dredging cycle. However, the water content of sludge dredged from the sewage treatment system can be up to 90%, which requires a significant capacity increase in the accumulation, transportation, and subsequent treatment of sludge. If this sludge is not rapidly and effectively treated, risks to safety and the environment increase. Firstly, the crude oil component in the sludge easily volatilizes, which makes the total hydrocarbon concentration exceed the standard in the production area. Secondly, many toxic and hazardous wastes are present in the sludge, such as petroleum, sulfide, benzene series, and phenols.

At present, the harmless treatment methods of oily sludge mainly include ultrasonic pretreatment, incineration, pyrolysis, and extraction (Leonardo et al. 2012, Galil et al. 2015, Wang et al. 2013). Ultrasonic treatment has a sponge and local heating effect on sludge, which can increase sludge dewatering (Hu et al. 2014, 2016, Gao et al. 2015, Zhang et al. 2013). Short-term and low-intensity ultrasonic treatment can simultaneously reduce the sludge water content to below 85% and reduce the flocculant dosage by 25%–50%. Incineration obviously reduces the volume of sludge and eliminates pathogenic bacteria, and it is the primary method of sludge harmless treatment (Braguglia et al. 2016, Heidarzadeh et al. 2010, Nima et al. 2009). The cost of incineration is high, and burning one ton of sludge uses 18.5 kg of fuel. When oxygen is sufficient, pyrolysis is used to convert the heavy components in oily sludge into light components, and then the volatile and semi-volatile organic compounds are recovered (Wu et al. 2003, Hou et al. 2012, Marcelo et al. 2016). Using the different solubilities of the solutes in the solvent, the extraction method can be used to extract the lighter oil components, and the residual heavy oil components are combined with other processes for treatment (Kumar et al. 2015, Liang et al. 2014, Zubaidy et al. 2010, Hu et al. 2015, Kumar et al. 2013). These sludge harmless treatment methods are expensive. Therefore, it is necessary to reduce the water content in sludge that is produced by

Table 1: Analysis of crude oil components in sludge.

Crude oil component	Content (%)
saturated hydrocarbons	50.76-51.97
aromatic hydrocarbon	16.03-17.36
non-hydrocarbon	7.91-8.56
asphaltene	13.68-14.27
colloid	9.09-10.15

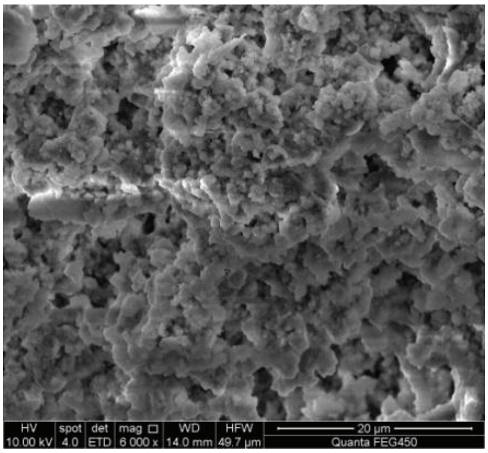

Fig. 1: Sludge micro-morphology (6,000 magnification).

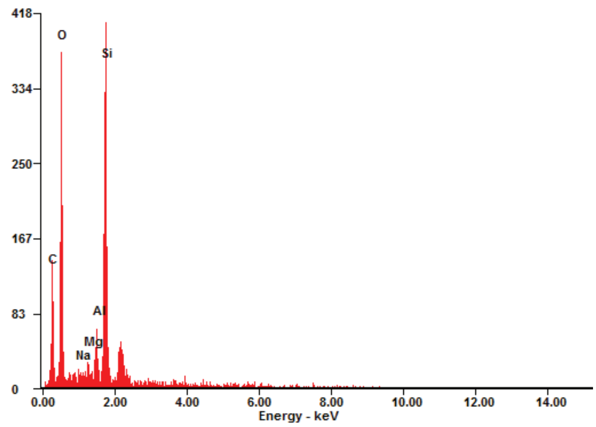

Fig. 2: Energy spectrum of spectrometer.

the continuous sludge dredging process. Such a method would help reduce transportation costs and the amount of subsequent processing, and ensure the efficient operation of harmless treatment processing and devices.

Oilfield sewage stations are common and widely distributed. Considering treatment capacity, energy consumption, and costs, the conditioning-mechanical separation method is used for sludge reduction treatment. By adjusting the characteristics and arrangement of the sludge solid particles, the method can ensure the sludge solid particles are suitable for mechanical separation, which can remarkably improve the dehydration effect. This method is often applied when the water content of sludge is 30%-70%. However, the water content of sludge dredged from the sewage treatment system can reach 90%. Therefore, a centrifugal reduction process must be designed to manage high-water-content sludge in oilfields. This process could be employed to determine the factors influencing the reduction effect and to optimize the process' parameters.

OILY SLUDGE COMPONENT ANALYSIS

In the continuous sludge dredging process, sludge samples were obtained from the sludge outlet of the gravity sedimentation tank. According to the analysis of the oil component in the sludge in Table 1, we found that the volatile organic compound content in the sludge was high. If not treated in time, the total hydrocarbon concentration of the ambient air in the production area may exceed the limit, posing a security risk. From the micro-morphology presented in Fig. 1, oily sludge is formed by the accumulation and cementation of fine particles, and the minerals within it show no regular morphology, with spherical calcium carbonate and amorphous silicon dioxide displaying a packing appearance. According to the analysis of the relative content of the elements (Fig. 2), the main elements of inorganic substances in oily sludge are Si, O, C and Al. Table 2 shows that the main inorganic substances in oily sludge were aluminosilicate (66.24%-67.64%) and carbonate (16.37%-18.29%), produced during the process of oilfield development, and iron oxide (11.21%-11.93%), due to the corrosion of pipelines and facilities in the process of transportation. These inorganic substances are characterized by high density and loose structure. Therefore, a good separation effect could be obtained by centrifugation.

CENTRIFUGAL REDUCTION PROCESS FOR OILY SLUDGE

According to the structure, working principle, and efficiency of factors influencing a horizontal screw centrifuge, the centrifugal reduction process for oily sludge was designed

Table 2: Analysis of inorganic components in sludge.

Inorganic component	Content (%)	Inorganic component	Content (%)
SiO_2	53.08-53.77	Na_2O	0.67-1.01
Al_2O_3	13.16-13.87	K_2O	0.72-0.88
Fe_2O_3	11.21-11.93	$SrSO_4$	0.34-0.46
$BaCO_3$	9.36-10.04	TiO_2	0.21-0.31
$CaCO_3$	3.89-4.42	ZnO	0.27-0.36
$MgCO_3$	3.12-3.83		

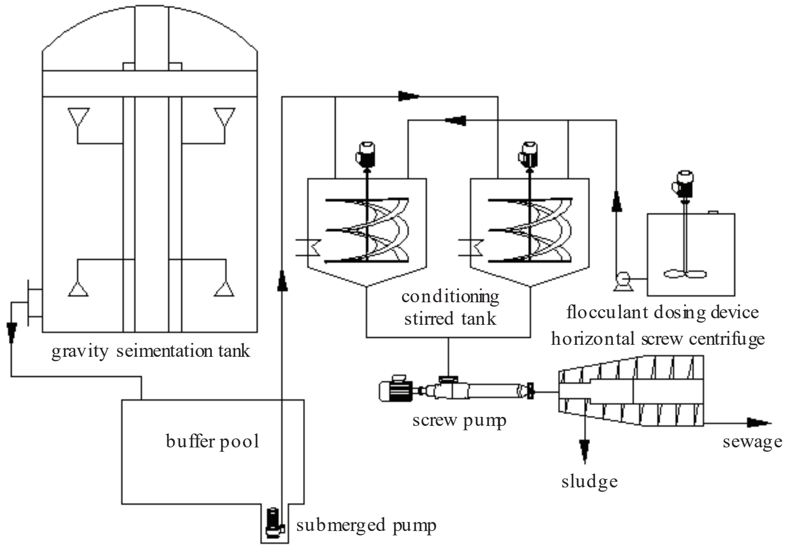

Fig. 3: Centrifugal reduction process for oily sludge.

as shown in Fig. 3. Here, pressurized-boiler hot water is applied to jet and strip oily sludge when artificial dredging is engaged, and sludge is then discharged to the buffer pool outside the gravity sedimentation tank. The submerged pump in the buffer pool delivers high-water-content sludge to the conditioning stirred tank to heat, mix, and homogenize it. Flocculant is added to the tank to create the suspended solids, and solids in the sludge flocculate reduce the fragmentation and dispersion of the solid phase during high-speed centrifugal treatment. Mixing in the tank can significantly reduce the required dosage of the flocculant. After centrifugal treatment, the water phase in the sludge is discharged into the recovery pool, and the concentrated sludge loading is outbound. Before treatment, the water content, oil content, and solid content of sludge were 92.9%, 4.43% and 2.67%, respectively.

SCREENING AND DOSAGE OF FLOCCULANT

Flocculant Screening

Adding flocculant in the centrifugal test helped with sludge dewatering, so it was necessary to screen the commonly used flocculants in the laboratory, including PAC, CPAM, and alum. The high-water-content sludge that is produced by a continuous sludge dredging process is a kind of suspension liquid, so the standard *Q/SY90-2007 Technical Requirements for Flocculant Used in Oilfield Water Treatment* was adopted to screen the flocculant (Zhao et al. 2007). The specific operation method was as follows. Take 500 mL of high-water-content sludge at a 50°C constant temperature and stir for 5 min at 11,000 rpm. Add 5 mL flocculant solution, so that the concentration is 100 mg/L, and mix the sludge and flocculant solution using inertia after the blender is closed. Then, pour the suspension liquid into the cylinder with a plug, and invert and shake the cylinder 60 times. After 15 min static settlement, use a pipetting gun to extract a sample from the central section. The absorbance was measured at the wavelength of 650 nm using a spectrophotometer, with distilled water as the reference. The following formula was applied to calculate absorbance decrease rate, and the specific results are given in Table 3.

$$R = (A_0 - A_1)/A_0 \times 100\% \quad \ldots(1)$$

Where, R is the rate of absorbance decrease after adding flocculant, A_0 is the absorbance of the blank suspension liquid, and A_1 is the absorbance of suspension liquid after adding flocculant.

The experimental results showed that compared with the other two kinds of flocculant, CPAM has a neat interface, fast settling speed, and high absorbance decrease rate. The positivey charged group of CPAM has a good electrical neutralization effect on the negatively charged organic colloids of sludge. Through its excellent polymer bridging and aggregation ability, CPAM prompts colloidal particles to gather into large pieces of flocs and obviously separates them from the suspension liquid. Therefore, CPAM was chosen for the field test.

Flocculant Dosage

A flocculant can be used to flocculate the dispersed particles in the sludge and enhance the solid-liquid separation effect with a centrifuge. The solid and water contents in sludge before and after the centrifugal treatment provides an evaluation index of the field test results. Using *the Device and Method for Measuring Oil or Water Content in Samples* that was published by the China University of Petroleum for reference, the assembled sludge testing device is shown in Fig. 4 (Zhang et al. 2012). The device, through the distributed tube, reads out the water content, and the solid content is obtained by Soxhlet extraction and dry weighing, after which the difference is obtained to determine the oil content.

As shown in Fig. 5, the change law of the flocculant dosage and the treatment effect was determined with a flocculant dosage of 100-350g/m^3, centrifuge rotational speed of 2,530 rpm, differential speed of 11 rpm, and feeding quantity of sludge of 6 m^3/h.

The sludge particles are negatively charged and repel each other. After the addition of the flocculant, the particles' potential decreases, and the particles attract each other to form flocs. Simultaneously, the adsorption and bridging action of the flocculant cause the small flocs to form larger flocs. This is beneficial to the solid phase separation under centrifugal action. Therefore, as shown in Fig. 5, with the increase in flocculant dosage, the water content of treated sludge decreases and the solid content of treated sludge increases. The dosage increases from 100 to 200 g/m^3, and the water content of sludge decreases sharply. When the dosage was within 200-350 g/m^3, the water content of sludge decreases slowly. When the dosage increases within 100-350 g/m^3, the solid content of sludge increases continuously. The sludge in the conditioning stirred tank is maintained at 60°C, which helps the flocculant play a better role in flocculation. Because the water viscosity is related to temperature, the higher temperatures reduce the water viscosity. This enhances the Brown exercise intensity of solid particles and oil-containing

Table 3: Flocculant screening.

Flocculant	Phase interface	Settling speed	Absorbance decrease rate (%)
PAC	neat	fast	45.01
CPAM	neat	fast	81.65
Alum	relatively neat	slow	25.97

Fig. 4: Oily sludge testing device.

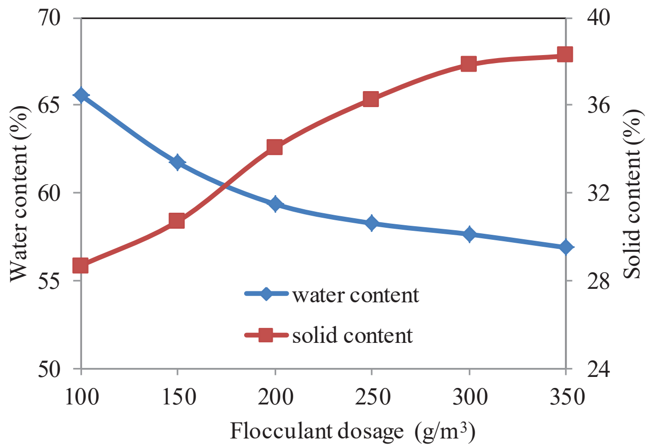

Fig. 5: Flocculant dosage on treatment effect.

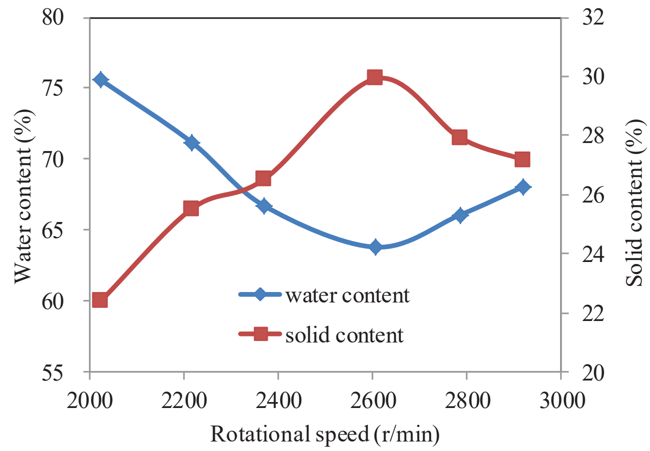

Fig. 6: Rotational speed on treatment effect.

colloidal particles, thus increasing the chance of collision and condensation.

CENTRIFUGE PARAMETERS TEST

Rotational Speed

The treatment effect of different rotational speeds on sludge in the same conditioning was studied. The samples were obtained 10 min after adjusting the speed to ensure that the sample corresponded to the rotational speed. The specific process parameters were as follows: centrifuge rotational speed 2000-3000 rpm, differential speed 10 rpm, the feeding quantity of sludge 5 m^3/h, and flocculant dosage 100 g/m^3.

Fig. 6 shows that when the rotational speed ranges from 2,000 to 2,600 rpm, with the increase in rotational speed, the sludge discharged from the sludge-outlet has a lower water content and a higher solid content. However, when the rotational speed is more than 2,600 rpm, the water content increases and the solid content decreases with the increase in rotational speed. This occurs because the flocs formed by flocculation are not stable and can be separated by an external force. The interior of the oily sludge is combined by the bridging action and Van der Waals forces, including flocculant, solid phase, and oil-contained colloidal particles. For the three as a whole, the density is slightly higher than the oil-water mixture. However, at the individual level, the density of oil-containing colloidal particles is lower than that of the flocculant. Therefore, with the increase in the centrifuge rotational speed, the centrifugal force caused by the density difference increases. When the centrifugal force is larger than the bridging action and Van der Waals forces

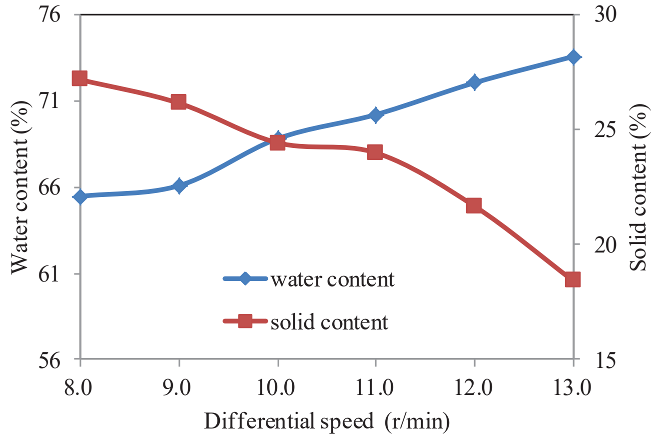

Fig. 7: Differential speed on treatment effect.

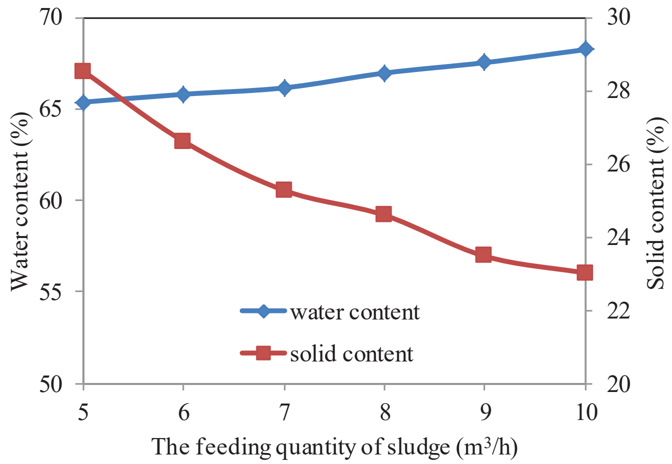

Fig. 8: The feeding quantity of sludge on the treatment effect.

that are between internal components of relatively stable flocs, the flocculation is weakened and the stable flocs are destroyed. Therefore, an excessively high rotational speed will result in a poor treatment effect.

Differential Speed

The speed difference of the rotary drum and screw conveyor push the solid phase to separate the solids and liquids. The magnitude of the differential speeds has an important influence on the treatment effect. As shown in Fig. 7, the change law of the differential speed and the treatment effect were determined under a differential speed of 8-13 rpm, rotational speed of 2,300 rpm, the feeding quantity of sludge 6 m^3/h, and flocculant dosage of 100 g/m^3.

In the test, with the increase in differential speed, the water content of the sludge increased and the solid content of sludge decreased after treatment. This occurred because the magnitude of the differential speed influences the amount of solids resulting from the centrifuge. If the differential speed is too high, the disturbance effect of the fluid in the rotary drum is strengthened. This strengthens the fluid scoured to the deposited solid phase on the inner wall of the rotary drum, thereby affecting the separation effect.

The Feeding Quantity of Sludge

The amount of sludge determines the processing load, which is the residence time of the sludge in the centrifuge, which influences the treatment effect. As shown in Fig. 8, the change law of the feeding quantity of sludge and the treatment effect were determined under the feeding quantity of sludge of 5-10 m^3/h, rotational speed of 2,370 rpm, differential speed of 11 rpm, and flocculant dosage of 150 g/m^3.

With the increase in the feeding quantity of sludge, the water content of the sludge increased and the solid content of sludge decreased after centrifugal treatment. The centrifugal force generated by the high-speed rotation of the rotary drum forces the solid phase to cling to the inner wall of the drum. Under the effect of the axial force of the spiral vane of the screw conveyor, sludge is tightly pressed to the drum cone and the solid phase is discharged from the sludge-outlet along the spiral flow path of the screw conveyor. With the increase in the feeding quantity of sludge, the residence time of the unit volume sludge in the centrifuge decreases, and the treatment effect worsens.

PROCESS OPTIMIZATION

Parameter Optimization

The combined action of the rotational speed, differential speed, the feeding quantity of sludge, and flocculant dosage determines the effect of the centrifugal treatment of oily sludge. The orthogonal experimental design method was used to optimize the process plan (Jean et al. 1999, Lin et al. 2005, Bo et al. 2004, Chang et al. 2001, Verma et al. 2010). The test scheme and results are shown in Tables 4-6.

After centrifugal treatment, the lower the water content and the higher the solid content of the sludge, the better the treatment effect. The calculation results for the ranges of water and solid contents are $R_{W\_A} > R_{W\_B} > R_{W\_D} > R_{W\_C}$ and $R_{S\_A} > R_{S\_B} > R_{S\_D} > R_{S\_C}$, respectively. Within the numerical range of the factor level, the range results show that the rotational speed is the main factor affecting the centrifugal treatment effect, and the other influential factors are the differential speed, the flocculant dosage, and the feeding quantity of sludge, in decreasing order. The factor level change of factor A influences the experimental result. The results of $k_{W\_A3} < k_{W\_A2} < k_{W\_A4} < k_{W\_A1}$ and $k_{S\_A3} > k_{S\_A2} > k_{S\_A4} > k_{S\_A1}$ show that A3 is the optimal factor level

Table 4: Factor levels table.

S. No.	A (rotational speed) (rpm)	B (differential speed) (rpm)	C (the feeding quantity of sludge) (m^3/h)	D (flocculant dosage) (g/m^3)
1	2023	8	5	100
2	2371	9	7	200
3	2607	11	10	250
4	2920	13		350

Table 5: Test scheme and results.

S. No.	A	B	C	D	Water content (%)	Solid content (%)
1	1	1	1	1	68.91	28.15
2	1	2	3	4	71.44	25.09
3	1	3	1	2	72.01	21.38
4	1	4	2	3	74.95	19.83
5	2	1	1	3	64.34	29.58
6	2	2	2	2	65.17	28.91
7	2	3	1	4	66.25	27.72
8	2	4	3	1	68.24	24.96
9	3	1	2	4	58.8	33.71
10	3	2	1	1	61.20	32.45
11	3	3	3	3	63.08	28.68
12	3	4	1	2	65.86	27.39
13	4	1	3	2	65.08	28.58
14	4	2	1	3	67.19	27.96
15	4	3	2	1	67.87	27.43
16	4	4	1	4	70.44	24.39

Table 6: The results of range calculation.

Index	Water content				Solid content			
Factors	A	B	C	D	A	B	C	D
K1	287.31	257.13	536.20	266.22	94.45	120.02	219.02	112.99
K2	264.00	265.00	266.79	268.12	111.17	114.41	109.88	106.26
K3	248.94	269.21	267.84	269.56	122.23	105.21	107.31	106.05
K4	270.58	279.49		266.93	108.36	96.57		110.91
k1	71.83	64.28	67.03	66.56	23.61	30.01	27.38	28.25
k2	66.00	66.25	66.70	67.03	27.79	28.60	27.47	26.57
k3	62.24	67.30	66.96	67.39	30.56	26.30	26.83	26.51
k4	67.65	69.87		66.73	27.09	24.14		27.73
R	9.59	5.59	0.33	0.84	6.95	5.86	0.64	1.74

of factor A (rotational speed). Similarly, B1, C2, and D1 can be identified as the optimal factor levels for factors B, C, and D, respectively. The best factor level combination of this test is $A_3B_1C_2D_1$, which means that the optimal operation scheme of this test is a rotational speed of 2,607 rpm, differential speed of 8 rpm, the feeding quantity of sludge of 7 m^3/h, and flocculant dosage of 100 g/m^3.

Process Stability Analysis

To examine the stability of the process, the optimal scheme was operated continuously for three hours. During this period, samples were taken five times each hour from the inlet, water outlet, and sludge outlet. The test results are given in Table 7. As shown in Fig. 9, the physical properties of the treated sludge were stable under these process parameters. The fluctuation in water content and solid content of the sludge discharged from the sludge outlet was small. After treatment, the average water content of sludge decreased from 92.75% to 56.57%, and the average solid content of sludge increased from 2.30% to 36.72%.

The split ratio is the ratio of the amount of fluid media flowing out from the water outlet and sludge outlet, which is a key parameter for evaluating centrifuge performance. The total mass flow of sludge that flows into the centrifuge through the inlet is defined as 1, and the mass flows of fluid medium discharged from the water outlet and sludge outlet are a and b. The mass conservation equations of oil, water, and solid phases are established:

$$1 \times W_{win\_w} = 1 \times a \times W_{wout\_w} + 1 \times b \times W_{sout\_w}$$
$$1 \times W_{win\_o} = 1 \times a \times W_{wout\_o} + 1 \times b \times W_{sout\_o}$$
$$1 \times W_{win\_s} = 1 \times a \times W_{wout\_s} + 1 \times b \times W_{sout\_s} \quad \ldots(2)$$

Where, W_{win_w} is inlet water content, W_{win_o} is inlet oil content, W_{win_s} is inlet solid content, W_{wout_w} is water outlet water content, W_{wout_o} is water outlet oil content, W_{wout_s} is water outlet solid content, W_{sout_w} is sludge outlet water content, W_{sout_o} is sludge-outlet oil content, and W_{sout_s} is sludge-outlet solid content.

The equations are overdetermined equations that the number of equations is greater than the number of unknowns. The least square method was used to calculate the equations in Lingo software, and the results show that the split ratio of the water outlet and the sludge outlet is in the range of 8.71:1 to 12.57:1, meaning the sludge reduction ratio is 89.70% to 92.63%. The aim of sludge reduction was thus achieved.

CONCLUSIONS

In this paper, we introduced a centrifugal reduction process for oily sludge using a horizontal screw centrifuge as the key piece of equipment, which is combined with a buffer pool, submerged pump, conditioning stirred tank, flocculant dosing device, and recovery pool. The flocculant was important in the field test, and according to the standard, the CPAM flocculant was screened from PAC, CPAM, and alum in the laboratory as the ideal flocculant. Field tests were conducted to analyze the factors influencing the centrifugal reduction process for oily sludge, including the rotational speed, differential speed, the feeding quantity of sludge and flocculant dosage. The results show that if the rotational speed is higher, the differential speed is lower, the feeding quantity of sludge remains at a lower level, and the flocculant dosage remains higher, which considerably reduces the water content and improves the solid content of sludge. The optimal parameters of the centrifugal reduction process were obtained through an orthogonal experimental design as follows: rotational speed 2,607 rpm, differential speed 8 rpm, the feeding quantity of sludge 7 m^3/h, and flocculant dosage 100 g/m^3. After treatment, the average water content of sludge decreased from 92.75% to 56.57%, and the average

Table 7: Sludge test results of process stability.

	Inlet			Water outlet			Sludge outlet		
S. No.	Water content (%)	Solid content (%)	Oil content (%)	Water content (%)	Solid content (%)	Oil content (%)	Water content (%)	Solid content (%)	Oil content (%)
1	92.10	2.11	5.79	97.26	0.97	1.77	56.11	36.67	7.62
2	92.23	2.79	4.98	97.64	1.09	1.27	55.06	38.04	7.30
3	92.52	2.16	5.32	97.52	0.81	1.67	56.18	35.72	8.51
4	92.88	2.39	4.73	97.86	0.83	1.31	56.08	37.41	6.91
5	93.16	2.73	4.11	97.17	1.27	1.56	58.05	38.04	4.31
6	92.41	2.19	5.40	97.57	0.79	1.64	55.92	37.56	6.91
7	93.27	2.06	4.67	97.97	0.68	1.35	58.13	37.08	5.19
8	93.42	2.29	4.29	98.09	0.75	1.16	57.27	36.44	6.69
9	91.53	2.69	5.78	97.15	1.07	1.78	54.96	38.23	7.21
10	92.76	2.15	5.09	97.52	0.95	1.53	55.19	35.93	9.28
11	92.80	2.37	4.83	97.47	0.86	1.67	58.49	37.46	4.43
12	93.53	2.01	4.46	97.43	0.93	1.64	56.49	35.69	8.22
13	92.94	2.33	4.73	98.09	0.77	1.14	57.54	34.46	8.40
14	92.96	2.18	4.86	97.99	0.80	1.21	56.59	36.59	7.22
15	92.75	2.07	5.18	98.26	0.61	1.13	56.48	35.52	8.40

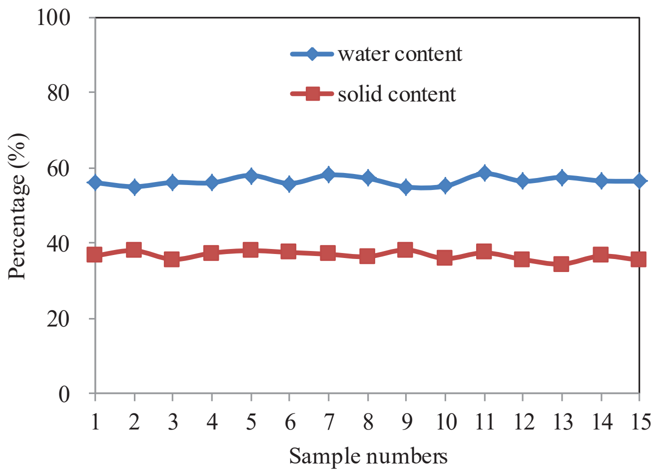

Fig. 9: Process stability test (15 samples).

solid content of sludge increased from 2.30% to 36.72%. The physical properties of the treated sludge were stable under these process parameters. The split ratio of the water outlet and the sludge outlet ranged from 8.71:1 to 12.57:1, and the corresponding sludge reduction ratio was 89.70% to 92.63%. The sludge was therefore effectively reduced.

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