

Article

Metal Cation and Surfactant-Assisted Flocculation for Enhanced Dewatering of Anaerobically Digested Sludge

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Abstract: Flocculation and dewatering of anaerobically digested sludge is known to be a major cost factor in the economy of wastewater treatment plants. Hence, several endeavors have been underway in search of affordable and effective alternatives. This study focuses on the effects of different metal cations, including FeCl₃, CaCl₂ and MgSO₄, on the dewaterability of digested sludge. The effects of these metal flocculants were also investigated in the presence of co-polymers and surfactants, which can be considered the novelty of this study. The polymers and surfactants investigated in this study were emulsion polymer, CTAB and SDS. Sampling and characterization of digested sludge was conducted, and total solid (TS), volatile solid (VS), dewaterability in capillary suction time (CST), total dissolved solids (TDS), chemical oxygen demand (COD), pH and conductivity of the unconditioned digested sludge samples were determined. The dewaterability of FeCl₃, CaCl₂ and MgSO₄ conditioned digested sludge samples were compared, and MgSO₄ conditioned digested sludge showed better dewaterability compared to the other two metal conditioning agents at a pH of 6.8. The dewaterability was further improved by the addition of emulsion polymer (EMA 8854), cetyltrimethyl ammonium bromide (CTAB) and sodium dodecyl sulfate (SDS). FeCl₃ was found to perform better under an acidic pH of around 3. The dual conditioning using polymer and CTAB resulted in better dewaterability, with CaCl₂ as metal conditioning agent. Moreover, the effects of pH, metal dose and polymer dose on the dewaterability of digested sludge were also investigated. The effects of metal and polymer conditioning on the particle size of the sludge flocs was also investigated. Optimum dewatering performance was achieved for metal doses of 0.16 v/v, 0.075 v/v and 0.16 v/v for FeCl₃, CaCl₂ and MgSO₄, respectively, and a corresponding CTAB dose of 0.1 v/v and EMA dose of 15 kg/TDS were found to be the optimum. SDS as a polymer conditioning agent resulted in the deterioration of dewatering performance.

Keywords: metal cations; surfactants; emulsion polymer; sludge dewatering



Citation: Shinde, S.; Yeneneh, A.M.; Jafary, T.; Al Balushi, K.; Hong, E.; Sen, T.K.; Rupani, P.F. Metal Cation and Surfactant-Assisted Flocculation for Enhanced Dewatering of Anaerobically Digested Sludge. *Sustainability* **2023**, *15*, 3448. <https://doi.org/10.3390/su15043448>

Academic Editor: Agostina Chiavola

Received: 17 December 2022

Revised: 7 February 2023

Accepted: 9 February 2023

Published: 13 February 2023



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1. Introduction

Sludge handling and treatment processes and operations account for approximately 70% of the overall wastewater treatment plant operational cost. The digested sludge generated by wastewater treatment plants contains large amounts of water, usually about 90%; it is important for the sludge to undergo the process of dewatering, as this will significantly reduce transportation and handling costs. Moreover, with proper treatment, water generated from sludge dewatering can be used as a substitute for fresh water, for irrigation purposes in agriculture and aquaculture as well as for household use. The dewatered sludge, biosolid, can be used as fertilizer in farms. Sewage treatment is very crucial to produce a stabilized biosolid which is suitable for beneficial use. Landfilling and agricultural use have been traditional ways of disposing of the biosolids, which have been totally

restricted by legal actions and demands of food producers. Thus, huge sludge production increases the cost of sludge treatment, transportation, and storage space, which necessitates the reduction of biosolid production by improving dewatering performance. Therefore, the biosolid dewatering process becomes one of the important sewage treatments, due to its significant impact on the economics, functioning and capacity requirements in downstream processes [1]. The commonly used techniques, like centrifuges and filter presses, in sludge dewatering only have the capability to remove about 15–30% of excess water from thickened sludge, which originally contains more than 95% water. The process of sludge treatment and disposal can then be regarded as the bottleneck in the wastewater treatment process due to the issue of its high water content, and it is necessary to find ways to further increase sludge dewatering performance [2]. Compared to other technologies, metal cation and surfactant-assisted flocculation has several advantages. For example, it is a low-cost, efficient and environmentally friendly process that can effectively remove pollutants, including heavy metals and organic pollutants [3]. Moreover, the addition of metal cations and surfactants has been found to reduce the residual chemical oxygen demand and total suspended solids in the treated wastewater [4]. Sludge's stability and dewatering capability can be enhanced by the use of flocculants, which reduces the mutual repulsion between sludge particles and increases their size [5]. Sun et al. [6] observed that improvement in sludge dewatering was caused by a reduction of EPSs and increase in floc size. Negative charges on the surface of sludge and the repulsion between sludge particles can be mitigated with the help of surfactants and flocculants, respectively. Because of this, EPSs and bound water in sludge were easily released into the aqueous phase, and thus, the sludge aggregates become more compactable and stable. Sludge flocculation is facilitated by flocculants in three ways: charge neutralization, absorption bridging and the mechanism of the electrostatic route [7]. The water trapped in digested sludge can be free water, interstitial water, vicinal water or water of hydration. Interstitial water volume is about 20% of the total volume, where this water type is usually trapped within floc and physically bound by capillary forces. Therefore, the floc must be destroyed or broken to remove the water trapped within the cell. On the other hand, vicinal water is water molecules in multilayers that are held to the particle surface tightly with a hydrogen bond [8]. Thus, this water will not be able to move freely as it is adhered to solid surfaces. Lastly, the water of hydration is the water that is chemically bound to the particles and usually can be removed with thermal processes. Sludge dewatering processes can be characterized as either natural or automatic. Natural processes utilize drying beds and sludge lagoons, while mechanical process include centrifuges, vacuum filters, belt and filter press [9]. Sludge dewatering process can be enhanced by using different sludge conditioning agents, as the process is the most cost intensive [10]. The three most common types of sludge conditioning techniques used are inorganic chemical conditioners, organic polymers and thermal conditioning. Metal conditioning agents like FeCl_3 , CaCl_2 , CaCO_3 , CaSO_4 and AlSO_4 can be used for sludge conditioning alone or in combination with other polymers or surfactants [11–13]. Conditioning of sludge with aluminum sulphate, ferric chloride, calcium sulphate (gypsum), calcium carbonate (lime) and other divalent metals as coagulation and flocculation agents has resulted in significant outcomes. Besides organic chemical conditioners like PAA, CTAB and PMA have been used as flocculation agents to enhance digested sludge dewaterability [14,15]. Polymer conditioning has now become the most extensively used, economical and operable practice of all the pre-treatment methods for an improved dewatering process [16]. Some surfactants were found to change microorganism cell structure by making cell materials leave the attached surface and dissolving them in the water [17]. Hydrogen peroxide, ozone and other oxidizing agents have also been applied to enhance digested sludge dewaterability. Ultrasonication, hydrodynamic cavitation, thermal treatment and microwave treatment were also reported in literature as sludge dewatering performance enhancement methods [18]. The performance of the aforementioned chemicals and treatment methods depends on several factors, including chemical dose, pH, sludge type, floc particle size and charge distribution. One of the im-

portant factors which affects the process of conditioning of sludge is its particle size and distribution. A decrease in particle size, which results from mixing or shearing of particles, affects the sludge in such a way that there is an exponential increase in surface/volume ratio, which then results in an increased dewatering resistance [19]. The increasing order of sludge dewaterability for each metal cation was noted as follows: sodium < calcium < magnesium < ferric < aluminium. According to Sanin et al. [20], potassium (and other monovalent ions) does not improve the floc structure as much as the divalent cations, such as calcium and magnesium. This may be explained by their inability to form linkages between the EPSs within the sludge matrix and floc surfaces, due to their monovalent nature. Ozkan et al. [21] found that magnesium was more effective in the coagulation of celestite suspension than calcium at a neutral pH, because magnesium has a higher ionic potential (ionic charge/radius) [22]. A limited amount of research reported the use of mono-, di- and trivalent metal salts in municipal digested sludge dewatering. Moreover, the effects of dual conditioners, such as the combination of metal cations with polymers and surfactants, on sludge dewaterability have not been reported on much [23–26]. Very little published research reported the comparative performance of different metal cations as sludge conditioners in the presence of polymers and surfactants. Many researchers have also investigated applicability of polymers (individual and dual polymers) for efficient flocculation, but the effect of dual conditioning with different metals cations and surfactants and polymers has not been thoroughly investigated. Furthermore, excessive consumption of polymer has always been an economic and environmental challenge. Hence, this research focuses on alternative dewatering performance enhancement options which have significant impact on wastewater treatment plant economy. Innovative sludge pre-treatment with different metal-based conditioning, coupled with polymers and surfactants to reduce the cost of dewatering, enhances flocculation and improves the quality of biosolid coming out of the process. The comparison between various metal cations and polymer and surfactants and their dual-conditioning mechanism in charge neutralization as well as bridging for enhanced dewaterability has been investigated in this study.

2. Methodology

2.1. Materials and Sampling

Anaerobically digested sludge samples were collected from the Beenyup Wastewater Treatment Plant of the Water Corporation, Western Australia. The collected samples were all stored at 4 °C during the research. Intensive characterization of all samples was conducted, including determination of TS, VS, TCOD, TDS, conductivity, pH and functional group analysis, using the FTIR technique and particle size analysis.

2.2. Metal, Polymer and Surfactant Conditioning Tests

Digested sludge samples were conditioned in jar experiments using 50 mL of a digested sludge sample. These samples were mixed with different doses of chemical-grade FeCl_3 , CaCl_2 , MgSO_4 , EMA 8845 MBL polymer, CTAB and SDS. CaCl_2 doses of 2.5, 3.75, 5, 6.25 and 7.5 mL/50 mL, polymer doses of 4, 6, 8, 12, 15, 18 and 20 kg/TDS, and MgSO_4 doses of 1, 2, 3, 3.75, 4, 6 and 8 mL/50 mL, CTAB doses of 2, 3, 5 and 6 mL/50 mL were used in the conditioning and dewatering tests. All tests were conducted using a simulated jar test of 50 mL duplicate sample volumes. Apart from the experiment on doses of conditioning agents, effects of factors like pH (1.4, 3.3, 5, 7, 9), and dual conditioning tests based on metal cations and EMA polymer or surfactants were investigated for how they affect the dewaterability of the samples. The pH adjustment was achieved using 0.1 M hydrochloric acid (HCl) and sodium hydroxide (NaOH) as required.

2.3. Characterization

All experimental work included the characterization required in this study; measurements of the sludge's TS, VS, SCOD, TCOD, pH, dewaterability (CST) were conducted. The total and volatile solid contents were determined according to *Standard Methods for*

the Examination of Water and Wastewater [27]. pH was measured with WP-90 and WP-81 conductivity/TDS-pH/temperature meter equipped with glass electrodes according to *Standard Methods* by the APHA of 2000 [27]. Chemical oxygen demand was determined by using an oxidation method with HACH COD reagent and colorimetric analysis on an ORION UV/Vis spectrometer. The dewaterability of different sludge samples was measured using a capillary suction timer (Type 304 CST equipment) [28]. The particle size distribution of digested sludge samples before and after pre-treatment/conditioning were determined using a Malvern Mastersizer 2000 laser diffraction particle size analyzer. Fourier transform infrared spectroscopy (FTIR) with a Perkin Elmer Spectrometer 100 was used to investigate the functional group in the digested sludge samples. The essential characteristic functional groups and changes that the flocs undergo due to the pre-treatment and conditioning were analyzed.

3. Result and Discussion

3.1. Sampling and Characterization

The digested sludge was characterized soon after collection from the Beenyup wastewater treatment plant dewatering unit, Centrifuge No. 1. The total solid concentration, volatile solid concentration, total dissolved solid concentration, pH, temperature, conductivity and total chemical oxygen demand were determined. The total solid content, volatile solid content, temperature, pH, chemical oxygen demand, total dissolved solids, conductivity and dewaterability of the digested sludge sample were found to be 1.8%, 1.4%, 31 °C, 6.8, 14,358 ppm, 5200 ppm, 9800 ppm and 312 s, respectively, as shown in Table 1.

Table 1. Characterization of Digested Sludge Collected from BWWTP.

Characterization Parameters	Value
Volatile Solids (%)	1.4
Temperature (°C)	31
pH	6.8
COD (ppm)	14,358
TDS (ppm)	5200
Conductivity (us)	9800
CST (seconds)	312
Total Solids (%)	1.8

An FTIR test was also carried out to find the functional group in the digested sludge sample, as shown in Figure 1. The sample was placed mounted on the sample disc, the spectroscopic imaging test was carried out, and transmission spectra of the essential functional groups present in the sludge were obtained, as shown Figure 1. The FTIR interpretations of peaks showed that the first peak is in the range of 3600–3300, indicating the presence of the hydroxyl group; the next peak is from 1600–1500, indicating the presence of the carboxyl group (COOH); the next peak ranges from 1100–1000, indicating the presence of the (C=O) group; and the next peak indicates the presence of the phosphate group (PO₄), confirming the presence of amino acids, polysaccharides, humic acid and other extracellular polymeric substances (EPS) from microbial activities in the anaerobic digester.

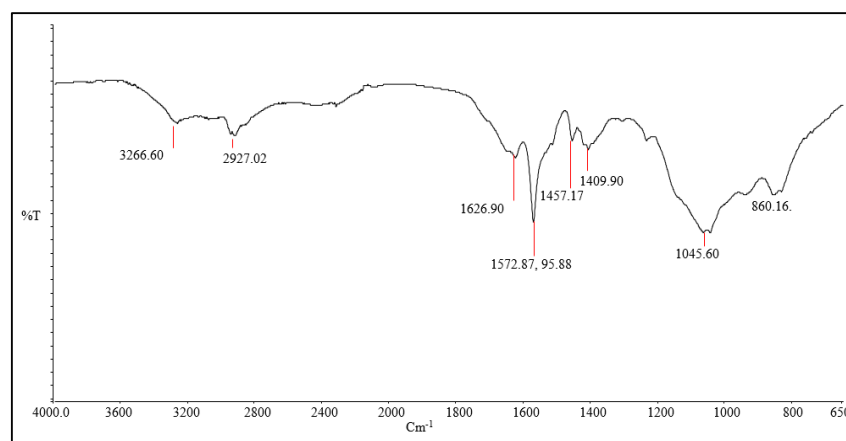


Figure 1. FTIR Plot for Unconditioned Raw Digested Sludge.

3.2. Effects of Ferric Chloride, Calcium Chloride and Magnesium Sulphate on Digested Sludge Dewaterability

The effects of three metal cations, FeCl_3 , CaCl_2 and MgSO_4 , when the metals are used as conditioners were investigated. Figure 2 shows that when the FeCl_3 dose was increased from 20 mL/L DS to 160 mL/L DS, the dewaterability, as measured in CST, decreased from 396 s down to 165 s. The optimum metal dose with respect to percentage reduction in CST was found to be 160 mL/L DS. Similarly, calcium chloride caused a reduction in the CST value by more than 50%. The optimum dose of CaCl_2 was found to be 75 mL/L DS, as shown in Figure 3. Likewise, for MgSO_4 conditioning the optimum dose was found to be 160 mL/L DS, as shown in Figure 4. Optimum doses of 120 mL/L DS, 75 mL/L DS and 160 mL/L DS were used for further experimentation on FeCl_3 , CaCl_2 and MgSO_4 , respectively. CaCl_2 resulted in comparably much better improvement in dewaterability compared to FeCl_3 and MgSO_4 . The dewaterability improvement due to CaCl_2 was found to be relatively better than the other two metal cations because of the bigger atomic radius that calcium ions provide compared to Mg and Fe ions [22].

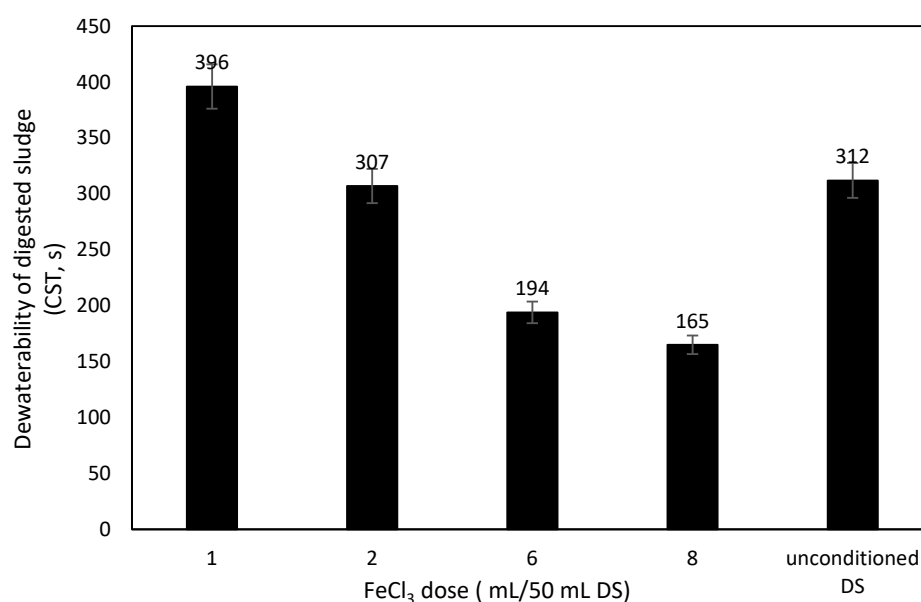


Figure 2. Effect of FeCl_3 dose on dewaterability of digested sludge.

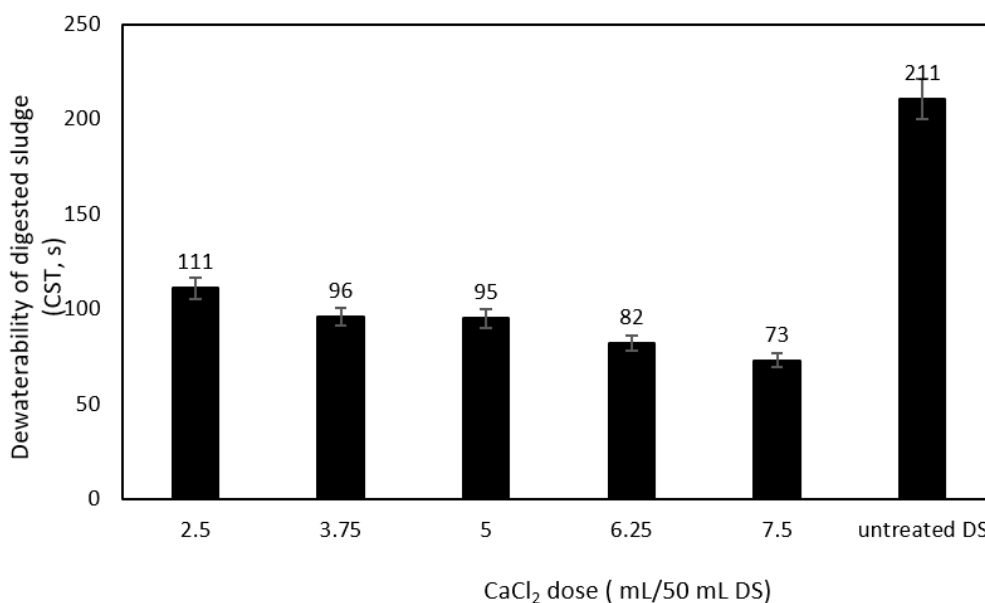


Figure 3. Effect of CaCl₂ dose on dewaterability of digested sludge.

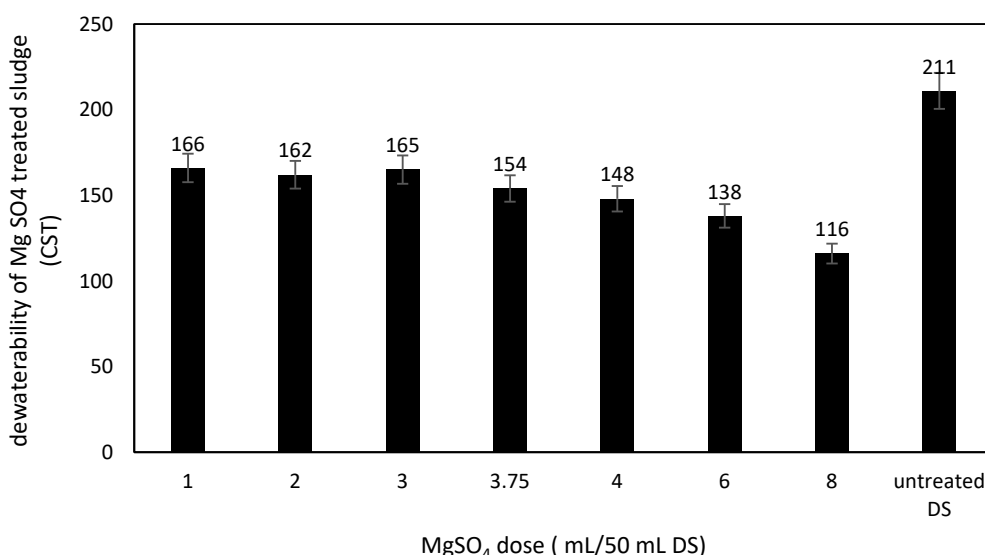


Figure 4. Effect of MgSO₄ dose on dewaterability of digested sludge.

3.3. Effect of Conditioning of Digested Sludge with Metal Cations and Polymers

The effect of the addition of EMA 8845 MBL polymer along with metal cations on dual conditioning was also investigated in this study. The effect of a polymer dose in the range of 4 kg/t DS—20 kg/t DS was first investigated, as shown in Figure 5, and it was observed that a polymer dose of 12–15 kg/t DS was the optimum. Furthermore, the effects of dual conditioning of digested sludge for three different metal cations and EMA MBL polymer was studied. Figure 6 shows that the dewaterability of the anaerobically digested sludge was increased due to the addition of the polymer compared to the performance of the metals alone. In particular, the dewaterability for CaCl₂ and MgSO₄ was significantly improved compared to that achieved in the case of FeCl₃, as shown in Figure 6b,c. This is due to the synergistic chemical complexation between calcium and magnesium salts with the emulsion polymer [6,29].

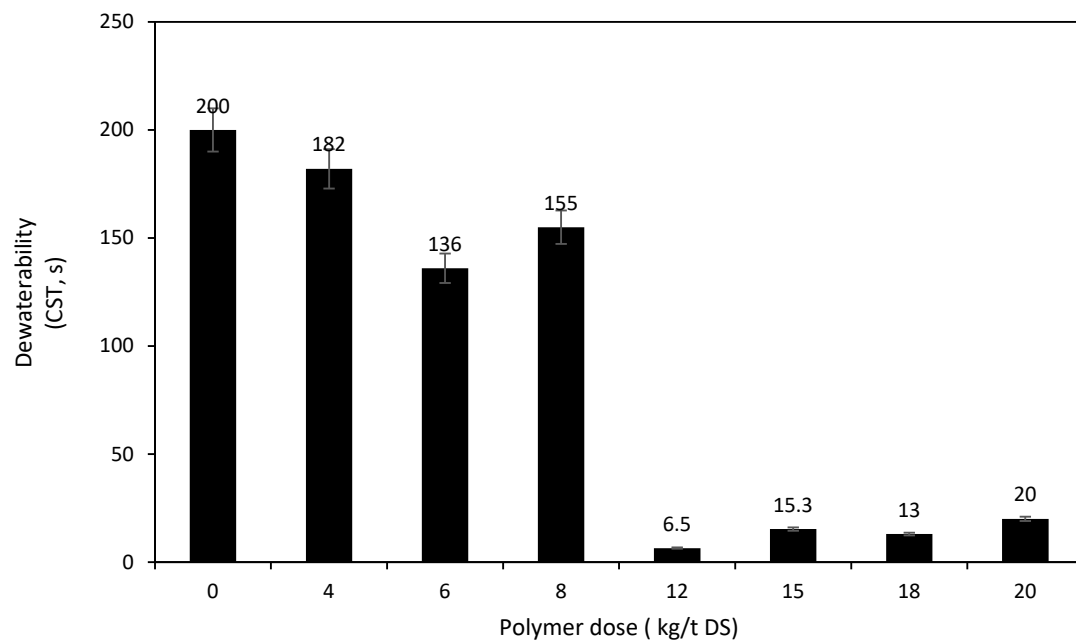


Figure 5. Effect of polymer dose (EMA) on digested sludge dewaterability.

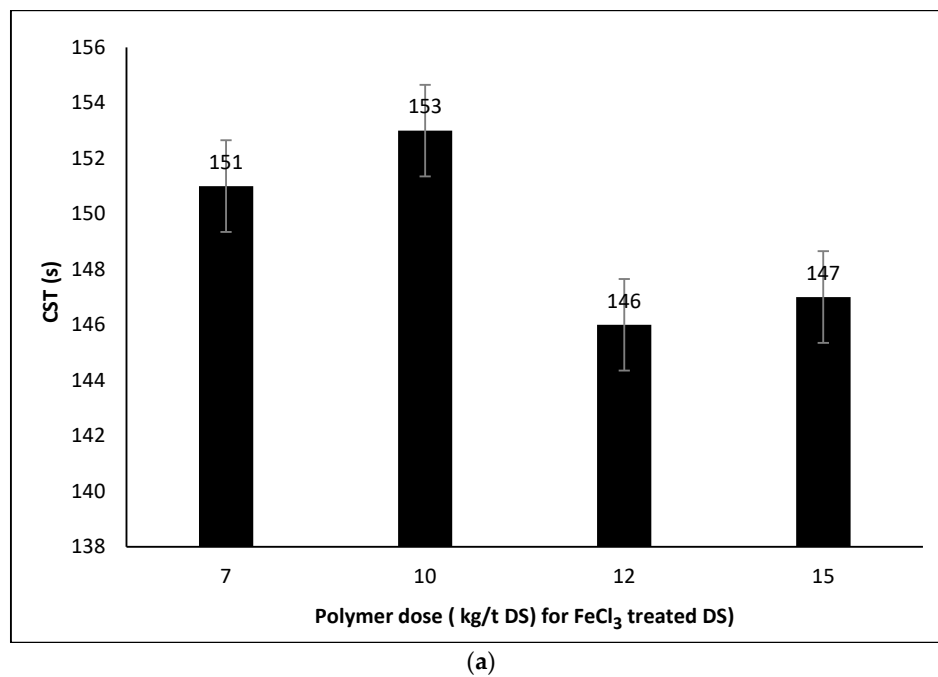


Figure 6. Cont.

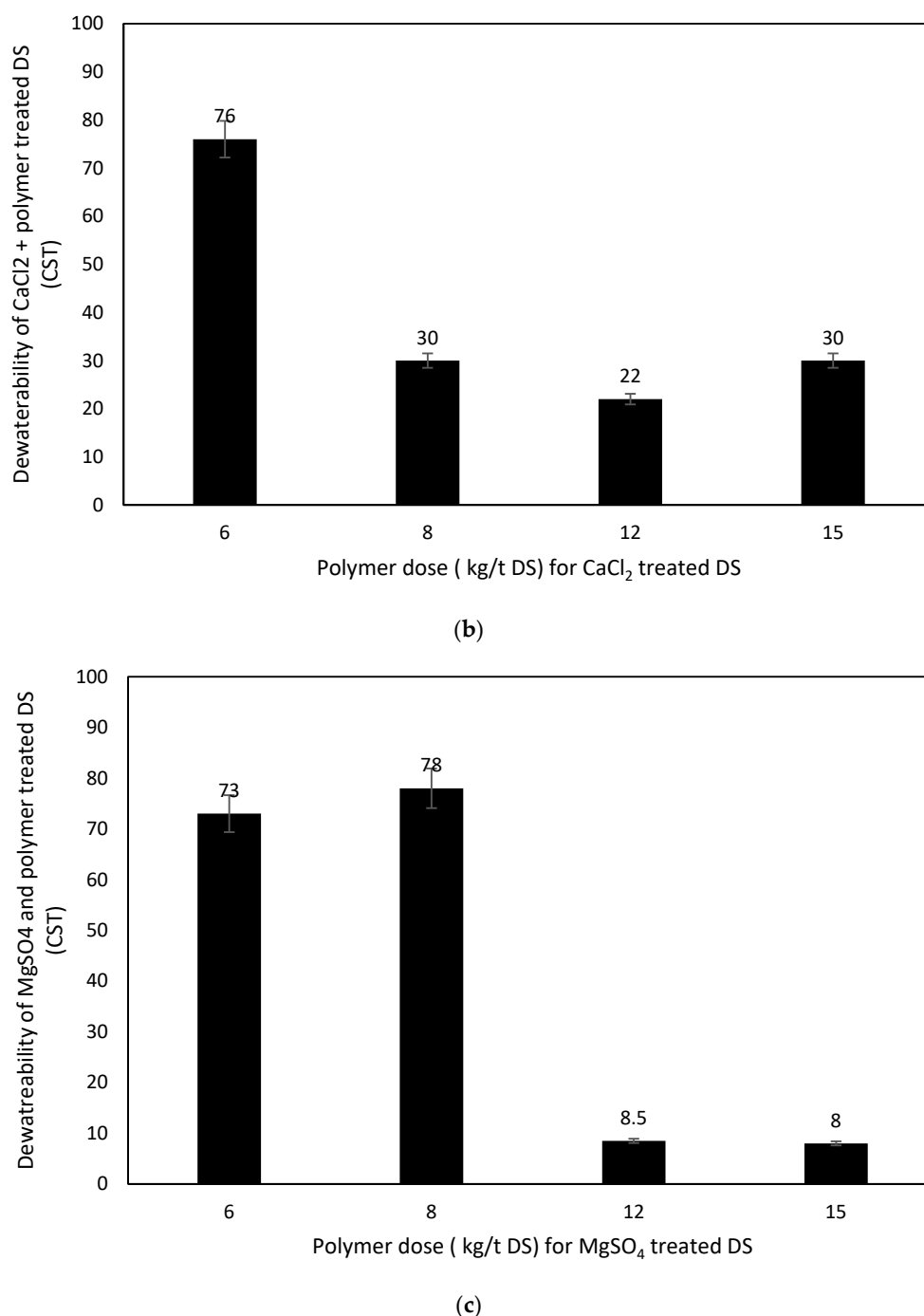


Figure 6. Effect of polymer dose on FeCl₃ (a), CaCl₂ (b) and MgSO₄ (c) conditioned digested sludge.

3.4. Effect of Surfactants on the Dewaterability of Digested Sludge Alone and in the Presence of Metal Cations

The effects of the addition of cationic surfactant CTAB and anionic surfactant SDS for the enhancement of flocculation and dewaterability of digested sludge were also investigated in this study. Dual conditioning of sludge metal cations and the surfactants was also investigated. Figure 7 shows that the dewaterability of digested sludge was enhanced by the dual conditioning of the metal cations and the CTAB, as the cationic charge of the sludge surface could be increased and better flocculation achieved [6]. Unlike the case with CTAB, the addition of SDS resulted in no improvement of the dewaterability of the digested sludge. Hence, further study on the surfactants was conducted on CTAB alone. Figure 8 shows that the optimum dose of CTAB for efficient dewaterability of digested sludge was

60 mL/LDS; any further increase in CTAB dose did not result in any improvement of the dewaterability of the digested sludge. The effect of pH on the performance of CTAB was also investigated in this research in the pH range of 2–9, as shown in Figure 9. The dewaterability was observed to be better at a neutral and alkaline pH than in the acidic range [6,30]. This clearly shows the surface charge which favors dewatering.

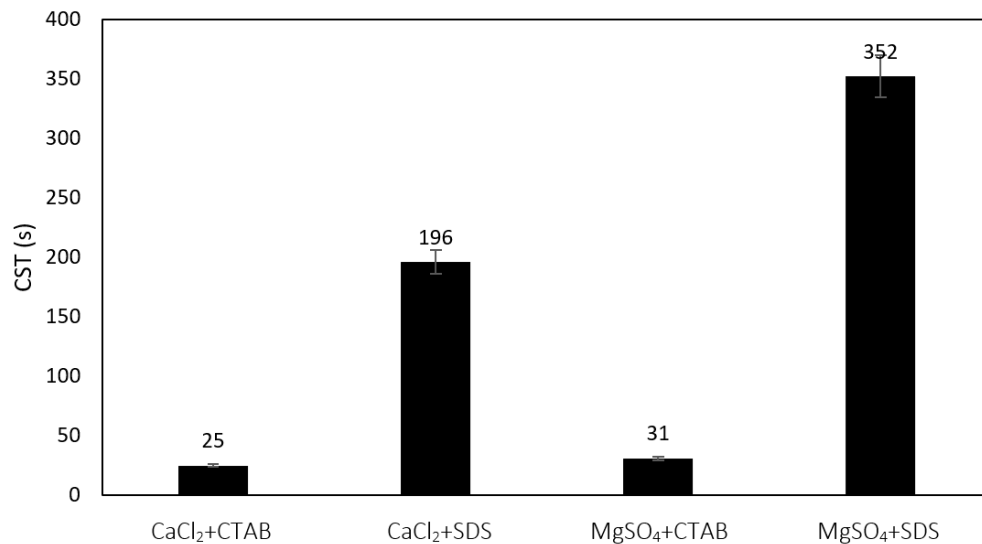


Figure 7. Effect of digested sludge conditioning with metal cation and surfactants.

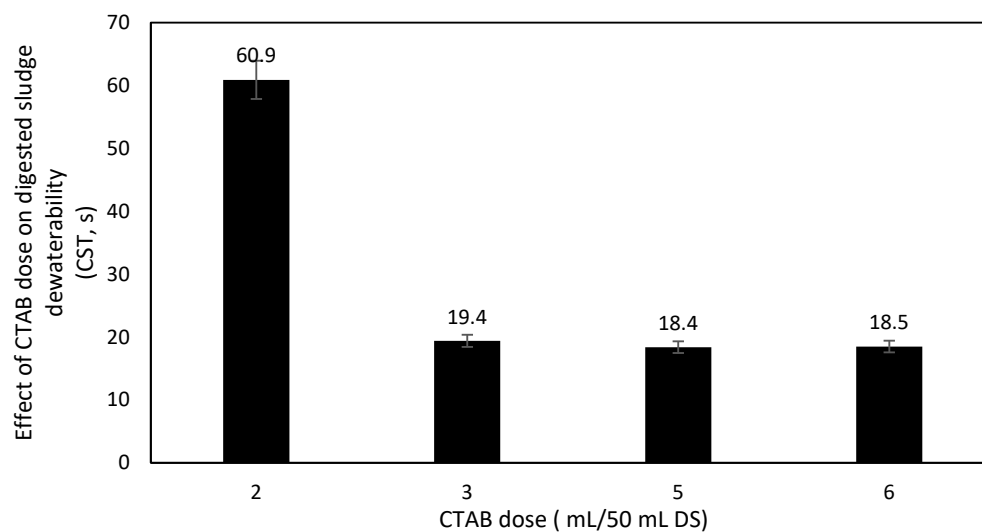


Figure 8. Effect of CTAB dose on the dewaterability of digested sludge.

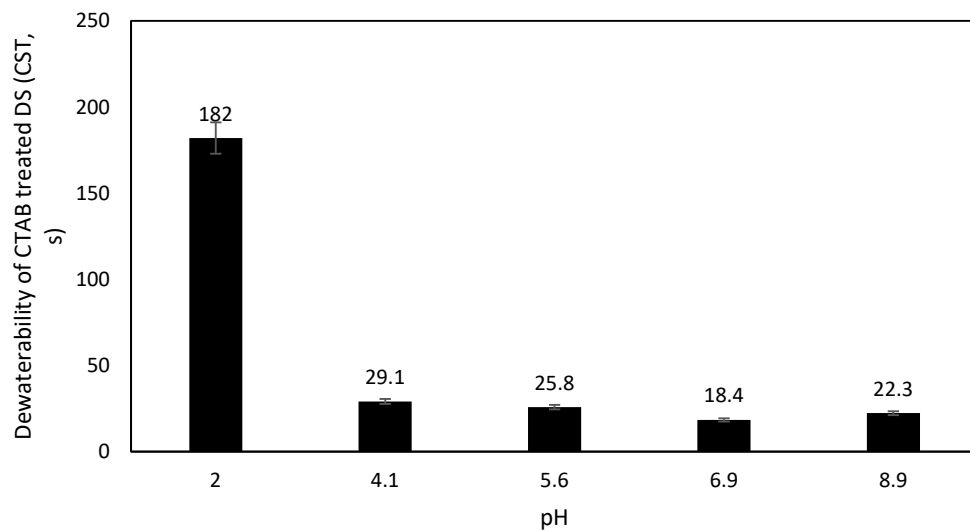
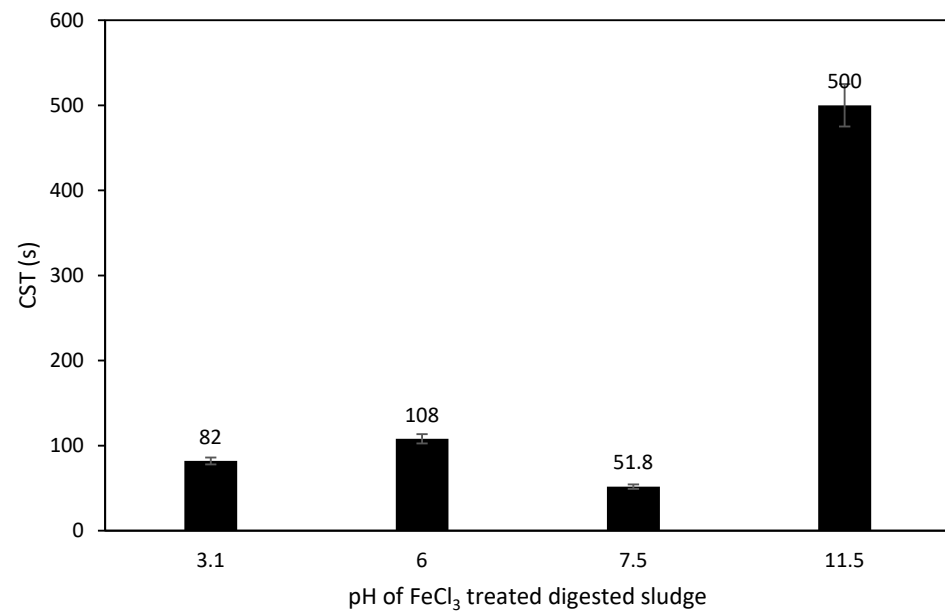


Figure 9. Effect of pH on the dewaterability of CTAB conditioned digested sludge.

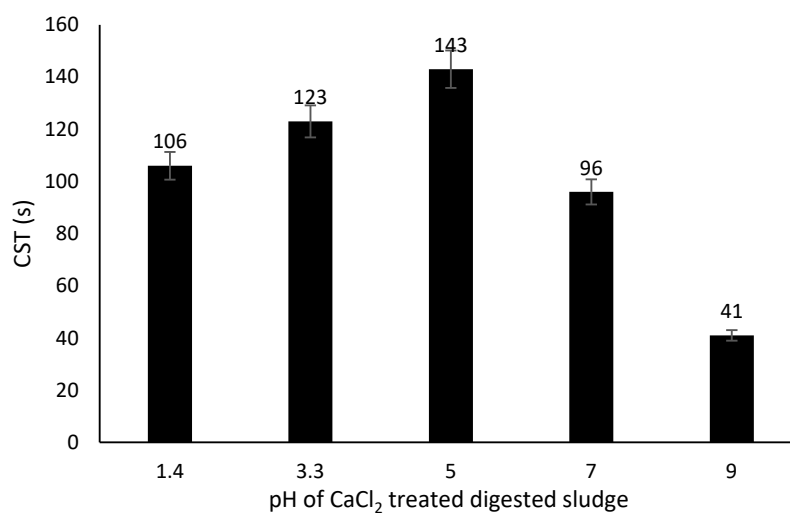
3.5. Effect of pH on the Dewaterability of Metal Conditioned Digested Sludge

The effect of pH on the dewaterability of metal cation conditioned digested sludge was investigated for the pH range of 1–12 for FeCl_3 , CaCl_2 and MgSO_4 conditioned digested sludge as shown in Figure 10a–c. FeCl_3 was observed to provide optimum dewaterability of 82 s at a pH of 3.1 as shown in Figure 10a. Similarly, MgSO_4 conditioned digested sludge showed better dewaterability of 88 s at a pH of 2.3 as shown in Figure 10c, whereas the dewaterability of CaCl_2 conditioned digested sludge was better at an alkaline pH of 9, as shown in Figure 10b.

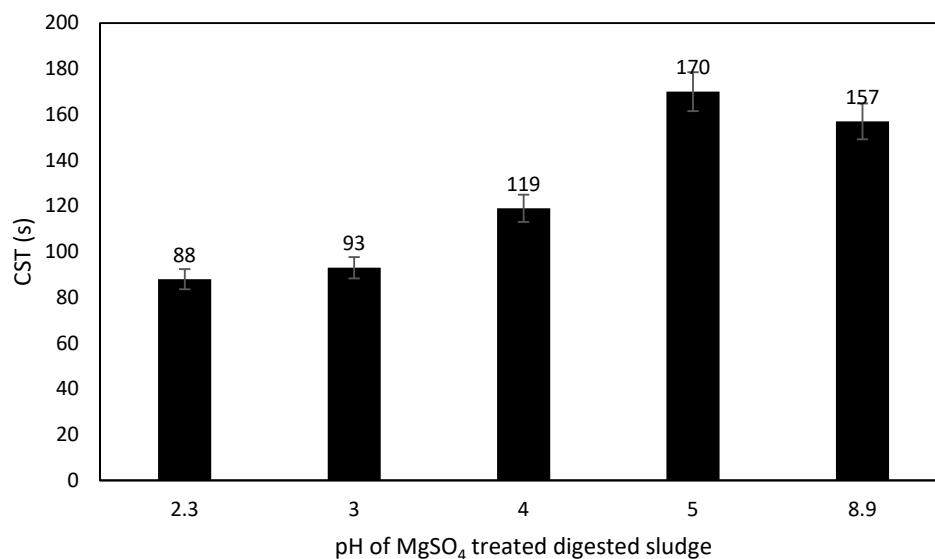


(a)

Figure 10. Cont.



(b)



(c)

Figure 10. Effect of pH on the dewaterability of digested sludge after conditioning with FeCl₃ (a), CaCl₂ (b), and MgSO₄ (c).

3.6. Effects of Metal Cations, Surfactants and Polymer on Particle Size Distribution of Digested Sludge Flocs

The effect of metal cation, polymer and surfactant conditioning on floc particle size distribution of digested sludge was also investigated in this study. The particle size distribution with respect to varying doses of EMA 8854, CaCl₂ and MgSO₄ was investigated, as shown in Tables 2–4 and the corresponding Figures 11–13.

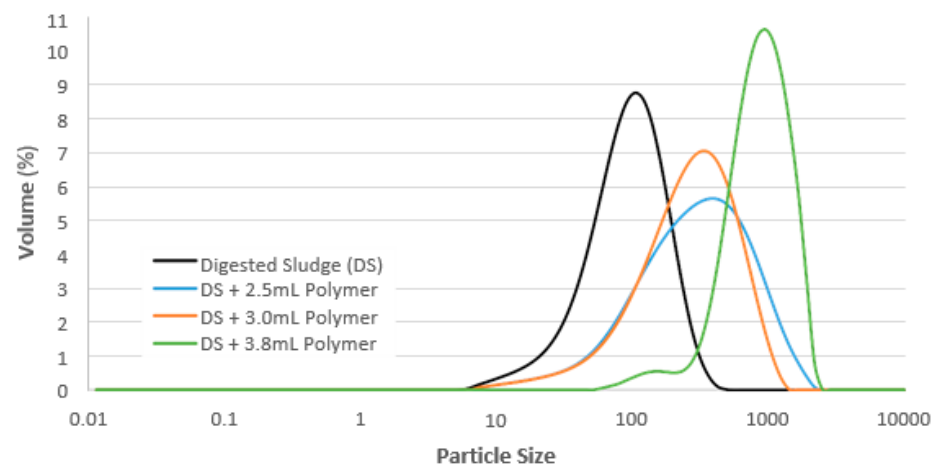


Figure 11. Effect of polymer dose on particle size distribution of digested sludge (DS).

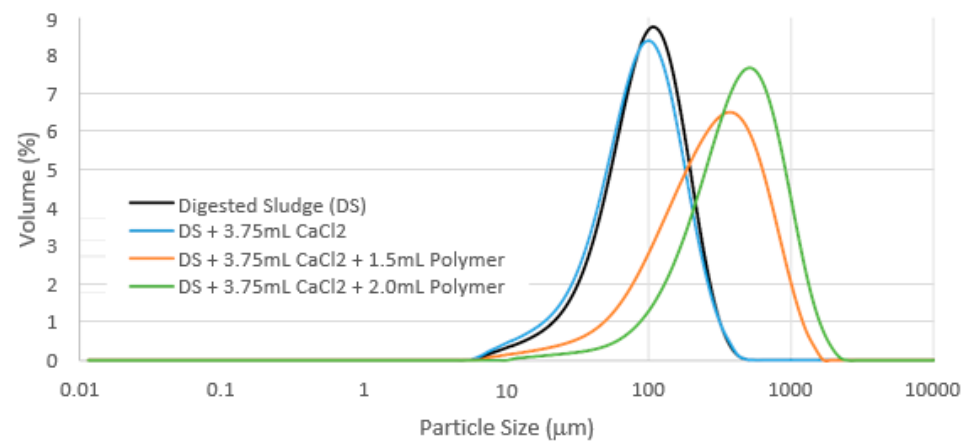


Figure 12. Effect of CaCl_2 and polymer conditioning on particle size distribution of digested sludge (DS).

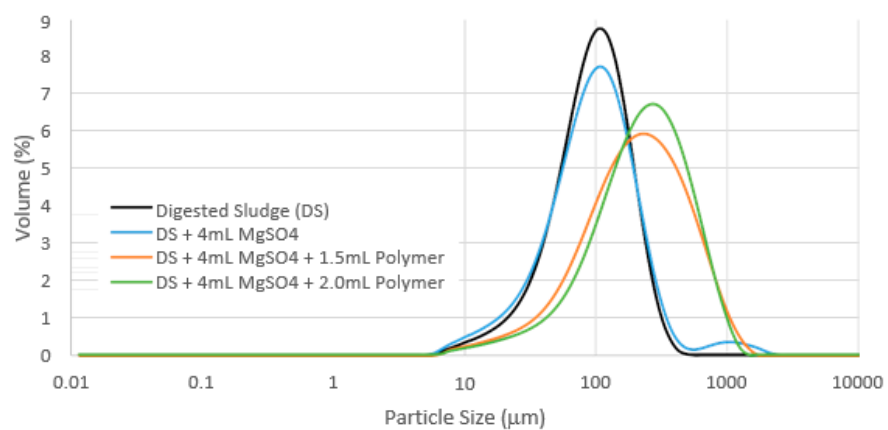


Figure 13. Effect of polymer dose and MgSO_4 on particle size distribution of digested sludge (DS).

Table 2. Characteristics of DS conditioned with polymer.

Characteristics	d (0.1) (μm)	d (0.5) (μm)	d (0.9) (μm)	Surface Mean Diameter (μm)	Volume Weighted Mean (μm)	Specific Surface Area (m^2/g)
Digested Sludge (DS)	32.960	88.318	183.519	61.566	100.356	0.098
DS + 2.5 mL Polymer	69.811	280.131	830.859	140.794	378.971	0.043
DS + 3.0 mL Polymer	72.856	255.283	612.233	138.710	305.556	0.043
DS + 3.8 mL Polymer	386.336	808.073	1444.528	611.007	862.703	0.010

Table 3. Characteristics of CaCl_2 and polymer conditioned digested sludge.

Characteristics	d (0.1) (μm)	d (0.5) (μm)	d (0.9) (μm)	Surface Mean Diameter (μm)	Volume Weighted Mean (μm)	Specific Surface Area (m^2/g)
Digested Sludge (DS)	32.960	88.318	183.519	61.566	100.356	0.098
DS + 3.75 mL CaCl_2	28.972	81.831	177.409	55.762	94.888	0.108
DS + 3.75 mL CaCl_2 + 1.5 mL Polymer	70.871	264.039	672.716	139.070	326.359	0.043
DS + 3.75 mL CaCl_2 + 2.0 mL Polymer	129.575	398.379	901.586	238.788	467.936	0.025

Table 4. Characteristics of MgSO_4 and polymer conditioned digested sludge.

Characteristics	d (0.1) (μm)	d (0.5) (μm)	d (0.9) (μm)	Surface Mean Diameter (μm)	Volume Weighted Mean (μm)	Specific Surface Area (m^2/g)
Digested Sludge (DS)	32.960	88.318	183.519	61.566	100.356	0.098
DS + 4 mL MgSO_4	29.144	88.908	210.840	58.139	124.180	0.103
DS + 4 mL MgSO_4 + 1.5 mL Polymer	51.369	191.011	556.328	104.482	256.855	0.057
DS + 4 mL MgSO_4 + 2.0 mL Polymer	61.511	214.254	544.804	119.417	265.647	0.050

It can be seen from Figure 11 that the addition of varying polymer doses to DS changes the distribution of particle size. There is significant increase in surface mean diameter from 61.56 μm for unconditioned digested sludge to 611.07 μm for polymer-conditioned digested sludge at a polymer dose of 18 kg/t DS, due to formation of large flocs. Likewise, the volume-weighted mean diameter increased from 100.3 μm to 862.7 μm , whereas the specific surface area decreased from 0.098 m^2/g down to 0.01 m^2/g . Substantial increase in particle mean diameter and reduction in surface area clearly show the flocculation performance for an increasing dose of the polymer, until a saturation condition is achieved.

It can be seen from Figure 12 that conditioning with CaCl_2 and dual conditioning with polymer and CaCl_2 resulted in significant changes in the distribution of particle size compared to the distribution obtained with EMA 8854. There is some reduction in surface mean diameter from 61.56 μm for unconditioned digested sludge to 55.7 μm for CaCl_2 conditioned digested sludge and an increase to 238 μm for dual conditioning of digested sludge with CaCl_2 and a polymer dose of 15 kg/t DS. The volume-weighted mean diameter increased from 100.3 μm to 467.9 μm , whereas the specific surface area decreased from 0.098 m^2/g down to 0.025 m^2/g . For divalent metal cations, decrease in floc size has also been reported earlier [31], but the addition of polymer resulted in a synergistic effect that contributed to the formation of large stable flocs, where the particle diameter d (0.5) increased from 81.83 to 264 and further to 398, for DS + 3.75 mL CaCl_2 , DS + 3.75 mL CaCl_2 + 1.5 mL polymer, and DS + 3.75 mL CaCl_2 + 2.0 mL polymer, respectively.

Figure 13 shows that conditioning of digested sludge with MgSO_4 and dual conditioning with polymer and MgSO_4 resulted in significantly different distributions of particle size compared to the distribution observed in the case of EMA 8854. There is some reduction in surface mean diameter from 61.56 μm for unconditioned digested sludge to 58.7 μm for MgSO_4 conditioned digested sludge and an increase to 119.4 μm for dual conditioning of digested sludge with MgSO_4 and polymer dose of 15 kg/t DS. The volume-weighted mean diameter increased from 100.3 μm to 265.85 μm , whereas the specific surface area decreased from 0.098 m^2/g down to 0.05 m^2/g , as shown in Table 4. In all the above cases, the dual conditioning resulted in a significant increase in floc size unlike the case where the divalent metal cations were used, confirming the effect of dual conditioning against the case of a single divalent-metal conditioning agent.

4. Conclusions

In this study, the effects of three different metal cations— FeCl_3 , CaCl_2 and MgSO_4 —two surfactants, CTAB and SDS, and an emulsion polymer, EMA 8854 were investigated. The dewatering performances of the three metal cations were compared for individual-metal conditioning tests and dual metal-and-polymer or metal-and-surfactant conditioning tests. It was observed that CaCl_2 resulted in better dewaterability both for the individual metal cation and dual metal-cation—polymer-based dewatering tests. Moreover, the effects of metal dose, polymer dose, surfactant dose, and solution pH on digested sludge dewaterability were investigated, and the optimum operating doses and pH were determined. The effect of metal cation, polymer and surfactant conditioning on floc particle size distribution of digested sludge was also investigated in this study. It was observed that the optimum metal and polymer dose resulted in larger floc particle size and aggregation effects. The FTIR imaging of metal-cation-conditioned digested sludge and metal-cation—polymer/surfactant conditioned digested sludge were also conducted in this work. The overall analysis on metal cation and polymer conditioning tests shows that CaCl_2 and MgSO_4 , as single conditioning agents, resulted in acceptable dewatering performance enhancement effects, whereas floc size and dewaterability as CST increased significantly in the case of dual conditioning tests with CTAB and EMA polymers. The consumption of EMA 8854 can also be significantly reduced by coupling the polymer conditioning with metal cation treatment, which will have a substantial cost impact in the economy of large-scale wastewater treatment plants. Further study can be conducted to better understand the molecular mechanism of flocculation for dual conditioning agents (SEM, XRD, EPS, etc.) particularly for metal cations coupled with polymers or surfactants. The effect of dual conditioning on cell lysis, amount of dissolved salt and recoverable salt at the end of the jar tests can be further investigated.

Author Contributions: Formal analysis, S.S. and E.H.; Methodology, S.S., A.M.Y. and E.H.; Resources, S.S.; Supervision, T.K.S.; Writing—original draft, S.S., A.M.Y. and E.H.; Writing—review & editing, T.J., K.A.B. and P.F.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors. The data are not publicly available due to commercial restriction.

Conflicts of Interest: The authors declare no conflict of interest.

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