ELECTRO-OSMOTIC DEWATERING OF SEWAGE SLUDGE: PRELIMINARY RESULTS

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ABSTRACT

At present, the activated sludge process is the cheapest way to remove colloidal and soluble organic pollutants from sewage, but it produces a considerable amount of waste sludge, with a low dry solid (DS) content, rich in biodegradable organic substances. Therefore, it needs further processes to reduce its volume, by decreasing its water content, and to lower its polluting potential, due to its high content of biodegradable organic matter. Industrially, mechanical dewatering (centrifuge, filter press and belt press) increases the DS of sewage sludge up to 20-25% to decrease transport and disposal costs. Electro-osmosis could be a suitable technique that can further reduce the water content of the dewatered sludge by the application of an electric field. Preliminary tests carried out by applying an electric field, from 10 to 20 V/cm, in a lab-scale device, confirmed the possibility to increase the final dry solid content (DS_f) by 10% to 15% higher than the initial content, with a relatively low energy consumption if compared to thermal treatments. Here, we investigated the characteristics and properties of sludge that affect pressure-driven electro-dewatering. Sludge samples were taken from four different WWTPs around the city of Milan (Italy). First of all, we characterized the sludge samples by measuring capillary suction time (CST), time to filter (TTF) and the zeta potential of the filtered liquid fraction. Then, we measured the final solids percentage and energy consumption in a lab-scale device, under the application of an applied voltage of 15 V, at 3-bar pressure and tried to find a relation between the characteristics of sludge and DS_f.

Conditioned and thickened sludge samples reached ΔDS between 8-17%. Results on mechanically dewatered sludge samples have shown an increase of DS content up to values around 14%, with a total primary energy consumption lower than the primary energy needed for thermal drying. This highlights the efficiency of electro-dewatering as a post dewatering treatment. Electro-dewatered sludge may self-sustain combustion at 850°C without any preliminary thermal drying. CST, TTF and zeta potential are not suitable predictors of the efficiency of the electro-dewatering process. A lab-scale test is necessary to assess the DS_f that electro-dewatering can achieve.

KEYWORDS

electro-osmosis - dewatering - sewage sludge - sludge filtration – liquid/solid separation - electric field

1. INTRODUCTION

About half of the organic pollution load treated by the activated sludge process is oxidised and converted into water and carbon dioxide, while the remaining is converted into biomass, called “excess biological sludge” or “waste sludge”. However, the liquid waste sludge produced has a low dry solid (DS) content and needs to reduce its volume and to reduce its polluting potential, due to the high content of biodegradable organic matter.

Nowadays, to reduce sludge water content, filter presses, centrifuges and belt presses are the most used in Wastewater Treatment Plants (WWTPs) and can produce wet sludge with 20-30% dry solid (DS) content. Usually, mechanical dewatering alone cannot achieve the high DS values required for thermal valorisation of sludge, but it is often necessary to add thermal drying units.

Seeking new and efficient methods for dewatering, many authors (Yoshida, 1993; Barton et al., 1999; Gingerich et al., 1999) exploited electro-osmosis in order to improve water removal from sludge. The application of an electric field, sometimes in combination with pressure, seems capable to increase the DS content in sludge up to 45% (Mahmoud et al., 2010), well beyond the values achievable by mechanical means.

Among electrokinetic phenomena, electro-osmosis rules this process and leads to a transport of water molecules to the negative electrode (cathode), increasing the dry matter significantly and lowering the energy consumption with respect to conventional techniques, such as thermal drying.

Many experimental factors can influence the reduction of water content and, consequently, the process yield. The main critical processing factors of electro-dewatering are: (i) the properties of the sludge, in terms of volatile to total solids ratio, water amount and zeta potential; (ii) process parameters, such as applied voltage (or current), temperature, pressure, time; (iii) chemical conditioning.

Although electro-mechanical dewatering processes require further research, many authors think that water is removed from sludge according to the following steps (Barton et al., 1999; Mahmoud et al., 2010; Mok, 2006).

- Applied pressure reduces the volume of the pores and squeezes the water out.
- The charged particles (negative colloids) are still free to move in the fluid suspension. They tend to migrate towards the electrode carrying the opposite charge (the anode).
- When the cake has formed, the particles are locked in their position and hence unable to move. Water is transported through the porous medium by electro-osmosis towards the cathode.
- Electrochemical reactions at the electrodes are essential to restore charge equilibrium.
- Finally, water ceases to be the continuous phase in the cake, and the electrical resistance rises, leading to ohmic heating; we should keep this effect at the lowest possible level, as it would lead to higher energy consumption, with very little increase in final DS content.

Studies about electro-dewatering reported final DS of up to 45%, much higher than 20-30% usually obtained by mechanical methods (Olivier et al., 2014). As a side effect, electro-migration may slightly reduce the concentration of heavy metals in the sludge, as they tend to migrate towards the cathode, where water is collected.

The main aim of this work was to investigate how sludge characteristics affect pressure-driven electro-dewatering. The process was performed by means of a lab-scale device. We studied different waste sludge samples taken from four WWTPs located in the Milan metropolitan area.

2. MATERIALS AND METHODS

2.1 Sludge samples

Four WWTPs located in the Milan metropolitan area (Italy) provided twelve different sludge samples for the tests. Aerobically stabilised sludge came from WWTP 1, 2 and 3 while WWTP 4 provided anaerobically stabilised sludge samples. Moreover, WWTP-1, 2 and 4 produced waste sludge from conventional activated sludge processes, while WWTP-3 is equipped with a Membrane BioReactor (MBR). Before the tests, samples were stored at 4°C up to no more than one week, in order to keep their properties as constant as possible.

We performed tests on

1) unconditioned (UC) sludge samples, taken from the plant thickeners,
2) conditioned and thickened (CT) sludge samples, and
3) on mechanically dewatered (DW) sludge.

We conditioned the sludge samples into jar-test bottles by adding the same polyelectrolyte at the same dose used in each WWTP and mixing at 30 rpm for 15 min. All the polyelectrolytes were polyamidic and high cationic. Then, the samples were centrifuged at 4000 rpm for 5 min.

The electrical conductivity was measured by a conductivity meter (B&C Electronics-C 125.2) and pH by a pH-meter Metrohm 827 pH Lab.

Dry solid amount (DS), volatile solid content (VS), capillary suction time (CST) and time-to-filter (TTF) were measured according to Standard Methods (APHA et al., 2012).

We double filtered the supernatant of the centrifuged CT samples under vacuum with Munktell filters (12-15 µm pores size) and Whatman 42 filters (2.5 µm pores size). Zeta potential was determined on this liquid sample by the instrument Malvern Zetameter ZS90, which could not measure zeta potential of suspensions with particles larger than 100 µm. Turbidity of the supernatant was measured by a turbidity-meter (Horbeco-Hellige Model 966).

After separation from the supernatant, the centrifuged sludge, with DS content of around 5-9%, was used for the electro-dewatering tests.

In order to assess the feasibility of electro-dewatering to increase DS of mechanically dewatered sludge, we performed additional tests on samples taken in the four WWTP after mechanical dewatering (DW). Sludge samples had an initial DS (DS_i) in the range 18.1-21.8% (WWTP 2 and 4, equipped with centrifuges) and in the range 15.6-16.6% (WWTP 1 and 3, equipped with belt-presses).

2.2 Lab-scale device

We built a lab-scale dewatering device (Figure 1), by which we could apply both a mechanical pressure and an electric field to the sludge. This device consists 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-CP96 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 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 discharges to a graduated cylinder that is put on a precision scale balance. At regular intervals, we recorded the weight of the collected liquid, in order to calculate the rate of sludge dewatering.

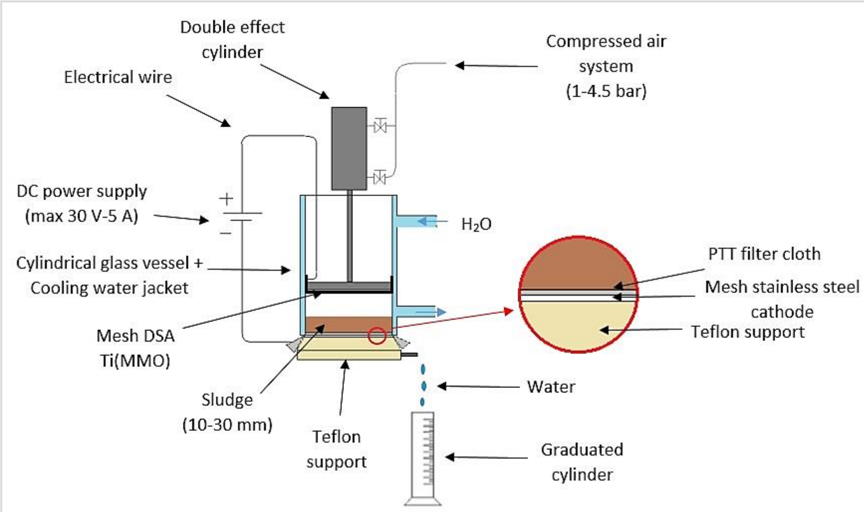

Figure 1 - Schematic of the lab-scale electro-dewatering device.

2.3 Electro-osmosis tests

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

- filtration/compression by applying pressure (duration: 5 min);
- application of an electric field at the selected operating voltage, keeping the applied pressure constant (duration: 15 min).

After the cover closes the cell, the piston starts applying pressure (300 kPa) on the sludge. Approximately 60 g of wet sludge (UC or CT samples, 5 to 9% DS) or 45 g of mechanically dewatered sludge (DW samples, 16 to 25% DS) form a 1-cm thick layer in the cell. Sludge is pressed between the upper anode (on a support made of polytetrafluoroethylene, PTFE) and the lower PTT filter cloth (placed on the cathode mesh). After 5 min, when no water drains by simply applying pressure, we switch the 15 V potential on, corresponding to an electric field intensity of 15 V/cm. Values of currents vs time are recorded. At the same time, recording of extracted water weight takes place at a pace of one per minute.

3. RESULTS AND DISCUSSION

3.1 Sludge characteristics

Table 1 lists the main characteristics of sludge samples. UC sludge samples from WWTP-4 and, to a lesser extent, from WWTP-1, showed the highest CST and TTF and the lowest zeta potential values.

As for B and C-samples, we reported CST, TTF and zeta potential values before (UC) and after (CT) sludge conditioning. Conductivity was in the range 1-2 mS/cm for aerobically stabilised sludge types, while for anaerobically stabilised sludge samples (WWTP 4) it exceeded 4 mS/cm, due to the high presence of ammonium nitrogen, which is typical of an anaerobically digested sludge. Specific polyelectrolyte dose (expressed as g/kg_{DS}) varies among the sludge samples. As said before, we applied the same doses adopted at the four WWTPs, in terms of grams of polyelectrolyte dosed per m^3/h of thickened sludge. These doses are usually set on the sludge flow rate coming from thickeners. Operators do not apply dynamic control over varying DS concentration (2 to 3.4% w/w). Consequently, the specific dose of polyelectrolyte in terms of grams per kg of DS can vary greatly and, at low DS content values, can be excessive. This happened with samples 2-B, 3-B and 4-B. In the first two cases, which refer to aerobically digested sludge, zeta potential was positive, TTF could not be measured (filter paper broke before the time), and CST increased with respect to the UC sludge. In case of sample 4-B (anaerobically digested sludge), this did not happen. In order to avoid overdosing, we set a maximum dose of 9 g/kg_{DS} for polyelectrolyte addition in the last series of samples, named "C" samples.

Table 1 - Characteristics of unconditioned (UC) and thickened/conditioned (CT) sludge samples taken from the four WWTPs.

Parameter		**WWTP 1**			**WWTP 2**			**WWTP 3**			**WWTP 4**		
		1-A	**1-B**	**1-C**	**2-A**	**2-B**	**2-C**	**3-A**	**3-B**	**3-C**	**4-A**	**4-B**	**4-C**
pH		6.9	7.2	7.0	7.2	7.1	7.3	7.1	7.0	6.9	7.1	7.2	7.1
Conductivity (mS/cm)		1.1	1.7	1.7	0.7	1.3	4.9	0.8	1.0	1.2	3.9	4.3	4.6
DS_o (%)		2.8	3.0	3.4	0.6	1.9	2.5	1.9	1.4	2.2	2.8	3.0	3.2
VS/DS (%)		69.7	73.1	68.3	65.3	67.9	64.4	74.3	74.0	75.4	59.5	66.0	63.9
CST (s)	**UC**	22.1	34.0	27.0	8.4	12.4	29.6	11.2	11.8	-	89.6	129.0	101.7
	CT	-	11.7	12.0	-	23.8	8.7	-	12.0	6.7	-	58.0	27.2
TTF (min)	**UC**	14.0	25.0	21.0	<1.0	4.0	27.0	4.0	6.0	-	88.0	91.0	96.0
	CT	-	3.0	5.0	-	-	4.0	-	-	2.0	-	53.0	16.0
Zeta potential (mV)	**UC**	-13.1	-13.2	-13.2	-8.7	-9.2	-11.3	-11.6	-13.3	-	-13.8	-15.2	-14.1
	CT	-	-9.9	-9.5	-	+32.2	-8.6	-	+2.5	-9.1	-	-11.8	-12.1
Turbidity (NTU)	**UC**	80.4	-	-	15.8	-	-	45.6	-	-	220.0	-	-
Polyelectrolyte dose (g/kg_{DS})		-	5.7	5.1	-	26.9	9.0	-	9.0	<8.0	-	20.0	9.0
DS_{DW} WWTP (%)		17 - 18			16 - 18			16 - 18			25 - 26		

3.2 Tests on unconditioned (UC) sludge

These test aimed at comparing the electro-dewatering efficiency and electric energy consumption of sludge samples from different WWTPs. Liquid sludge samples taken from the WWTPs were centrifuged in laboratory in order to increase the DS_i of each sample to be treated under the electric field, to reduce to a minimum the preliminary pressure-driven phase. We repeated the experiments twice for each sample.

Electro-dewatering results are strictly dependent on the polyelectrolyte type and the dosage used for each sample. For this reason, firstly we performed tests on unconditioned (UC) sludge samples, aiming at establishing a direct relation between sludge characteristics and their behaviour under electric field application. Table 2 reports the results.

Table 2 - Results of electro-dewatering tests on unconditioned (UC) sludge samples. The last column reports the DS content of mechanically dewatered sludge at each WWTP.

UC sludge sample	DS_o raw sludge (%)	DS_i centri-fuged (%)	Electric energy consumption during t_E (Wh)	Specific electric energy consumption during t_E (Wh/kg_{H_2O})	DS_f (%)	ΔDS (%)	DS_f WWTP average (2013 – 2014) (%)
P=300 kPa; E=15 V/cm; t_E=20 min							
1-A-UC	2.8	9.5	1.492	65.5	15.0 ± 0.64	5.5	17 – 18
2-A-UC	0.6	6.3	0.725	47.1	9.4 ± 0.21	3.1	16 – 18
3-A-UC	1.9	7.1	0.902	49.7	10.9 ± 0.92	3.8	16 – 18
4-A-UC	2.8	8.4	1.073	51.9	12.9 ± 0.14	4.5	25 – 26

By applying the electric field for 20 min, specific energy consumptions were in the same range of the tests performed on CT-samples (Section 3.3). However, as expected, after electro-dewatering, unconditioned sludge samples reached a low DS_f content, with a limited dry solid content increase (ΔDS), ranging from 3.1 to 5.5%.
Figure 2 shows diagrams of collected water/current density vs time and diagrams of DS vs time of UC samples from WWTPs-1, 2, 3 and 4.

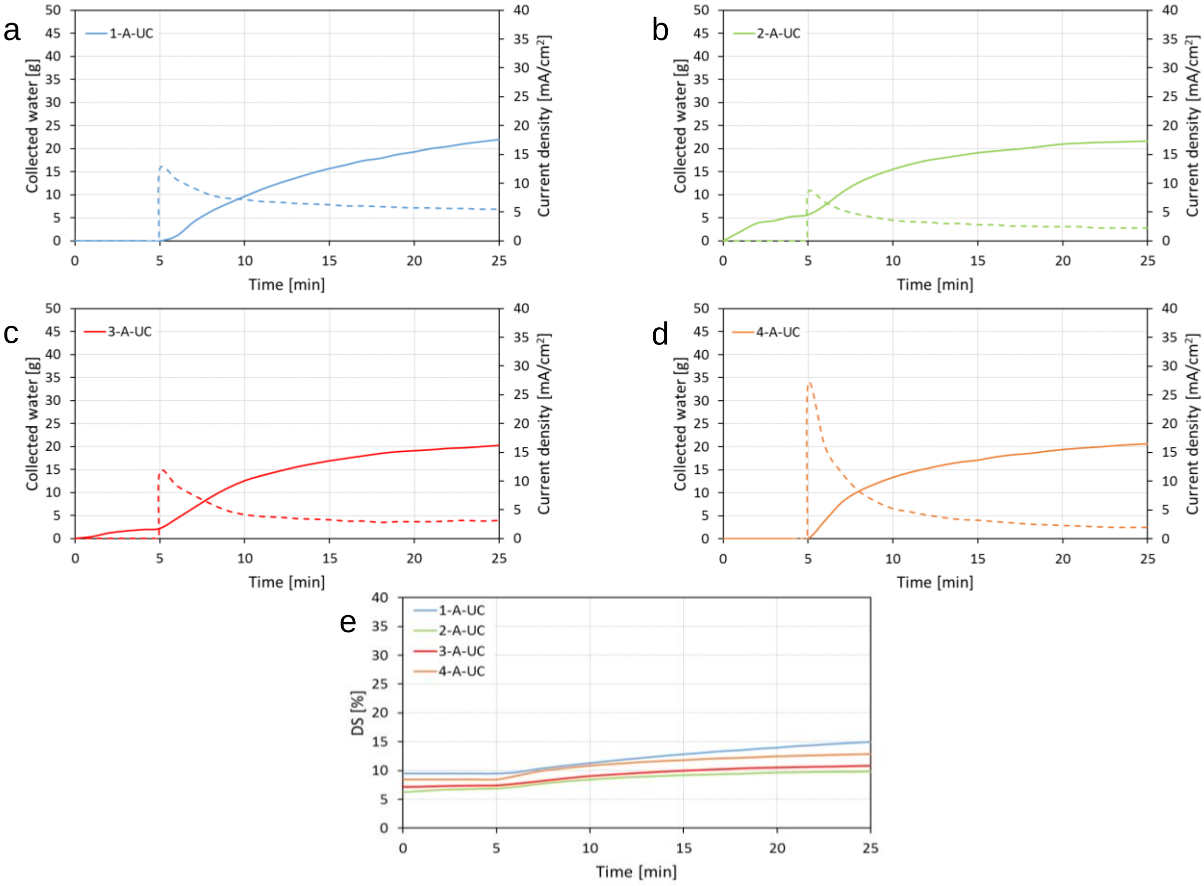

Figure 2 - Electro-dewatering tests on UC-samples from WWTPs-1, 2, 3 and 4: collected water vs time and current density vs time (a, b, c, d), DS amount vs time (e).

Samples 1-A-UC and 4-A-UC have no water loss without electric field application. This fact highlights that a DS_i > 8% is needed to reduce energy consumptions and tests duration of the pressure driven phase for UC samples.

Sludge sample taken from WWTP-1 showed the highest ΔDS among the samples taken from the four WWTP. This is in contrast with CST, TTF and zeta potential values of the same samples, which would indicate better filterability for sludge samples from WWTP-2 and 3.

3.3 Tests on conditioned and thickened (CT) sludge

Liquid sludge samples were conditioned and then centrifuged in laboratory, in order to study the effective electro-dewatering efficiency under the influence of the polyelectrolyte. Experiments were repeated three times for each sample. Table 3 shows the results of these electro-dewatering tests.
It should be emphasised that the electric field has been applied for 15 min only. If we had not stopped the process, we would have got higher DS_f values.
The specific energy consumption values are around 46-82 Wh/kg$_{H_2O}$, and, taking into account the national electrical energy efficiency equal to 0.47 (Caputo et al., 2015), the corresponding total equivalent primary energy consumption is as low as 98-175 Wh/kg$_{H_2O}$, much lower than the primary energy needed for thermal drying (617-1200 Wh/kg$_{H_2O}$; Olivier et al., 2014). As energy consumption is about 20 to 40 times higher than for purely mechanical dewatering, this technology is suitable as a post-dewatering treatment, as it can reduce energy consumption in thermal drying or as it allows self-sustained combustion of sludge at 850°C (Olivier et al., 2014; Gronchi et al., 2016).

Table 3 - Results of electro-dewatering tests on conditioned and thickened (CT) sludge samples; thickening achieved by centrifugation in the lab.

CT sludge sample	DS_o raw sludge (%)	DS_i centri-fuged (%)	Electric energy consumption during t_E (Wh)	Specific electric energy consumption during t_E (Wh/kg$_{H_2O}$)	DS_f (%)	ΔDS (%)	DS_f WWTP average (2013 – 2014) (%)
P=300 kPa; E=15 V/cm; t_E=15 min							
1-B-CT	3.0	8.6	1.562	48.3	23.8 ± 0.23	15.2	17 – 18
1-C-CT	3.4	6.6	1.728	45.9	23.8 ± 1.59	17.2	
2-B-CT	1.9	8.0	1.346	69.6	20.4 ± 1.76	12.4	16 – 18
2-C-CT	2.5	8.3	2.419	82.1	21.7 ± 2.88	13.4	
3-B-CT	1.4	5.2	2.070	58.5	19.8 ± 1.39	14.6	16 – 18
3-C-CT	2.2	5.5	1.402	45.7	13.5 ± 0.44	8.0	
4-B-CT	3.0	8.6	2.394	74.7	19.2 ± 0.78	10.6	25 – 26
4-C-CT	3.2	9.0	2.546	76.0	23.3 ± 0.46	14.3	

Figure 3 shows diagrams of collected water/current density vs time and diagrams of DS vs time of CT samples from WWTPs-1, 2, 3 and 4.
In the first 5 min of pressure application, dewatering rate is low and DS content increases of no more than 3%. After switching the potential on, dewatering rate (i.e., the slope of the collected water curve) is high at first, and decreases with time afterwards, together with current density values. The explanation is that water content in sludge decreases and this leads to reduced sludge conductivity and increased electrical resistance.
In general, the dewatering rate is higher at lower DS_i, which implies higher free water content, as it is shown in Figure 3a (DS_i of sample 1-C-CT is 2% lower than sample 1-B-CT).
Samples 2-B-CT and 2-C-CT show different electric energy consumptions, which is mainly due to their different conductivity values (1.3 mS/cm vs 4.9 mS/cm, Table 1).

For the same reason, sample 2-B-CT shows a lower DS increase during the electrically driven dewatering phase, since weaker current densities are developed.
The high electric energy consumption obtained with tests on sample 3-B-CT contrasts with its relatively low conductivity, around 1 mS/cm. This behaviour is due to an increase of current densities detected after 2 min of potential application, possibly related to the overdose of polyelectrolyte. Sample 3-C-CT showed a low DS increase, even if there was no polyelectrolyte overdose. DS_f was only 13.5%, in spite of its very low CST and TTF values (see CT samples, in Table 1).

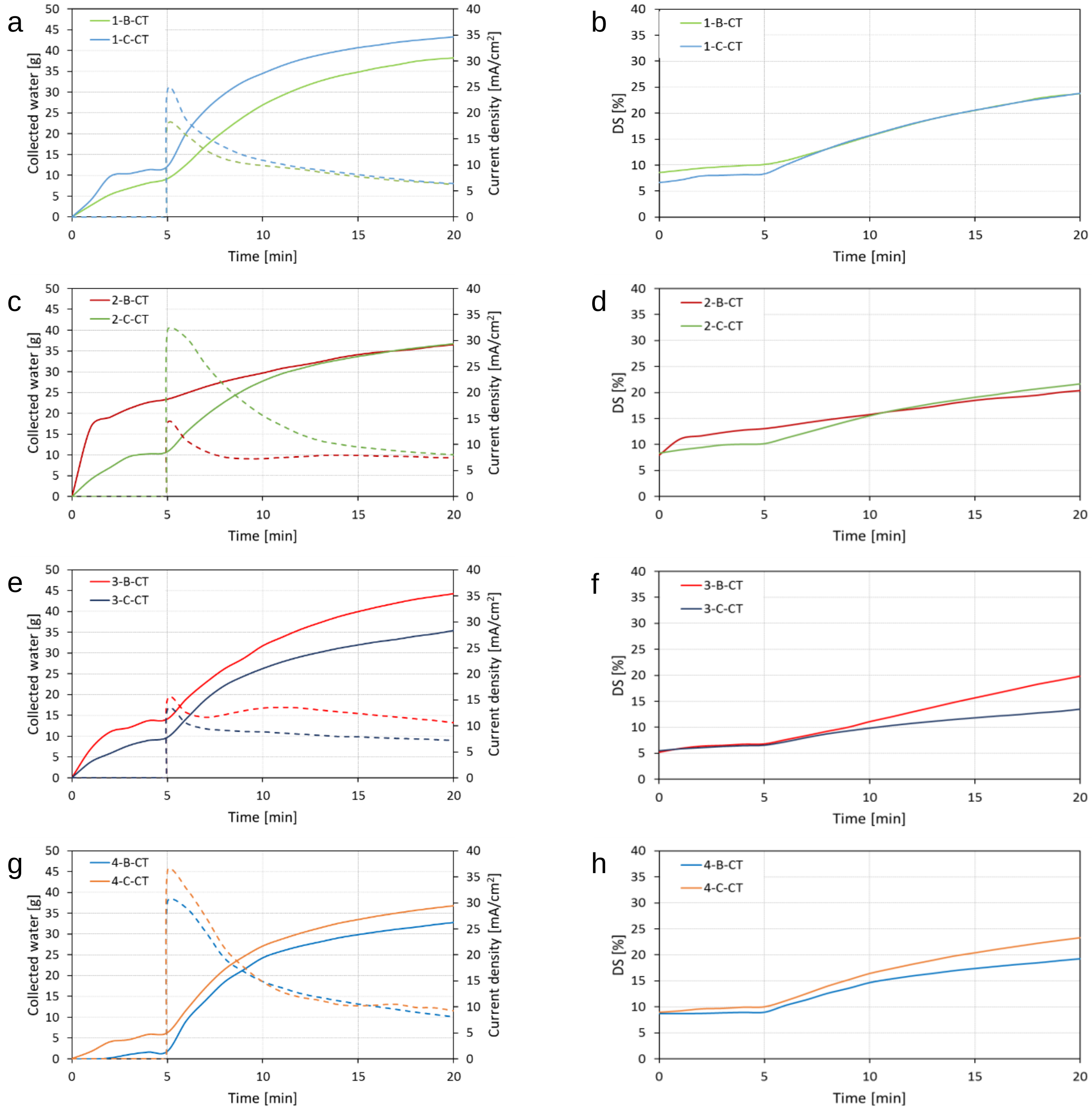

Figure 3 - Electro-dewatering tests on CT-samples from WWTPs-1, 2, 3 and 4: collected water vs time and current density vs time (a, c, e, g), DS vs time (b, d, f, h).

Electro-dewatering tests on samples 4-B-CT and 4-C-CT entailed a considerable energy consumption, higher than that measured in tests with aerobically digested sludge samples. This fact is strictly related to the presence of ammonium nitrogen, which is typical of anaerobically digested sludge, as already discussed. Here, conductivity is almost three times higher than that of aerobically stabilised samples and causes a development of stronger current densities. If compared to sample 4-C-

CT, sample 4-B-CT showed lower DS_f, which is coherent with higher TTF and CST values than 4-C-CT. Moreover, by applying the electric field, more water is removed from sample 4-C-CT, thanks to its slightly higher conductivity (4.6 mS/cm vs 4.3 mS/cm) and its correspondingly higher current density.
Looking at the results achieved by mechanical dewatering in the WWTPs (Table 3), electro-dewatering seems to achieve higher DS_f for sludge samples from WWTP-1 and, to a slightly lesser extent, to WWTP-2 and WWTP-4, but not for sludge samples taken from WWTP-3. We notice that sludge from this plant had the highest VS/DS ratio (≥74%), higher than all the samples taken from the other plants.

3.4 Tests on mechanically dewatered (DW) sludge

We added tests on sludge samples taken after mechanically dewatering at the four WWTPs (belt press in WWTP-1 and 3; centrifuge in WWTP-2 and 4). This was done to check the actual increase due to electro-dewatering and to compare the results between the four different plants. Table 4 shows the results.

Table 4 - Results of electro-dewatering tests on mechanically dewatered (DW) sludge samples.

DW sludge sample	DS_i (%)	Electric energy consumption during t_E (Wh)	Specific electric energy consumption during t_E (Wh/kg_{H_2O})	DS_f (%)	ΔDS (%)
P=300 kPa; E=15 V/cm; t_E=15 min					
1-B-DW	16.0	1.675	83.2	29.8 ± 0.49	13.8
1-C-DW	16.6	1.506	83.7	27.7 ± 0.42	11.0
2-B-DW	20.5	1.215	108.9	27.3 ± 1.27	6.8
2-C-DW	18.1	1.442	95.4	27.6 ± 2.97	9.5
3-B-DW	16.0	1.479	90.1	25.1 ± 0.00	9.1
3-C-DW	15.6	1.734	95.2	26.3 ± 0.71	10.7
4-C-DW	21.8	1.763	99.7	36.5 ± 1.77	14.7

The increase in DS values is remarkably high, and the final values of DS are from 1.5 to 2 times higher than the initial DS values (DSi).
Figure 4 shows the diagrams of electro-dewatering tests with mechanically dewatered (DW) sludge samples listed in Table 3. The trend of the plots is similar to those depicted for UC and CT sludge samples. However, we can highlight two main differences:

1) no water is collected during the first 5 min of the tests, since water that could be removed mechanically was already removed during centrifuge or belt press treatment at each WWTP;

2) dewatering rates seem to be still very high at the end of the 15 min of potential application; longer test duration may lead to higher DS_f values, but at the cost of higher energy consumption (Olivier et al., 2014). Energy consumptions were in the range 83-109 Wh/Wh/kg_{H_2O} (176-231 Wh/kg_{H_2O} of primary energy), much lower than the energy needed for thermal drying, which may justify a 5 min longer duration.

As DS_i and DS_f content in DW sludge samples were much higher than in thickened/conditioned (CT) sludge samples, we might expect a considerable change in current density values between tests on CT and DW sludge samples. However, this is not. We may explain this fact by considering that the electric resistance is affected mainly by the dry sludge layer that develops at the anode, rather than by the entire cake itself. This is because this thin dry sludge layer that develops in contact to the anode dissipate currents by Joule effect without an effective improvement in water removal: the resistance inside the cell between CT and DW sludge samples is therefore similar, especially at the end of the process.

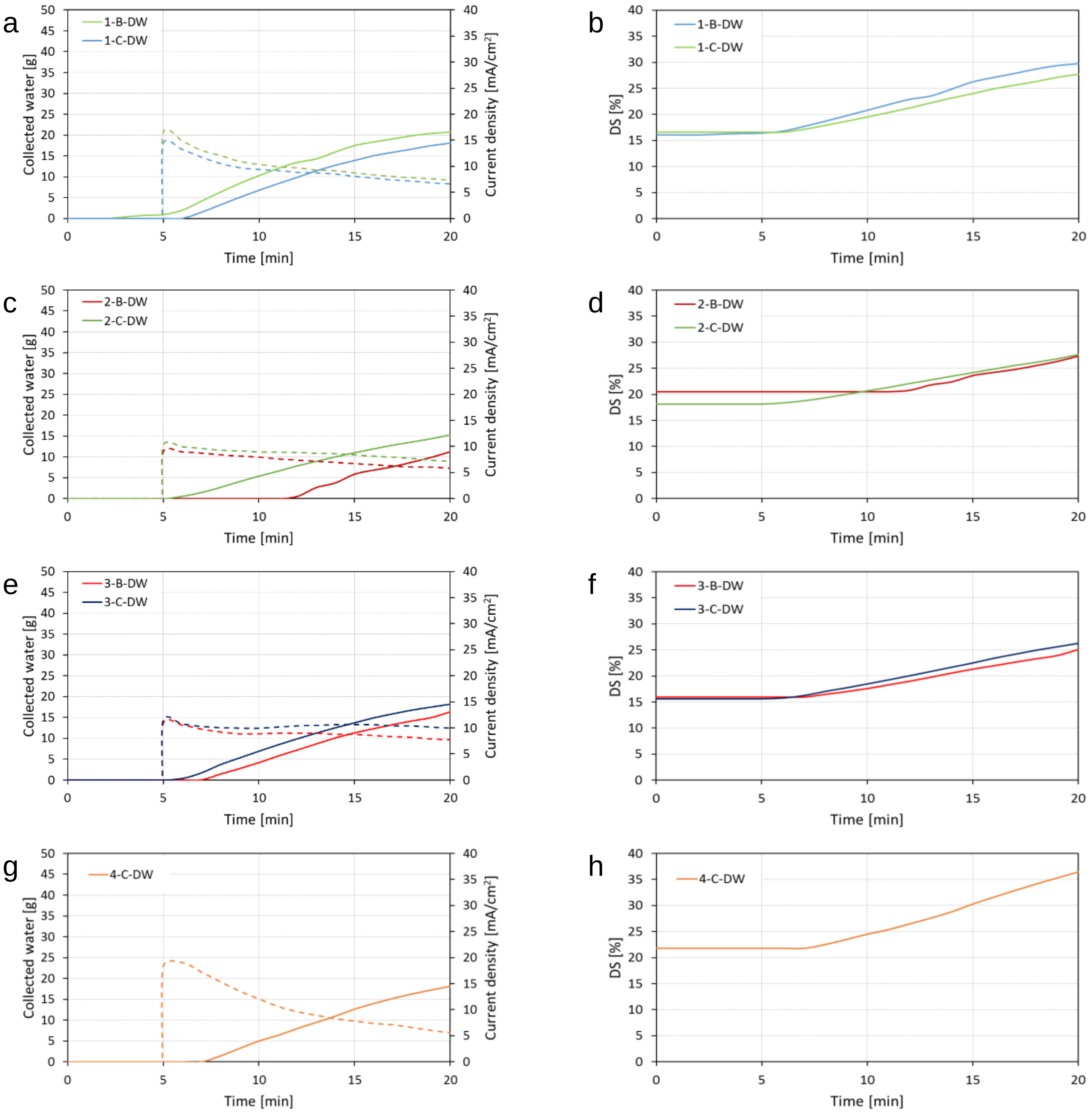

Figure 4 - Electro-dewatering tests on DW-samples from WWTPs-1, 2, 3 and 4: collected water vs time and current density vs time (a, c, e, g), DS amount vs time (b, d, f, h).

The influence of the dry cake near the anode on the development of current densities is the reason of the reduced water removal in the last minutes of the tests.
Stradi et al. deposited a patent (N°: WO 2011/161568 A1) of an industrial electro-dewatering device which may be a possible solution to improve electro-dewatering. The device is similar to a screw-press. The motion of the screw mixes the sludge and delays the formation of a dry cake next to the anode, homogenizing the sludge and possibly producing a drier cake with a lower energy consumption.

3.5 Relationships between sludge indicators

CST, TTF and zeta potential are usually known to be the best indicators to predict and relate sludge dewatering. Results of unconditioned sludge samples (Table 1) confirm the good correlation between CST and TTF values (Figure 5). We can define the filterability of sludge by any of the two methods.

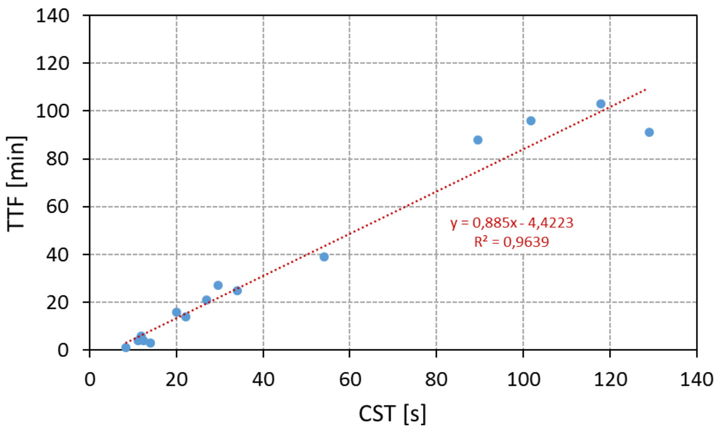

Figure 5 - CST and TTF correlation for UC sludge samples from the four WWTPs.

Figure 6 shows the trend of zeta potential vs CST (a) and vs TTF (b): the higher the absolute value of zeta potential, the greater CST and TTF values.

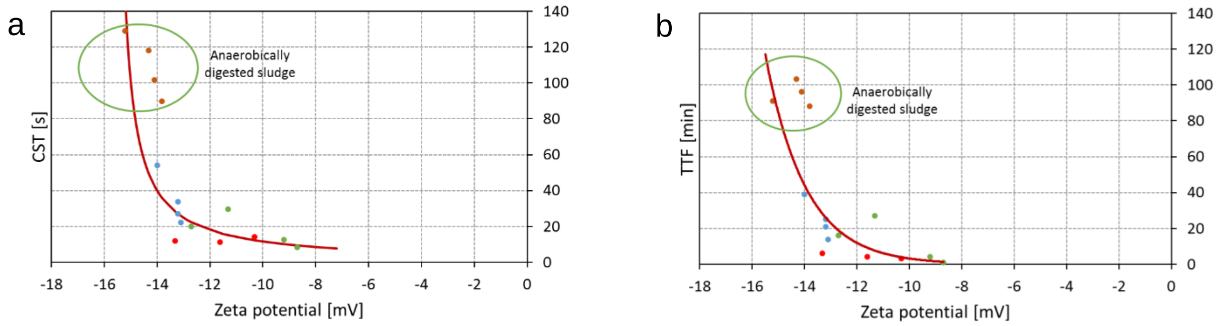

Figure 6 - CST and TTF vs zeta potential for UC sludge samples taken from WWTPs-1, 2, 3 and 4.

This confirms that zeta potential is also related to CST and TTF.

However, none of these indicators can suitably predict how electro-dewatering can increase the DS.

Figure 7 shows that a direct relation is not possible between CST and DS_f or ΔDS achieved through tests with conditioned/thickened (CT) sludge. Therefore, an electric field-assisted lab-scale device is necessary to predict more reliably how efficient electro-dewatering can be with different sludge samples.

Mechanical dewatering and electro-dewatering efficiency may depend more on the fraction of volatile solids, conductivity and, obviously, initial DS content, rather than CST and TTF.

The results achieved through electro-dewatering tests on UC, CT and DW samples have clearly shown that electro-dewatering is more effective on sludge from WWTP-1 than on the others. Its DS_f and ΔDS values are always the highest among the investigated samples, in contrast with the low water removal efficiency in the WWTP after belt press dewatering (DS_{DW} = 17-18%). On the other hand, sludge from

WWTP-4 had a considerable DS_f increase too, but dewatering by centrifuge is already effective (DS_{DW} = 25-26%).

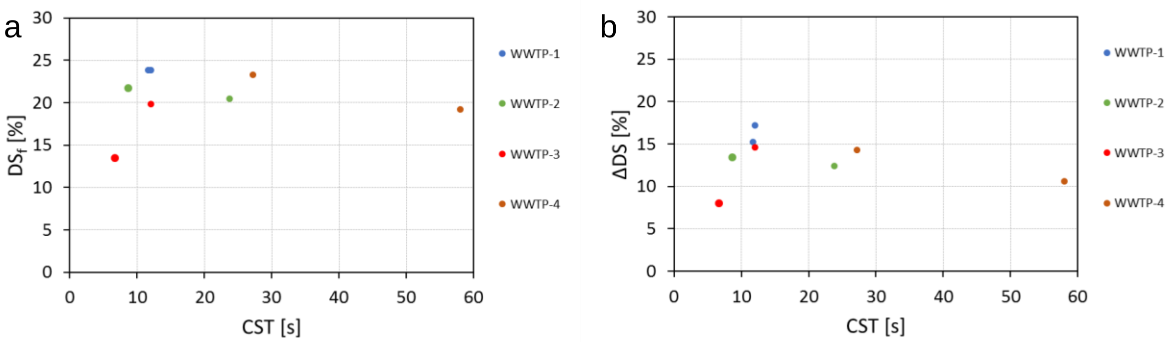

Figure 7 - Diagrams of DS_f vs CST (a) and ΔDS vs CST (b) for conditioned and thickened sludge samples from the four WWTPs.

4. CONCLUSIONS

In this work, we carried out pressure driven electro-osmotic dewatering tests out using a lab-scale device. The aims were to test electro-osmotic dewatering on sludge coming from different WWTPs, and to determine the dewatering efficiency in terms of DS_f and energy consumption. We tested liquid unconditioned sludge samples taken after thickening (UC samples), the same after conditioning (in a Jar-Test rig) and further thickening in a lab centrifuge (CT samples) and samples taken after mechanical dewatering (DW samples) by centrifuge or belt press directly in the WWTP.

Characterization involved measurement of pH, conductivity, dry solids (DS), volatile fraction (VS/DS), capillary suction time (CST), time-to-filter (TTF) and zeta potential of the liquid fraction of the sludge. During the electro-dewatering experiments, we set the electric field value at 15 V/cm with a pressure of 300 kPa and we have measured:

- the current densities that developed during the tests and the corresponding energy consumption,
- the drained water and the corresponding DS evolution with time until the end of each test and.

Although the results presented here are only preliminary and further tests are planned, we may draw the following conclusions:

- sludge with lower VS/DS can be dewatered much better than sludge with VS/DS exceeding 70%, and this apply to electro-dewatering as well; electro-dewatering can add a DS increase as high as
- anaerobically digested sludge develops higher current densities due to its high conductivity, which is due to the high concentration of ammonium ion;
- aerobically stabilised sludge appears to be the most suitable for electro-dewatering as we obtained the highest ΔDS (from 7 to 14% DS increase over conventionally dewatered sludge;
- electric energy consumption needed to increase DS of mechanically dewatered sludge of 10.7% ± 2.7% is 94.0 ± 9.1 Wh/kg_{H_2O}, which is less than 1/4 of the equivalent primary energy for thermal drying, if we assume a thermodynamic conversion factor of 0.47 (average Italian grid efficiency);
- CST, TTF and zeta potential are not good predictors of the dewaterability and the electro-dewaterability of a sludge;
- a lab-scale electro-dewatering test on conditioned and thickened sludge may give useful indications about the applicability of this technique.

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