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Investigating the effects of different cationic charge flocculation polymers on municipal wastewater sludge dewatering

Megan Abrahams, Mujahid Aziz* and Godwill Kasongo

Environmental Engineering Research Group (EnvERG), Faculty of Engineering and the Built Environment, Department of Chemical Engineering, Cape Peninsula University of Technology (CPUT), Bellville 7435, Cape Town, South Africa

*Corresponding author. E-mail: azizm@cput.ac.za

ABSTRACT

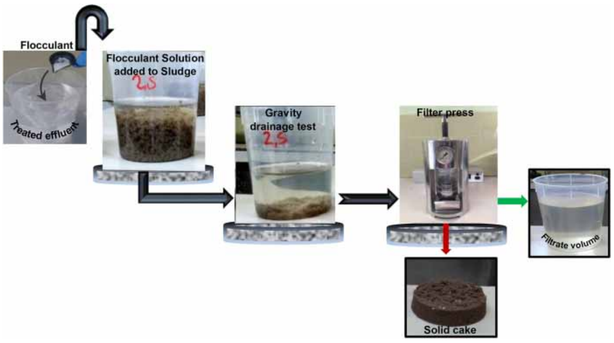
The minimization of sludge produced by municipal wastewater treatment plants (MWWTPs) is critical as its handling accounts for approximately 50% of the total operating cost. The challenges in predicting dewatering performance can be overcome by optimizing the sludge treatment process, especially conditioning and dewatering. This study aimed to investigate sludge dewaterability at four different MWWTPs, using a gravity drainage test unit and a bench-scale press. The effect of differently treated effluent used as a solvent to mix the flocculation polymers was observed during dewatering. The membrane bioreactor (MBR) treated effluent yielded the highest filtrate volume in the lowest amount of time, with the least polymer flocculant dosage. The Box Behnken Design model fitted the data and proved a relationship between polymer dosage, cake solids concentration, and cake height during the bench-scale press tests.

Key words: activated sludge, cationic polymer, dewatering, flocculant, gravity drainage, sludge treatment

HIGHLIGHTS

- The type of water used for polymer flocculant dissolution has, to an extent, a considerable impact on the gravity drainage of the sludge.
- Increasing polymer flocculant dosing is not directly proportional to the cake height and cake dryness.
- Significant correlation between sludge characteristics (e.g. feed solids) and the cake formed.

GRAPHICAL ABSTRACT



INTRODUCTION

Biological sludge tends to form highly compressible cakes, and the sludge properties change continuously. These bio-sludges need to be adequately dewatered before disposal. It contains many fine particles and high water content, which formulates its highly compressible nature, making it very hard to dewater (Zhao *et al.* 2013). The high water content found in sewage sludge is responsible for the large volumes produced, preventing the sludge from being processed, such as in landfilling or incineration (Kasongo Wa Kasongo 2018). Due to the total cost for transportation, incineration and drying, energy would increase tremendously (Dominiak *et al.* 2011). The

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highly compressible nature of sludge necessitates pre-treatment before dewatering to enhance water removal during the dewatering process. The most commonly used pre-treatment method is chemical treatment using charged organic polymers, also referred to as polyelectrolytes. This is then followed by the dewatering step, mainly performed by mechanical techniques based on centrifugation or filtration; for example, by belt or filter press (Ginisty *et al.* 2014). The following sludge characteristics are known to influence dewaterability: extracellular polymeric substances (EPS), suspended solids concentration, optimal polymer dose, sludge viscosity, hydrophobicity, physiological and physicochemical effects, mono- and divalent cations, COD/phosphorus ratio, pH and surface charge. Other than sludge characteristics, polyelectrolyte characteristics also play an essential role in dewatering performance (Saveyn & Van Der Meeren 2005).

Currently, there is a void in reliable bench-scale methodology as a guide to dewatering effectiveness. Due to a thorough investigation regarding the use of standard methods for assessing sludge dewatering, it was observed that there is a need to obtain a viable method that can be used. During the conventional activated sludge process, various municipal sewage wastewater treatment works (MSWWTPs) generate large amounts of waste activated sludge to be processed by the dewatering facilities. The bio-solid cake produced during the dewatering processes were characterized by a low solid content, where it is below the expected levels (15 to 25%) stipulated by US EPA (1987). This study aims to evaluate the effects of sludge characteristics and flocculant concentration on dewatering, and to provide an experimental method that measures sludge drainability that can be used to assess belt filter press operations on a full scale. This will result in effective measure and control of the dewatering operation to save cost and obtain a standard lab-scale method used as a sludge dewatering index.

MATERIAL AND METHODS

Materials and reagents

There are many variables associated with assessing the dewaterability of municipal sludge that previous researchers have identified. For this study, dewatering was evaluated based on the characteristics of four MSWWTPs within the CoCT (Plants A, B, C, D) were chosen. These MSWWTPs were selected based on their continuous operability and reliability when needing to collect sludge samples. Two polymer flocculants were used, FLOPAM 4650 and FLOPAM 4800. FLOPAM 4650 has a medium cationicity of 55%, and FLOPAM 4800 a high cationicity of 80%. These two were selected based on availability; all the MSWWTPs within the CoCT use either one of the two polymers at their dewatering facilities. Various water types for flocculant dissolution were used, namely (i) treated effluent before filtration, (ii) treated effluent after filtration, (iii) MBR permeate (Aziz & Ojumu 2020) and (iv) potable water. These 'water types' are currently being utilized at the MSWWTPs for flocculant dissolution and 'service water'. All four water types were investigated to obtain the full-scale dewatering operations' representative results using the sludge lab-scale unit. MSWWTPs sludge collection was waste activated sludge (WAS) only.

Experimental set-up and procedures

The experimental tests were conducted for seven months. Each month, a sample was collected in a sequence of the four plants (A, B, C and D). Two independent experimental tests were conducted: the drainage control test, which simulated the linear screen and the bench press, which simulated the belt press. Samples used for conditioning tests were stored in the laboratory's fridge at 5 °C and warmed up when needed to room temperature within four days after collection to limit the biological activity and enable acceptable experimental tests' reliability. The parameters considered when selecting the water quality for the flocculant polymer dissolution are shown in Table 1. According to Kim *et al.* (2016) and Park *et al.* (2019), the parameters to be considered

Table 1 | Characteristics of different makeup water used for polymer flocculant dissolution

Parameter	Recommended values	MBR treated effluent	Treated effluent before filtration	Treated effluent after filtration
Conductivity	$< 1{,}000$ µS/cm	104	156	154
Alkalinity	< 300 mg $CaCO_3$	186	328	333
pH	$6 < pH < 8$	7.4	7.5	7.4
E. coli	$<1{,}000$ CFU/100 mL	35	20	16
Suspended solids	< 5 mg/l	6	10	24

when selecting polymer dilution water are conductivity, alkalinity, pH, *E. coli*, and TSS. Table 1 shows the analysis results obtained for the different types of effluents. The flocculation polymer solution (2 g/l and 3 g/l) was prepared a day before its use. A magnetic stirrer was used to mix the polymer flocculant with water. The polymer was measured using a TANITA mass balance. The solution (water and polymer) was mixed for 1 hour and allowed to age for 30 mins before use.

Sludge analysis and characteristics at different plants

Sludge samples were transferred to the laboratory for characterizing their physical and chemical parameters; dry solids (DS), volatile solids (VS), total suspended solids (TSS) content and sludge volume index (SVI). The feed solids (FS) concentration in the sludge plays a crucial role when determining the polymer consumption, which was calculated in kg polymer per ton of solids, using Equation (1). The moisture analyser ASTM Standard Test Method was used to determine the DS content. The VS and TSS were determined soon after the sludge's dry solid content using method 1684 (EPA-821-R-01-015) (U.S. EPA 2001). The SVI was calculated (in $\text{mg}\cdot\text{l}^{-1}$) after the sludge sample had settled in a granular cylinder for 30 mins, using Equation (2).

$$\frac{\text{P.D. } (g.L^{-1}) \times \text{polymer } [c]}{1000} \times \frac{1000}{\text{Sludge Flow Rate (mL)} \times \text{feed solids}[c]} = \text{kg/DTS} \tag{1}$$

$$\text{SVI } (mL.g^{-1}) = \frac{\text{Settled Sludge Volume } (mL.L^{-1})}{\text{Mixed Liquor Suspended Solids } (g.L^{-1})} \times 1000 \tag{2}$$

The sludge characteristics are displayed for the four WWTPs used for this study in Table 2. The volatile suspended solids and feeds solids concentration of WAS are important characterization parameters to estimate the sludge dewaterability (Corsino *et al.* 2016; López Zavala & Patlán 2016).

Table 2 | Main parameters for makeup water quality selection

Parameter	Units	Plant A	Plant B	Plant C	Plant B
Total suspended solids (TSS)	mg.L^{-1}	3,903	9,282	8,512	7,746
Volatile suspended solids (VSS)	mg.L^{-1}	3,230	7,162	7,162	7,068
Sludge volume index (SVI)	mg.L^{-1}	148	104	117	103
Feed solids (FS)	%	1.1	1.2	1.1	3.4

Drainage control tests

The drainage control test was set up via a computer program and provided the drained filtrate's weight. The sludge was mixed with the flocculant solution and induced at a given volume through a porous medium. The solids present in the sludge mixture were drained and deposited as a cake on the porous medium. The drained water was measured in the beaker, and logged online with a specialised software program. The drained water (filtrate) was measured and plotted on a graph against time. The drainage test was conducted to detect the overdosing of polymer flocculant and the impact of polymer concentrations, as reported by Blankenburg (2005). The test further showed how different water types performed for gravity drainage and how various sludges performed depending on their feed solids concentration. Each test was conducted using 200 ml of sludge.

Bench-scale test

A bench press rig was used to apply pressure to a flocculated sludge sample trapped between two circular filter discs. The flocculated sludge sample was poured onto the filter belt and free water drained through it like a belt press's gravity stage. After gravity drainage was completed, a second filter belt disc was placed on the sludge, and a second perforated metal disc placed on top. The pressure was applied to the upper, perforated disc, forcing out water from the sludge sandwich, which passed through the filter belts and the perforated plates. The optimum polymer dose rate, the cake dryness, and the floc's strength were determined during the belt press.

Dewatering tests statistical analysis

Single-factor ANOVA and a T-test were performed on the gravity drainage experimental data. This was done to see if there was an implication when changing the polymer, polymer concentration and water types. The confidence level for these experimental test results was 95%, hence $\alpha = 0.05$. During the bench press results, the design expert software program was used to verify the interaction that was observed by the polymer dosage (ml), feed solids concentration (%), solids concentration in the cake (%) and the cake height (mm). Respond surface methodology-based Box-Behnken Design (BBD) was used to compute the relationship between the input and output variables. For these experimental runs, a three-factor two-level Box-Behnken Design was used to statistically analyse the effect of the operating parameters and their interactions on the belt filter press performance using Stat-Ease Design Expert V 10.0.7 version.

RESULTS AND DISCUSSION

Effects of sludge characteristics on sludge dewatering

The difference in VSS for the four plants sludges is shown in Figure 1. Blankenburg (2005) stated that the higher the VSS, the more complex the dewatering, thus the solid concentration in the cake and mechanical properties would be low. This causes an increase in flocculant consumption. The volatile suspended solids (VSS) of Plant A sludge was found to be approximately 50% lower than the rest of the plants' sludges. Hence, after dewatering, the VSS of Plant A sludge produced a drier cake, followed by Plant B, D and C. The feed solids percentage was in the expected range of the WAS feed solids, which is generally between 0.4% and 1.5% (Severin & Grethlein 1996). Plant D, however, had a feed solids content of 3.4%. This could be due to the gravity thickening process before the sludge dewatering operation at the plant.

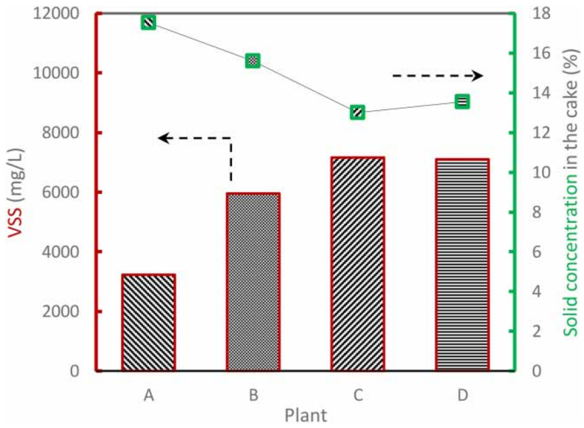

Figure 1 | Volatile suspended solids effects on cake dryness.

The highest solids concentration of 18% was found at a VSS of 3,230 mg/l, with the lowest solid concentration of 13% at a VSS of 7,162 mg/l. This suggests that a thickening step needs to be added before the dewatering step to enhance the higher VSS concentration's dewatering process. Only WWTP D had a thickening step before dewatering, but the VSS was still high compared to WWTP A, without a thickening step.

Gravity drainage tests and effects of polymer flocculant dissolution water characteristics

WAS from all four WWTPs were used to conduct gravity drainage tests. Figure 2 shows drainage curves for the two polymer flocculants in all four plants with the four different makeup water types. Plants A, B, and C sludges all followed a similar trend with the same volume drained. This is due to similar feed solids concentration (%) sludge characteristics. Plant D shows that the sludge drained at a much lower captured volume but with a higher polymer dosage. At high feed solids concentration, the polymer required for sludge dewatering increases. This slows the rate of gravity drainage due to an increased build-up of solids on the filter cloth (De Milieux 2012).

When comparing the drainage curves of both polymers, from Figure 3 it was observed that FLOPAM 4800 dosage was lower than FLOPAM 4650 for WWTPs A, B and D. This could be due to FLOPAM 4800 having a

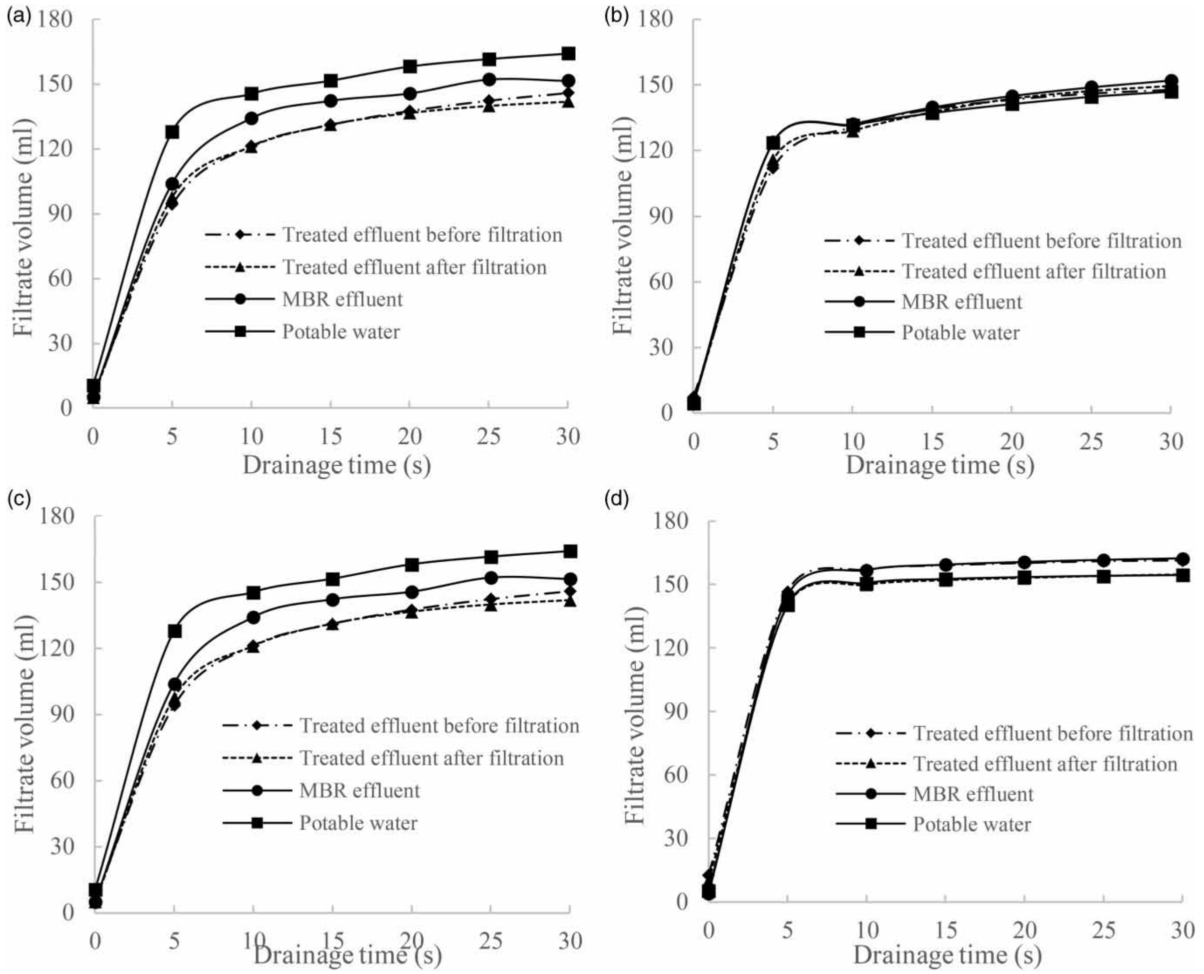

Figure 2 | Drainage curves for FLOPAM 4650 polymer with various polymer dilution waters: (a) WWT Plant A, (b) WWT Plant B, (c) WWT Plant C, (d) WWT Plant D.

cationicity of 80% and FLOPAM 4650, 55% (De Milieux 2012). The higher the cationicity, the lower the polymer demand to establish sludge flocculation for dewatering. All water types produced similar trends with the drainage curves, where Vaxelaire & Olivier (2006) concur. However, for WWTP D using FLOPAM 4800, the drainage curve had a wider gap in-between each water type graph. The filtered water showed a distinctive difference with a lower filtrate volume as well. A higher molecular weight polymer had a lower filtrate volume than a medium molecular weight polymer (Vaxelaire & Olivier 2006; Ginisty *et al.* 2014).

Within the first 10 seconds of the drainage test, Plant A had the highest drained volume of 157 ml with treated effluent before filtration as polymer makeup water. Hard water used as polymer dissolution water produced better sludge filterability results than softer water, which concurs with these results (Wu *et al.* 2003). Plant B generated the highest gravity drained volume of 150 ml within the first 10 seconds of the experimental run when using 2 mL FLOPAM 4800 dissolved in a treated effluent before filtration water type. When the polymer type changed from FLOPAM 4650 to FLOPAM 4800, a difference in results was observed. The significant difference was determined with 'polymer makeup water types' at the exact polymer dosage and different polymers using Anova (FLOPAM 4650 (treated effluent before filtration) p-value $= 0.9241$ and FLOPAM 4800 (MBR permeate) p-value $= 0.7575$). The analysis of water types in Table 1 shows that the alkalinity for treated effluent before and after filtration is slightly higher than the recommended value. The suspended solids for all the effluents are also slightly higher, as well as the bacteria *Escherichia coli* (*E. coli*). None of the water types is fully compliant with the recommended makeup water standard. According to De Milieux (2012), it could lead to the flocculant mixture's degradation and hydrolysis if not compliant.

A decrease in the filtrate volume was also observed in plants A and C when changing the polymer type. This was due to a higher molecular weight polymer producing sticky cakes, resulting in a reduced water flow through

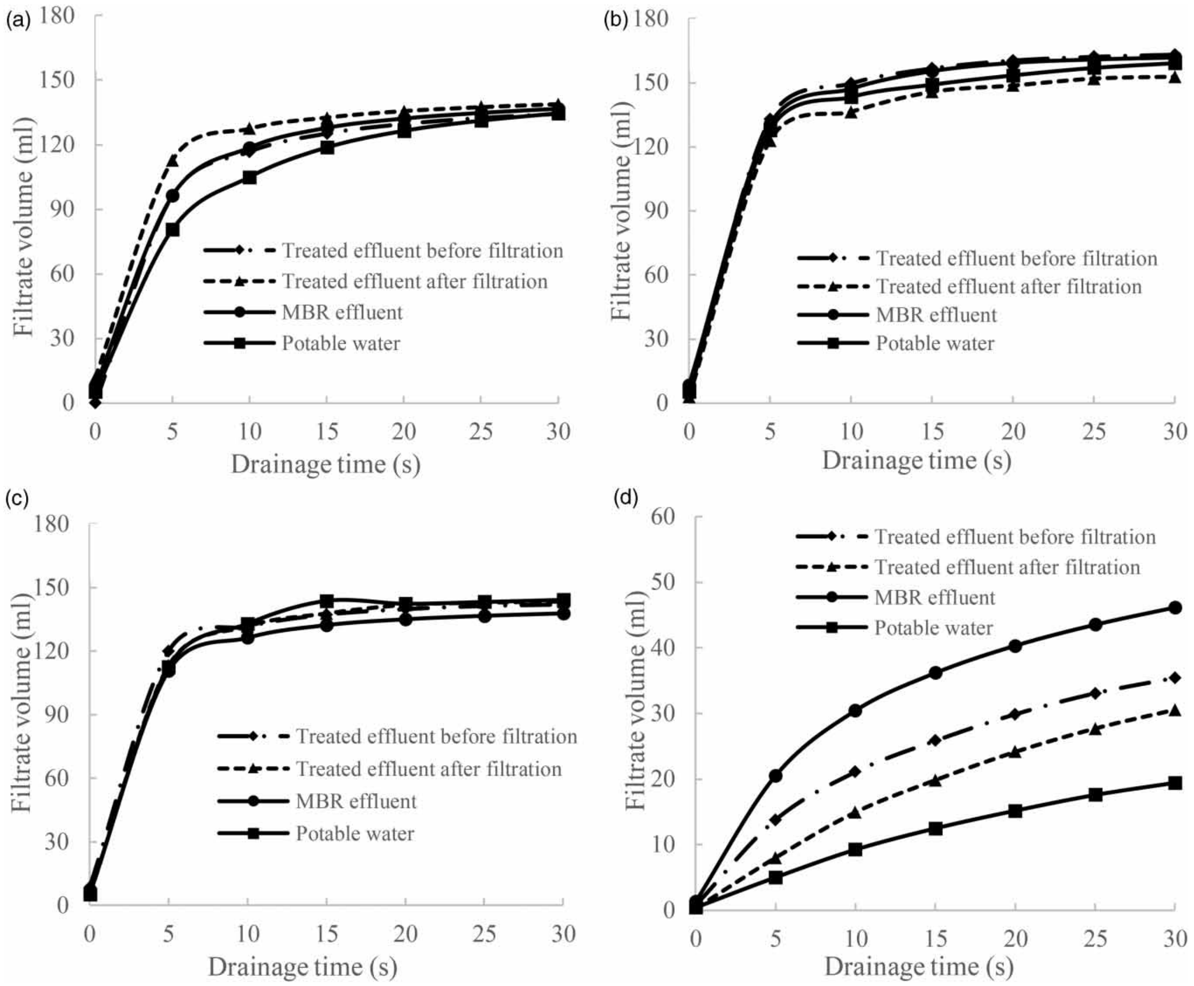

Figure 3 | Drainage curves for FLOPAM 4800 with various flocculation polymer dilution waters are (a) WWTP A, (b) WWTP B, (c) WWTP C, (d) WWTP D.

the formed cake (De Milieux 2012). Furthermore, the filtrate volume was observed to be affected by the total suspended solids (TSS) of the sludge indicated in Table 2. An increase in TSS resulted in poor dewatering. The increased TSS created a thicker sludge, which reduced the amount of filtrate during the gravity drainage test.

Effects of specific resistance of filtration (SRF) on polymer dosage

The SRF was obtained assuming constant at atmospheric pressure (101.325 kPa), the viscosity of the filtered liquid was 8.90×10^{-4} Pa·s, and the C value was constant (weight of the solids/unit volume of filtrate, g/ml), as suggested by Qi *et al.* 2011. At the dewatering operation's filtration stage, the average SRF is constant, and the inverse flux (t/V) against the filtrate volume (V) plot gave a straight line, therefore, as shown in Figure 4. A constant value b was obtained using the line's slope from the inverse flux versus volume straight line. The SRF was then calculated, and the values are shown in Table 3. Treated effluent before filtration was arbitrarily chosen as the polymer makeup water.

It was observed that a change in polymer and polymer dosage influenced the SRF at the condition represented in Table 3. The SRF decreased with an increase of polymer dosage, as confirmed by Zhu *et al.* (2017). However, the change in SRF was minimal, which was possible since the same sludge type was used, and the main influencing parameter, feed solids concentration, remained constant for three of the four WWTPs.

Effects of polymer dosage on cake height and solids concentration of the cake obtained in belt-press tests

The bench-press experimental runs observed polymer dosage interaction on cake height formed after dewatering and solids concentration measured in the cake. Figure 5 represents the solids in the cake and cake height for all

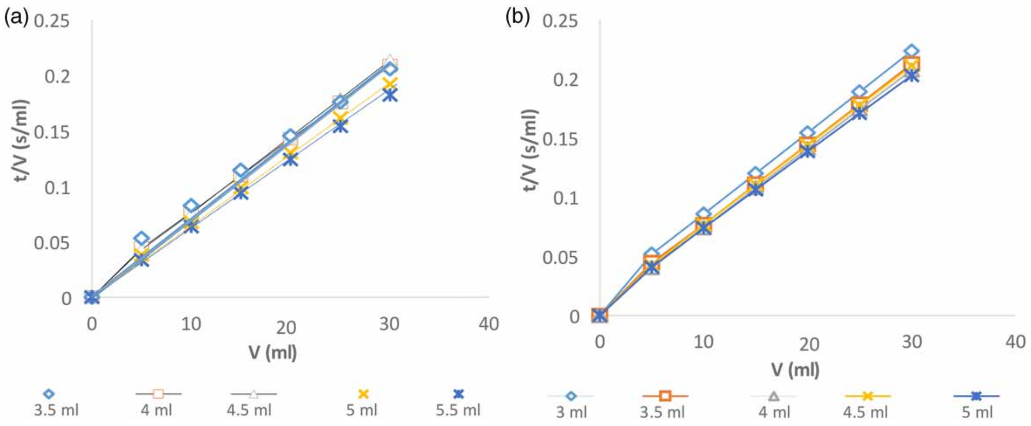

Figure 4 | Overall dewatering lines for sludge conditioned by (a) FLOPAM 4650, (b) FLOPAM 4800 from WWTP A.

Table 3 | SRF values for FLOPAM 4650 and FLOPAM 4800 obtained in WWTP A

	Polymer			
	FLOPAM 4650		**FLOPAM 4800**	
Polymer dosage (ml)	**b value (sec/ml^2)**	**SRF (sec^2/g)**	**b value (sec/ml^2)**	**SRF (sec^2/g)**
3.0	0.0072	3×10^5	0.0072	3×10^5
3.5	0.0071	3×10^5	0.0069	3×10^5
4.0	0.0071	3×10^5	0.0068	3×10^5
4.5	0.0065	3×10^5	0.0069	3×10^5
5.0	0.0062	3×10^5	0.0067	3×10^5

four WWTPs. A direct correlation between the sludge cake height and solid concentration was observed. When the cake height decreased, the optimum polymer dosage (OPD) was achieved. Therefore, with WWTP A, the optimum dosage obtained was 5.21 kg/DTS using a 400 ml sludge sample. WWTP B OPD at 4.83 kg/DTS, WWTP C OPD at 4.93 kg/DTS and WWTP D OPD at 10.67 kg/DTS. All the WWTPs followed a similar trend except WWTP D. The optimal polymer dosage for Plant D was attained at 10.67 kg/DTS. The very high amount of polymer required for Plant D flocculation is due to the sludge having a high feed solids concentration.

Development of the sludge dewatering model

A model predicting the solids concentration in the cake was developed to select an appropriate range of parameters for the dewatering process optimization. The ANOVA results for the sludge dewatering quadratic model presented variance analysis and showed the significant model term affecting sludge dewatering. The quadratic model was a good fit; the R^2 (0.9950) was higher than 0.8. Furthermore, a *P*-value lower than 0.05 was obtained. The final model is presented in Equation (3) and Equation (4) in terms of coded and fundamental factors, respectively, predicting the response for given levels of each factor. *A* represents cake height, and *B* feeds solids. *A.B.* represents the interaction between cake height and feed solids. A^2 is the cake height's quadratic effect. A positive sign before a term indicates an increasing effect in the model equation, while a negative sign indicates a decreasing effect on the cake's solids concentration. From the interactions between the different parameters investigated, the cake height and feed solids concentration appeared to have significant interaction. The cake's solids concentration appeared to be significantly affected by the sludge's feed solids than the cake height. According to the model, a unit increase in the feed solids increases solids concentration in the cake by a factor of 4.25.

$$Solids\,in\,cake = +8,00 - 2,50 * A + 4,25 * B - 1,00 * AB + 0,75 * A^2 \tag{3}$$

$$\begin{aligned} Solids\,in\,cake = {} & +11,41667 - 4,00000 * cake\,height + 7,91667 * feed\,solids \\ & - 0,66667 * cake\,height * feed\,solids + 0,33333 * cake\,height^2 \end{aligned} \tag{4}$$

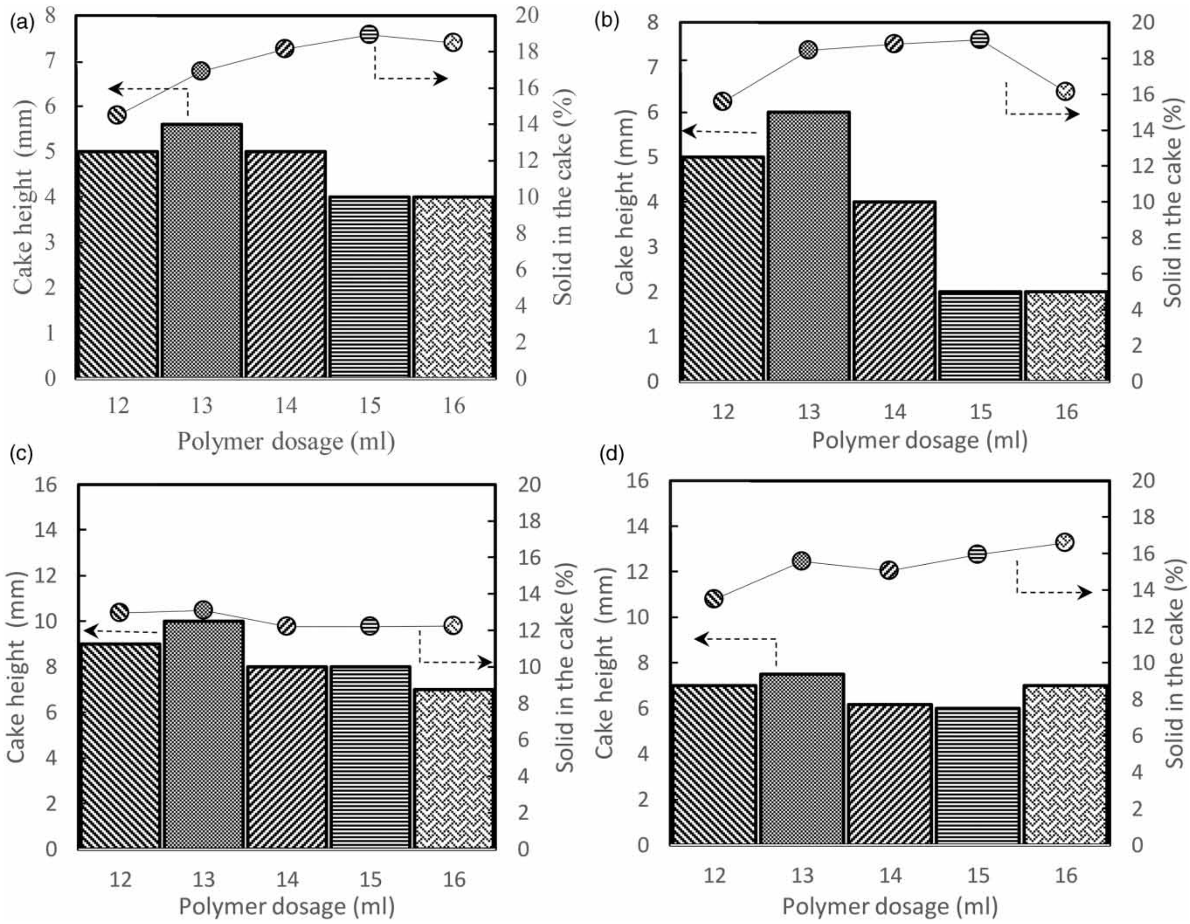

Figure 5 | Influence polymer dosage has on cake height and sludge dryness: (a) MSWWTP A, (b) MSWWTP B, (c) MSWWTP C, (d) MSWWTP D.

CONCLUSION

This study investigated polymer flocculant conditions affecting sludge dewatering through a drainage control and compression test. The experimental test runs represented a linear screen. The belt press of the full-scale dewatering operation from wastewater treatment plants sludges attained similar results, except for Plant D. This is mainly due to higher feed solids content. The polymer dilution water type impacted the sludge dewatering, whereas the polymer flocculant type impacted polymer dosage. Less flocculant was required for the higher molecular weight polymer flocculant than the medium molecular weight polymer flocculant. A relationship existed between the feed solids concentration, cake height, and cake solids concentration for the bench press experimental results. Data analysis showed that experimental results followed a Box-Behnken Design, and a quadratic model was formed. The selected factors (cake height, feed solids concentration) and response (cake solids concentration) were significant with an $R^2 = 0.9950$. An investigation of different types of sludge other than waste activated sludge in the wastewater treatment plants is recommended to assess results and the effectiveness of the dewatering operations more broadly.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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