Chapter

Optimization of Polymer Dosing for Improved Belt Press Performance in Wastewater Treatment Plants

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Abstract

A factorial trial approach was used to determine the relationship between process parameters and filtrate suspended solids, solids capture, cake solids, and yield stress. The work was conducted in a large-scale wastewater treatment plant where there is sludge thickening on a linear screen before filter press. The work demonstrated that there is a relationship between filtrate suspended solids, the rheology of sludge, and the optimum dewatering of the filter belt press. A relationship between the yield stress of the sludge on the BFP and the filtrate suspended solids was found. The sludge flow rate was the most influential parameter on the filtrate suspended solids and solids capture as well as yield stress. The linear screen speed was a significant main parameter for cake solids. The results showed clearly that the interaction between sludge flow rate and either polymer dosing rate or polymer concentration was consistently more significant than polymer concentration and polymer dosing rate individually. An important outcome from this work is that it shows that changes in polymer concentration rather than polymer dosing rate are more important for optimization and control.

Keywords: belt filter press, filtrate suspended solids, rheology, sludge

1. Introduction

Belt filter presses (BFPs) are mechanical dewatering equipment commonly used in municipal wastewater treatment plants (WWTP)[1]. The main reasons for sludge dewatering are to reduce the volume as it relates to the cost of sludge handling, especially transportation cost, increase in sludge heating capacity[2], and reduction of leachate [1].

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[1] Plate Filter Press installations present a greater capital cost, but have comparatively low running costs. The high running costs of belt presses are mainly attributable to the cost of polymer dosing, and it is the optimization of this cost that is the predominant motive for this chapter.

[2] Dewatered sludge is sometimes incinerated to provide heat energy.

The mechanical components of a BFP include dewatering belts, rollers and bearings, belt tracking and tensioning system, controls and drives, and a belt washing system. The operation of the BFP includes a polymer conditioning zone, gravity drainage zone, low-pressure zone, and high-pressure zone [2]. A schematic diagram of a BFP is provided in **Figure 1** [1].

The water is released in three stages: (a) free water is allowed to drain through belt pores in the gravity zone and then it is passed through (b) the low-pressure zone where it is gently compressed, and (c) the interstitial water is released in the high-pressure zone where it is further compressed through a series of rollers of different sizes [3]. The dewatered sludge also known as the cake is removed by scrapers. The belts are washed by high-pressure jets to remove sludge and polymer deposits from the belt.

The process parameters that affect the BFP performance, that is, the final cake solids concentration and filtrate suspended solids, are the influent sludge characteristics and flow rate, solid feed rate, polymer concentration, dosage and mixing energy, belt speed, and belt tension [4]. There are no fundamental models relating the process conditions to the final cake solid concentration, filtrate suspended solids, or cake solids.

Johnson and coworkers conducted tests to evaluate the effect of process conditions on BFP performance [4]. They evaluated the effect of sludge flow, solid feed, polymer dosage, belt speed, belt tension, and polymer mixing energy. Their tests were conducted over a 6-month period.

The solid feed rate was found to be one of the most critical variables for the optimization of BFP performance. They also emphasized the importance of using polymer prepared at plant scale as mixing energy influences the performance of the polymer. They used both cationic and nonionic polymers. Under-dosing resulted in poor flocculation causing a thin, dry cake. Johnson and coworkers determined the optimum value for each parameter individually and then ran the BFP at the optimized value for each condition. They found that there was no correlation between the process parameters and the sludge production or cake solids and that it was not

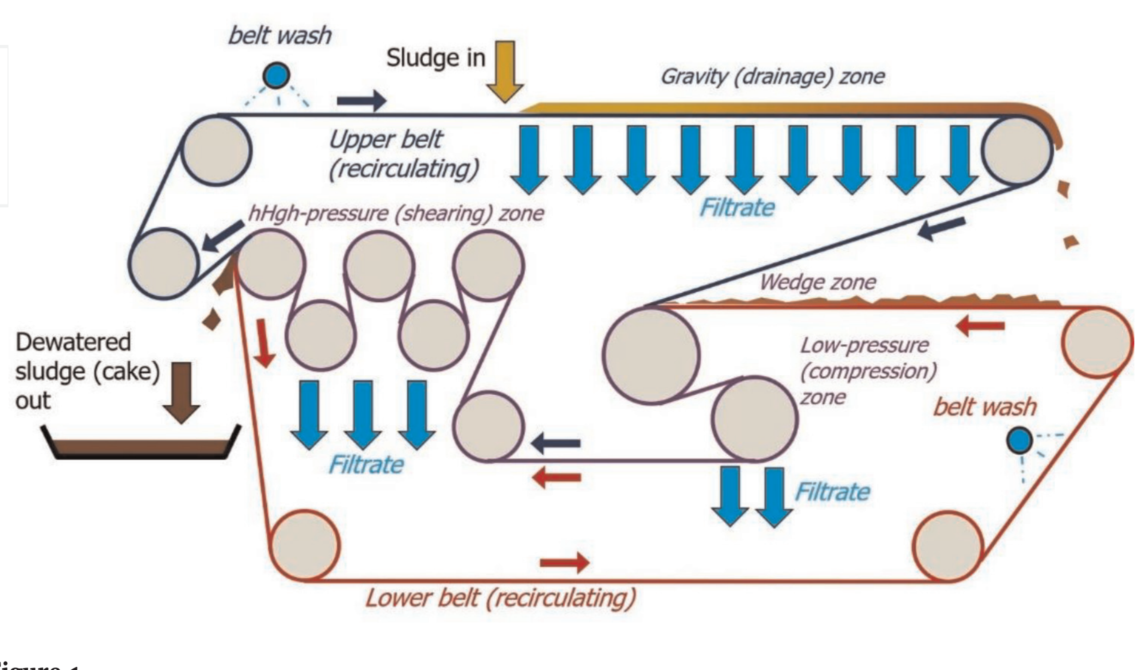


Figure 1.
Schematic diagram of the operation of a BFP [1].

predictable and that similar optimization studies should be done when parameters need to change.

Kholisa and coworkers used a factorial trial design and response surface methodology to evaluate the interaction between process parameters for BFP optimization [5]. The work was also conducted at the WWTP at full scale. The plant co-thickens secondary sludge using a cationic poly-electrolyte Flopam 4800, holds it in an aerated holding tank, and dewaters using belt filter press. A four-factor three-level Box–Behnken response surface experimental design (BBD) was used to determine the effect of process conditions on BFP performance. The operating parameters were polymer concentration, polymer dosing, sludge flow rate, and belt speed. The performance measures were sludge cake solid percentage, filtrate suspended solids, and solid capture. The sludge cake solid concentration was found to be constant over the wide range of experimental conditions tested. They found that the sludge flow rate was the most important parameter affecting the filtrate suspended solids and solid capture while the belt speed was insignificant. The results showed clearly that the interaction between sludge flow rate and either polymer dosing rate or polymer concentration was consistently more significant than polymer concentration and polymer dosing rate individually. This was important information that cannot be established by varying single parameters at a time, as in the work of Johnson et al. [4].

Kholisa and coworkers [5] proposed quadratic models to describe the relationship between operating parameters and the filtrate suspended solids (FSSs) and solid capture (SC) based on response surface model as shown in Eqs. (1) and (2)

$$\sqrt{FSS} = -5.805 - 29.906 * A + 17.013 * B + 0.5495 * C - 1.286 * AC - 1.325 * BC + 87.184 * A^2 + 0.034 * C^2 \tag{1}$$

$$SC = 81.03 + 855.42^* A - 85.85^* B - 8.35^* C - 592.68^* AB + 21.96^* AC + 18.14^* BC - 1274.35^* A^2 - 0.47^* C^2 \tag{2}$$

Where

A = polymer concentration g/L; B = polymer dosing m^3/hr; C = sludge feed m^3/hr; D = belt speed Hz; and E = linear screen speed Hz

In addition, Kholisa et al. [5] found a relationship between the yield stress of the sludge and the filtrate suspended solids. An optimum yield stress of 90Pa of sludge was found that was suitable to produce filtrate suspended solid concentrations that were within acceptable limits.

It is important to verify the trend with other filter belt presses and another WWTP especially a plant where there is sludge thickening on linear screen before filter press, which was the objective of this work.

2. Experimental work

2.1 Experimental facility

The experimental work was conducted on a large scale at the WWTP. The municipal wastewater treatment works are designed for an average dry weather flow (ADWF) capacity of 24 Ml/d, with the current flow of about 14 M/l/d, mostly of domestic origin. All inflow is pumped from the catchment to the inlet works, consisting of screening, degritting, and flow division. The plant is equipped with two biological reactors, which are arranged in the University of Cape Town (UCT) process configuration for enhanced biological phosphorus removal (EBPR). The mixed liquor is thereafter distributed to four secondary settling tanks (SSTs). The SST overflow gravitates to maturation ponds followed by Ultraviolet (UV) disinfection, and the underflow gravitates to the return activated sludge (RAS) pump station where it is pumped back to the anoxic zone in the reactors. Two variable-speed-driven pumps (duty/standby) pump the waste-activated sludge (WAS) directly out of each reactor's final zone to the sludge dewatering building, where the WAS is thickened in two linear screens (Siemens Gravity table GTN 2500), followed by dewatering in two belt filter presses (Siemens BPF 2000 CMF Optima S11 Cascade). The filtrate and wash water from the thickening/dewatering trains gravitate back to the RAS division box where it is mixed with the RAS before entering the anoxic zones of the bioreactors. The pressed sludge (cake) is discharged via a centerless screw conveyor to a reinforced concrete hopper, from which sludge is discharged to trucks for removal from site for beneficial agricultural reuse application. A schematic diagram of the WWTP is given in **Figure 2**.

The loading on the belt presses can be controlled according to solids or flow loading. Control using solid loading is the preferred operation and is managed based on the output from the total suspended solids (TSSs) meter in the reactor aeration

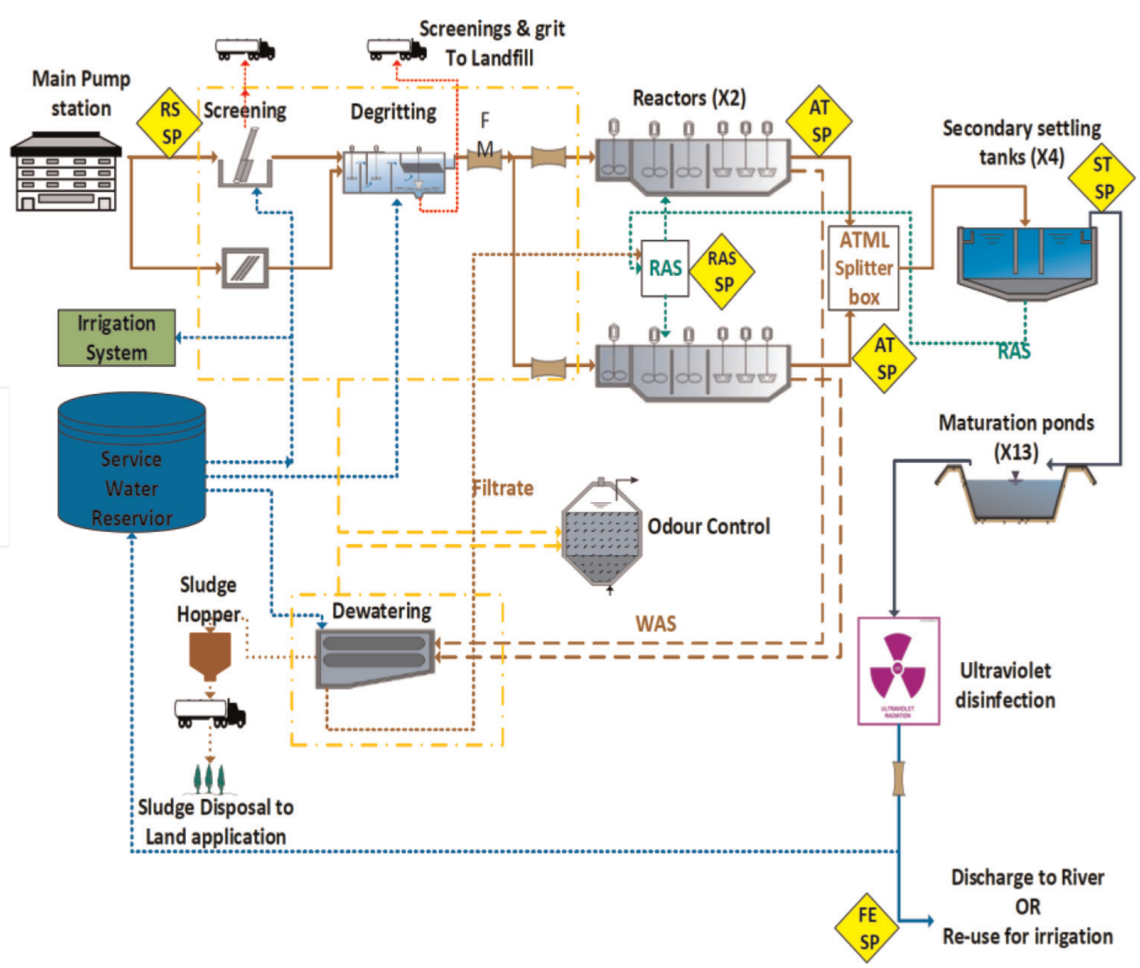


Figure 2.
Schematic diagram of the WWTP.

basin. The design parameters of the Linear Screens require a minimum WAS feed of 4500 mg/l mixed liquor suspended solids (MLSSs) from the reactors. Treated effluent is reused with an automated in-line filtration stage and is available as process water in the dewatering building, both for belt washing and polymer makeup purposes. The sludge-conditioning polymer (Flopam FO4650) is provided in 25kg bags in powder form, and powder is pneumatically transferred and wetted for blending and storage in two makeup tanks. This polymer solution flows into a sump from where it is withdrawn by the polymer dosing pumps and dosed in-line into the WAS before it is fed to the linear screens. The dosing rate is set at the supervisory control and data acquisition (SCADA), based on analysis data and visual observations. The dewatering performance is guided by a minimum cake solid content of 14% and a solid recovery of 95%, respectively, which is affected by the ageing infrastructure that is due for a major refurbishment.

2.2 Experimental design

In this work, a Box-Behnken response surface experimental design (BBD with five factors at three levels was used to examine the effect of process operating parameters on the BFP performance measures. The process conditions were polymer concentration (%) [**A**], polymer dosing rate (m^3/hr) [**B**], sludge feed rate (m^3/hr) [**C**], filter belt speed (Hz) [**D**], and linear screen speed (Hz) [**E**]. The BFP performance measures were sludge cake, filtrate suspended solids, and solid capture, and these were selected as responses with the addition of the yield stress. The range of the operating parameters investigated was chosen based on the preliminary trials. The ranges and levels of the selected operating parameters are presented in **Table 1**. The final design matrix consisted of 31 experiments including five center points. Due to difficulty in changing the polymer concentration according to the normal randomization of results, a grouped approach was selected to run a polymer concentration per day (The polymer concentration was defined as “hard to change” in the Design-Expert V11 software). Random repeats and intermediate conditions were selected by the Design-Expert software to ensure randomization.

2.3 Experimental procedure

The complete Box-Behnken design parameters are provided in **Table 2**. The trials were run over a period of 6 days to allow for the required polymer concentration to be

Factors	Factorial label	Levels used		
		Low	Medium	high
Polymer concentration (%)	A	0.2 (−1)	0.25 (0)	0.30 (+1)
Polymer dosing (m^3/hr)	B	0.4 (−1)	0.5 (0)	0.6 (+1)
Sludge feed (m^3/hr)	C	40 (−1)	50 (0)	60 (+1)
Belt speed (Hz)	D	40 (−1)	45 (0)	50 (+1)
Linear screen speed (Hz)	E	60 (−1)	65 (0)	70 (+1)

Table 1.
Factors in Box-Behnken experimental design.

Group	Run	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
		A: Polymer concentration	B: Polymer dosing	C: Sludge feed	D: Belt speed	E: Linear screen speed
		%	m^3/hr	m^3/hr	Hz	Hz
1	1	0.25	0.50	50.00	45.00	65.00
	2	0.25	0.50	50.00	45.00	65.00
	3	0.25	0.50	50.00	45.00	65.00
2	4	0.20	0.40	60.00	50.00	70.00
	5	0.20	0.60	60.00	40.00	66.10
	6	0.20	0.56	60.00	50.00	60.00
	7	0.20	0.60	40.00	43.20	65.00
	8	0.20	0.40	55.00	40.00	60.00
	9	0.20	0.41	40.00	50.00	61.75
	10	0.20	0.50	48.60	44.55	70.00
3	11	0.30	0.60	40.00	50.00	60.00
	12	0.30	0.40	46.00	50.00	70.00
	13	0.30	0.60	60.00	49.75	70.00
	14	0.30	0.40	51.00	40.00	60.00
	15	0.30	0.52	50.80	50.00	65.00
	16	0.30	0.52	40.00	44.85	70.00
4	17	0.24	0.54	40.00	40.00	60.00
	18	0.24	0.60	50.20	46.40	60.00
	19	0.24	0.60	40.00	50.00	70.00
	20	0.24	0.40	40.00	40.00	70.00
	21	0.24	0.40	60.00	45.10	64.43
	22	0.24	0.51	60.00	40.00	70.00
5	23	0.30	0.40	40.00	45.40	60.00
	24	0.30	0.40	60.00	41.20	70.00
	25	0.30	0.47	44.00	40.00	64.95
	26	0.30	0.60	47.35	40.00	70.00
	27	0.30	0.40	60.00	50.00	60.00
	28	0.30	0.59	60.00	41.00	60.00
6	29	0.25	0.50	50.00	45.00	65.00
	30	0.25	0.50	50.00	45.00	65.00
	31	0.25	0.50	50.00	45.00	65.00

Table 2.
Complete Box-Behnken design parameters.

prepared for each day in the plant at large scale. Each experiment was run for 30 min to reach steady state before samples were collected. The responses were measured three times, and the average value was recorded.

The response variables measured were the sludge cake solids, the filtrate suspended solids, solid capture, and the yield stress. The solids were measured using the standard oven drying technique for the cake, filtrate suspended solids, and the feed. The percentage solid capture (recovery) was calculated using the Eq. (3):

$$\text{Solid capture } (\%) = \frac{\text{solids in the feed} - \text{solids in the filtrate}}{\text{solids in the feed}} \times 100 \quad (3)$$

A Paar-Physica MCR-51 rheometer fitted with a parallel-plate geometry, with a measuring cell CP50 of 50 mm diameter and a gap of 1 mm, was used for determining the sludge yield stress. The rheological tests were conducted in the controlled shear rate mode with the shear rate being the control parameter. Rheological measurements were performed by decreasing the shear rate linearly from 700 s^{-1} to 100 s^{-1} to exclude data with secondary flows at high shear rates and low torque at low shear rates. Thirty data points were collected, and each point was measured for 5 seconds. This protocol was repeated three times for each sludge sample to ensure reproducibility of the measurements. The data were then fitted with the Bingham model to obtain the yield stress.

The sludge samples tested were collected on the linear screen just after rake number 6. Before this point, the sludge proved to be difficult to measure due to dilute nature with rapid separation of sludge flocs and water as the shear force was applied. Due to the nature of sludge, there is some initial structure that is broken down when sheared several times. The sample was run several times to obtain representative sets of curves from repeat runs of three fresh samples. The average of the yield stress of the highest and lowest curve was determined for each run as a comparative result. It is recommended that the structure of the flocs be interrogated in future in subsequent test runs using oscillation tests. For this work to determine the comparative trends, the analysis was deemed sufficient. A typical rheogram is shown in **Figure 3**.

3. Results and discussion

3.1 Feed, filtrate, and cake solids

The objective of these trial runs was to determine the operational factors of the belt filter press that contributes to efficient dewatering, indicated by the filtrate suspended solids and the percentage of solids in the cake. The rheological parameter describing the floc type produced by the specific polymer dosage rate, polymer concentration, the sludge feed rate, the belt speed, and the linear screen speed, with specific emphasis on determining the interaction that significantly affects the performance of the belt filter press. The factorial trial matrix with the responses is given in the Appendix. A summary of the feed solids concentration, the cake solids, and the filtrate suspended solids is shown in **Figure 4**. Cake solids of more than 14% were only obtained for one out of 31 runs.

3.2 Relationship between FSS and cake solids and yield stress

A power-law relationship was found between the filtrate suspended solids and the yield stress for the values obtained over the full range of the experimental results. Yield stress values between 1 and 5 Pa are sufficient to obtain FSS of between 0.9 and

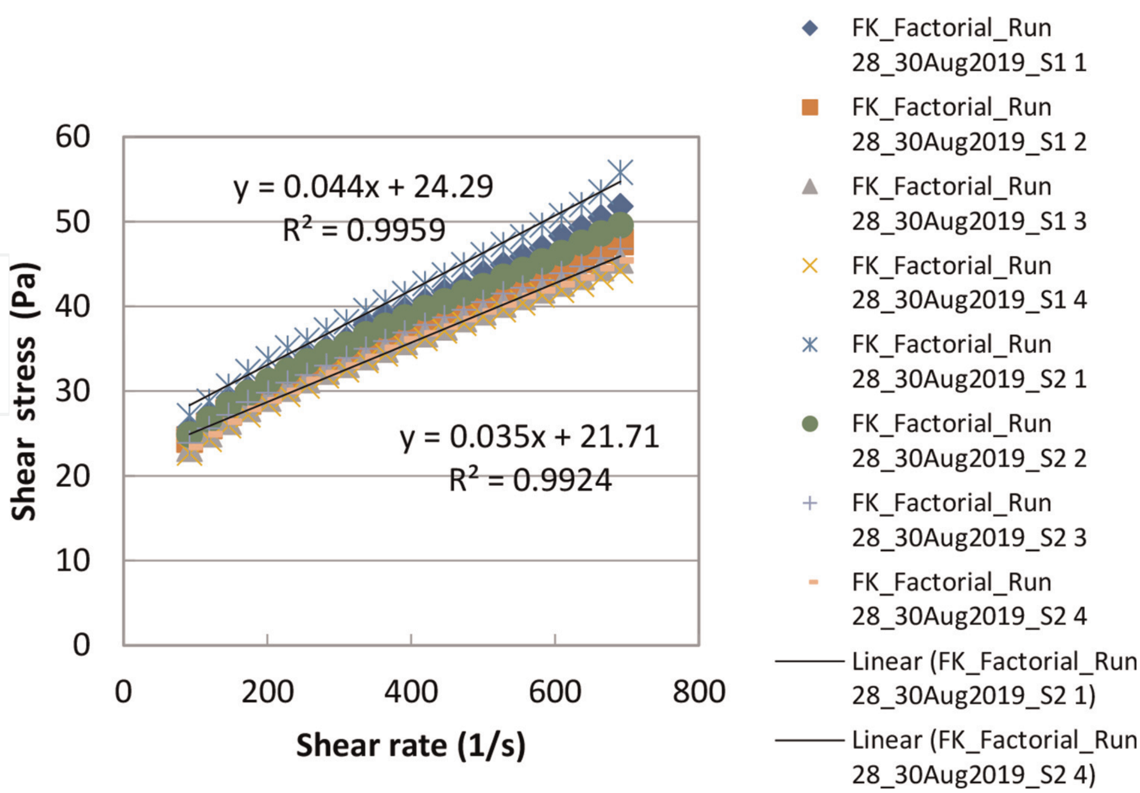


Figure 3.
Typical rheogram.

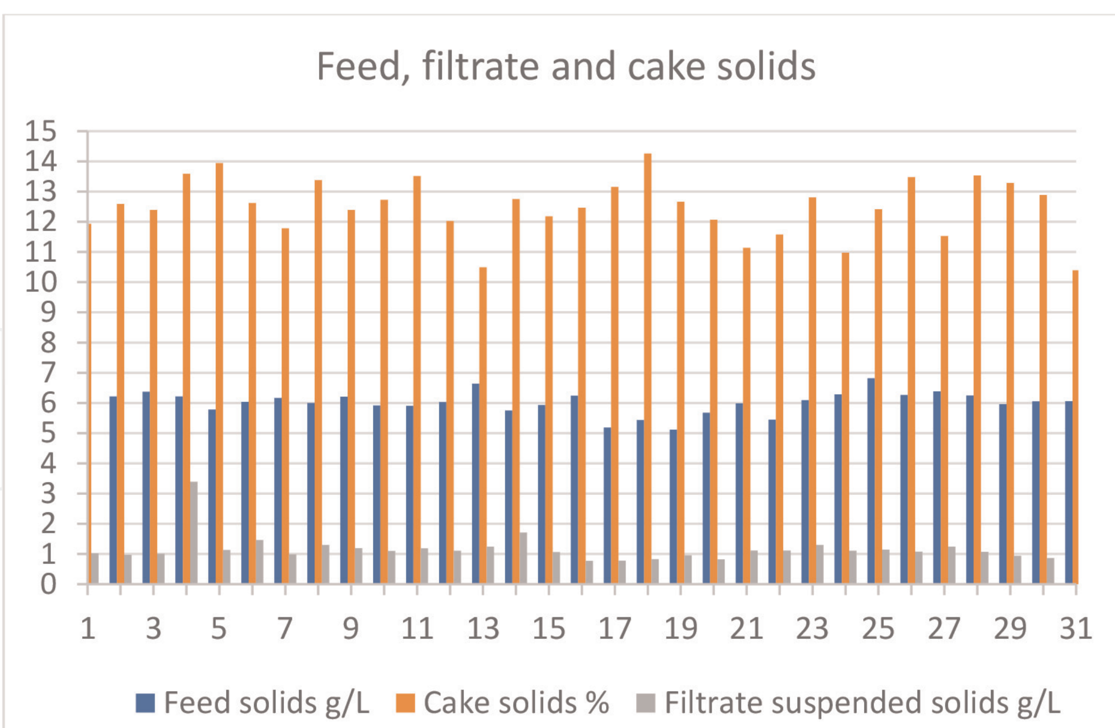


Figure 4.
Feed, filtrate, and cake solids results for all trial runs.

0.5 g/L. **Figure 5** is useful to demonstrate the relationship between the yield stress and the FSS, but it does not give an indication of the process conditions required to obtain these yield stress values. The FSS was less than 0.5 g/L for 58% of the trial run

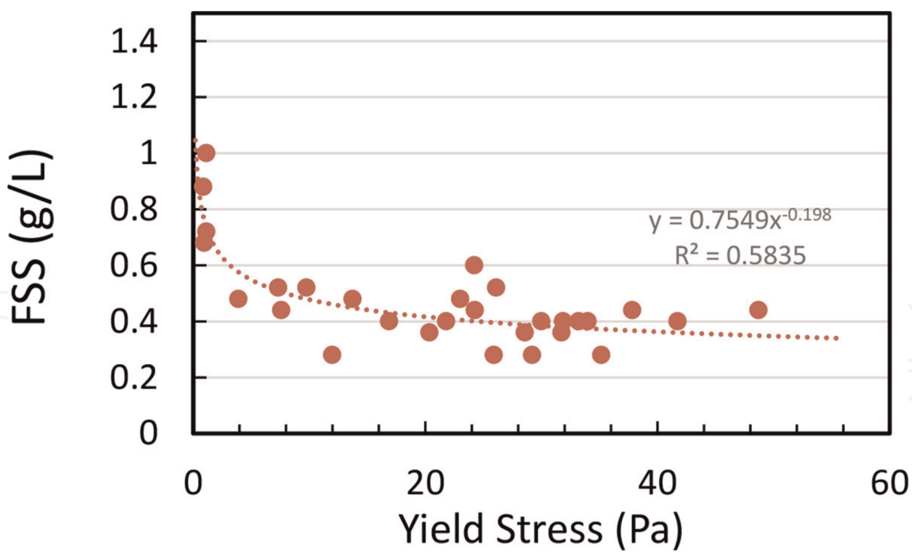


Figure 5.
Filtrate suspended solids as a function of yield stress.

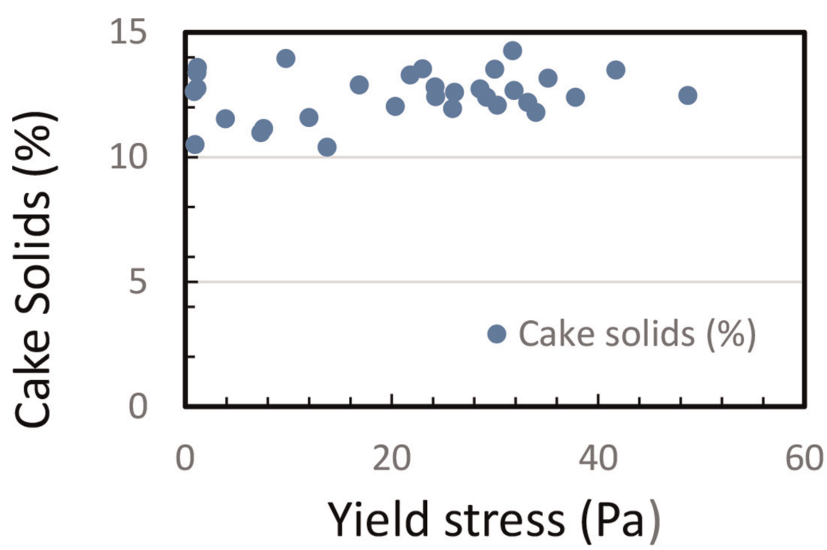


Figure 6.
Cake solids as a function of yield stress.

conditions. In contrast, there was no relationship found between the cake solids and the yield stress as shown in **Figure 6**.

3.3 The effect of process conditions on belt filter press performance

3.3.1 Filtrate suspended solids

The effect of process conditions on the filtrate suspended solids was investigated to determine the optimum process conditions. A split-plot design was used because of the number of variables as it also enabled the identification of process interactions that would normally not be seen when only one parameter was changed at a time. The filtrate suspended solids were measured at the outlet of the belt filter press. A sample was collected 20 minutes after the conditions were changed. The online FSS sensor was not responsive for the low readings obtained, and hence, a sample was collected, and the standard drying test was conducted as well as filtration through 0.45μm Millipore filter.

3.3.1.1 Analysis of variance

The analysis of variance (ANOVA) is presented in **Table 3**. A quadratic model was selected without any transformation, with a step-wise backward selection, a p-value criterion, and an alpha value of 0.1. However, based on the Box-Cox analysis, an inverse square root transformation was required. P-values less than 0.0500 indicate that model terms are significant. Values greater than 0.1000 indicate that the model terms are not significant. Only the sludge feed (C) and the belt speed (D) were significant with p-values equal to or less than 0.05. The polymer concentration (a), polymer dosing, and linear screen speed (E) were not significant, with a p-value of 0.99, 0.40, and 0.32, respectively. However, the interaction between polymer concentration (a) and sludge feed and belt speed and linear screen speed as well as B^2 was significant. In this case C, aC, aD, aE, CD, DE, B^2 are significant model terms with a, B, and E added to maintain hierarchy. The final fit statistics obtained is showing an R^2 value of 0.7415 and adjusted R^2 of 0.5919 and a C.V. of 13.42%. These could be improved if Run 4 is excluded, but we are certain of the results even though it seems out of range, it is expected from such low polymer dosing.

The final equation obtained to determine the contribution of each factor is given in Eq. (4) (coded), and the equation for the prediction of filtrate suspended solids is given in Eq. (5) (actual).

$$1/\sqrt{FSS} = 1.62 + 0.0007a + 0.0323B - 0.1352C + 0.0647D + 0.0371E + 0.1122\,aC + 0.1420aD - 0.1042DE - 0.1920B^2 \quad (4)$$

$$1/\sqrt{FSS} = -6.245 - 38.61a + 20.00B - 0.080C + 0.138D + 0.215E + 0.261aC + 0.570aD - 0.0046DE - 19.65B^2 \quad (5)$$

Source	Term df	Error df	F-value	p-value	
Whole-plot	1	3.53	0.0001	0.9937	not significant
a-Polymer concentration	1	3.53	0.0001	0.9937	
Subplot	8	18.60	5.34	0.0014	significant
B-Polymer dosing	1	17.85	0.7344	0.4028	
C-Sludge feed	1	18.09	12.29	0.0025	
D-Belt speed	1	19.17	2.48	0.1315	
E-Linear screen speed	1	18.05	1.04	0.3216	
aC	1	18.28	5.98	0.0248	
aD	1	19.13	9.24	0.0067	
DE	1	18.93	5.58	0.0290	
B^2	1	21.00	5.69	0.0265	

Table 3.
ANOVA for filtrate suspended solids.

3.3.1.2 Evaluation of the filtrate suspended model

The normal probability plot of the residuals is approximately linear, which shows that the model fits the data well as shown in **Figure 7**.

3.3.2 Cake solids

The resulting cake solids as a function of process conditions were investigated. The cake solids ranged from 10.39% to 14.26% over the full range of conditions used during the factorial trial. For the cake solids, it was found that an interaction exists between the polymer concentration and the sludge feed rate. Based on the statistical analysis (**Table 4**), the linear screen speed is a significant model term as well as the interaction between the polymer concentration and sludge feed, both of which had p-values less than 0.05. The terms a and C and B were added to maintain hierarchy. The statistical analysis of the model showed that the model was acceptable based on the linear plot of normal plot of the residuals, Box-Cox plot confirmed a Lambda of 1 and that no further transform of the data was necessary. It is interesting to note that the

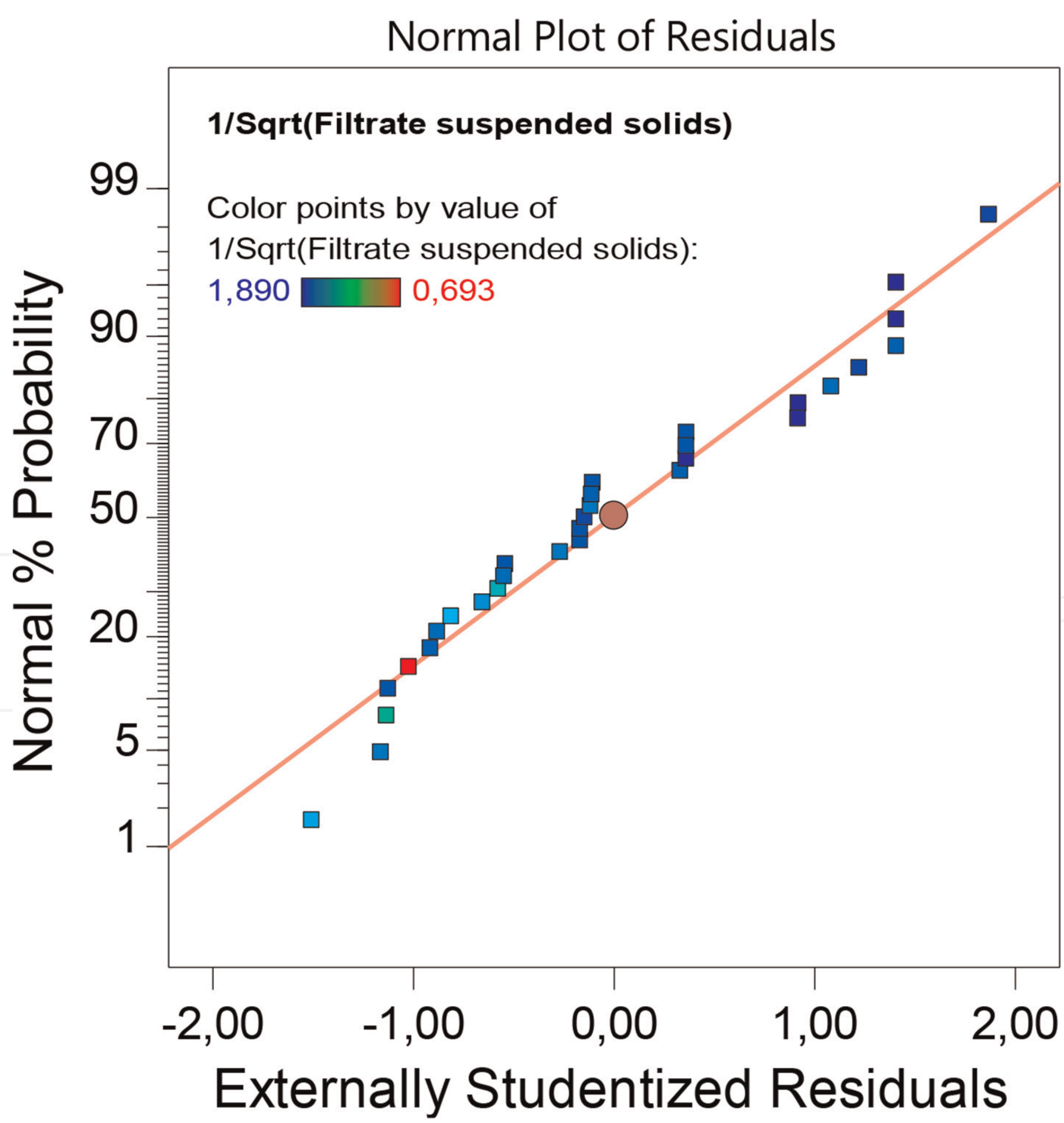


Figure 7.
Normal probability plot of residuals for filtrate suspended solids.

Source	Term df	Error df	F-value	p-value	
Whole-plot	1	25.00	1.11	0.3014	not significant
a-Polymer concentration	1	25.00	1.11	0.3014	
Subplot	4	25.00	3.87	0.0139	significant
B-Polymer dosing	1	25.00	2.99	0.0960	
C-Sludge feed	1	25.00	0.4113	0.5271	
E-Linear screen speed	1	25.00	4.36	0.0472	
aC	1	25.00	7.19	0.0128	

Table 4.
ANOVA for cake solids.

belt speed is not a statistical significant operational factor in the prediction of the cake solids. Although the diagnostics are good, the Adj.R^2 of 22.9% shows a very poor fit.

3.3.3 Yield stress

The process conditions affecting the yield stress were evaluated. The experimental yield stress values obtained during the test runs ranged from to 0.86 Pa to 48.70 Pa. No transformation of the data was required according to the Box-Cox theory. In this case, parameters B, C, aB, and BD were found to be significant at the 5% level as shown in **Table 5**. In the case of the yield stress, the linear screen speed is not significant, but there is an interaction between belt speed and linear screen speed. The adjusted R^2 is 0.78.

Eq. (6) shows the coded equation and Eq. (7) the actual equation.

Source	Term df	Error df	F-value	p-value	
Whole-plot	1	1.72	1.32	0.3849	not significant
a-Polymer concentration	1	1.72	1.32	0.3849	
Subplot	8	18.00	16.49	< 0.0001	significant
B-Polymer dosing	1	16.95	9.48	0.0068	
C-Sludge feed	1	17.52	85.60	< 0.0001	
D-Belt speed	1	20.65	0.6446	0.4312	
E-Linear screen speed	1	17.60	1.34	0.2627	
aB	1	16.76	5.44	0.0325	
BD	1	20.35	9.20	0.0065	
DE	1	19.10	3.45	0.0786	
D^2	1	18.78	3.44	0.0795	

Table 5.
ANOVA for yield stress.

$$\text{Yield stress} = 24.1843 + 2.24613a + 4.38B - 13.38C - 1.277D + 1.581E + 3.833\,aB - 5.554BD - 3.0768DE - 5.33D^2 \tag{6}$$

$$\text{Yield stress} = -848 - 333a + 334B - 1.35C + 30.5D + 5.84184E + 754aB - 10.6BD - 0.1223DE - 0.194D^2 \tag{7}$$

3.3.4 Solid capture

The experimental values obtained for solid capture ranged from 66.5 to 95.6%. The significant model terms are C, aC, aD, aE, CD, DE, and B^2 as shown in **Table 6**.

Eq. (8) shows the coded equation and Eq. (9) the actual equation.

$$\text{Solid capture} = 93.5726 + 1.2131a + 0.787295B - 2.380C - 1.369D - 0.608E + 2.82703aC + 3.24954aD + 1.78aE - 1.84CD - 2.34DE - 3.71B^2 \tag{8}$$

$$\text{Solid capture} = -31.33 - 1256.6a + 369.42B - 0.215C + 5.005D + 2.912E + 6.11aC + 12.36aD + 6.457aE - 0.035CD - 0.1032DE - 361.3B^2 \tag{9}$$

The normal probability plot (**Figure 8**) of the residuals is approximately linear. Removing run 4 from the analysis could improve the adjusted R^2 from 68% to 71%, but the assumption that Run 4 is due to experimental error and based on experience it is not. Such a change to improve the statistics will also result in significant factor changing from polymer dosing (B2) to linear screen speed (E2) in the final equation.

Source	Term df	Error df	F-value	p-value	
Whole-plot	1	2.80	1.38	0.3305	not significant
a-Polymer concentration	1	2.80	1.38	0.3305	
Subplot	10	16.40	7.81	0.0002	significant
B-Polymer dosing	1	15.99	1.42	0.2516	
C-Sludge feed	1	16.41	12.53	0.0026	
D-Belt speed	1	18.09	3.58	0.0745	
E-Linear screen speed	1	16.15	0.8575	0.3681	
aC	1	16.73	12.46	0.0026	
aD	1	17.84	15.99	0.0009	
aE	1	16.31	5.45	0.0326	
CD	1	16.11	5.55	0.0315	
DE	1	17.69	9.22	0.0072	
B^2	1	18.26	7.45	0.0137	

Table 6.
ANOVA for solid capture.

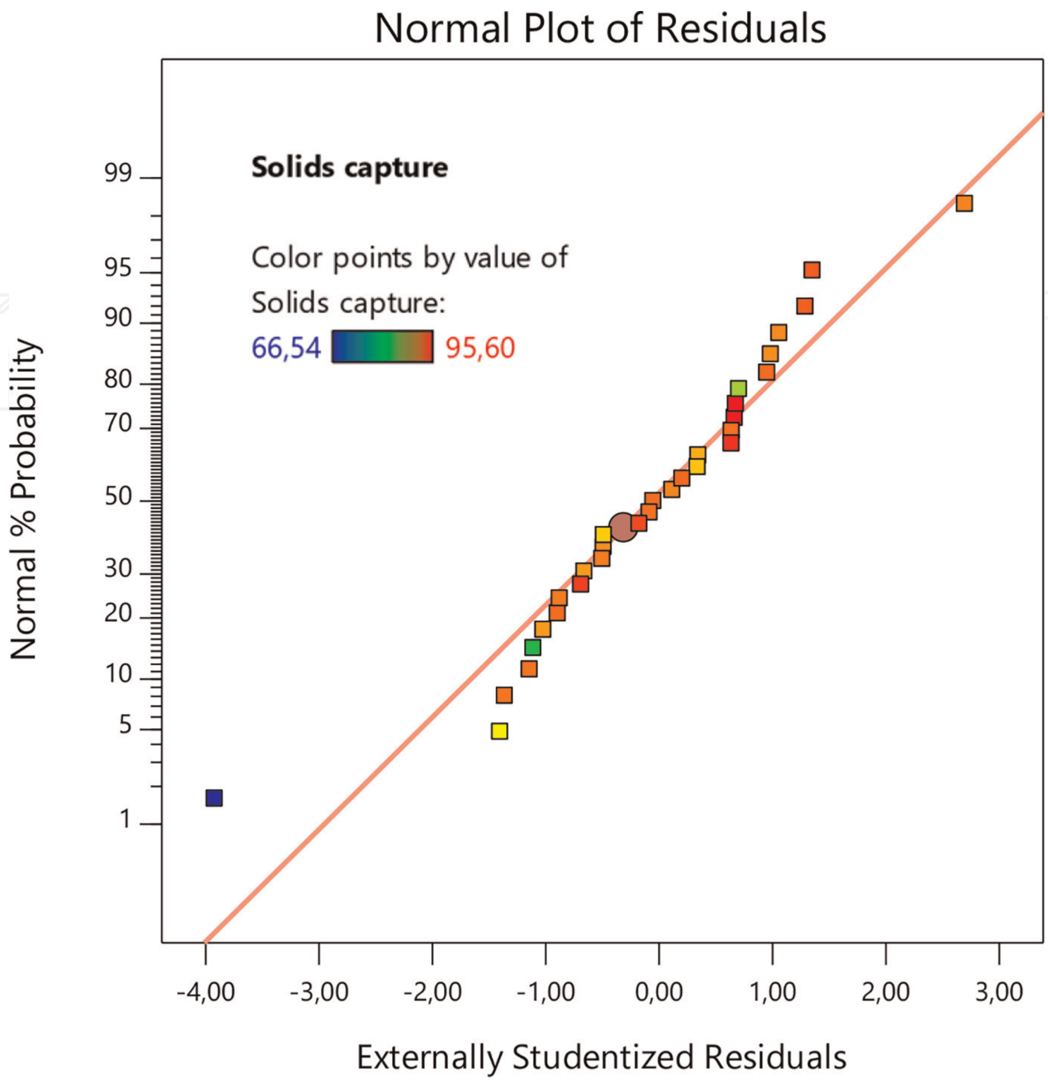


Figure 8.
Normal probability plot of residuals for solid capture.

4. Results and discussion

In order to understand the effect of the process conditions on belt filter press performance, 3D surface plots are utilized **Figure 9a** shows FSS as a function of sludge feed and polymer dosing at the lowest polymer concentration, belt speed, and linear screen speed. The filtrate suspended solids were all below 1 g/L. A minimum value of FSS is obtained at the maximum sludge flow rate and a medium polymer dosing rate due to process interaction. The situation remains the same if all the conditions are set at the maximum values as shown in **Figure 9b**.

When the polymer concentration is minimized with maximum belt and linear screen speed, the FSS is above 1 g/L. However, an acceptable FSS can be obtained by dosing the polymer at 0.5 m^3/hr, which is the midpoint. This interaction between polymer dosing and sludge flow rate is very useful to obtain acceptable FSS at high production rates as shown in **Figure 9c**. Furthermore, the amount of polymer usage can be reduced by decreasing the linear screen speed to the minimum and the sludge feed rate to just under the maximum at 59 m^3/hr; the resulting FSS will be below 1 g/L as shown in **Figure 9d**.

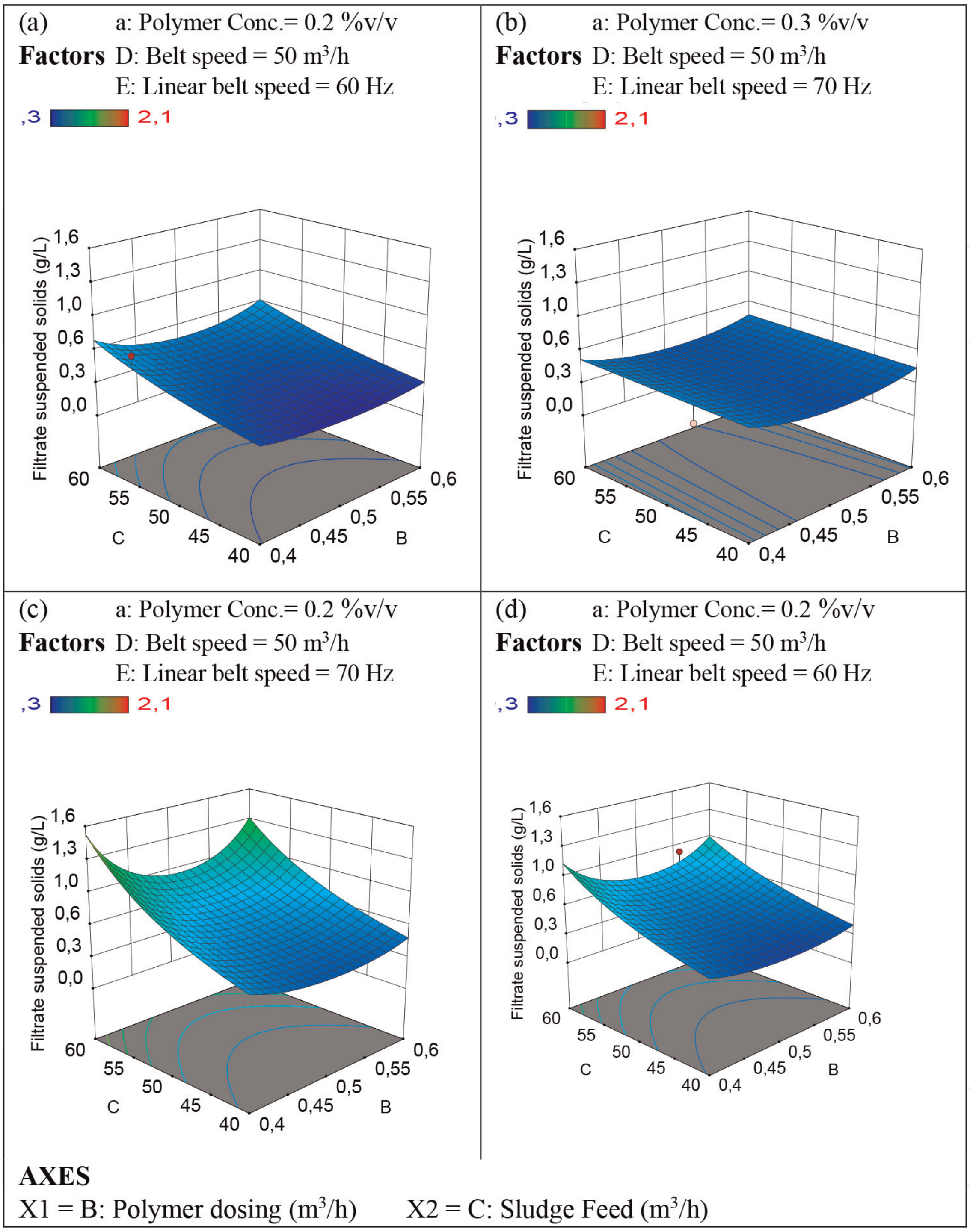


Figure 9.
3D surface plot of FSS as a function of sludge feed and polymer dosing.

To ascertain the performance of the filter cake, the prediction of cake solids is presented under the similar conditions as for the FSS. In contrast to the FSS, the cake solids increase linearly with increasing polymer dosage, with no minima or maxima observed at maximum sludge feed rate. **Figure 10a** shows that at the minimum settings for polymer concentration, belt and linear screen speed, the maximum cake solids of almost 14% can be obtained at the maximum polymer dosing rate and maximum sludge feed rate. Increasing the parameters has a detrimental effect on the cake solids, unlike the case of filtrate suspended solids, and a maximum of 13% cake solids are obtained at the minimum sludge feed rate and maximum polymer dosing as

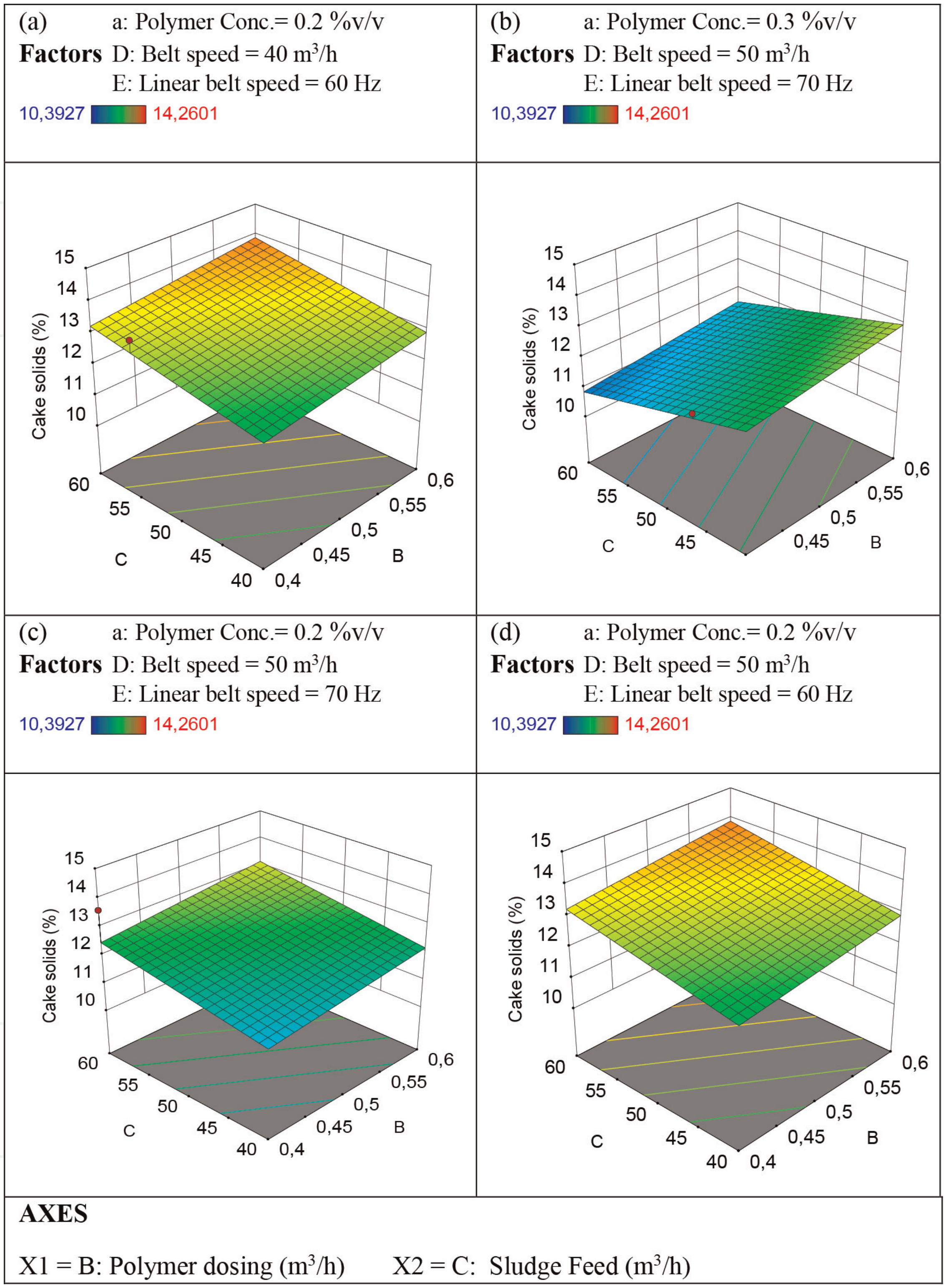


Figure 10.
3D surface plot of cake solids as a function of sludge feed and polymer dosing.

shown in **Figure 10b**. However, surprisingly, by minimizing the polymer concentration, production can be increased and maximum sludge feed rate and maximum polymer dosing with result in 13% cake solids. It should also be noted that the design point is higher than the prediction under these conditions as shown in **Figure 10c**. Similarly to the FSS, when reducing the linear screen speed, the cake solids can be improved by nearly 1% as seen in **Figure 10d**. Even though better FSS can be obtained

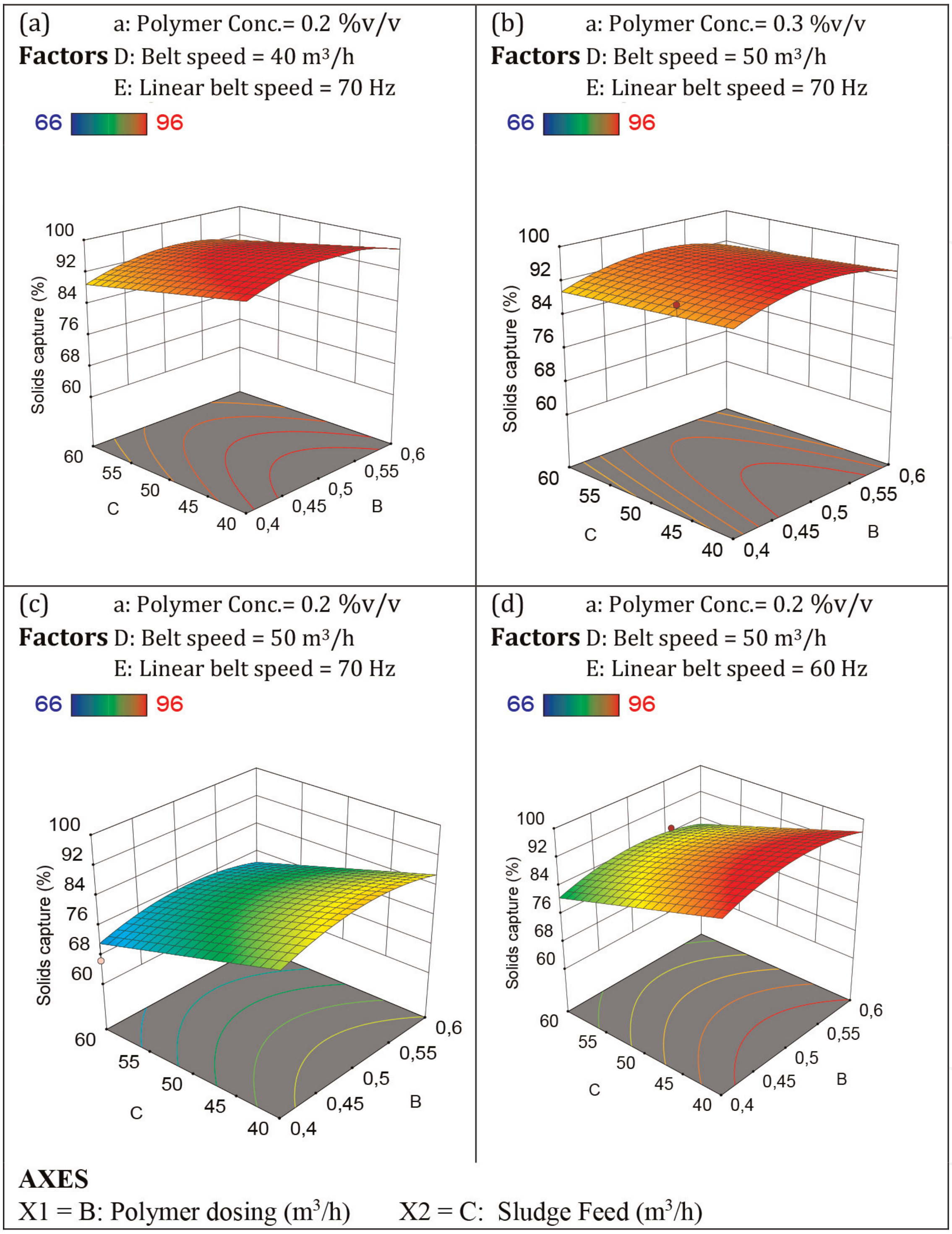


Figure 11.
3D surface plot of solid capture as a function of sludge feed and polymer dosing.

at the medium polymer dosing rate, the maximum polymer dosing rate is required for the maximum cake solids, and based on the prediction, the FSS will still be within the 1 g/L limit. A detailed study of polymer cost versus cake removal costs is needed to manage these limits to an optimum.

For the solid capture, similar graphs are presented in **Figure 11**. These are the inverse of FSS with a maximum obtained at the maximum sludge feed rate and the medium polymer dosing rate (**Figure 11a**). Running all conditions at maximum has

	Significant main effects	Interactions
Filtrate suspended solids	Sludge feed rate	Poly concentration * Sludge feed rate Poly concentration * Belt speed Belt speed * Linear screen speed
Cake solids	Linear screen speed	Poly concentration * Sludge feed rate
Yield stress	Polymer dosing Sludge feed rate	Poly concentration * Poly dosing rate Poly dosing rate * Belt speed Belt speed * Linear screen speed
Solids Capture	Sludge feed rate	Poly concentration * Sludge feed rate Poly concentration * Belt speed Poly concentration* Linear screen speed Sludge feed rate* Belt speed Belt speed * Linear screen speed

Table 7.
Summary of significant main factors and interactions.

limited impact on the performance of the belt filter press as shown in **Figure 11b**. Reducing the polymer concentration impacts the performance of the belt filter press negatively as the solid capture is reduced to less than 70% (**Figure 11c** compared with 90% under all minimum or all maximum conditions. Reducing the linear screen speed at the minimum polymer concentration improves the solids capture but only to mid- or low sludge feed rates as shown in **Figure 11d**, but it is ultimately the reduction of the belt speed at lower polymer concentration that will ensure maximum solid capture at high sludge flow rates (**Figure 11a**) at the mid-range polymer dosing rate.

A summary of the significant main factors and interactions is provided in **Table 7**. It shows that the polymer concentration is much more important than polymer dosing rate in interactions with the other conditions. Current practice in the plant is to keep the polymer concentration constant and to change polymer dosing rate. This work demonstrates that a control system that can incorporate changes to concentration is required for a fully automated polymer control system to reduce cost.

5. Conclusion

A factorial trial was conducted at a WWTW to establish correlations to predict the filter belt press performance as a function of process conditions. Correlations to predict the FSS, Cake solids, Yield stress, and Solid Capture were developed based on the factorial trial design. From the results obtained, it was found that a power-law relationship exists between FSS and the yield stress. There is no relationship between the yield stress and the cake solids. The cake solids are affected by the linear screen speed and the interaction between the polymer concentration and sludge feed. It is recommended that more work be done around the optimization of the cake solids based on this information. It is also the only parameter for which the linear screen is the most significant factor, and the belt speed is insignificant in this case. An important outcome from this work is that it shows that changes in polymer concentration rather than polymer dosing rate are more important in the control system. This is contrary to current practice where the polymer concentration is constant and only the polymer dosing rate is adjusted.

Acknowledgements

I would like to acknowledge the Technology Innovation Agency (TIA) South Africa and CPUT for funding this work. Further, I would like to acknowledge Richard du Toit for assistance with experimental work and the staff of the Wastewater Treatment Plant for assistance during the live scale trial work. Thanks are due to Dr D.W. Brown for assistance in reviewing this chapter.

Conflict of interest

The authors declare no conflict of interest.

Terminology used in this chapter

ADWF	Average Dry Weather Flow
ANOVA	Analysis of Variance
BBD	Box-Behnken Design
BFP	Belt Filter Press
EBPR	Enhanced Biological Phosphorus Removal
FSS	Filtrate Suspended Solids
MLSS	Mixed Liquor Suspended Solids
RAS	Return Activated Sludge Station
SCADA	Supervisory and Data Acquisition
SST	Secondary Settling Tanks
TTS	Total Suspended Solids
UCT	University of Cape Town
WAS	Waste Activated Sludge
WWTP	Municipal Wastewater Treatment Plant

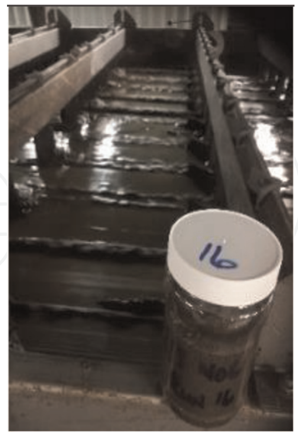
A. Appendix: Box-Behnken experimental matrix and responses

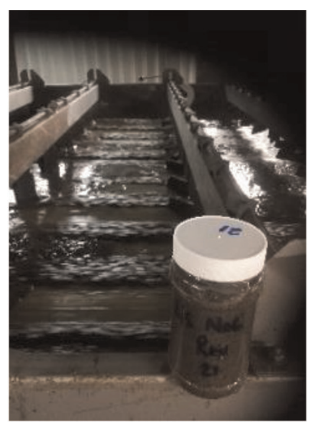
Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
1/1	0.25	0.50	50.00	45.00	65.00		25.90	1.02	11.94	83.83
1/2	0.25	0.50	50.00	45.00	65.00		26.10	0.97	12.59	84.40
1/3	0.25	0.50	50.00	45.00	65.00		29.20	1.01	12.39	84.15

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
2/4	0.20	0.40	60.00	50.00	70.00		1.18	3.39	13.59	45.42
2/5	0.20	0.60	60.00	40.00	66.10		9.76	1.13	13.95	80.46
2/6	0.20	0.56	60.00	50.00	60.00		0.86	1.46	12.62	75.81
2/7	0.20	0.60	40.00	43.20	65.00		33.90	0.99	11.79	84.01

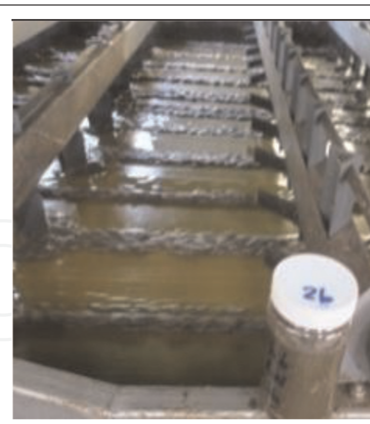
Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
2/8	0.20	0.40	55.00	40.00	60.00		1.15	1.30	13.38	78.37
2/9	0.20	0.41	40.00	59.00	61.75		37.82	1.20	12.39	80.74
2/10	0.20	0.50	48.60	44.55	70.00		28.57	1.10	12.73	81.37
3/11	0.30	0.60	40.00	50.00	60.00		29.90	1.19	13.52	75.92

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
3/12	0.30	0.40	46.00	50.00	70.00		20.35	1.11	12.02	81.61
3/13	0.30	0.60	60.00	49.75	70.00		0.95	1.24	10.49	81.31
3/14	0.30	0.40	51.00	40.00	50.00		1.14	1.71	12.75	70.24
3/15	0.30	0.52	50.80	50.00	65.00		33.20	1.06	12.18	82.09

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
3/16	0.30	0.52	40.00	44.85	70.00		48.70	0.77	12.46	87.60
4/17	0.24	0.54	40.00	40.00	60.00		35.16	0.78	13.15	85.04
4/18	0.24	0.60	50.20	46.40	60.00		31.72	0.83	14.26	84.81
4/19	0.24	0.60	40.00	50.00	70.00		31.86	0.96	12.67	81.24

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
4/20	0.24	0.40	40.00	40.00	70.00		30.24	0.82	12.07	85.55
4/21	0.24	0.40	60.00	45.10	64.43		7.59	1.11	11.14	81.42
4/22	0.24	0.51	60.00	40.00	70.00		11.99	1.11	11.58	79.55
5/23	0.30	0.40	40.00	45.40	60.00		24.21	1.30	12.81	78.67

DOI: http://dx.doi.org/10.5772/intechopen.108978

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
5/24	0.30	0.40	60.00	41.20	70.00		7.32	1.10	10.98	83.43
5/25	0.30	0.47	44.00	40.00	64.95		24.26	1.14	12.42	83.23
5/26	0.30	0.60	47.35	40.00	70.00		41.73	1.08	13.48	82.79
5/27	0.30	0.40	60.00	50.00	60.00		3.90	1.25	11.53	80.49

Group/ Run	A % v/v	B m^3/h	C m^3/h	D Hz	E Hz	Image	Yield stress Pa	FSS g/L	Cake solids %	Solids capture %
5/28	0.30	0.59	60.00	41.00	60.00		23.00	1.07	13.53	82.91
6/29	0.25	0.50	50.00	45.00	65.00		21.79	0.94	13.29	84.23
6/30	0.25	0.50	50.00	45.00	65.00		16.87	0.87	12.89	85.69
6/31	0.25	0.50	50.00	45.00	65.00		13.74	1.12	10.39	81.58

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