Full paper

Influence of sludge characteristics on pressure-driven electro-dewatering of stabilized sewage sludge

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Abstract

The feasibility of the pressure-driven electro-dewatering (EDW) on aerobically and anaerobically stabilised sludge samples, taken from four different wastewater treatment plants around the metropolitan area of Milan (Italy), has been assessed. First, sewage sludges were characterized by measuring DS content, VS/DS ratio, pH, conductivity, zeta potential and capillary suction time (CST) of the liquid fraction. Then, after a preliminary centrifugation of the sludge samples in the laboratory, pressure-driven EDW tests have been performed in a lab-scale device, under the application of 300 kPa of pressure and an applied voltage of 15 V. The DS content increased up to 18.4-31.1%, (with an increase of 8.6% to 23.0% from the initial DS value) depending on the characteristics of the sludge samples and the polymer dosage. If compared with EDW tests, the increase due to the sole effect of pressure ranged from 3 to 10% and strictly depended on polymer dosage. The characteristics of sludge that affect the increase of the DS content were investigated during both the pressure-driven stage and the EDW stage. Polyelectrolyte addition (4 and 8 g/kg_{DS}) mainly affected the pressure-driven phase of the tests. However, the VS/DS ratio was the main factor affecting the pressure-driven stage on the unconditioned aerobically stabilised samples. CST values could also reliably predict the efficiency of this stage during experiments.

Key words

Sewage sludge, dewatering, electro-osmosis, electric field, dry solids

Introduction

During operation, wastewater treatment plants (WWTPs) produce relevant amounts of sewage sludge. With more stringent disposal and environmental regulations, a lower water content in the sludge is required, which greatly benefits the sludge disposal, by decreasing the transport costs and by increasing the energy efficiency for incineration (Yu et al. 2010). Nowadays, to reduce sewage sludge water content filter presses, centrifuges and belt presses are the most widespread technologies in WWTPs and can produce wet sludge with 20-30%

dry solid (DS) content (Lee et al. 2002, Yang et al. 2011, Zhan et al 2016). Usually, mechanical dewatering alone cannot achieve the high DS values required for the combustion of sludge, but it is often necessary to add thermal drying units, in order to increase the calorific value for incineration (Flaga 2006). Recently, pressure-driven electro-dewatering (EDW) was shown to be an efficient technique to improve water removal from sludge and increase the DS content up to 40-45% (Tuan et al. 2008; Mahmoud et al. 2010; Weng et al. 2013; Feng et al. 2014), well beyond the values achievable by mechanical means. The high sludge dryness that is reached by the EDW process suggests that it is a promising alternative to the thermal drying techniques, thanks to the lower energy consumption involved. Sludge thermal drying indeed requires, at industrial scale, energies ranging from 617 $Wh/kg_{evaporated\ water}$ (the enthalpy of water vaporization) to as high as 1200 $Wh/kg_{evaporated\ water}$ (Olivier et al. 2014). On the other hand, depending on the potential and the pressure values applied, the EDW process is capable to reduce the energy consumption by 10 to 25% of the theoretical energy required for thermal drying (Mahmoud et al. 2011).

The pressure-driven EDW process of sewage sludge has been investigated by many authors in the past, including Yuan et al. (2003), Tuan et al. (2008) Mahmoud et al. (2011) and Feng et al. (2014), by assessing the influence of operating parameters such as pressure, potential values, tests duration and cake thickness on process performance. The influence of sludge conditioning, by using different polyelectrolyte types and dosing, on EDW efficiency was also studied (Saveyn et al. 2005, Citeau et al. 2011).

However, so far the high variability of sludge samples produced by different WWTPs and the use of different lab-scale devices prevented from proposing predictive models for EDW efficiency valid for all the sludge types. In particular, thorough assessments on the influence of sludge characteristics on pressure-driven EDW process are still scarce in literature and, therefore, further investigations are strongly required, especially in the view of developing prototypes for full-scale application.

The most common method to assess the dewaterability of sludge is the CST test, which is a rapid and simple measurement procedure. CST is usually used to determine the required amount of a specific conditioning chemical to achieve optimal properties of dewaterability (Sawalha et al. 2007). The zeta potential is a further tool that allows investigating the flocs stability and how they affect the dewaterability of sludge. By its measure, precipitation and flocculation agents can be optimized for the processes involved in a WWTP. Indeed, the addition of counter-ions, usually by highly cationic polyelectrolyte, into the surroundings of the negatively charged surface, weakens the electrical potential, increases the force of attraction and leads to coagulation and agglomeration of the suspended solid particles (Kleimann et al. 2005). The flocculation and aggregation induced by a decrease in zeta potential increase the particles size and, thus, the dewatering rate (Citeau et al. 2016).

In the present work, the efficiency of the pressure-driven EDW tests, by means of a lab-scale device, on different sewage sludge samples taken from four WWTPs located in the metropolitan area of Milan (Italy), was assessed. Both aerobically and anaerobically stabilised sludges, after the thickening stage in the WWTPs, were studied under the application of 300 kPa of pressure and 15 V of potential. The influence of initial DS content (DS_i), volatile to total solids ratio (VS/DS), conductivity, zeta potential, capillary suction time (CST) and conditioning, by addition of polyelectrolyte at different dosages, on EDW performance in terms of final dry solid content was investigated.

Materials and Methods

Sludge samples

Sludge samples were taken from four different WWTPs around the metropolitan area of Milan (Italy). WWTP 1, 2 and 3 provided aerobically stabilised sludge, whereas WWTP 4 provided anaerobically digested samples. The thickened sludge samples were collected before the conditioning step. Conditioning tests were performed in three jar test beakers, one used as control and the other two operated with different doses (4 and 8 g/kg_{DS}) of polyamidic and high cationic polyelectrolyte (Tillflock CL-1480). Electrical conductivity was monitored by a conductivity meter (B&C Electronics-C 125.2) and pH by a pH-meter (Metrohm 827 pH Lab). DS amount, VS/DS content and CST were measured according to Standard Methods (APHA/AWWA/WEF 2012). Sludge samples were filtered under vacuum with a Whatman 42 filter cloth (2.5 µm pores size) and the zeta potential of the filtrate was determined by the instrument Malvern Zetameter ZS90. CST and zeta potential values are the average of at least three replicate measurements. After centrifugation at 4,000 rpm (Relative Centrifugal Force ≈ 1789 g) for 5 min, the centrifuged sludge, with DS content (DS_{CFG}) between 7.5 and 13.9%, separated from the supernatant was used for the EDW tests. Prior to use, sludge samples were stored at 4°C up to a maximum of 1 week in order to keep their properties constant.

Lab-scale device

A lab-scale dewatering device was built, as shown in Figure 1, by which a mechanical pressure and an electric field were simultaneously applied to the sludge.

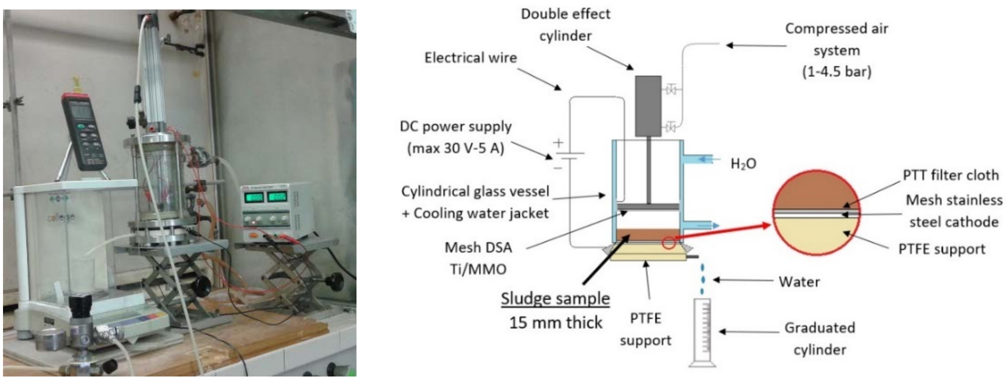

Figure 1 Lab-scale device for pressure-driven EDW tests.

This device consisted of:

- a cylindrical glass vessel (176 mm high, 80 mm diameter) provided of a cooling water-jacket, which keeps the device at room temperature;
- a double effect cylinder SMC-CP96SDB32-200 with a piston (200 mm stroke) connected to the laboratory pressurised air system (1-4.5 bar), equipped with manometer and valves to set pressure values;
- a DC power supply (GBC-34121070 bench scale generator, maximum 30V/5A);
- a dimensionally stable anode DSA® (manufactured by Industrie De Nora, Milan, Italy) made of titanium coated with mixed metal oxide (Ti/MMO);
- a stainless steel mesh (AISI 304) as cathode;
- a PTT (polytrimethyleneterephthalate) filter cloth.

Drained water discharged into a graduated cylinder positioned on a precision balance.

Electro-dewatering tests

The electro-dewatering procedure consisted of two successive stages (Citeau et al. 2012):

- filtration/compression by applying pressure (duration: 10 min);
- application of an electric field at the selected operating voltage, keeping the applied pressure constant (duration: 25 min).

After the closure of the cell by the cover, the piston started applying pressure (300 kPa) on the sludge. Approximately 90 g of wet sludge formed a 15-mm thick layer in the cell. Sludge was pressed between the upper anode (on a support made of polyvinyl chloride, PVC) and the lower PTT filter cloth (placed on the cathode mesh). After 10 min of pressure application, the 15 V potential was switched on. Values of currents vs. time were recorded. At a regular pace of one per minute, the weight of the collected liquid was recorded, in order to calculate the rate of sludge dewatering.

Results and Discussion

Sludge characteristics

Table 1 lists the main characteristics of each sludge sample collected from the four WWTPs. The A-named samples are related to the unconditioned (control) sludge, whereas samples B and C refer to the sludge conditioned with two different doses of polyelectrolyte (4 and 8 g/kg_{DS}) by jar tests. The DS amount was in the range 2.0-3.2% for aerobically stabilised samples and 4.3% for anaerobically stabilised sludge. As expected, sludge from WWTP 4 had a lower VS/DS ratio and a higher conductivity, due to the high presence of ammonium nitrogen, with respect to aerobically stabilised samples.

The CST values, as shown in Table 1, tend to decrease by increasing the amount of polyelectrolyte (with the exception of sample 4-C) and highlight how the conditioning step may improve the efficiency of the mechanical dewatering step of each sludge.

Table 1 Characteristics of sludge samples taken from the four WWTPs.

Sample	Stabilisation	Polymer dosage	DS_i	VS/DS	pH	Conductivity	CST	Zeta potential	DS_{CFG}
		g/kg_{DS}	%	%	-	mS/cm	s	mV	%
1-A		0	2.0	68.3	7.5	1.34	32.0	-11.9	8.8
1-B	Aerobic	4	2.4	68.3	7.4	1.33	22.5	-11.5	7.7
1-C		8	2.2	68.3	7.4	1.29	19.8	-11.5	8.6
2-A		0	3.3	78.4	6.9	1.84	103.3	-13.1	7.5
2-B	Aerobic	4	3.2	78.4	6.5	1.79	92.7	-12.6	7.8
2-C		8	3.2	78.4	6.6	1.68	68.8	-11.9	8.0
3-A		0	3.2	72.7	6.9	1.28	35.7	-13.4	8.4
3-B	Aerobic	4	3.0	72.7	6.9	1.26	28.3	-12.9	8.2
3-C		8	2.8	72.7	7.0	1.26	17.8	-12.1	8.1
4-A		0	4.3	64.8	6.7	4.00	155.6	-11.3	9.8
4-B	Anaerobic	4	4.3	64.8	6.7	4.00	81.6	-11.5	9.7
4-C		8	4.3	64.8	6.7	4.00	102.3	-11.0	13.9

Regarding the sludge from WWTP 4, the sample 4-C has a higher CST value than the sample 4-B. The higher value of CST may suggest a polyelectrolyte overdosing in sample 4-C, but the corresponding DS_{CFG} content is higher than the control sample, which seems to contradict the indication given by the CST.

Good control of polyelectrolyte dose is critical in sludge conditioning, since overdosing increases the costs and, in general, reduces the sludge dewaterability. The optimal polyelectrolyte dosage, for the conventional dewatering techniques, is associated to lowering the charge on the surface of the colloidal particles near to zero, which should lead to the tendency to aggregate these particles into large flocs (Lee et al. 2000). The zeta potential values showed a slight increase with the polyelectrolyte dosage for aerobically digested sludge from WWTP 1, 2 and 3, pointing out that a more stable and flocculated sludge is formed. The increase of zeta potential values for a specific sludge indicates that mechanical dewatering could be improved by polyelectrolyte dosage. However, a correlation between zeta potential values of samples taken from different WWTPs involves also the comparison of DS, VS/DS contents and conductivity. Similarly to CST, the sludge from WWTP 4 shows a different trend also for zeta potential.

Before performing the pressure-driven EDW tests, sludge samples were centrifuged in the laboratory to reduce the pressure application time and to avoid leakage of water from the reactor during the first stages of tests. Differently from what expected, the DS content after centrifuging (DS_{CFG}) did not show a higher dewaterability of conditioned samples. This was due to the centrifuging process in the lab device, since it did not allow the removal of the

separated water during the rotation of the centrifuge tubes. Indeed, the lab centrifuge causes a compression of the sludge and the water does not drain away, but is removed only after the end of the centrifugation (5 min), while this drainage is effective and continuous in real centrifuges. Under these conditions the polymer cannot exert its effect on the residual water retained in the compressed cake.
The relationships between CST, zeta potential and EDW performance will be further investigated in the next sections.

Electro-dewatering tests

Initially, sludge 3 has been tested under constant pressure at 300 kPa, initial cake thickness of 15 mm, duration 35 min, without the application of an electric potential. The average final DS content reached at the end of the tests without applying the electric potential was: 15.2% for the unconditioned samples, 16.9% for the sludge conditioned with 4 g/kg$_{DS}$ polyelectrolyte (B samples) and 18.7% for the sludge conditioned with 8 g/kg$_{DS}$ polyelectrolyte (C samples).
Similar tests have been carried out with the same duration (35 min), but an electric potential of 15 V has been applied in the last 25 minutes (pressure-driven EDW tests). The average final DS content reached at the end of the tests with the electric potential was: 30.9% for the unconditioned samples, 30.6% for the sludge conditioned with 4 g/kg$_{DS}$ polyelectrolyte (B samples) and 31.1% for the sludge conditioned with 8 g/kg$_{DS}$ polyelectrolyte (C samples).

Later on, sludge samples taken from the four WWTPs have been tested, with an initial cake thickness of 15 mm, duration 35 min, under constant pressure (300 kPa) and by applying a potential of 15 V in the last 25 minutes. The results obtained are shown in Figure 2. Here, the initial dry solids (DS_i) content, the dry solids obtained after centrifugation (ΔDS_{CFG}), after 10 min of pressure (ΔDS_p) and after 25 min of application of electric potential (ΔDS_V) are shown. In order to compare the efficiencies of EDW and conventional methods, the average DS content reached after mechanical dewatering in the WWTPs is reported.

Samples from WWTP 1, 2 and 4, refer to unconditioned sludge, had a lower DS_V content than the conditioned samples (B-C). Indeed, the colloidal and compressible nature of the unconditioned sludge hampers its dewatering and polyelectrolytes addition is needed to induce the formation of flocculated particle networks, resulting in a structure with reduced water retention (Saveyn et al. 2005). However, this behaviour was not shown by sludge 3, where DS_V was approximately the same between control and conditioned samples.
Most authors agree on the fact that a minimum polyelectrolyte dose is necessary in order to guarantee fast filtration during EDW and to reduce the EDW energy requirement. However, in most cases, polyelectrolyte dosage has not a significant effect on the EDW process (Gingerich et al. 1999), but affects more the mechanical dewatering, which is applied in the pressure-driven stage (Saveyn et al. 2005; Snyman et al. 2000).
In particular, Figure 2 shows that for sludge 1 and sludge 4 the highest dosage of polyelectrolyte is needed to reach the highest value of DS_V. Sludge 2 showed a different behaviour, as a dosage equal to 8 g/kg$_{DS}$ does not correspond to an increase in the DS content, if compared to lower dosages. Finally, sludge 3 reached a DS content of 30.9% without adding

polyelectrolyte. This result opens some chances that EDW may have the potential to lower the costs of sludge dewatering in reducing the required dosage of the conditioning polymer.

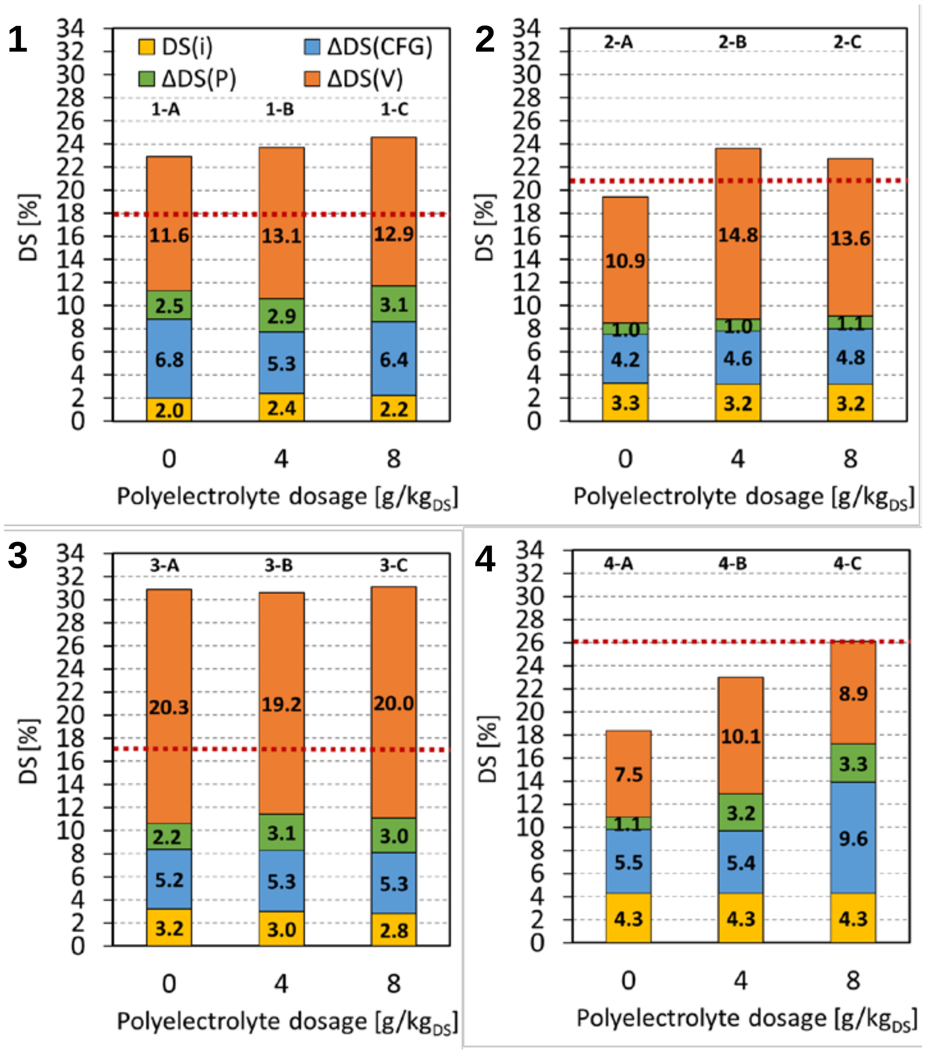

Figure 2 Pressure-driven EDW results of sludge samples from WWTP 1, 2, 3 and 4. The red dotted lines show the average DS content reached after mechanical dewatering in the WWTPs (1, 2, 4: sludge is centrifuged; 3: sludge is belt pressed).

Generally, for aerobically stabilised sludge, the DS content of the conditioned samples obtained after the pressure-driven EDW tests was higher than values reached by conventional mechanical dewatering in the WWTPs. On average, the DS amount increased by 2-14%. The anaerobically digested sludge, instead, reached comparable values with mechanical dewatering only with the highest polyelectrolyte dosage. This fact can be ascribed to the higher dewaterability by mechanical methods of anaerobically digested sludge, which has a lower organic fraction and can reach higher DS content. It must be highlighted also that the conditioning in the four WWTPs is performed with different polyelectrolytes and dosages with respect to those studied in this research. However, it is remarkable the fact that sludge 1 and sludge 3, without polyelectrolyte addition, reached a DS content higher than those obtained after mechanical dewatering.

Sludge 3 resulted to be the most suitable for the EDW process: the DS content reached after 35 minutes of test was higher than values achievable by mechanical methods in the WWTPs. Indeed, the aerobically stabilised sludge can hardly overcome 25-30% of DS content, even when dewatered with the far more efficient filter-presses. The increase of test duration, or the application of a higher electric potential, may lead to reach even higher DS values, which would reduce considerably the disposal costs with respect to conventional methods.
The results reported in Figure 2 evidenced a different behavior for each sludge, both for the pressure-driven stage and for the EDW stage. This fact can be explained by the characteristics of sludge (DS, VS/DS, conductivity, zeta potential) and to the response of each sample to the conditioning with a specific polyelectrolyte, and to the application of pressure and electric potential. Indeed, the pressure-driven EDW results highlight a constraint in finding a general trend valid for all the types of sludge.

Influence of sludge characteristics on the pressure-driven stage

According to figure 3, it looks like that the higher the organic fraction, the higher the filtration time measured in aerobically digested sludge, but not in anaerobically digested sludge, probably due to its higher DS content (Figure 2). Skinner et al. (2015) demonstrated that volatile solid content could be used as a parameter to predict sludge dewaterability and that it is connected to the measure of extracellular polymeric substances (EPSs), which are known to hinder removal of water from sludge. In detail, they showed that the efficiency of mechanical dewatering of unconditioned samples decreased with increasing values of VS/DS.

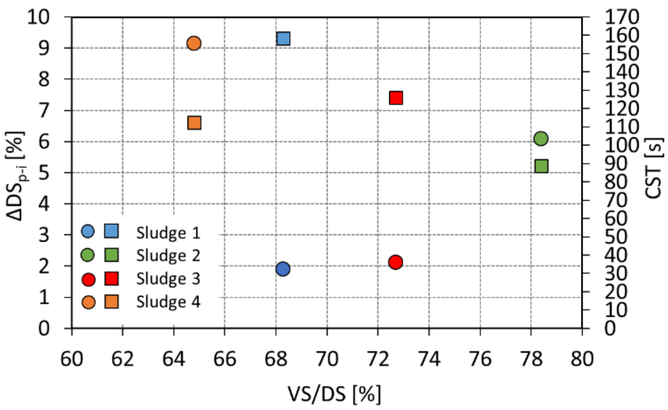

Figure 3 Relationships between the VS/DS ratio with CST values (circles) and DS content increase obtained during the pressure-driven stage (squares). Sludge samples 1, 2 and 3: aerobically stabilised, unconditioned sludge. Sludge sample 4: anaerobically stabilised, unconditioned sludge.

Moreover, the polyelectrolyte addition affects differently the flocculation of each sludge. As a consequence, CST values cannot be compared among sludge samples of different origin, unless the concentrations of suspended solids are similar, as also stated in APHA et al. (2012).

Thus, in the present case, CST can be taken as an indicator of filterability after polyelectrolyte addition, only to compare sludge samples coming from the same WWTP and having the same solid concentration.
The removal of water during the mechanical pressure-driven stage may be studied by considering the VS/DS ratio. As shown in previous sections, for the aerobically digested and unconditioned sludge, the higher the organic fraction, the higher is the filtration time measured. Figure 3 shows how the mechanical dewatering, in terms of the dry solids obtained after the mechanical pressure stage (DS_p-DS_i = $\Delta DS_{p\text{-}i}$), and CST values are affected by the organic fraction: more water is removed at lower VS contents (Skinner et al. 2015).

However, each sludge sample is affected differently by the polyelectrolyte addition. The CST is a fast method to predict filterability and dewaterability of sludge and to select the appropriate polyelectrolyte type and dosage, in order to maximise the DS content after mechanical dewatering in the WWTPs (Sawalha et al. 2007).

As shown in Figure 4, the reduction of CST values with the dosage of polyelectrolyte, for aerobically stabilised samples, is respected by the higher DS content obtained after the pressure-driven stage. Indeed, sludge 1, sludge 2 and sludge 3 showed a trend between the CST values and the efficiency of the pressurized mechanical dewatering, expressed both as $\Delta DS_{p\text{-}i}$ (Figure 4a) or as the average dewatering rate (Figure 4b). On the other hand, anaerobically digested sludge has a DS_i content too high to be compared with the other samples.

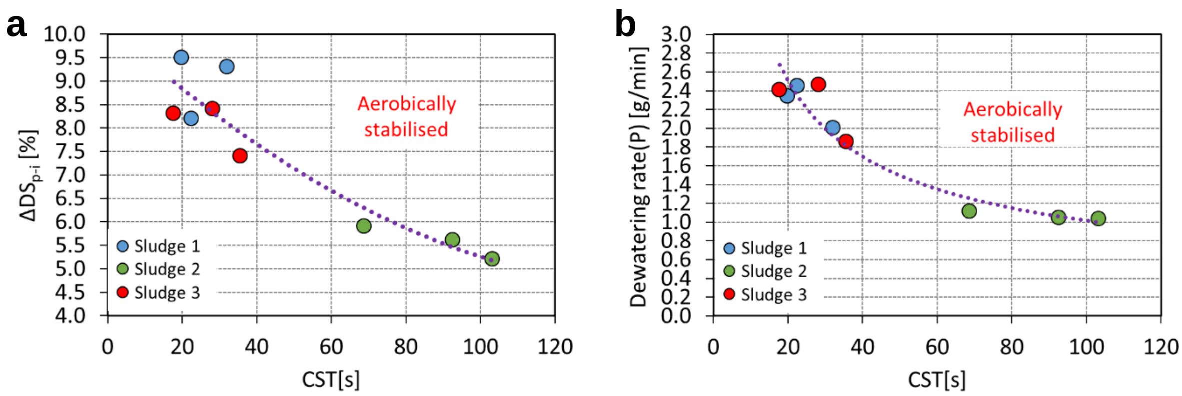

Figure 4 Relationships between CST values and (a) DS content increase or (b) average dewatering rate obtained during the pressure-driven stage for aerobically stabilised sludge.

In conclusion, the pressure-driven stage of the aerobically digested sludge samples, with similar DS_i content, is dependent on the VS/DS ratio and the polyelectrolyte dosage. The CST measure is a rapid and reliable method to predict the efficiency of the mechanical stage during the pressure-driven EDW process.

Influence of sludge characteristics on the EDW stage

The efficiency of EDW process is conditioned by many characteristics of the sludge. The conductivity of sludge, for example, controls the maximum current density values developed in the first stages of the EDW tests.

The mechanical dewatering is known to be more efficient in water removal when the colloidal fraction is more stable, that is when the zeta potential increases at less negative values. The EDW process instead follows the Helmholtz-Smoluchowski theory, which deals with electro-osmotic velocity of a fluid of a certain viscosity μ (Pa·s) and dielectric constant ε (F/m) through a surface-charged porous medium of zeta potential ζ (V) under an electric gradient ∇Φ (V/m). According to this theory, the electro-osmotic velocity $\overrightarrow{v_{eo}}$ (m/s) and the electro-osmotic flow rate $\vec{Q}$ (m^3/s) can be derived based on the balance of the electrical and frictional forces between water and the wall of the capillary (Mok 2006, Mahmoud et al. 2010).

$$\overrightarrow{v_{eo}} = \frac{\varepsilon\zeta}{4\pi\mu}\nabla\Phi \quad (1)$$

$$\vec{Q} = \frac{\varepsilon\zeta}{4\pi\mu}\mathrm{A}\cdot\nabla\Phi \quad (2)$$

where A (m^2) is the cross-section area.

According to equations (1) and (2), the EDW process strongly depends on the zeta potential of the sludge samples. Figure 5 shows that a higher efficiency of the EDW stage, in terms of DS_V, is obtained when the zeta potential values are more negative.
These results show how the conditioning step is a fundamental step to study the efficiency of the pressure-driven EDW process. The dosage of the polyelectrolyte must be evaluated by considering that the increase of zeta potential values improves the preliminary pressure stage, thanks to flocculation of sludge, but may decrease the water removal during the application of the electric potential due to a lower electro-osmotic flow.

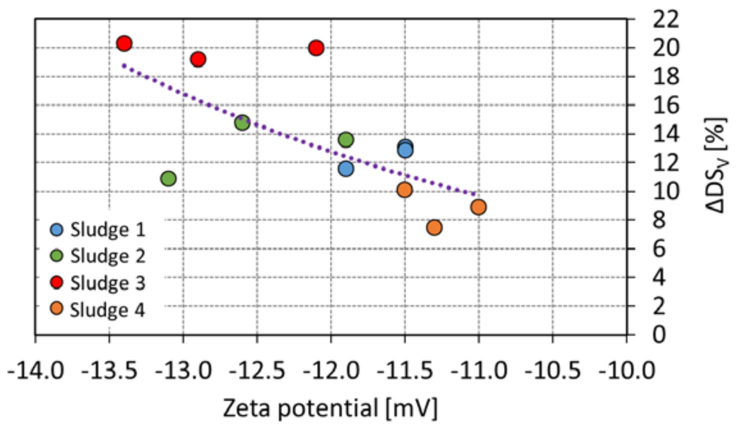

Figure 5 Relationship between the zeta potential and ΔDS_V content.

Conclusions

The influence of sludge characteristics on pressure-driven electro-dewatering of stabilized sewage sludge was investigated by lab-scale testing. The VS/DS ratio resulted to be the main factor affecting the pressure-driven stage on the unconditioned aerobically stabilised samples, while the CST values could reliably predict the efficiency of this stage during experiments.
The addition of polyelectrolyte reduces the negative zeta potential of sewage sludge, which is commonly related to better dewaterability. On the other hand, the lower absolute value of the zeta potential reduces the effect of the electric potential, which may slow down the dewatering rate during the application of the electric potential.
The reduction of the dosage of polyelectrolyte, or even its non-use, maybe a challenge to be better investigated for the application of the EDW process on an industrial scale.
The effect of the polyelectrolyte is that it improves dewatering during the sole application of pressure, so that the EDW phase can act on a drier cake, saving energy and time. In view of designing a full-scale machine, we can observe that (i) the dose of polyelectrolyte should be carefully chosen to avoid over-dosage, which can worsen the overall efficiency of the process, and that (ii) polymer can help in reducing the time of operation by speeding up the first part, which is only pressure-driven. Finally, dewatering without polymer addition on a full-scale device may pose problems in getting the required capture efficiency.

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