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Influence of the sludge characteristics on sludge dewatering and electro-dewatering

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ABSTRACT

In this thesis, the influence of polymer dosage in mechanical dewatering and electro-dewatering and the relationship of sludge characteristics with sludge dewaterability was investigated. Moreover, a preliminary economic assessment was carried out.

Thickened unconditioned (TU) sludge samples were collected from eight different WWTPs located in Milan, Italy. Thickened conditioned (TC) sludge samples at selected dosages of 4 and 8 g/kg$_{DS}$ were prepared in the laboratory by means of jar test.

Initially, characterisation of TU and TC samples in terms of dry solids (DS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), pH, conductivity, zeta potential (ZP), capillary suction time (CST) and specific resistance to filtration (SRF) was carried out. Then, multiple centrifugation (mCFG), mechanical dewatering (MD) and electro-dewatering (EDW) tests were carried out on TU and TC samples from the eight WWTPs. The final cake DS content after mCFG, MD and EDW ranged 10.3-15.1%, 12.8-20.8% and 29-45.3% respectively. As expected, it was observed that addition of polymer had a positive effect over dewatering. In EDW, polymer dosage did not directly contribute to the final DS content: the addition of polyelectrolyte enhanced the water removal during compression phase but showed no observable effect when electric field was applied.

Relationship between different sludge characteristics like VS, conductivity, ZP, DS after centrifugation and dewaterability was established with a preliminary statistical evaluation. It was found that sludge characteristics does not affect the performance of MD and EDW in a similar way. Certainly, CST and SRF was found to be good indicators of filterability but cannot be used as an indicator for estimating sludge dewaterability. However, CST and SRF were confirmed to be excellent tools for assessing the conditioning process.

Remarkably, EDW was able to produce sludge cakes with DS up to 45%, which is significantly higher than conventional mechanical dewatering process (CMD). In some cases, EDW allowed to achieve savings due to reduction in the cost of disposal in comparison to CMD that is adopted in the WWTPs.

SOMMARIO

In questa tesi, sono state studiate l'influenza del dosaggio di polimero nella disidratazione meccanica e nella disidratazione elettro-assistita e la relazione tra le caratteristiche dei fanghi e la loro disidratabilità. Inoltre, è stata effettuata una valutazione economica preliminare.

Sono stati raccolti campioni di fango ispessito non condizionato (TU) da otto diversi impianti di depurazione situati a Milano, Italia. Campioni di fango ispessito condizionato (TC) a dosaggi selezionati di 4 e 8 g/kgSS sono stati preparati in laboratorio mediante jar test.

Inizialmente, è stata effettuata la caratterizzazione dei campioni TU e TC in termini di sostanza secca (SS), solidi volatili (SV), solidi sospesi totali (SST), solidi sospesi volatili (SSV), pH, conducibilità, potenziale zeta (PZ), tempo di suzione capillare (CST) e resistenza specifica alla filtrazione (SRF). Successivamente, sono stati condotti test di centrifugazione multipla (mCFG), disidratazione meccanica (MD) e disidratazione elettro-assistita (EDW) su campioni TU e TC dagli otto impianti. Il contenuto finale di SS dopo mCFG, MD ed EDW era rispettivamente del 10,3-15,1%, del 12,8-20,8% e del 29-45,3%. Come previsto, è stato osservato che l'aggiunta del polimero ha un effetto positivo sulla disidratazione. Nell'EDW, il dosaggio dei polimeri non ha contribuito direttamente al contenuto finale di SS: l'aggiunta di polielettrolita ha migliorato la rimozione dell'acqua durante la fase di compressione ma non ha mostrato alcun effetto osservabile quando è stato applicato il campo elettrico.

Mediante una valutazione statistica preliminare, è stata stabilita la relazione tra le diverse caratteristiche dei fanghi come SV, conducibilità, PZ, SS dopo centrifugazione e disidratabilità. È stato riscontrato che le caratteristiche dei fanghi non influiscono in modo simile sulle prestazioni di MD e EDW. Sicuramente, CST e SRF sono risultati buoni indicatori di filtrabilità ma non possono essere usati come indicatore per la stima della disidratabilità dei fanghi. Tuttavia, CST e SRF si sono dimostrati strumenti eccellenti per la valutazione del processo di condizionamento.

Sorprendentemente, l'EDW è stata in grado di produrre pannelli di fango con SS fino al 45%, che è significativamente superiore al processo di disidratazione meccanica convenzionale

(CMD). In alcuni casi, l’EDW ha permesso di ottenere risparmi grazie alla riduzione dei costi di smaltimento rispetto alla CMD adottata negli impianti

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LIST OF ABBREVIATIONS

CE: Capture efficiency

CFG: Centrifugation

CMD: Conventional mechanical dewatering

CST: Capillary suction time

DC: Direct current

DS: Dry solids

DSC: Differential scanning calorimeter

DTG: Differential thermogravimetry

EDW: Electro-dewatering

EPS: Extracellular polymeric substances

GLM: General linear model

mCFG: Multiple centrifugation

MD: Mechanical dewatering

MMO: Mixed metal oxide

PRS: Pressure

PTFE: Polytetrafluoroethylene

PTT: Poly-trimethylene terephthalate

SEC: Specific energy consumption

SRF: Specific resistance to filtration

TC: Thickened conditioned

TGA: Thermogravimetric analysis

Ti: Titanium

TSS: Total suspended solids

TU: Thickened unconditioned

VS: Volatile solids

VSS: Volatile suspended solids

WWTP: Wastewater treatment plant

ZP: Zeta potential

1 INTRODUCTION

1.1 BACKGROUND

A rapid increase in urbanization and industrialization has led to increased wastewater production. As a consequence, the municipal and industrial wastewater treatment is challenged with increasing sludge flowrates. Wastewater is treated either aerobically or anaerobically and both processes produce sludge (Yin et al., 2004). Thus, sludge is inevitable in a wastewater treatment process and it is characterized by the high water content and by its compressible and colloidal nature (Mahmoud and Olivier, 2013). The water content in sludge is usually higher than 90% (Dominiak et al., 2011), which makes the sludge to occupy a large volume of space. Sludge creates lot of undesirable impacts to public health and to the environment. Therefore, more stringent rules on sludge disposal and restrictions on huge volumes of sludges were introduced, which creates complications in sludge treatment. To reduce the negative effects of microorganisms, sludge is stabilized before disposal. Dewatering is the process of reducing the moisture content from the sludge (Sawalha and Scholz, 2007) and allows a reduction of its volume and thereby reduces the handling and transportation costs (Dominiak et al., 2011). Dewatering is the most expensive process among the wastewater treatment processes (Wójcik and Stachowicz, 2019). Therefore, selecting a proper dewatering technique with high efficiency in water removal and low energy consumption is necessary.

Mechanical dewatering (MD) devices like centrifuges, filter presses or belt presses are the most commonly employed in WWTPs, thanks to their relatively low energy requirement. However, the compressible and colloidal nature of the sludge along with the presence of extracellular polymeric substances (EPS) in sludge hinders high performances in dewatering even at high pressure (Mahmoud et al., 2011). It has been found that MD can be improved by the application of an electric field, which can remove significantly more water compared to MD techniques. Indeed, electro-dewatering (EDW) can particularly remove water that

cannot be removed by MD with an energy consumption lower than thermal drying processes and high dry solid (DS) content in the final sludge cakes (Mahmoud et al., 2018).
The absence of physical quantities or indices that can predict the maximum achievable DS of the sludge (dewaterability of the sludge) makes it hard to distinguish a suitable cost-effective dewatering technique. To optimize and improve the dewatering processes, it is essential to investigate the characteristics of sludge that affect dewatering. Indeed, characteristics like floc/particle size and shape, water distribution, rheology, floc structure, floc porosity, floc density, pH, DS, surface charge, hydrophobicity, EPS are collectively affecting dewatering (Sanin et al., 2011).

1.2 AIM OF THE THESIS

The objectives of the thesis are:

- To characterize different sludge samples collected from 8 different WWTPs.
- To study the effect of polyelectrolyte dosage in MD and EDW.
- To investigate the relationship of sludge characteristics with sludge dewaterability.
- To conduct an economic assessment of MD and EDW.

1.3 STRUCTURE OF THE THESIS

The general outline of the thesis is as follows:

- **Chapter 1** provides a general introduction to the problems associated with sludge disposal and treatment worldwide. It presents the different dewatering techniques and the problems associated in understanding and implementing a cost-effective technique. It also describes the goals of the thesis and its structure.
- **Chapter 2** provides a brief summary of the issues in sludge disposal in Europe**.** It describes the dewatering processes with a focus on MD and EDW, followed by an investigation of the main sludge properties. The relationship between those properties and sludge dewaterability are then presented.

- **Chapter 3** shows the materials and methods used for sludge characterization, MD and EDW experiments.
- **Chapter 4** presents the results obtained from sludge characterization, MD and EDW experiments. It discusses the relationship of different indicators with dewaterability. It also details about the economic assessment of MD and EDW at different dosages.
- **Chapter 5** summarizes the main findings of this work and points out the areas of interest for future investigation.

2 STATE OF ART

2.1 SLUDGE TREATMENT AND MANAGEMENT IN EUROPE

The quantity of sludge produced are increasing every year because of increasing WWTPs (Olivier et al., 2014). The European Council Urban Wastewater Treatment Directive (UWWTD) 97/271/EC (21 May 1991) implementation forced to make changes in the wastewater treatment processes (Commission of the European Communities, 1999). According to the directive, the WWTPs should establish secondary treatment if the population equivalent exceeds 2000. According to the article 4 and 5 of the directive, nutrients (especially nitrogen and phosphorous) and organic substances ought to be removed before discharging into the receiving water bodies. Article 14 of the directive prohibits the discharge of sludge into the sea and freshwater (Bresters et al., 1997).

As a consequence, new additional infrastructures are looked-for to handle increasing volumes of sludge and more intense treatment methods to accomplish nutrient allowable limits (Shaddel et al., 2019). All these additional unit processes generate huge volumes of inevitable sludge.

Although the sludge produced in the WWTP is 1% of the wastewater stream, the cost of handling and management of the sludge is about 40-50% of the total operational cost of a WWTP (Stefanakis et al., 2014). Before transportation and disposal of sludge, sludge is usually thickened, stabilized, conditioned and dewatered. The different processes of sludge treatment and its respective sludge qualities are illustrated by Figure 1.

Sludge stabilization is employed before dewatering to reduce pathogens, decrease odour and to reduce the organic content. Sludge is stabilized to prevent aerobic decomposition that occurs while storage. Stabilization of sludge can be aerobic or anaerobic. Aerobic stabilization has low capital cost and is an energy intensive process. Aerobic stabilization is not highly effective in reducing the pathogens content and sludge produced is difficult to dewater (Peirce et al., 1998b). On the contrary, anaerobic stabilization is interesting due to energy recovery (production of biogas) and reduction of volume of sludge (Elalami et al., 2019). Highly concentrated sewage sludge and industrial sludge are usually anaerobically stabilized.

Thickening reduces the volume and consequently the cost, but the sludge still contains a large portion of water. Solid compaction is obtainable due to differences in liquid and solid particle densities which is driven by gravity (Peirce et al., 1998a). Treatment of sludge with chemicals or by other means changes its characteristics and favours dewatering. Thickened sludge is subjected to dewatering to further reduce the volume and improve the quality of the sludge to enhance sludge handling, transportation and disposal.

Sludge can be disposed of through different routes such as agricultural use, landfill and incineration. Each of this disposal method has different constraints. Land application of sludge can improve the physical and biological properties of the soil and mineral recovery (Nitrogen, Phosphorous, Potassium) as a fertilizer. Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment and of the soil should be followed when sewage sludge is used in agriculture. The requirements of sludge for the use in farmlands include pre-treatment, restriction on the heavy metal content in sludge, limitation on the micro pollutant content, restriction on the nutrient content etc. (Bresters et al., 1997).

Sludge can also be deposited in sanitary landfills to prevent some degree of pollution. Sanitary landfills are used because they prevent the contamination of water and air. Higher dry solid content of the sludge should be obtained to ensure compaction during landfill process. Directive on the landfill of waste (1999/31/EEC) recommends reduction of biodegradable waste disposed in landfill and forbids the disposal of liquid and untreated wastes. However, different countries in EU have different limitations on disposal of sludge in landfills and in some countries it already is prohibited (European Commission, 2001).

Incineration allows harmful and hazardous substances to be burnt, and energy is recovered from the sludge. High calorific value is preferred for incineration and is achieved by removing water from sludge. There is no specific directive for sludge incineration (European Commission, 2001). Draft Directive on Incineration of Waste (94/08/20) has control over waste incineration as well as sludge incineration and has restrictions on air emission, solid residues after incineration and gas cleaning, wastewater after flue gas cleaning, leachate of ash deposit (Bresters et al., 1997).

The cost of sludge transportation and disposal are directly proportional to the moisture content of the sludge. Therefore, to minimize the sludge management cost and to be environmentally responsible as well as lawful, it is necessary to reduce the water content in the sludge. Apparently, dewatering will enhance the quality of sludge and thereby reduce the cost of sludge management (Sharma and Sanghi, 2013). Pre-treatments modify the sludge properties, especially the dewaterability.

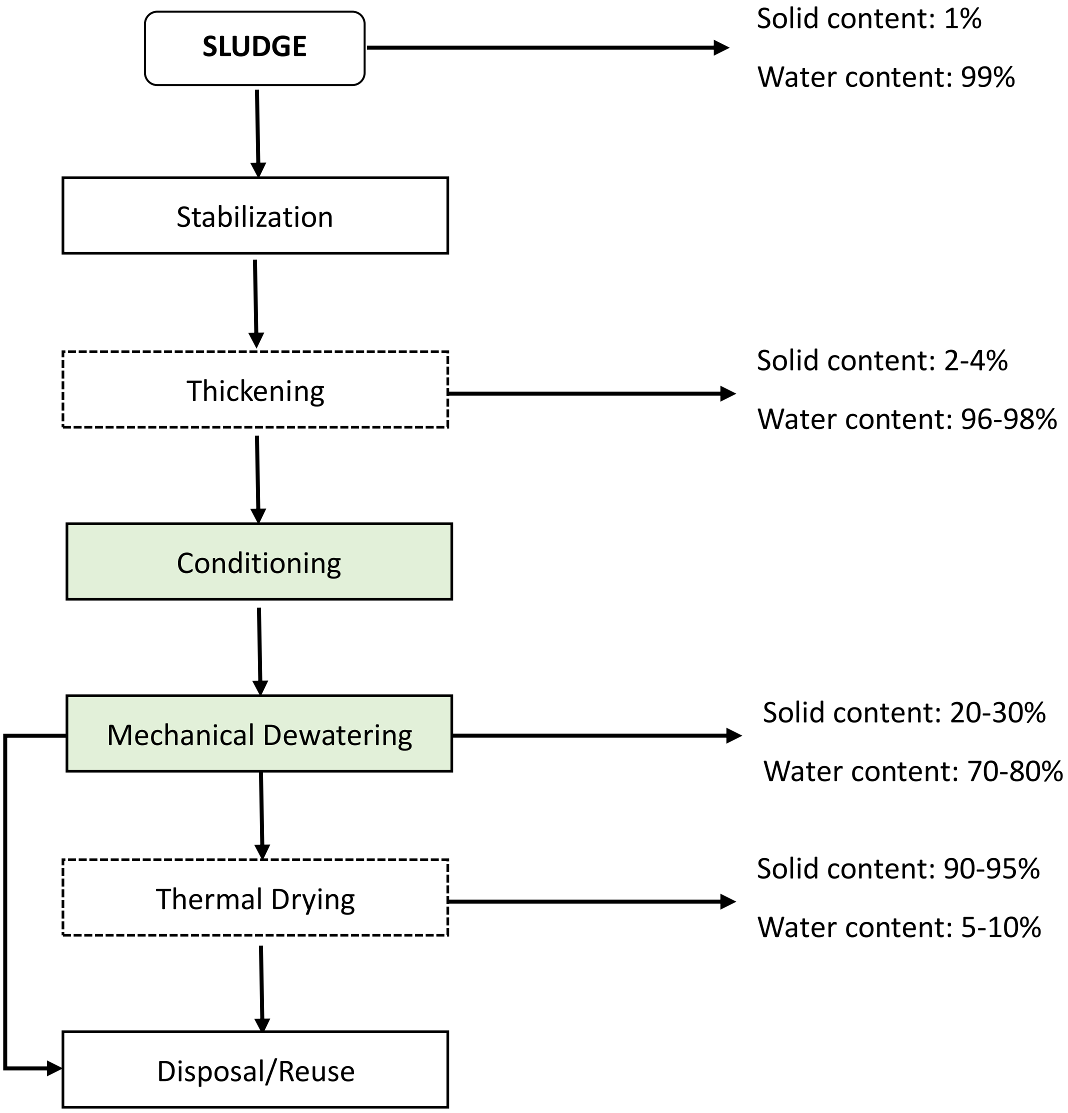

Figure 1 Typical sludge treatment processes and DS content achieved after each process.

2.2 SLUDGE DEWATERING

The objective of sludge dewatering is to remove as much as water possible to increase the dry solid concentration. Sludge dewatering is performed to:

- Improve the sludge handling properties
- Reduce the transportation and disposal cost (reduce the volume of sludge)
- Reduce leachate production if landfilled
- To make sludge suitable for incineration by increasing its calorific value

The conventional dewatering techniques are gravitational settling, mechanical dewatering devices, such as centrifuges, belt presses and filter presses, and thermal drying. Thermal drying produces higher solid concentration but consumes enormous amount of energy, while MD is employed in most of the wastewater treatment because of its low energy consumption and the final high DS content in sludge compared to gravity settling (Mahmoud and Olivier, 2013).

As shown in Figure 1, 96-98% of the sludge is moisture and the rest is dry matter. The DS in sludge consist of 50-80% of organic matter while the inorganic portion is usually made of sand, calcium, iron salts and aluminium salts. An increase in cake DS from 2% to 30% reduces the volume of the sludge up to 90% (Schaum and Lux, 2011). Therefore, dewatering may lead to significant saving in the sludge handling and management costs.

2.2.1 MECHANICAL DEWATERING

MD techniques involve either centrifugation or filtration/compression devices, such as belt press, plate filter press, vacuum filter and screw press. In centrifugation technique, gravity field is generated mechanically by high centrifugal forces to provoke liquid-solid separation. Centrifugation can produce dewatered cake dryness in the range of 18-35%, depending on the sludge nature and its characteristics (Visigalli et al., 2018). In filtration technique, the sludge dewatered by applying mechanical pressure to drain the water out (Mahmoud et al., 2013). Filter presses and belt presses are commonly used because of their simplicity, versatility and low energy consumption. Belt presses allows to achieve final DS contents in the range 16.5-29.5%, while belt press can get dryness values up to 28-45%. On the other hand, screw presses achieve final DS in the range of 17.5-25% (Visigalli et al., 2018). Therefore, the maximum DS that can be achieved with MD depends on the dewatering technique used, sludge characteristics and the effectiveness of conditioning.

In pressure driven MD, there are two phases that control solid/liquid separation, namely filtration phase, where cake is formed, and compression phase where more water is squeezed out of the cake (Sharma and Sanghi, 2013). Pressure-driven MD tests are usually carried out in laboratory in a cylindrical cell along with a piston setup (Mahmoud and Olivier, 2013). During the filtration stage, the piston pushes the sludge down and drains the water out through a filter medium forming a cake. During the compression stage, the piston enters in contact with the cake and is further compressed to obtain high final DS contents. The filter medium used can be cloth or polymer membrane which has the capacity to retain solid particles and allow water to pass through. The maximum obtainable dry solid content after MD is in the range of 20-25%. It can also be more than 25% but can never exceed 35%. Indeed, 35% DS is the maximum cake solid content after MD reported in the literature (Olivier et al., 2014). There is a limit to the applied pressure and the application time (Sørensen and Sørensen, 1997; Yin et al., 2004). Initially when the pressure is applied dewatering is proportionally enhanced, but after a while it reaches an equilibrium where increase in pressure or the application time has no effect on the dewatering rate (Mahmoud et al., 2011). This can be justified by the compressible nature of the sludge. Sludge, after reaching an equilibrium during MD, forms a skin like thin layer (compressible nature) over the filter which will prevent further water removal. Therefore, future improvement in the traditional MD techniques are investigated, through integrating MD along with other force driven mechanism. The combination for further improving dewatering performance as suggested by Mahmoud et al. (2013) are as follows:

- Thermal mechanical dewatering: MD is enhanced by increasing temperature.
- Shear force assisted mechanical dewatering: shear force is integrated along with compressive force.
- Acoustic mechanical dewatering: sound waves are used to reduce viscosity and surface tension of the sludge.

- Magnetic mechanical dewatering: a magnetic field is applied in the direction or in the opposite direction of the applied mechanical generated pressure.
- Microwave mechanical dewatering: application of microwaves vaporize moisture allowing the formation of a dryer cake.
- Electrical mechanical dewatering: application of electric field along with MD.

By now, the most effective dewatering technique that is identified is the electrical mechanical dewatering or electro-dewatering (EDW).

2.2.2 ELECTRO-DEWATERING

The principle of EDW is the application of an electric field to the sludge cake that is placed between an anode and a cathode. EDW produces sludge cakes with final DS contents of 40-45% (Feng et al., 2014; Mahmoud et al., 2011; Tuan et al., 2012; Weng et al., 2013) or even higher (Citeau et al., 2015; Conrardy et al., 2016). On the other hand, the energy consumption of EDW is obviously higher than mechanical dewatering but lower than thermal drying (Mahmoud et al., 2010). The electric field is usually induced during filtration or compression phase. Moreover, EDW can be applied both on thickened sludge, with DS contents in the range 2-4%, and on mechanically dewatered sludge in order to further increase its DS content. Figure 2 shows the phenomena involved in the EDW process.

2.2.2.1 Electro-kinetic phenomena involved in EDW

The word “electro-kinetic” means the motion of particles induced by an electric field. The addition of electro-kinetic phenomena to the MD process accelerates dewatering by improving solid-liquid separation. Application of electric field on the sludge provokes electro-kinetic effect because sludge is an aqueous suspension of colloids. In the following, the four electro-kinetic phenomena involved in the EDW process are described.

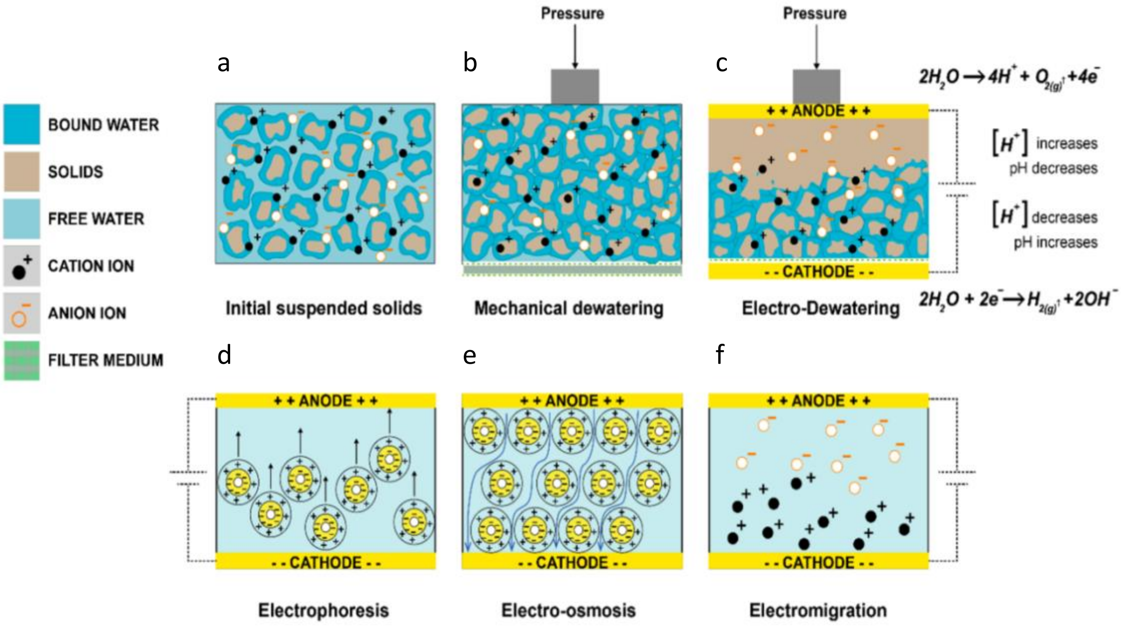

Figure 2 Phenomena occurring during the pressure-driven electro-dewatering process (Mahmoud et al., 2010).

Electrophoresis

Electrophoresis is the movement of charged particles relative to the stationary liquid water under the influence of electric field. The electrophoresis effect has its significance at the initial stages of EDW. During the initial stages, the particles are free to move in the liquid water phase. As the particles are negatively charged, they tend to move towards the positive anode (Figure 2d). This creates a delay in the cake formation of sludge cake in the filter medium allowing more water to be drained. When the dry solid of the cake is too high, the particles cannot move towards the anode anymore and the further water removal is due to electro-osmosis.

Electro-osmosis

Electro-osmosis displaces bulk water molecules at the solid-liquid interface of the medium. It consists in the flow of water in contact with charged solid surface when electricity is applied to the sludge cake. The fine particles in the sludge possess surface charges which are usually negative. In a solid-liquid interface, oppositely charged ions are developed in the surrounding liquid forming an outer layer around the negatively charged particle to maintain the global electroneutrality. Two layers are formed, inner layer consist of anions that are chemically bonded with the particle and the outer layer consist of cations that are electrostatically attracted with the surface charge of the particle. These two layers are called as electrical double layer. When an electric field is applied, the outer layer is forced to move due to the coulomb force which forces the bulk water to be released and the water starts flowing out. As the zeta potential of the sludge is negative, the particles in the sludge move towards the anode and the water and the surrounding cations move towards the cathode, where water is collected (Lin et al., 2012). The electro-osmotic flow is represented by Equation 1.

$$\frac{dV}{dt} = \frac{\varepsilon_0 \, . \, \varepsilon_r \, . \, \zeta}{\eta} \, EA \qquad (1)$$

Where,

V: filtrate volume (m^3)

t: time (s)

ε_0: dielectric permittivity of vacuum (8.854×10^{-12} $C \cdot V^{-1} \cdot m^{-1}$)

ε_r: dielectric constant of the liquid

ζ: zeta potential of sludge (V)

E: electric field strength across the cake ($V \cdot m^{-1}$)

A: cross-sectional area (m^2)

η: viscosity of the liquid medium ($kg \cdot m^{-1} \cdot s^{-1}$).

The equation shows that higher the intensity of the electric field higher will be the water drained out from the sludge cake.

Electro-osmosis is the electro-kinetic phenomena that is majorly contributing for efficient water removal during EDW (Tuan et al., 2012).

Electromigration

Electromigration is the movement of ions with respect to the liquid according to its own ionic mobility. Ionic mobility is a function of electrical charge, diffusion coefficient and temperature (Mahmoud et al., 2010).

Electrochemical reactions

EDW system is an electrochemical cell with anode and cathode (Mahmoud et al., 2010). Due to the application of an electric field, oxidation, reduction, corrosion and precipitation reactions occur at the electrodes' surface. Electrolysis of water occurs to maintain charge equilibrium. At anode, oxygen and proton are produced and at cathode, hydrogen and hydroxyl anions are produced. Consequently, pH near anode decreases (protons are produced). The reactions at the anode and the cathode are shown in Equation 2 and 3.

Anode

$$\begin{aligned} &2H_2O \longrightarrow 4H^+ + O_2 + 4e^- \\ &M \longrightarrow ne^- + M^{n+} \end{aligned} \tag{2}$$

Cathode

$$\begin{aligned} &2H_2O + 2e^- \longrightarrow 2OH^- + H_2 \\ &ne^- + M^{n+} \longrightarrow M \end{aligned} \tag{3}$$

Where M denotes the metal used for the electrode.

2.2.2.2 Practical aspects and operating conditions

For electro-osmosis and electrophoresis to happen, the anode and cathode should be in contact with the sludge to ensure that electricity flows. This is guaranteed by the constant pressure applied mechanically and by imposing a constant voltage or current using an external power source. According to Mahmoud et al. (2010), the combination of MD and electro-kinetic phenomena enhances water removal through the following steps:

I. During MD, the volume of the pores decreases and squeezes out the water from the sludge.
II. Initially, particles are free to move in the suspension. When electric field is applied, the negatively charged particles move towards the anode (electrophoresis effect).
III. When sludge cake is formed, the particles in the sludge become locked in their existing positions and become stationary. The water molecules are transported from anode to cathode by viscous and/or molecular interactions and/or hydration sheath (electro-osmotic effect).
IV. The electrochemical reactions take places to restore charge equilibrium.

V. Gradually, water stops to be in a continuous phase in the cake, electrical resistance increases and leads to ohmic heating.
VI. Joule effect helps in decreasing the viscosity of the sludge which accelerates further water removal from the sludge.

Generally, a cylindrical cell with pressure application is used to perform EDW. According to Mahmoud et al. (2010), the kinetics of pressurized EDW are better than the kinetics of non-pressurized EDW. Most of the EDW methods are based on kinetics of pressurized dewatering having a vertical setup with anode on the top and cathode at the bottom with devices for application of vacuum or mechanical compression on the anode (Mahmoud et al., 2013).

2.2.2.3 Influence of parameters on EDW performance

Factors such as voltage, time, pressure, polyelectrolyte dosage and floc size distribution, affect the EDW performance. It is necessary to understand about how these factors influence the performance in order to improve the efficiency of the dewatering process.

Pressure

High pressure is advantageous for EDW because it improves the electrical contacts leading to better EDW kinetics and more dry cake. Therefore, a minimum of 4 to 6 bar pressure is essential to have the minimum contact surface (Mahmoud et al., 2016; Tuan et al., 2012). There is a threshold for the pressure to be applied, beyond which there is not effect on the EDW performance and may also damage the cake structure (Yin et al., 2004).

Duration

MD should be performed before application of electric field as suggested by Mahmoud et al. (2010) and Saveyn et al. (2005). Indeed, initially pressure-driven liquid flow rate is greater than the electro-osmotic flowrate and the application of electric field is merely a waste of energy. During the initial stage of dewatering, power consumption is significantly high because electric resistance in the sludge is very low. Therefore, according to Mahmoud et al. (2011) and Olivier et al. (2015), a setup for laboratory pressurized EDW is following a two-step protocol:

- Compression/Filtration phase: a selected constant pressure is applied for a given time.
- Electrically assisted compression phase: at the same selected pressure, a constant voltage is applied for a given time.

It was observed that 70% of the total water removal is due the first stage of MD (Mahmoud et al., 2011).

The duration of the process usually ranges from several minutes to hours. EDW performance depends on the duration of application of electric field, which should not be too short or too long (Saveyn, Pauwels, et al. 2005). Electric field applied for short duration is not enough for establishing dewatering effect. On the other hand, application of electric field for long durations is not energy efficient and economical. In order to optimize the EDW in terms are final DS content and electricity consumption, a compromise between electric potential applied and the duration of application must be found (Tuan 2011).

Intermittent application of electric field during EDW produces better water removal than continuous application. Rabie, Mujumdar, and Weber (1994) performed the EDW tests with bentonite and concluded that intermittent application of electric field process resulted in 20% improvement in water removal than continuous supply of current.

Voltage and current intensity

Intense electric field (higher current densities) improves the EDW kinetics leading to increased final cake DS. Therefore, higher current densities or voltages will lead to better dewatering performance. Although the dewatering is enhanced, higher current densities cause high ohmic losses which decreases the overall efficiency of the process. Therefore, application of high electric field in order to reduce the application time becomes invalid. It is always a compromise between the final cake DS, dewatering rate and energy consumption. The optimum point will be decided between the process time and energy (Larue et al., 2006).

EDW can be performed using constant current or constant voltage. In a constant current configuration, the voltage steeply rises following Ohm’s law. Consequently, there is a huge temperature rise which causes an interruption in dewatering before it completes. This forces the operator to stop the dewatering process even before the desired cake DS is achieved. Stopping the process saves the filter cell and the filter cloth from damaging. In a constant voltage configuration, the current intensity rises and reaches the maximum before steadily decreasing. In other words, the distance between the two electrodes rapidly reduces which makes the current intensity rise to maximum while the increasing cake resistance steadily decreases the current intensity. In constant voltage configuration, the dewatering process can be performed till the end unlike constant current configuration. Still the overheating at the beginning is an issue and leads the same damage as in constant current mode. Yet the limiting the initial voltage would limit the temperature peak and so the damage is avoided (Citeau et al., 2012).

From literature, it is quite evident that constant voltage is a better configuration than constant current. Comparatively constant voltage mode is better in terms of the risk associated with ohmic heating, the limitation in the final cake solid content and the process time.

Cake thickness

When cake thickness is higher, the distance between the electrodes increases. This results in a higher electrical resistance and a lower intensity of the electric field that slows down the kinetics of dewatering (Tuan et al., 2012).

Sludge characteristics and pre-treatments

Chapter 2.3 describes in detail the influence of the sludge characteristics and dewatering.

2.3 SLUDGE CHARACTERISTICS AND DEWATERABILITY

Sludge is variable and complex in nature. Therefore, understanding its properties and behaviour can help in identifying the best treatment methods.

Sludge nature and the dewatering device highly affect the dewatering performance (Schaum and Lux, 2011). In this section, the relationship between sludge properties and dewatering are discussed.

2.3.1 ORIGIN OF THE SLUDGE

Sludge is a biologically active flow composed of water, organic substances, inorganic substances, nutrients, dead and alive micro-organisms, pathogens, organic and inorganic toxic compounds like heavy metals and polycyclic aromatic hydrocarbons (Kacprzak et al., 2017). The physical, chemical and biological properties of the sludge solely depend on the characteristics of the wastewater treated and the type of treatment used. Sludge can be classified as primary, secondary, tertiary or digested inside a single WWTP according to the stage of treatment the sludge is obtained. Figure 3 shows the typical treatments stages of wastewater and sludge in a WWTP.

Primary sludge is obtained after primary treatment and are easily dewaterable because are their composition are detached particles. Primary sludge is generally consisting of settleable solids. Secondary sludge consists of micro-organisms, dead cells and their residues along with absorbed/adsorbed suspended solids and colloids. Secondary sludge or activate sludge is the residue formed after biological treatment of the wastewater and consists in around 75% of organic matter. The sludge obtained from biological treatment process after long solid retention time are usually easy to dewater. Due to the long solid retention time, non-degraded and colloidal organics decreases which enhances dewaterability of the sludge.

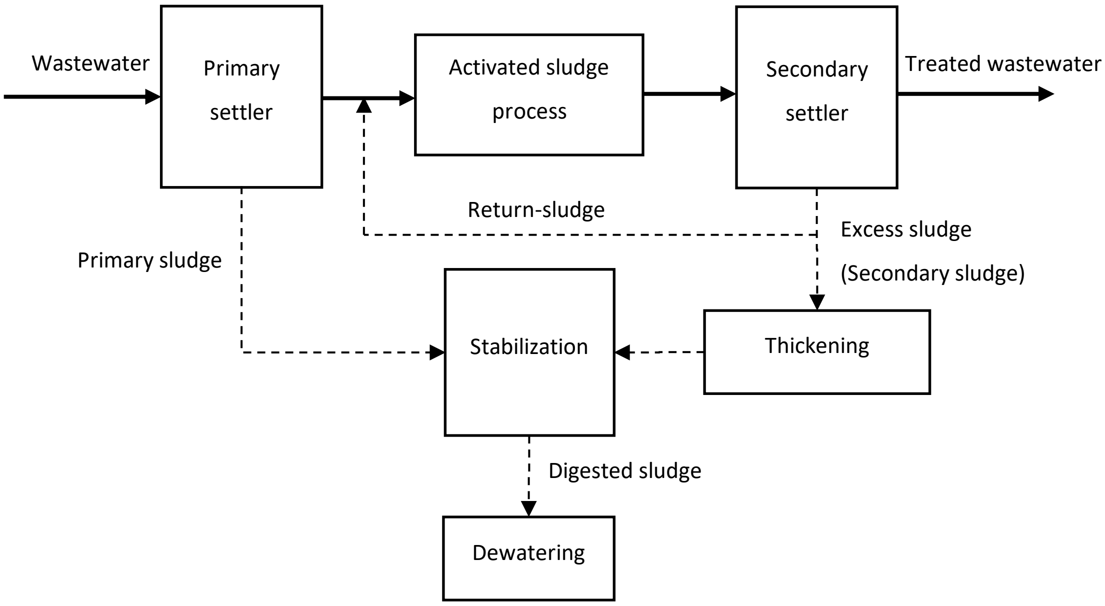

Figure 3 Typical wastewater treatment processes.

Therefore, dewaterability of sludge depends on the type of sludge (Citeau et al., 2012). This is due to the fact that sludge come from different unit processes in a WWTP vary in composition and properties.

2.3.2 STABILIZATION

Bio-stabilization is required for both primary and secondary sludges. Bio-stabilization transforms the putrescible organic matter into more stable organic matter before dewatering or final disposal to avoid bad odours and uncontrolled biogas production. Moreover, it reduces the number of solids present in the sludge. Aerobic digestion is the process of conversion of organic matter into carbon dioxide, water and stabilized organic residues by bacteria in the presence of oxygen. During anaerobic digestion, the organic matter is converted into methane and carbon dioxide by anaerobic bacteria in the absence of oxygen.

Dewatering of sludge after digestion is more difficult when compared to the dewatering of undigested primary and secondary sludge. This is due to the fact that organic substances are converted into more fine particles during digestion (Tuan et al., 2012). Aerobic digestion of sludge ensures more bacterial growth succeeded by its decay and high mechanically shear stress. This supports disintegration of the organic substances into finer particles (Mahmoud et al., 2006). Higher the fine particles, higher is the water holding capacity. Therefore, smaller particles in sludge produce a negative effect during sludge dewatering. These fine particles are reduced by improving sludge flocculation. Therefore, digested sludge is conditioned to improve the dewaterability and prevent clogging in the MD devices.

2.3.3 CONDITIONING

Sludge is difficult to dewater because of the negative charges on the surface of the particles. The particles are electrostatically repulsive and do not agglomerate and thus hinder the solid-liquid separation. Conditioning improves the dewatering ability by reducing the repulsive forces by acting on the surface of the particles (Tuan et al., 2012).

There are two kinds of conditioning, physical and chemical. Physical conditioning changes the sludge properties by varying physical parameters. On the other hand, addition of chemical to the sludge changes its properties and improves floc formation. It improves agglomeration through flocculation or co-precipitation by addition of charge carriers which can be organic (polymers) or inorganic (iron, aluminium, calcium). Addition of organic or inorganic flocculants makes the small particles to aggregate and form large flocs. Formation of large flocs promotes easy separation of water from sludge (Chen et al., 2016). Organic flocculants are usually preferred because they are dosed in lower quantities unlike inorganic flocculants (iron or lime chlorides). Flocculation can be achieved through two main mechanisms: charge neutralization or bridging. According to charge neutralization theory, addition of cationic polymers neutralizes the negative charges on the surface of the particles, thereby reducing the electrostatic repulsive force existing between the particles and promoting short-range attractive forces to form flocs. According to bridging theory, the cationic polymers added to sludge act as a bridge between the negatively charged particles. The polymer particles attract the negative sludge particles to form flocs. Conditioning is known to be strongly effective on MD processes, while EDW kinetics are mostly influenced by the electric field applied rather than the dosage of polyelectrolyte used (Saveyn et al., 2005b). Therefore, polyelectrolyte characteristics and dosage play a significant role in water removal during pressure driven dewatering and had no major effect on EDW.

However, conditioning remains essential since it improves the structure of the sludge network and reduces water retention in sludge (Mahmoud and Olivier, 2013). Conditioning improves sludge filterability because some fraction of trapped water is released and becomes free water. Chemical conditioning has a positive effect of significantly reducing the entrapped water in the sludge matrix (Liu and Fang, 2003). On the other hand, overdosing of polyelectrolyte may cause absorption of water molecules to polymer particles which is not desired (Phuong To et al., 2016). The choice of appropriate chemical and its dosage depends on the sludge composition and dewatering device used (Mahmoud et al., 2013).

2.3.4 EXTRACELLULAR POLYMERIC SUBSTANCES

Extracellular polymeric substances (EPSs) are high molecular weight biopolymers found in the surface of bacterial cells. They are produced by active secretion from micro-organisms, shedding of cell surface material, cellular lysis, hydrolysis of macromolecules and adsorption from the environment (Laspidou and Rittmann, 2002). EPS are made of different organic substances like polysaccharides, proteins, DNA, lipids and other polymeric compounds. Carbohydrates and proteins are the major component. Proteins play a significant role in floc stability, settling and dewatering. Water enclosed in EPS is by polysaccharides and protein (Jin et al., 2004; Neyens et al., 2004). EPS represent a significant portion of the sludge (Citeau et al., 2012), being the third major component in activated sludge after water and cells and accounting for 60-70% of the total mass of sludge (Chen et al., 2016; Liu and Fang, 2003). EPS binds the loose network-like structure in sludge due to its strong interactions occurring in the network and its composition (Sheng et al., 2010; Wingender et al., 1999).

EPS are classified into following three categories:

1. Soluble EPS (S-EPS)
2. Loosely Bound EPS (LB-EPS)
3. Tightly Bound EPS (TB-EPS)

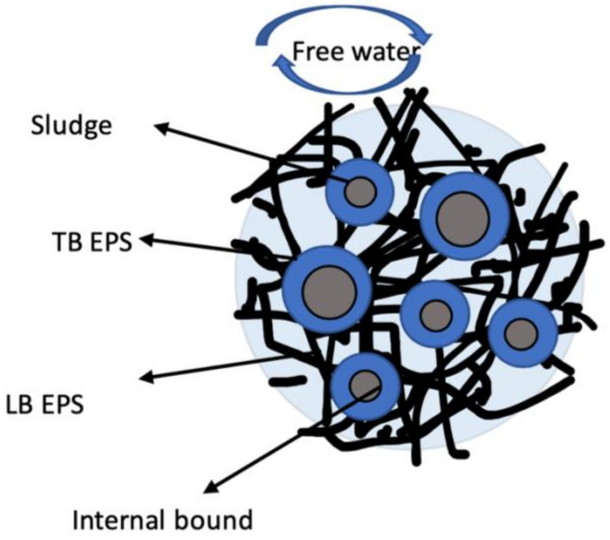

Figure 4 EPS and water distribution in sludge.

The amount and distribution of EPS can influence the water holding potential of the sludge and therefore affects dewaterability. EPS and flocs can hold a large amount of water as bound water. Flocculation, settling and dewatering are affected by EPS (Liu and Fang, 2003; Zhang et al., 2015). Higher the EPS content in sludge, lower its dewaterability (Tuan et al., 2012). Sludge with high EPS has better filterability due to low shear sensitivity and degree of dispersion (Mikkelsen and Keiding, 2002). EPS in sludge leads to increased interstitial bound water and lowers the settleability (Chen et al., 2001). Yet the effect of EPS in sludge dewatering is not well documented. This might be due to the varying nature of the sludge and EPS (Tuan, 2011; Yin et al., 2004).

2.3.5 WATER CONTENT AND TYPES OF WATER

Sludge is hydrophilic and contains large amount of water. The water present in sludge is not homogenously distributed because of the presence of solids particles. Therefore, there are different types of water present in the sludge and it varies in properties such as density, viscosity, vapor pressure, enthalpy and entropy. The behaviour of the water molecules depends on its interaction with the solid particles in proximity during dewatering. It is important to understand the distribution are water in sludge to improve the efficiency of dewatering process. Knowing the distribution of water in activated sludge is an effective method in o characterize its dewatering ability (Vaxelaire and Cézac, 2004).

According to the binding strength, water is classified into two types, namely free water and bound water. Free water is the portion of water in sludge that is not influenced by the solid particles. Free water accounts for the major part of water in sludge. Bound water is a smaller portion in sludge and its properties are affected by the presence of solid particles. Another major difference is that free water freezes at 0 °C while the bound water does not. Bound water freeze at temperature from -8 °C to -20 °C (Tuan et al., 2012) or even lower (Deng et al., 2011; Erdincler and Vesilind, 2003; Hong et al., 2015). Sludge dewatering efficiency directly depends upon bound water content because it requires more energy to be removed compared to free water.

However, this simple classification of water is not enough to understand the mechanisms involved in conditioning and dewatering of sludge. A more detailed classification of water was introduced by Vesilind and Hsu (1997), which is well acknowledged and is sufficient for dewatering aspects. The defined four types of water are as follows,

I. **Free water**

Free water is not attached to solid particles and includes void water that is not affected by capillary forces, which can be easily removed through filtration/compression, gravitational settling or centrifugation.

II. **Interstitial water**

Water is trapped inside floc structures or a cell which can partially be removed by MD. It can be removed by breaking the flocs or by disrupting the cell. It freezes at temperature lower than normal freezing point due to the presence of high dissolved solid concentration.

III. **Surface or vicinal water**

The water molecules that are physically attached to the surface of solid particles by adsorption or adhesion. This type of water cannot be removed by MD.

IV. **Intracellular or chemically bound water**

Water that is chemically bound to the solid particles. It does not freeze at freezing temperatures. It can be removed through thermo-chemical destruction of the particles at temperatures above 105 °C (Mowla et al., 2013).

Figure 5 shows the different types of water in sludge.

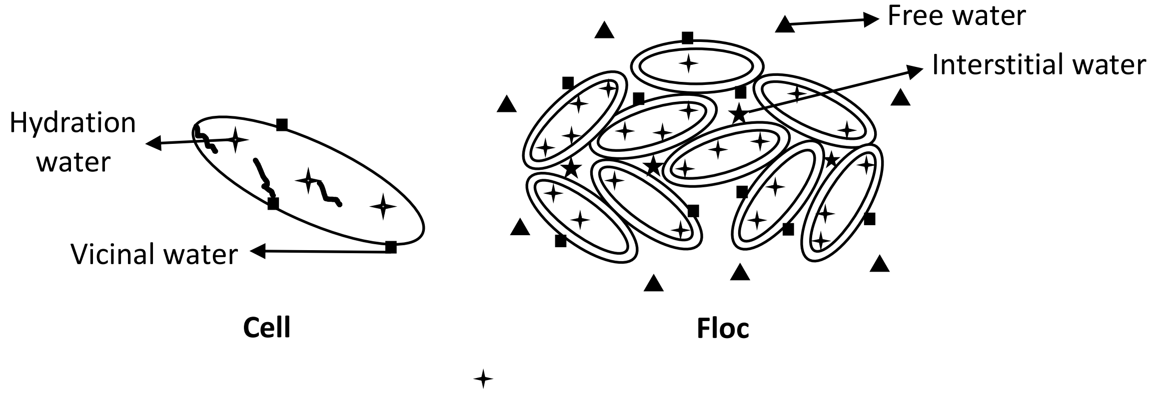

Figure 5 Schematic model of various forms of water in sludge.

To remove all types of water from sludge thermal drying is required while mechanical drying can just remove free water and a small portion of interstitial water (Mahmoud et al., 2010). Figure 6 shows the effect of the different dewatering techniques on the different types of water in sludge.

However, this classification has some limitations since it does not consider the water entrapped in proteins and polymer. Moreover, the status of water is not enough to understand the nature of sludge and its dewaterability. It just overlooks the structure of sludge which possess a large network polymer that can entrap water. Considering surface water, osmotic water and water trapped within polymer matrix, a concept of water holding was introduced but it also did not provide any information regarding dewaterability (Mikkelsen and Keiding, 2002).

Floc size, floc structure, bound water content, which are often associated to EPS content, are strongly affecting the sludge dewaterability (Liu and Fang, 2003).

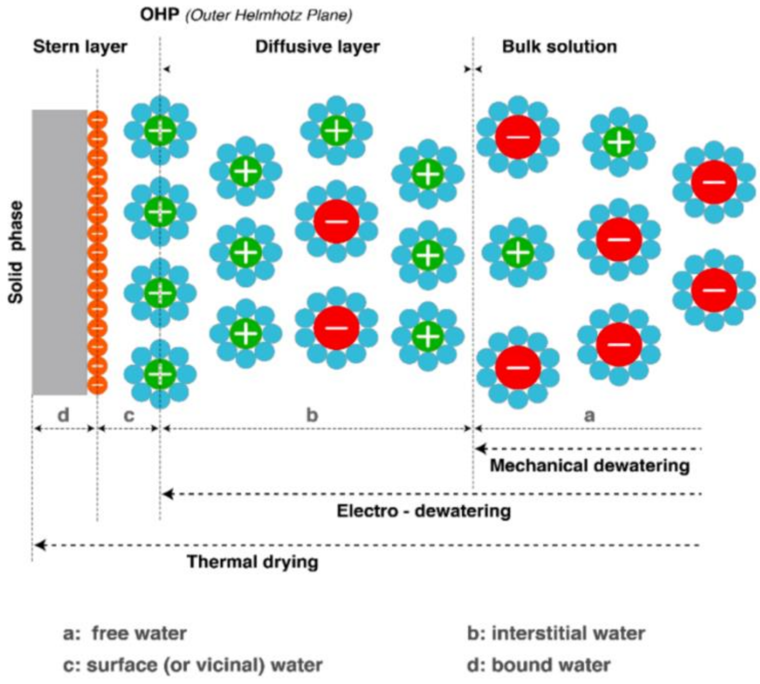

Figure 6 Distribution of water in sludge and dewatering technologies (Tsang and Vesilind, 1990).

2.3.6 pH AND ZETA POTENTIAL

Zeta potential, measured in Volt (V) or millivolt (mV), is the charge possessed by the solid particles or flocs surfaces interacting with water in the sludge. As the basic purpose of conditioning is charge neutralization, the effectiveness of conditioning can be found by measuring zeta potential. In other words, the magnitude of zeta potential is the measure of potential stability of the colloidal system. If the particles in the sludge have large negative or positive zeta potential, then they tend to repel each other, and floc formation is hindered. If the zeta potential is low, the repulsion between the particles is reduced and they tend to flocculate. When the charges are neutralized, the measure of zeta potential will be zero (Abu-Orf and Dentel, 1997). Therefore, lower values of zeta potential (both in positive and negative direction) result in rapid coagulation.

pH of the sludge is one of the most important factors that affect the zeta potential. This is quite evident from the studies by Citeau et al. (2011), Tuan et al. (2008) and Weng et al. (2013) which showed that lowering of pH of the sludge, resulted in increase of zeta potential values on the positive side. If sludge is acidic, the particles in the sludge tend to acquire more positive charges. Therefore, in a zeta potential versus pH plot, at highly acidic pH the zeta potential will be high (positive) and at high pH the zeta potential will be low (negative). Therefore, it is important to know the pH of the sample to better understand the zeta potential measure.

2.3.7 DRY SOLIDS AND VOLATILE SOLIDS

DS is the measure of concentration of solid particles in the sludge. The main aim of dewatering is to increase the DS of the sludge. Higher the DS of the sludge, lower is the consumption of polyelectrolyte but at the same time the mixing of polyelectrolyte becomes more difficult. Therefore, the dewatering efficiency is indirectly dependent upon the initial DS content of the sludge.

Considering EDW, when the water content in the sludge is high (low dry solid content), during the initial stages of mechanical compression, water removal is effective. When the DS content increases, free water is considerably decreased, and the electric field is needed to removed water strongly bound to solid particles. Moreover, dewatering process exhibits higher energy consumption when the sludge has high initial dry solid content due to its higher bound water content with respect to the free water portion.

The higher the volatile solids (VS), more difficult is the dewatering. Indeed, when the VS of the sludge is high, it is recommended to add a thickening step in the process in order to achieve a better dewatering. According to Skinner et al. (2015), there is a strong correlation between EPS and VS. As discussed earlier, EPS has a strong influence on sludge dewaterability. VS cannot be used as individual indicator to investigate dewaterability because it is difficult to distinguish the sludges due to narrow ranges of VS values. On the other hand, VS has the advantage of being easily determined in a laboratory.

2.4 DEWATERABILITY AND INDICATORS

Dewaterability can be characterized by the final DS content of the cake and ease of filtration (Chen et al., 1997). There is no reliable indicator that can predict the final DS content before sludge dewatering. The reason for this problem is the collective effect of sludge characteristics, conditioning and dewatering techniques on the dewatering performances. Traditional indicators can partially provide some information on dewaterability, but they are not precise due to lack of clarity in their definitions. A reliable dewaterability indicator should replicate the actual dewatering process and be able to predict the maximum final dry solid content of the cake. This is not possible because different dewatering methods use different techniques to remove water from sludge. Therefore, it is not feasible to use one dewaterability indicator for all dewatering methods.

Along with advancements in sludge dewatering to achieve the driest cake, it is important to have a consistent dewaterability indicator that is able to predict how easily water can be released from sludge (Pan et al., 2003).

Sludge has a varying nature in terms of physical, chemical and biological characteristics. This varying nature gives sludge an unpredictable behaviour during dewatering. This makes it difficult to measure certain parameters (Sanin et al., 2011). While some parameters are assessable but it is challenging to correlate these properties with dewatering performance (Phuong To et al., 2016).

Sludge properties such as pH, particle surface charge, organic content, cake porosity, compressibility, particle size, rheological characteristics, bound water content and solid concentration are variables that can affect sludge dewaterability. Still there is no evidence that which parameter is influencing the most (Phuong To et al., 2016).

2.4.1 DEWATERABILITY VS. FILTERABILITY

Both dewaterability and filterability describe how effortlessly sludge will release water (Sanin et al., 2011). Sludge filterability means separating solid and liquid mechanically using a porous medium (Burger et al., 2001). Sludge filterability is one of the aspect of sludge dewatering and hence improving sludge filterability improves sludge dewaterability (Mowla et al., 2013). However, filterability can evaluate only the efficiency of filtration process and not the whole dewatering process (Sawalha and Scholz, 2007). During MD, there exists two phases: a first phase of filtration (cake formation) and a following phase of compression, where more water is removed by application of mechanical forces (Lee and Wang, 2000; Mahmoud and Olivier, 2013; Sørensen and Sørensen, 1997). The amount of water removed from filtration does not quantify the final cake DS, since more water is removed during the compression phase (Novak et al., 1999). because of the compressible nature of sludge, higher dewatering performances are achieved when the filtration phase is shorter and the compression phase is longer (Saveyn et al., 2005a). Thus, sludge filterability has an impact on sludge dewaterability but cannot be used to evaluate full scale dewatering processes (Sawalha and Scholz, 2007). Therefore, an indicator for dewaterability should be able to predict the final DS content achievable after MD in a WWTP. Therefore, sludge dewaterability should be evaluated using filterability along with final DS content of the cake. So far filterability indicators have been used to investigate the dewaterability of sludge. The most commonly used filterability indicators are Capillary Suction Time (CST) and Specific Resistance to Filtration (SRF). Both CST and SRF measure the rate of filtration and give an outlook of the compression phase. Therefore, it is important to measure both the filterability and compression (which produces drier cakes) to better understand dewaterability.

2.4.2 SPECIFIC RESISTANCE TO FILTRATION

Specific resistance to filtration is used to investigate the filtration of sludge based on Darcy's equation which describes the flow of liquid through a porous medium. Specific resistance to filtration can be used to find the optimum polymer dosage to the sludge (Sanin et al., 2011). Specific resistance to filtration is the resistance of the sludge to release water when a constant pressure is applied. Specific resistance to filtration is expressed as meter per kilogram. Sludges with SRF values in the range 10^{10}-10^{11} m/kg are considered to be easy to be dewatered, whiel sludges that are hard with SRF values in the range 10^{14}-10^{15} m/kg are considered to achieve lower efficiencies in dewatering (Sanin et al., 2011). SRF values depend upon pressure, area, solid concentration and liquid viscosity.

SRF measurement resembles the filter press and vacuum filters (Olivier et al., 2007). Different dewatering devices have different techniques involved and sludge dewatering is achieved at different intensities. Therefore, SRF may be used as an indicator for dewatering devices such as filter presses, vacuum filters and belt presses (Christensen, 1983). On the other hand, SRF cannot be adapted for other dewatering methods, such as centrifugation or EDW. Moreover, SRF is a time consuming and complex procedure to perform (Barber et al., 1997; Vesilind and Örmeci, 2000). Figure 7 shows the SRF apparatus.

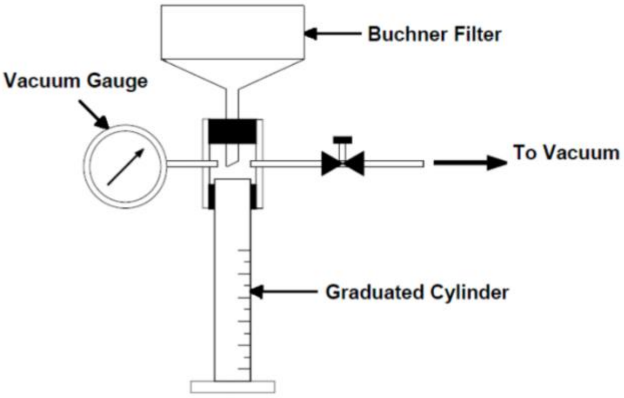

Figure 7 Experimental setup for Specific Resistance to Filtration (Sanin et al., 2011).

2.4.3 CAPILLARY SUCTION TIME

Capillary suction time is the measure of time required to drain some volume of filtrate out of sludge and absorbed by a filter paper by capillary forces (Vesilind, 1988). CST is mostly used to understand the effectiveness of the polymer dosage in conditioning (Graham, 1999). A small CST value refers to a sludge that can release water easily while higher CST values indicate a lower dewaterability.

CST does not resemble any of the real-time dewatering process. Since it is affected by the DS content, CST values of different sludge samples from different treatment plants cannot be compared (Vesilind, 1988). In order to compare the CST values of different sludges of different plants, a normalized CST value is obtained by dividing CST value by initial total suspended solids concentration of sludge. Normalized CST is expressed as seconds per litre per gram of total suspended solids (TSS) (Yu et al., 2008). It is useful in characterization of sludge but cannot be used to determine the optimum polymer dosage. One of the practical difficulties is the use of Whatman No. 17 chromatographic paper which is the standard filter paper for the test. Although it is available worldwide, some disadvantages are its anisotropic properties, relatively over–sized pores and comparatively expensive (Sawalha and Scholz, 2007).

CST is preferred over SRF because the procedure is relatively simple and quick (Sawalha, 2011). However, CST is not always reliable because it does not reflect floc strength to shear during dewatering (Pan et al., 2003) and it is not resembling any of the dewatering process. CST is just an empirical way to investigate filterability and cannot predict the maximum DS of the cake.

Both SRF and CST are not appropriate dewatering indicators because they do not truly reflect the dewatering process. Dewatering is not only dependent on the nature of the sludge but also on the employed dewatering method. Therefore, different indices are preferred according to the dewatering technology used. Currently, SRF and CST are widely used since there is a lack for a universal dewatering indicator. Figure 8 shows the CST apparatus.

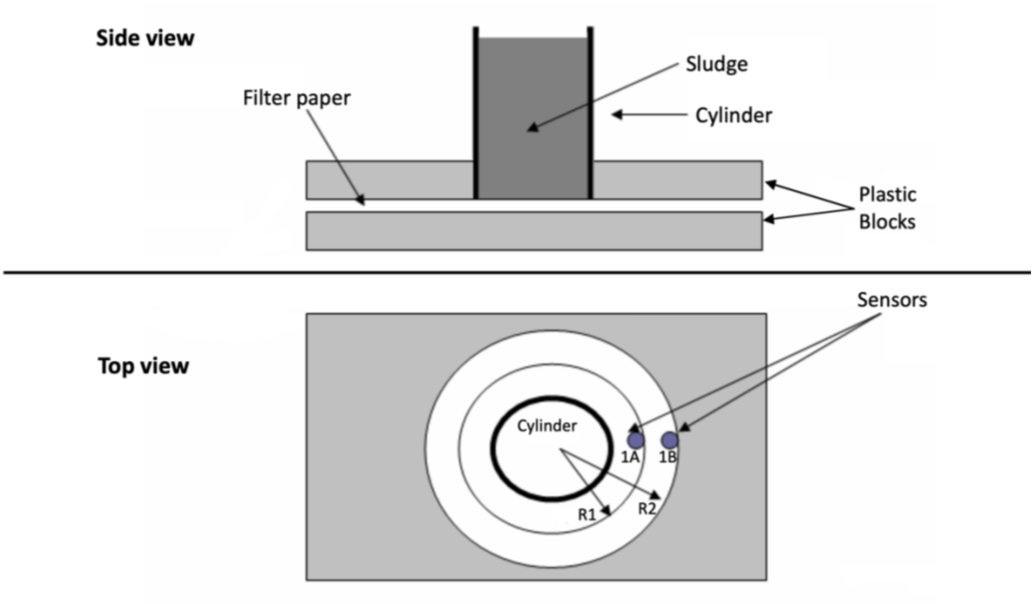

Figure 8 Experimental setup for Capillary Suction Time (Sawalha, 2011).

3 MATERIALS AND METHODS

In this chapter the approach, materials and methods used in this study are described. Sludge characterization and conditioning are carried out to obtain a good overview of the sludge properties and its association with the separation of solid and liquid phase. MD and EDW were performed on both thickened unconditioned and thickened conditioned sludge samples. The final cake DS along with the total suspended solids of the filtrate were also measured after dewatering. Figure 9 shows the framework of the thesis.

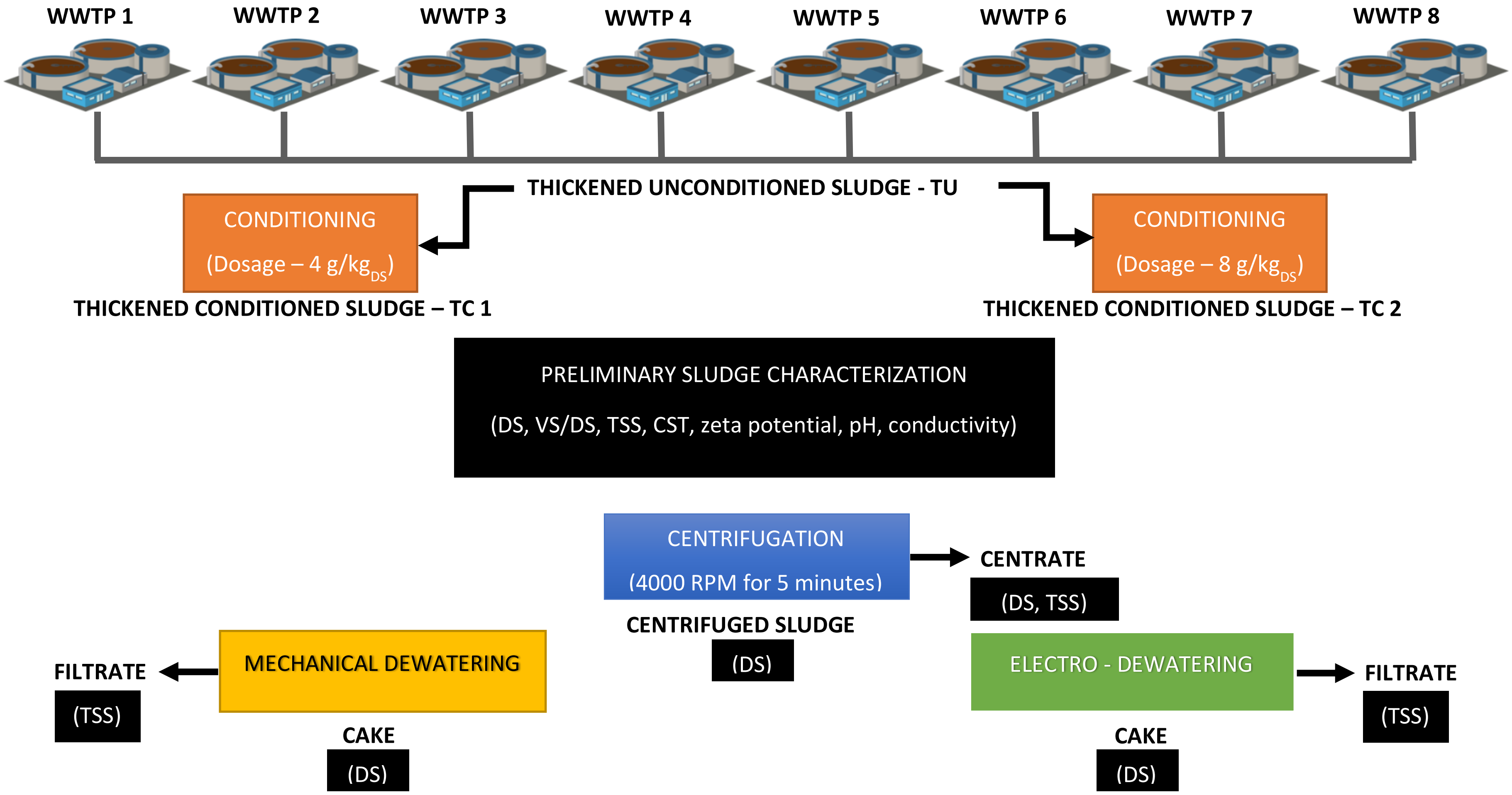

Figure 9 Framework of the thesis.

3.1 SLUDGE SAMPLES

Sludge samples have been taken from eight different WWTPs located in the Milan metropolitan area (Italy). Aerobically stabilized sludge samples were taken from WWTP 1, WWTP 3, WWTP 4 and WWTP 5 while WWTP 2, WWTP 6, WWTP 7 and WWTP 8 provided anaerobically digested samples. Table 1 shows some details of the sludge samples in the eight different WWTPs, including the population equivalent and the average DS and VS/DS values achieved after dewatering. Thickened unconditioned (TU) sludge samples were taken from the eight WWTPs. Before performing further operations, such as MD and EDW tests, the sludge samples were conditioned with dosages of 4 g/kgDS and 8 g/kgDS by jar test in the laboratory. TC is referred to the thickened sludge after conditioning.

To reduce biochemical changes of the sludge, the samples were stored for a maximum of five days at 4 °C and all experiments were performed within a week from the date of sampling.

Table 1 Main characteristics of the sludge samples taken from the eight different WWTPs.

WWTP	**Population equivalent**	**Stabilisation treatment**	**Dewatering treatment**	**DS**	**VS/DS**
No.	**PE**			**%**	**%**
1	79,280	Aerobic	Belt press	18.9	67.4
2	436,130	Anaerobic	Centrifuge	24.1	57.7
3	120,460	Aerobic	Centrifuge	20.4	70.5
4	56,320	Aerobic	Centrifuge	18.8	72.5
5	16,350	Aerobic	Belt press	17.1	71.9
6	17,470	Anaerobic	Belt press	16.7	60.2
7	366,100	Anaerobic	Centrifuge	23.0	57.9
8	124,250	Anaerobic	Centrifuge	25.2	65.8

3.2 SLUDGE CONDITIONING

The polyelectrolyte Praestol 645 BC (1-Propanaminium, N, N, N-Trimethyl-3-[(1-Oxo-2-Propenyl) Amino]-, Chloride, Polymer With 2-Propenamide) was used for conditioning through a jar test device. 1,000 ml of sludge sample was poured into a 2,000 ml beaker and the desired concentration of polymer was dosed in each backer. The solution was stirred at 200 rpm for the first 30 seconds, for rapid and complete mixing, followed by 15 minutes at 20 rpm, to enhance the formation of aggregates. Figure 10 shows the jar test device used during sludge conditioning in the laboratory.

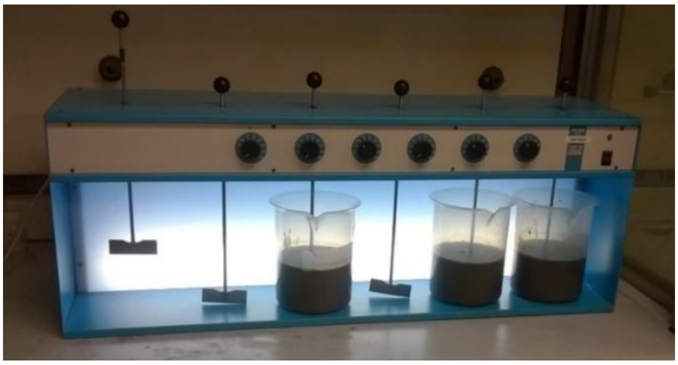

Figure 10 Conditioning of the sludge by jar test in laboratory.

3.3 CHARACTERIZATION OF SLUDGE

3.3.1 INITIAL DS CONTENT AND VS/DS RATIO

DS content and VS/DS ratio of the sludge samples have been determined according to the Standard Methods (APHA/AWW5A/WEF 2012).

The mass of an empty crucible is weighted, then sludge is put in the empty crucible, and the mass of the sludge is recorded. The crucible with the sludge is inserted in the oven at 105 °C for 12 h in order to evaporate all the water in sludge samples. The mass of the crucible with the sludge in, after drying in the oven, is recorded. Prior to measuring, the crucible is put in the desiccator to prevent errors in weighting by providing a 0% humidity atmosphere when the crucible cools down to room temperature. The DS content is calculated from the Equation 4.

$$DS = \left(\frac{mA - mB}{mC}\right) * 100 \tag{4}$$

Where,
mA: mass of the crucible and sludge after drying
mB: mass of the empty crucible
mC: mass of the sludge before drying.

After that, the crucible filled with the dried sludge sample is ignited in the muffle furnace at 550 °C for 6 hours. The mass of the crucible and sludge after incineration in the muffle is recorded after one hour of cooling in a desiccator. The ratio between volatile solid and dry solid is computed with Equation 5.

$$\frac{VS}{DS} = \left(\frac{mA - mD}{mA - mB}\right) * 100 \tag{5}$$

Where,
mA: mass of the dish and sludge after drying
mB: mass of the empty dish
mD: mass of the plate and sludge after incineration at 550 °C for 6 hours.

3.3.2 TSS AND VSS

Total suspended solids and volatile suspended solids were determined according to the standard methods (APHA/AWWA/WEF, 2012).

First an empty crucible and a weighed standard glass-fibre filter are put in oven to dry at 105 °C in order to eliminate any ambient humidity. They are both weighted afterwards. Then a sludge volume of 4 mL is filtered on the glass filter. The latter and the residue retained on it are then recuperated, put in the empty crucible and dried in oven at 105 °C to a constant weight. The increase in weight of the filter before and after oven represents the TSS, as presented Equation 6.

$$\mathrm{TSS} = \left(\frac{mA - mB}{V}\right) * 1000 \tag{6}$$

Where,

mA: mass (g) of crucible, filter and retained residue after oven

mB: mass (g) of empty crucible and filter

V: volume (mL) of sample subjected to filtration.

After this procedure, the crucible with the dried residue on the filter is ignited in the muffle furnace at 550 °C for 6 hours. The mass of the crucible and sludge after incineration in the muffle is recorded after one hour of cooling in a desiccator. VSS are hence obtained by Equation 7.

$$\mathrm{VSS} = \left(\frac{mA - mD}{V}\right) * 1000 \tag{7}$$

Where,

mA: mass (g) of crucible, filter and retained residue after oven

mD: mass (g) of crucible, filter and retained residue after muffle

V: volume (mL) of sample subjected to filtration.

3.3.3 PH AND CONDUCTIVITY

The electrical conductivity and pH were measured both on thickened unconditioned (TU) sludge and thickened conditioned (TC) samples, after polymer dosing in the laboratory. Conductivity was measured by using a conductivity meter (B&C Electronics-C 125.2) and pH by a pH-meter Metrohm 827 pH in a 250 ml beaker where 150 ml of liquid sludge (unconditioned or conditioned) was poured.

3.3.4 ZETA POTENTIAL

Zeta potential (ζ) is the electric potential and a key indicator of the stability of colloidal dispersions. The magnitude of zeta potential determines the capability of microbial flocs to aggregate. The closer the magnitude of zeta potential to zero the lower the repulsive forces between flocs and the higher the opportunity to form larger flocs. In other words, the higher the absolute value of zeta potential indicates a more stable colloidal system. To separate the particles and remove easily the surrounding fluid, a lower magnitude of zeta potential is needed.

Sludge samples were filtered under vacuum with a Whatman 42 filter paper (2.5 µm pores size) and the zeta potential of the filtrate was determined by the instrument Malvern Zetameter ZS90. Before the analysis, the cuvette was rinsed with methanol and deionized water and filled with the filtrate. Then the cuvette was placed in the zetameter viewing chamber where an electric field was activated. This leads to movement of colloids with a velocity proportional to their zeta potential, and positive or negative charge can be determined from the direction of colloids movement. Three to five repetitions were carried out and average values with standard deviations of the zeta potential were obtained for each sludge sample.

Zeta potential was measured for both conditioned and unconditioned sludge samples. The sludge samples from the eight WWTPs had a negative value for zeta potential, meaning that sludge particles were repelling each other. Zeta potential for conditioned sludge was generally expected to be lower than the unconditioned one. When polyelectrolyte was added the repulsive forces were decreased and zeta potential approached zero, thus allowing aggregation due to short-range attractive forces.

3.3.5 CAPILLARY SUCTION TIME

Sludge filterability and dewaterability was determined by capillary suction time (CST), which consists in timing the movement of water from the sludge sample through a filter paper (APHA/AWWA/WEF, 2012).

The apparatus consisted of two main components, an automatic time counter and a filtration unit, as shown in Figure 11. The filtration unit includes a thick filter paper (usually Whatman n° 17), inserted between two plastic rectangular blocks. A hollow cylinder as a sludge reservoir is placed on top of the paper filter at the centre of the upper plastic block. 1A and 1B are the sensors placed on the first concentric circle around the sludge reservoir (diameter of 32 mm). Sensor 2 is positioned on a second concentric circle (diameter of 45 mm). These three sensors are connected to a counter. The reservoir (diameter of 10 mm/18 mm) is filled with the sludge sample. As soon as the sludge reaches the filter paper in the bottom, it starts to wet the filter paper due to capillary suction phenomena through the spaces between the hydrophilic fibres of the filter paper and the water proceeds rapidly. When the water in the sludge-paper interface is absorbed by the paper, the sludge that contacts directly with paper becomes compact and acts as a barrier for further water loss. When the filtrate reaches the first two sensors (1A and 1B), the counter is automatically activated. When the filtrate reaches sensor 2, the counter stops and shows the value of CST. The rate at which the filtrate spreads concentrically on the filter paper points out the filterability and dewaterability of the sludge sample.

Figure 11 Standard CST apparatus.

The procedure for CST tests can be summarized as follows:

I. 100 ml of unconditioned sludge sample is poured in a 250 ml beaker on a magnetic stirrer;
II. 20 ml of water is added into the sludge and, after 10 s of stirring, the beaker is removed, and the CST is measured;
III. The beaker is replaced onto the stirrer and sludge is stirred for further 10 s, then CST is measured;
IV. The stirring procedure is repeated for further 30 s and 60 s and CST values are recorded;
V. The average CST of four values is computed.

For conditioned sludge, the same steps are repeated but with a known amount of conditioner instead of 20 ml of water in step 2.

CST tests were carried out with both 10 mm and 18 mm reservoirs: 10 mm reservoir was called *cone* and 18 mm reservoir was called *cylinder*.

3.3.6 SPECIFIC RESISTANCE TO FILTRATION

SRF has been mainly used as a measure of dewaterability and to optimize sludge conditioning. The apparatus consisted of a Buchner funnel, a filter paper, a graduated cylinder, a vacuum pump provided with a vacuum gauge and a stopwatch. The apparatus was arranged as shown in Figure 12. The Buchner funnel was placed over the graduated measuring cylinder ensuring airtight firmness. The DS of the sludge was measured before performing SRF tests. The vacuum pump along with vacuum gauge were attached to the graduated cylinder. The procedure for SRF tests was the following:

I. The filter paper (Whatman No. 41) is placed into the Buchner funnel.
II. The filter is wet with few drops of water while turning on the vacuum pump and opening the connecting valve.
III. 200 ml of sludge is poured on to the filter paper in the funnel and vacuum is set at 49 kN/m^2, while the filtration starts.

IV. Once a volume of filtrate equal to 10% (20 ml) of the initial volume is collected, the volumes of filtrate (V) and the relative time (t) are recorded. The pressure remains constant throughout the test.

V. The filtration process is stopped when one of the following conditions occur:

- Cracking of the cake (sudden drop in the vacuum pressure)
- Deviation of the straight-line t/V as a function of V
- Surpasses over 60 minutes of filtration time

VI. The DS content of the cake is measured.

The SRF is calculated by Equation 8.

$$\text{SRF} = \frac{2.P.A^2}{\mu.C}.b \qquad (8)$$

Where,

SRF: Specific Resistance to Filtration (m/kg)

P: vacuum pressure during filtration process (N/m^2)

A: area of the filter (m^2)

b: slope of the straight section of the curve obtained by reporting the values of *V* and tin the diagram having V for abscissa and *t/V* for ordinate (s/m^6)

μ: viscosity of the filtrate (kg/m.s)

C (kg/m^3) is calculated using Equation 9.

$$\text{C} = \frac{C_0.C_s}{(C_s - C_0)} \qquad (9)$$

Where,

C_0: initial concentration of sludge (kg/m^3)

C_s: concentration of the sludge cake) after filtration (kg/m^3).

The sludge is considered filterable when the value of specific resistance to filtration is lower than $5x10^{12}$ m/kg.

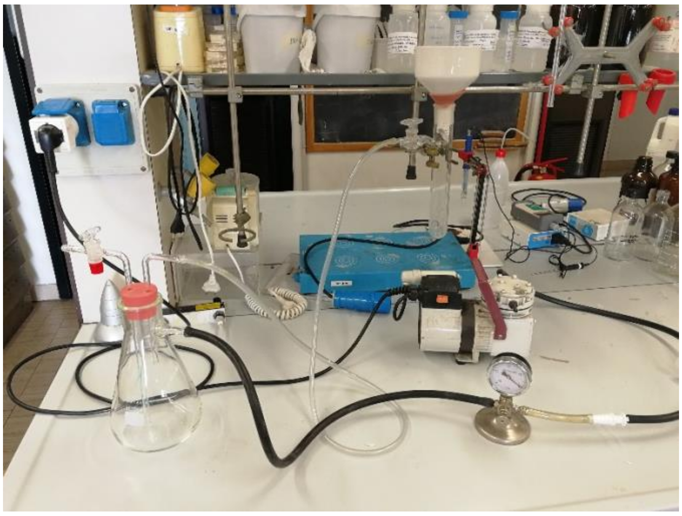

Figure 12 Experimental setup for Specific Resistance to Filtration.

3.4 FREE AND BOUND WATER CONTENT

To evaluate the different types of water in sludge, TGA (thermogravimetric analysis) and DSC (differential scanning calorimetry) techniques were used. TGA and DSC was performed on TU, TC with dosage of 4 g/kg$_{DS}$ and 8 g/kg$_{DS}$ after centrifugation for samples taken from the eight WWTPs to evaluate the influence of the polyelectrolyte dosage and the type of sludge on the binding energy of water with the sludge particles.

3.4.1 THERMOGRAVIMETRIC ANALYSIS (TGA)

Thermogravimetric analysis (TGA) is a technique in which the variation in mass of the sample is measured as a function of time when it is cooled or heated in a furnace in a controlled atmosphere.

3.4.1.1 TGA INSTRUMENT

The measurement was carried out by using a SII EXSTAR6000 TG/DTA 6300 instrument in the laboratory which is designed to perform the TG and DTA measurement simultaneously. The experimental setup is shown in Figure 13. TGA utilizes a horizontal differential type balance beam which provides the highest sensitivity and stability.

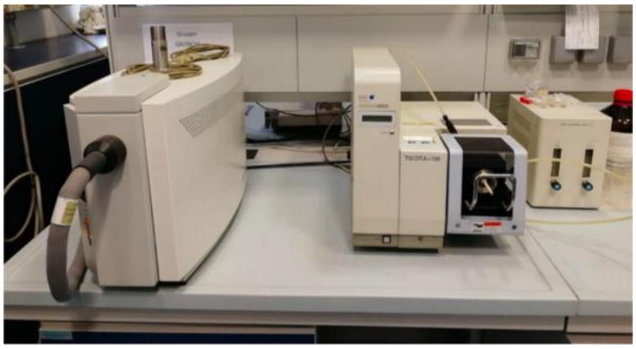

Figure 13 TG/DTA instrument in the laboratory .

3.4.1.2 TGA SAMPLE PREPARATION AND MEASUREMENT PROCEDURE

The procedure for the preparation of the samples and the TGA measurement is summarized below:

I. Centrifugation of the thickened sludge sample (unconditioned or conditioned with different dosages) to get initial DS content between 6-10%. It is important to note that a low DS content (less than 5%) leads to some errors in TGA measurement since the bound water content is too low with respect to free water. On the contrary, a high DS content (higher than 15%) means that the free water content in the sludge sample has been mostly lost during the test (Chen et al., 1997). Therefore, centrifugation of the sludge samples aims at getting a DS content of about 6-10%.
II. Weighing the sludge sample before starting the experiment. The mass of samples during the experiment were ranging from 20 to 30 mg.
III. Place the weighed sample in a pan (crucible dish) positioned in a furnace on a quartz beam attached to an automatic recording balance.
IV. Drying the sample at constant conditions, by increasing the temperature from 20 °C up to 80 °C with a heating rate of 1 °C /min. By increasing the cell temperature, the sample mass is reduced due to water evaporation.

V. The balance records the sample weight versus time during the drying procedure. The thermocouple is positioned in direct contact with the sample holder, to measure the precise temperature variation between the sample cell and the reference cell.

VI. The weight of the sample (TGA), the drying rate (DTG) and temperature are monitored by the instrument software and plotted.

VII. Excel sheet of recorded values and the curves for the interpretation of results were provided by the instrument.

3.4.1.3 TGA MEASUREMENT OF BOUND WATER

Figure 14 shows a typical diagram reporting TGA (%), DTG (mg/min) and T_{cell} (°C) as a function of time (min) for a sludge sample.

The sample mass decreases as the cell temperature increases, due to water evaporation. The phase II of the TGA test, where temperature stops increasing, shows an initial phase where DTG is almost constant. At the end of stage II, DTG values fall down rapidly (falling rate period), due to the presence of impurity or dissolved electrolytes, which results in vapor pressure reduction. When all removable water is exhausted, the process enters stage III and only a residue solid phase is obtained (Chen et al., 1997).

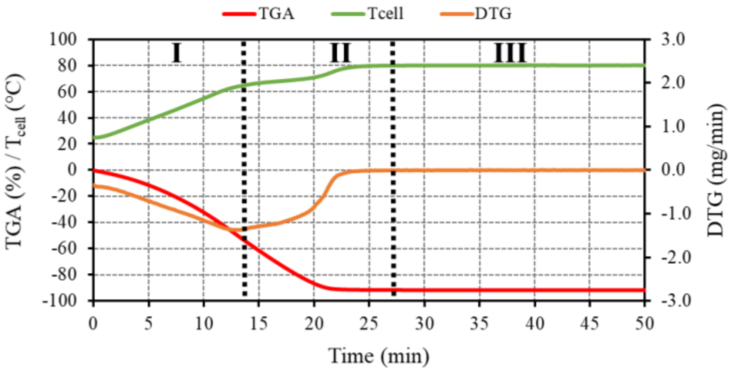

Figure 14 Sample of TGA/DTG and Tcell diagram for a sludge sample.

In order to measure the bound water content through this method, the time which shows the end point of DTG falling rate is recorded. DS content, free water (g/g_{DS}) and bound water (g/g_{DS}) contents corresponding to the recorded time are calculated.

3.4.2 DIFFERENTIAL SCANNING CALORIMETRY (DSC)

DSC is a technique in which the differences in heat flow between sample and reference is measured during its cooling or heating. In other words, DSC measures the electrical power (heat) required to keep the sample and the reference at the same temperature.

3.4.2.1 DSC INSTRUMENT

The measurement was performed by using the SII EXSTAR6000 DSC instrument (Figure 15).

Figure 15 DSC instrument in the laboratory .

3.4.2.2 DSC SAMPLE PREPARATION AND MEASUREMENT PROCEDURE

The assumption for this method is that the bound water remains unfrozen to up to a threshold temperature, assumed to be -20/-30°C for sludge samples (Deng et al., 2011; Erdincler and Vesilind, 2003; Hong et al., 2015). As for TGA, also for DSC TU and TC sludge samples were studied after centrifugation at laboratory at 4,000 rpm for 5 min.

The procedure used for DSC measure is listed below:

I. 10-20 mg of centrifuged sludge is collected.
II. The sample is put in a crucible and it's placed in the DSC instrument, equipped with a nitrogen cooling system

III. The temperature of the cell is decreased from 20 °C down to -25 °C at the constant rate of 1°C/min, and then increased again up to 20 °C at the same rate.
IV. The endothermic or exothermic curves are monitored by the software.

3.4.2.3 DSC MEASUREMENT OF BOUND WATER

The integration of the peak area of the endothermic curve corresponds to the heat absorbed during the process while the exothermic curve is related to the amount of heat released. To calculate the free water content in sludge, the area of the endothermic peak below the baselines is calculated. Since this area corresponds to the amount of heat that is required to melt the frozen water (free water), the heat uptake during the phase transition of free water can be calculated with Equation 10.

$$W_{free} = \frac{\Delta H}{\Delta H_0} \tag{10}$$

Where,
ΔH: amount of heat absorbed in the melting process (J/g_{DS})
ΔH_0: water heat of melting (J/g water = 334.7 J/g)
W_{free}: free water content (g/g_{DS}).

Therefore, the amount of bound water was determined as a difference between total water content and free water content of the sludge (Equation 11).

$$W_B = W_{tot} - W_{free} \tag{11}$$

Where,
W_B: bound water content (g/g_{DS})
W_{tot}: total water content (g/g_{DS}).

3.5 MECHANICAL DEWATERING METHODS

To study the effect of polyelectrolyte dosage and the maximum achievable DS content, MD methods like multiple centrifugation and compression at constant pressure were performed on TU and TC samples from the eight WWTPs. Figure 16 shows the procedure for carrying out MD tests at the laboratory.

Figure 16 Procedure of mechanical dewatering.

3.5.1 MULTIPLE CENTRIFUGATION

200 ml of TC sludge sample was centrifuged in the laboratory at 4,000 rpm for 5 min. Afterwards, the collected supernatant was removed, and the sludge cake was furtherly centrifuged at 4,000 rpm for 5 min. The test was repeated until no more supernatant could be collected.

3.5.2 COMPRESSION AT CONSTANT PRESSURE

The compression of TC sludge was carried out in the same laboratory scale device used for EDW tests (described in Section 3.5.1). The sludge was preliminarily centrifuged in the laboratory at 4,000 rpm for 5 min, to achieve a DS content of 8-9%. The cylindrical glass vessel was filled with centrifugated sludge sample (90 g). Constant pressure (300 kPa) was applied by a piston to compress the sludge and remove the water through the filter, placed at the bottom of the cell. The duration of the test was 35 mins, when no more than two drops of water were removed from the sample, meaning that the pressure application was not effective anymore in removing water from the sample. After this process, the DS content of the sludge cake and the TSS of the filtrate was measured. TSS of the filtrate is used to compute capture efficiency (described in Section 3.6.4).

3.6 ELECTRO-DEWATERING TESTS

EDW test was carried out on TU and TC samples from the eight WWTPs in order to study the effect of polymer dosage and maximum achievable DS content. EDW efficiency, in terms of final DS content, was compared to MD. Figure 17 shows the protocol followed to perform the tests.

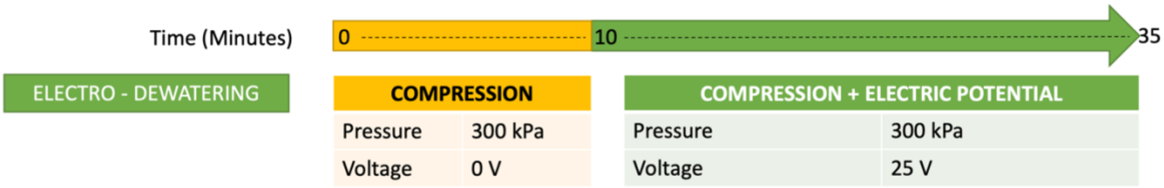

Figure 17 Procedure of electro-dewatering.

3.6.1 THE LABORATORY SCALE DEVICE

The laboratory scale set-up used for the study is described in Visigalli et al. (2017). This laboratory scale device (Figure 18) consists of a cylindrical filtration/compression cell made of glass (176 mm high, with a diameter of 80 mm) with a double effect piston (SMC-CP96SDB32-200). The upper dimensionally stable anode DSA® (manufactured by Industrie De Nora, Milan, Italy) made of titanium coated with mixed metal oxide (Ti/MMO) is fixed to the bottom of the piston, on a support made of polytetrafluoroethylene (PTFE). At the bottom of the cell, there is a cathode made of stainless-steel mesh (AISI 304), covered by a poly-trimethylene terephthalate (PTT) filter cloth to keep the sludge and let water flow through it.

Both cathode and anode are disc-shaped and are connected to the negative and the positive pole of the direct current (DC) power supply. The laboratory pressurized air system is connected to the piston, equipped with a manometer and valves to set the chosen value for pressure (max 450 kPa). The filtrate water is collected in a beaker, put on a precision scale balance. The mass of collected water in a beaker against time are recorded at regular intervals of 1 minute to calculate the dewatering rate.

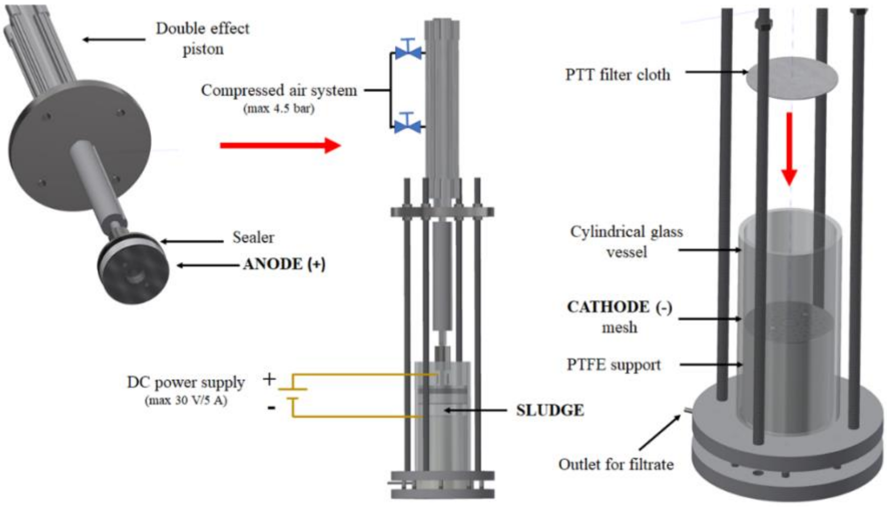

Figure 18 Schematic of the laboratory scale device used for EDW test.

3.6.2 PROCEDURE FOR ELECTRO-DEWATERING TEST

TU and TC sludge samples, after conditioning in the laboratory with a polymer dosage of 4 g/kg$_{DS}$ and 8 g/kg$_{DS}$, from the eight different WWTPs were used for EDW test.

The laboratory scale device provided mechanical compression and an electric field to increase the dewatering rate and final DS in the sludge cake. The procedure can be summarized as follows:

I. Centrifugation of the unconditioned (TU) or conditioned (TC) sludge samples in the laboratory (4,000 rpm for 5 minutes) to achieve a DS content around 6-10%.
II. Measuring 90 g of centrifuged sludge which corresponds to about 15 mm of cake thickness on the 80-mm diameter supporting plate.
III. Filling the glass cell with the sludge weighed in step II.
IV. Filtration of the sludge sample by applying mechanical pressure (P=300 kPa) by means of the piston for the first 10 min.

V. Application of a constant electric potential to the sludge cake by means of the DC power supply. This step is carried out with an applied voltage of 25 V for a time duration of 25 min. The pressure is kept constant at 300 kPa until the end of the EDW test. The total length of the EDW test is 35 min (10 min pressure + 25 min EDW).

VI. From the beginning until the end of the EDW test, the mass of filtrate and current values are recorded at regular intervals of 1 min.

VII. At the end of EDW test, a sludge cake sample is put in oven at 105 °C for 12 hours in order to compute the final DS content.

VIII. TSS of the collected filtrate are measured in order to compute the solid capture.

3.6.3 SPECIFIC ENERGY CONSUMPTION

As mentioned before, during the EDW test, the mass of water removed, and the electrical current value are recorded at intervals of 1 min. By using these data, DS content vs. time and current density against time are plotted. The specific energy consumption (Wh/kg_{H2O}) is computed from Equation 12 (Mahmoud et al., 2016)

$$\text{Specefic Energy Consumption} = \text{SEC} = \frac{V \cdot \sum_{j=1}^{n} I_j \cdot \Delta t}{m_{H_2O}} \tag{12}$$

Where,

V: applied electric potential (V)

n: number of recorded measures

I_j: measured current (A)

Δt: time interval between two recorded measures (hours)

m_{H2O}: total mass of water removed (kg) during the polarization phase.

The total equivalent thermal energy consumption can be computed by taking into account the national electrical energy conversion efficiency (Italy) equal to 0.47 (Caputo and Sarti, 2015).

3.6.4 CAPTURE EFFICIENCY

During the removal of water from the sludge, not all solid particles from the liquid are separated. A portion of sludge particles are present in the filtrate obtained after dewatering processes. Capture efficiency (*CE*) is defined as the total number of solids retained with sludge and sent to further processes. It is expressed in percentage (%). CE is an important indicator to know the quality of filtrate obtained after dewatering. Usually, filtrate after dewatering process contains particles and are mixed with the WWTP inflow to again undergo all the treatment processes. CE is calculated with Equation 13 on the filtrates obtained from MD and EDW tests.

$$\mathrm{CE} = \frac{DS_{CAKE}}{TSS_{IN}} \times \frac{(TSS_{IN} - TSS_{FIL})}{DS_{CAKE} - TSS_{FIL}} \times 100\% \tag{13}$$

Where,

DS_{CAKE}: dry solids of the cake after dewatering (%)

TSS_{IN}: TSS of the sludge sample before dewatering (TU/TC) (%).

TSS_{FIL}: TSS of the filtrate/centrate obtained after dewatering (%)

3.7 PRELIMINARY STATISTICAL EVALUATION

Statistical analysis was carried out to investigate the relationship between sludge characteristics and dewatering. General linear model (GLM) from ANOVA was used for the analysis. GLM compares how different independent variables affect the response variable, analysing the simultaneous effects of multiple variables. The GLM was carried on the data achieved by laboratory experiments using the Minitab software. The response variables and the independent variables were selected among the categories reported below:

I. Relationship between sludge characteristics and CST
II. Relationship between sludge characteristics and ZP
III. Relationship between sludge characteristics and MD

IV. Relationship between sludge characteristics and EDW

After the analysis, the software generates an equation to describe the statistical relationship between one or more variables and the response variable (dependent variable). Pearson correlation coefficient (p-value) was used to evaluate the linear correlation among the sludge characteristics. The correlations were considered as statistically significant at a 95% confidence interval ($p\text{-value} < 0.05$). In other words, a p-value less than 0.05 indicates than the changes in the variable are related to the response variable. The fit of the data to the model generated was evaluated by the R-squared (R^2). R^2 indicates the percentage of the variance in the response variable that the independent variables explain collectively. R-squared measures the strength of the relationship between the model and the response variable on a 0 – 100% scale. R^2 values near to 100% indicates that the data fits well with the generated model.

3.8 ECONOMIC ASSESSMENT

The sludge treatment cost is an important factor influencing the choice of dewatering technique. The cost of sludge treatment includes the following costs:

- Cost of conditioning – in terms of polymer cost
- Cost of dewatering – operational costs incurred in MD and EDW
- Cost of disposal

Site-specific data (averaged from yearly basis) have been extracted from the corresponding WWTPs and were used as the reference to compare with the EDW cases. The annual costs (€) of conditioning ($Cost_{COND}$), mechanical dewatering ($Cost_{MD}$), disposal ($Cost_{DISP}$) and EDW ($Cost_{EDW}$) have been computed as follow:

$$Cost_{COND} = \left[\left(\frac{DS_{TU}.V_{TU}}{100}\right).D_{POLY}\right].Cost_{POLY} \tag{14}$$

$$Cost_{MD} = E_{MD}.Cost_{EE} \tag{15}$$

$$Cost_{EDW} = Cost_{CFG} + Cost_{P} + Cost_{V} \tag{16}$$

$$Cost_V = \mathrm{SEC} \cdot \mathrm{V}_F \cdot Cost_{EE} \tag{17}$$

$$Cost_{DISP} = m_{MD|EDW}. Cost_{UNIT} \tag{18}$$

Where,

DS_{TU}: DS content (wt%) of TU sludge

V_{TU}: Annual volume (m^3/year) of TU sludge treated in the WWTP (data provided by WWTPs)

D_{POLY}: Dosage of polyelectrolyte (kg/t_{DS})

$Cost_{POLY}$: Specific cost of the polyelectrolyte active principle (€/kg_{POLY}) (assumed to be 1.82 €/$kg_{POLY\ (Powder)}$ and 2.4 €/$kg_{POLY\ (Emulsion)}$).

E_{MD}: Electric energy (kWh) consumed by mechanical dewatering (data provided by WWTPs)

$Cost_{EE}$: Specific cost of electric energy in Italy (≈0.16 €/kWh)

$Cost_{CFG}$: Cost of centrifugation process (€/year) at laboratory (estimation)

$Cost_P$: Cost of pressure-driven phase of EDW (€/year) at laboratory (estimation)

$Cost_V$: Cost of application of electric field in EDW (€/year)

SEC: Specific electric energy consumption (kWh/t_{H2O}) calculated by Equation 10

V_F: Volume of filtrate collected during polarization phase in EDW

$m_{MW/EDW}$: Mass of mechanically dewatered/electro-dewatered sludge (t/year)

$Cost_{UNIT}$: Unitary cost of disposal (€/t) (average value from the data provided by WWTPs).

Values of E_{MD} for some of the WWTPs were not available and have been calculated assuming specific energy consumption to be around 1-1.5 kWh/m^3_{sludge} for belt press and 2-3 kWh/m^3_{sludge} for centrifuge.

In order to allow better interpretation, costs of conditioning ($Cost_{COND}$), mechanical dewatering ($Cost_{MD}$), EDW ($Cost_{EDW}$) and disposal ($Cost_{DISP}$) were divided by annual flowrate of raw sludge (V_{TU}) to obtain annual specific costs of each category.

Table 2 provides some of the data collected from each WWTPs which are used in the calculation for economic analysis.

Table 2 Data from the eight WWTPs used in economic analysis.

WWTP	Volume of sludge treated	DS	Polymer dosage	Dewatering treatment	Energy consumption of dewatering	Final DS of the sludge cake	Mass of dewatered sludge	Disposal routes
No.	m^3/year	%	g_{AP}/kg_{DS}		kWh/m^3	%	t/year	
1	20,155.7	2.5	4.4*	Belt press	1.39	18.9	2,716.9	Incinerator
2	108,163.2	2.9	18.2**	Centrifuge	2.18	24.1	13,176.7	Fertilizer
3	22,260.2	2.6	13.3**	Centrifuge	2.26	20.4	2,836.6	Agriculture, fertilizer, dryer
4	10,992.8	3.5	23.4**	Centrifuge	2.92	18.8	2,032.7	Agriculture, fertilizer, incinerator
5	5,982.0	1.7	10.4*	Belt press	1.05	17.1	612.8	Agriculture
6	6,160.9	3.9	8.6*	Belt press	1.01	16.7	1,406.8	Dryer
7	47,516.1	3.4	27.4**	Centrifuge	2.27	23.0	6,995.9	Agriculture, dryer, incinerator
8	22,990.8	3.7	19.7***	Centrifuge	2.28	25.2	3,412.7	Dryer

* Tillmanns Tillflock 6480 (powder)

** Tillmanns Tillflock CL 1480 (emulsion)

*** Tillmanns Tillflock CL 1853/1953 (emulsion)

4 RESULTS AND DISCUSSION

4.1 SLUDGE CHARACTERIZATION AND CONDITIONING

Table 3 shows the results of the characterization tests performed on TU and TC sludge samples. TU sludges were directly collected from the eight WWTPs whereas TC sludges were prepared through jar test in the laboratory, by conditioning with polyelectrolyte at dosages of 4 and 8 g/kg_{DS}.

Table 3 Characteristics of the sludge samples from the eight WWTPs.

WWTP	**Polymer dosage**	**DS**	**VS/DS**	**TSS**	**VSS**	**pH**	**Conductivity**	**ZP**	**CST (cylinder)**	**CST (cone)**
No.	**g/kg_{DS}**	**(%)**	**%**	**g/L**	**g/L**		**mS/cm**	**mV**	**(s)**	**(s)**
1	0	1.56	67.4	17.0	11.5	7.4	1.7	-12.3	12.4	35.9
	4	1.51	67.4	18.5	11.5	7.0	1.8	-11.6	15.2	45.1
	8	1.44	67.4	15.2	11.5	7.0	1.9	-10.8	11.0	26.1
2	0	2.94	57.7	29.0	17.7	7.4	5.6	-10.8	171.7	647.9
	4	2.86	57.7	28.1	17.7	7.4	5.2	-9.7	150.6	601.3
	8	2.77	57.7	28.1	17.7	7.6	5.4	-8.6	118.2	466.7
3	0	2.60	70.5	26.1	18.9	7.1	2.6	-11.4	55.5	337.5
	4	2.50	70.5	24.8	19.4	7.3	2.6	-12.3	52.7	269.9
	8	2.35	70.7	23.5	16.8	7.4	2.5	-13.3	39.6	192.1
4	0	3.50	72.5	33.6	24.8	6.5	2.8	-12.4	85.4	396.7
	4	3.23	72.5	28.4	21.4	6.6	2.7	-10.7	37.0	175.0
	8	2.80	72.2	24.0	17.7	6.9	2.7	-10.3	20.4	87.9
5	0	1.74	71.9	18.1	13.3	7.5	1.2	-11.5	15.2	85.4
	4	1.88	70.2	17.6	12.9	7.1	1.3	-11.2	14.7	67.2
	8	1.58	70.2	14.9	11.0	7.1	1.3	-10.6	12.0	41.5
6	0	3.93	60.2	36.5	21.8	7.0	2.3	-12.8	34.6	170.6
	4	3.56	60.7	34.5	20.8	7.1	2.3	-12.3	25.2	119.8
	8	3.37	60.1	34.8	20.8	7.0	2.2	-9.9	15.5	70.7
7	0	3.40	57.9	31.9	19.1	7.5	3.3	-12.1	39.4	207.7
	4	3.20	57.7	29.8	17.3	7.8	3.1	-10.4	22.2	77.5
	8	3.04	58.4	28.9	16.7	7.4	3.2	-9.8	13.6	53.3
8	0	3.76	65.8	34.8	23.2	7.5	4.9	-12.5	92.4	512.5
	4	3.01	66.0	29.6	19.9	7.4	4.9	-12.2	55.2	259.4
	8	3.02	65.5	30.4	20.6	7.4	4.3	-11.9	18.5	68.3

Considering the TU samples, Table 3 shows that TSS ranged from 17.0 to 36.5 g/L while VS/DS values ranged from 57.7% to 72.5%, which evidenced the high variability of the sludge characteristics. By conditioning, the addition of water and polymer affected not only the DS and TSS contents, which tent to decrease, but also zeta potential and CST values. Only sample from WWTP 5 dosed at 4 g/kg$_{DS}$ showed a different behavior, with a slightly higher DS content after polymer addition. It is a matter of fact that the VS/DS ratio did not change significantly with polyelectrolyte dosage. Results on zeta potential and CST values are deeper discussed in the following sections.

4.1.1 ZETA POTENTIAL

The ZP values of TU samples were negative, confirming that sludge particles carry negative charge on the surface. Since cationic polyelectrolyte Praestol 645 BC was used to prepare TC sludges, the ZP value increased with the dosage. In simple words, ZP increases with the dosage used on the sludge (Figure 19). Similar results were obtained by Chang et al. (2001) and Ding et al. (2020). Unpredictably the ZP values reduced with the addition of polyelectrolyte in sludge from WWTP 3. This contradiction may be due to a slight increase in pH from 7.1 in TU sample to 7.3 in TC at 4 g/kg$_{DS}$ and to 7.4 in TC at 8 g/kg$_{DS}$. As already discussed in 2.3.6, an increase in pH decreases the ZP values. However, generally a pH value of 7 (neither acidic nor basic) does not significantly affect ZP.

It must be noted that by conditioning at 4 and 8 g/kg$_{DS}$, ZP increased up to values not higher than -8 mV, meaning that electroneutrality could not be achieved and particles were only slightly destabilized. However, after conditioning, sludge flocs were evident, and its effect was considered to be sufficient in improving the sludge dewaterability that was preliminarily assessed by CST. In conclusion, the ZP values can be used as a tool to assess the effectiveness of the sludge conditioning.

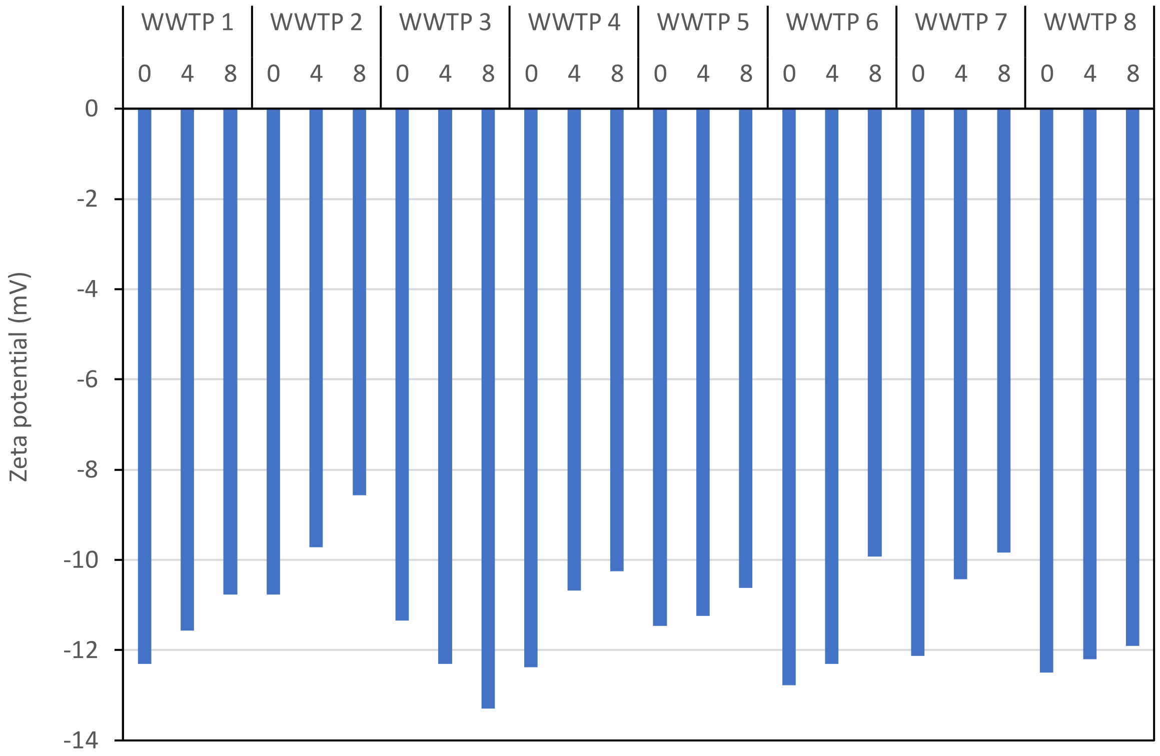

Figure 19 Polymer dosage vs. zeta potential diagram.

4.1.2 CAPILLARY SUCTION TIME

CST tests were carried out with both 10 mm and 18 mm reservoirs. Here, 10 mm reservoir is called *cone* and 18 mm reservoir is called *cylinder*. CST measured with cone was always higher than that measured with cylinder (Scholz, 2006). Indeed, the cone is useful to differentiate between fast filtering sludges, especially with low DS content, because the results achieved are distributed in a wider range. Figure 20 shows that CST measured with cylinder and cone follows the same trend. Looking at individual WWTPs, CST is observed to be decreasing with an increase in polymer dosage. In other words, CST is inversely proportional to the polymer dosage. The addition of polyelectrolyte to the sludge induces floc formation and reduces viscosity (Nguyen et al., 2008) which enhances the release of water from the particles. This trend confirmed that the sludges were well conditioned. Similar trends were previously observed by other authors (Lee and Liu, 2001, 2000; Nguyen et al., 2008; Phuong To, 2015; Sarikaya and Al-Marshoud, 1993). Moreover, lower CST values were obtained for sludge samples with lower DS contents, as already described by previous studies (Sarikaya and Al-Marshoud, 1993). Unpredictably, in WWTP 1, the CST value of TC dosed at 4 g/kg$_{DS}$ was higher than that of TU sample, which is the only deviation from the trend. This could be ascribed to a scarce flocculation during the conditioning step. However, this was not confirmed by ZP that increased with the polymer dosage. For all the other WWTPs, lower values of CST were obtained for TC samples dosed at 8 g/kg$_{DS}$. Therefore, according to CST, TC at 8 g/kg$_{DS}$ was the sample with a greater dewaterability.

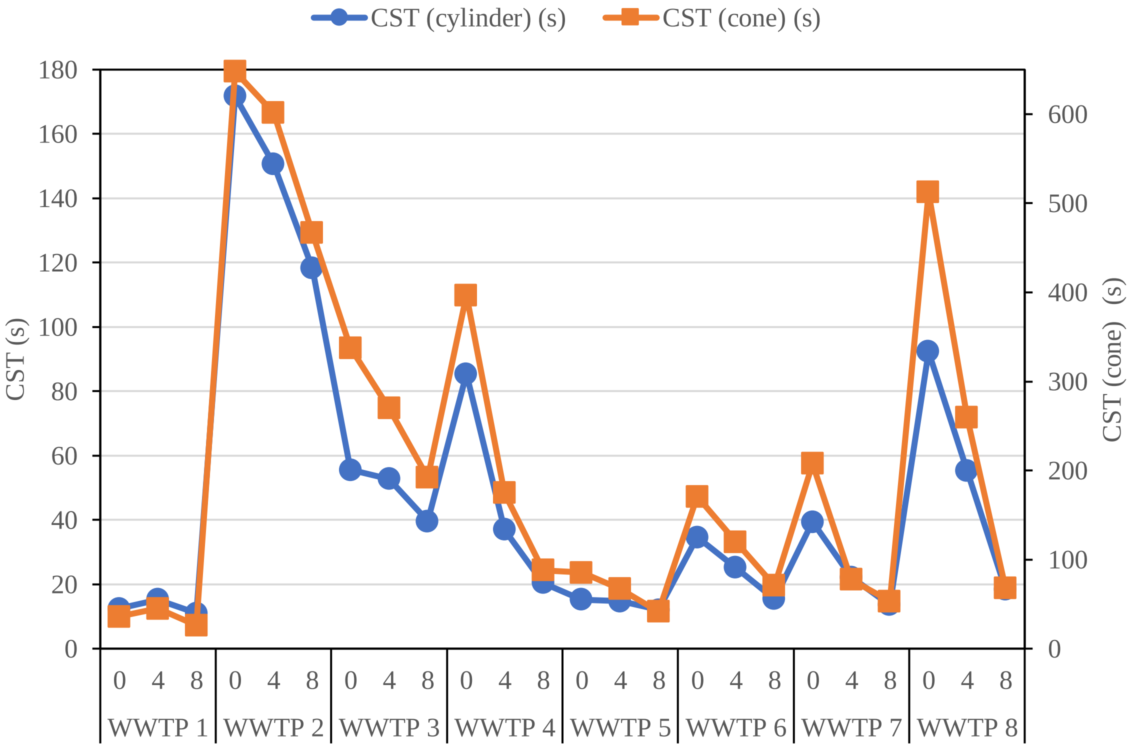

Figure 20 CST (cylinder) vs. CST (cone) diagram.

Figure 21 shows the dispersion diagram of CST values measured with cone and cylinder. It shows that there is good correlation between the two indicators. Therefore, the CST values obtained were considered accurate.

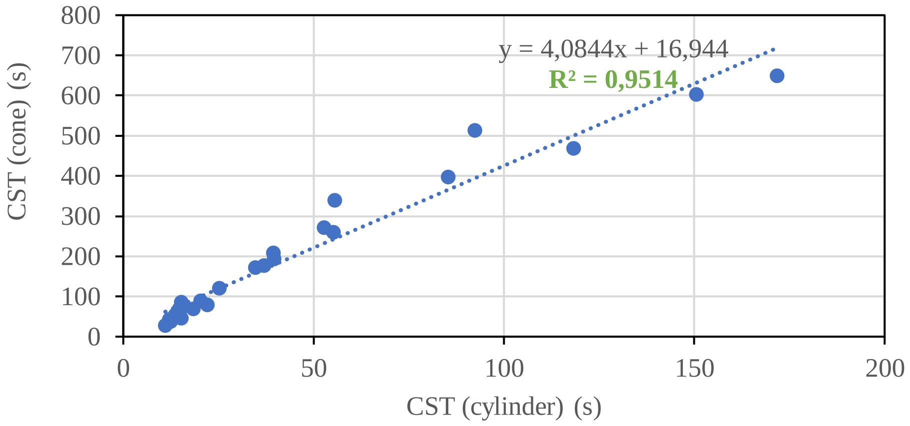

Figure 21 Dispersion diagram of CST (cylinder) and CST (cone).

4.1.3 SPECIFIC RESISTANCE TO FILTRATION

SRF test was carried out on four samples to check if this indicator could provide the same information of CST. Two aerobically stabilized and two anaerobically stabilized sludges were selected and SRF test was performed. The obtained results are presented in Table 4.

Table 4 Results of SRF test.

WWTP	Polymer dosage	SRF
No.	**g/kg_{DS}**	**m/kg**
1	0	6.86E+12
	4	3.94E+12
	8	3.37E+12
2	0	4.24E+13
	4	3.80E+13
	8	1.64E+13
3	0	1.91E+13
	4	4.31E+12
	8	9.46E+12
6	0	1.05E+13
	4	3.50E+12
	8	1.43E+12

Focusing on individual WWTPs, the SRF value decreased as the dosage increased i.e., SRF was inversely proportional to the polymer dosage. Therefore, SRF and CST followed a similar trend and provided the same information: lower is the value, more efficient is the sludge dewatering. For WWTP 1, 2 and 4, TC samples dosed at 8 g/kg$_{DS}$ were the samples with lower SRF values. There is a contradiction with CST in the trend for WWTP 3, where TC dosed at 4 g/kg$_{DS}$ had the lowest value of SRF.

The correlation of SRF and CST was analyzed. Figure 22 shows the dispersion diagram of CST and SRF values measured. There is good correlation between SRF and CST as stated by many authors (Arimieari and Ademiluyi, 2018; Peng et al., 2011; Sarikaya and Al-Marshoud, 1993). Peng et al. (2011) also stated that it is not necessary to use both CST and SRF at the same time to assess sludge dewaterability. Results presented include samples from four WWTPs, but to validate and firmly establish the relationship with CST, SRF should be carried out on samples from all the eight different WWTPs.

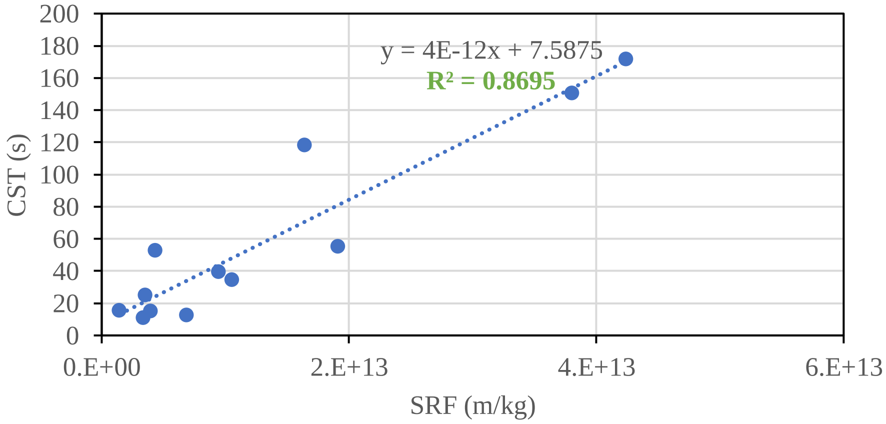

Figure 22 Dispersion diagram of SRF and CST (cylinder).

4.1.4 TGA AND DSC

TGA and DSC tests was carried out on centrifuged sludge (sludge before MD and EDW) to evaluate the effect of polymer dosage in the distribution of water. Table 5 summarizes consolidated results obtained after TGA and DSC analysis on the TU and TC samples from the eight WWTPs.

Table 5 Results of TGA and DSC.

				TGA				DSC			
Sample	**Polymer dosage**	**DS content**	**Total water**	**Free water**	**Bound water**	**FREE WATER**	**BOUND WATER**	**Free water**	**Bound water**	**FREE WATER**	**BOUND WATER**
		%	**g/gDS**	**g/gDS**	**g/gDS**	**%**	**%**	**g/gDS**	**g/gDS**	**%**	**%**
1	0	1.56	63.10	58.97	4.13	93.46	6.54	61.22	1.88	97.02	2.98
	4	1.51	65.23	61.95	3.28	94.97	5.03	63.44	1.79	97.26	2.74
	8	1.44	68.44	65.94	2.50	96.35	3.65	66.83	1.61	97.65	2.35
2	0	2.94	33.01	30.29	2.72	91.76	8.24	30.18	2.83	91.43	8.57
	4	2.85	34.09	32.67	1.42	95.83	4.17	30.73	3.36	90.14	9.86
	8	2.77	35.10	30.81	4.29	87.78	12.22	31.84	3.26	90.71	9.29
3	0	2.60	37.52	36.16	1.36	96.38	3.62	35.11	2.41	93.58	6.42
	4	2.50	39.00	35.89	3.11	92.03	7.97	37.00	2.00	94.87	5.13
	8	2.35	41.50	40.93	0.57	98.63	1.37	39.20	2.30	94.46	5.54
4	0	3.51	27.53	24.58	2.95	89.28	10.72	24.72	2.81	89.79	10.21
	4	3.23	29.99	27.26	2.73	90.90	9.10	28.35	1.64	94.53	5.47
	8	2.81	34.65	33.82	0.83	97.60	2.40	32.70	1.95	94.37	5.63
5	0	1.74	56.37	54.27	2.10	96.27	3.73	52.82	3.55	93.70	6.30
	4	1.88	52.11	48.80	3.31	93.65	6.35	49.73	2.38	95.43	4.57
	8	1.56	63.23	61.36	1.87	97.04	2.96	60.60	2.63	95.84	4.16
6	0	3.93	24.44	23.52	0.92	96.24	3.76	22.21	2.23	90.87	9.13
	4	3.56	27.10	26.25	0.85	96.86	3.14	25.20	1.90	92.99	7.01
	8	3.37	28.64	27.78	0.86	97.00	3.00	24.55	4.09	85.72	14.28
7	0	3.40	28.41	26.55	1.86	93.45	6.55	25.22	3.19	88.77	11.23
	4	3.20	30.30	29.74	0.56	98.15	1.85	28.17	2.13	92.97	7.03
	8	3.04	31.89	30.52	1.37	95.70	4.30	30.15	1.74	94.54	5.46
8	0	3.76	25.60	24.69	0.91	96.44	3.56	18.64	6.96	72.81	27.19
	4	3.01	32.22	30.63	1.59	95.07	4.93	22.88	9.34	71.01	28.99
	8	3.02	32.11	30.80	1.31	95.92	4.08	23.79	8.32	74.09	25.91

From literature, it is expected that free water content increases due to addition of water while conditioning. On the other hand, bound water content decreases because of the movement of water molecules bound to the particles. Indeed, conditioning replaces the water molecules on the solid surface with polymer molecule improving the release of water

(Katsiris and Kouzeli-Katsiri, 1987; Robinson and Knocke, 1992). Therefore, as the dosage increases, the free water increases and the bound water decreases.

The comparison of free water and bound water in terms of g/g$_{DS}$ is hard because of the different initial total water for different samples. Therefore, the comparison is based on the percentage of free water and bound water.

Considering TGA results of WWTPs 1, 4 and 6, the free water increased and bound water decreased with increasing dosage, confirming the data reported in literature. On the other hand, WWTPs 2, 3, 5, 7 and 8 showed a trend that is different from the literature. Bound water values for TGA in terms of percentage and g/g$_{DS}$ were in the range of 1.4-12.2% and 0.56-4.29 g/g$_{DS}$ respectively.

DSC results of WWTPs 1, 5 and 7 followed the trend mentioned by the literature that addition of polyelectrolyte increases free water and reduces bound water. On the contrary, WWTPs 2, 3, 4, 6 and 8 showed a higher bound water content with the conditioning step. The bound water content measured by DSC in terms of percentage and g/g$_{DS}$ were in the range of 2.3-29.0% and 1.61-9.34 g/g$_{DS}$ respectively.

With respect to free water, the results achieved by TGA and DSC had better correlation and almost followed the same trend (Figure 23a). Therefore, it is inferred that the values are reliable to some extent. On the other hand, there is a conflict with respect to bound water, since there is no correlation between the values obtained by TGA and DSC (Figure 23b).

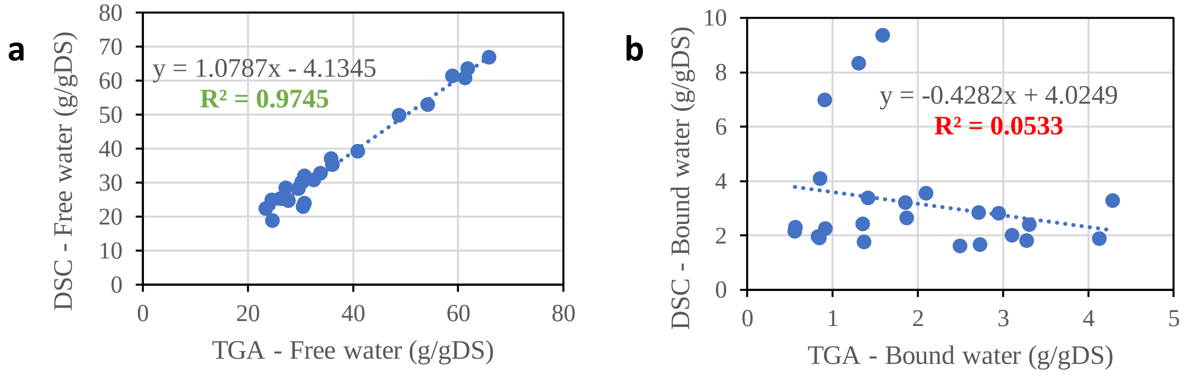

Figure 23 Dispersion of (a) free water and (b) bound water values achieved by TGA and DSC.

Despite conditioning at same dosage, the different results of TGA and DSC shows that the effect of polyelectrolyte on bound and free water is not the same for sludges from different WWTPs.

TGA and DSC results are useful in understanding the distribution of water and apparently the effectiveness of conditioning process. However, TGA and DSC cannot be fully relied for the investigation of the conditioning process because of the discrepancy in the measurement. The discrepancy between TGA and DSC is because these methods use different hypothesis to measure free water and bound water: TGA relates weight loss with respect to temperature and DSC relates the freezing of water molecules at different temperature range. It is to be noted that there is an issue in defining free water, some researchers measure water vapor at 80 °C as free water and some measure at 40 °C whereas others believe that free water is completely removed at a pressure higher than 28 MPa (Tuan et al., 2012). According to Zhang et al. (2019), TGA is not suitable for extremely heterogeneous samples. The variation of values may be also due to testing of a very little quantity of the sludge (Zhang et al., 2019). Thus, to have better perspective on the behavior of the sludge with respect to different polymer dosages, further study is necessary to establish correlation between TGA and DSC with CST, SRF and ZP.

4.2 MECHANICAL DEWATERING

Multiple centrifugation (mCFG) as well as compression at constant pressure (MD) were carried on TU and TC samples from the eight WWTPs. Initial DS, final DS of the cake, TSS of the filtrate and CE of mechanical dewatering processes are reported in Table 6.

The effectiveness of conditioning was proved by the ZP values. CST and SRF showed that TC dosed at 8 g/kg$_{DS}$ is easier to dewater, while DSC and TGA evidenced that conditioning increases the percentage of free water. Looking at the results achieved with mechanical dewatering, except for WWTP 3, it is observed that final cake DS content increased with the polymer dosage. Samples conditioned at 8 g/kg$_{DS}$ produced cakes with the maximum DS contents after mCFG as well as MD. Therefore, conditioning positively contributed to sludge dewatering. The cationic polyelectrolyte dosage allowed the negatively charged solid particles to form flocs. The aggregation of particles led to an easier release of free water, thus enhancing the dewatering process. Therefore, the information provided by CST, SRF and ZP seems to confirm the results obtained by MD. As previously said, ZP and SRF values achieved with sludge from WWTP 3 followed a trend different from the other WWTPs, evidencing some issues in the conditioning step. Here, the cake DS content of TC dosed at 4 g/kg$_{DS}$ was greater than that of TC dosed at 8 g/kg$_{DS}$.

Table 6 Sludge characteristics after mCFG and MD tests carried out in the laboratory .

WWTP	**Polymer dosage**	**DS**	**DS cake (mCFG)**	**DS cake (MD)**	**TSS filtrate (MD)**	**CE (MD)**
	g/kg$_{DS}$	**(%)**	**%**	**%**	**g/L**	**%**
WWTP 1	0	1.56	11.0	13.7	0.60	96.9
	4	1.51	11.5	15.8	0.75	96.4
	8	1.44	12.4	16.0	0.48	97.2
WWTP 2	0	2.94	10.3	12.9	0.32	99.1
	4	2.86	11.5	13.3	0.33	99.1
	8	2.77	11.7	15.1	0.43	98.8
WWTP 3	0	2.60	11.9	13.0	0.70	97.8
	4	2.50	15.1	18.3	0.17	99.4
	8	2.35	12.5	14.7	0.52	98.1
WWTP 4	0	3.50	12.0	12.8	0.72	98.4
	4	3.23	12.1	13.8	0.47	98.7
	8	2.80	12.6	15.6	0.65	97.7
WWTP 5	0	1.74	10.8	13.5	0.47	97.7
	4	1.88	11.3	14.1	0.42	97.9
	8	1.58	11.5	14.9	0.37	97.7
WWTP 6	0	3.93	13.0	19.7	0.20	99.6
	4	3.56	13.5	19.6	0.25	99.4
	8	3.37	13.5	20.8	0.13	99.7
WWTP 7	0	3.40	13.1	17.0	0.23	99.4
	4	3.20	14.6	19.1	0.20	99.4
	8	3.04	14.6	19.8	0.35	99.0
WWTP 8	0	3.76	11.5	15.1	0.25	99.4
	4	3.01	11.7	15.2	0.12	99.7
	8	3.02	12.3	15.4	0.28	99.3

The final DS contents achieved after the two different mechanical dewatering processes are compared in Figure 24. It was observed that the final DS achieved after MD was greater than that achieved after mCFG. From this observation, compression with constant pressure method was considered more efficient than multiple centrifugation. The range of DS achieved after MD was 12.8-20.8%, which is similar to the range reported by Visigalli et al. (2018) for mechanical dewatering devices. DS range achieved after multiple centrifugation was 10.3-15.1%, which is comparatively lower than that achieved in WWTPs. This is because centrifugation performed in WWTPs is a continuous process in which the supernatant is separated from the cake, while centrifugation performed in the laboratory is a batch process in which the supernatant remains in contact with the cake until it is manually removed.

Overall, the final cake DS achieved by TC sludge was not satisfactorily higher than that of TU samples. The sludges might require higher dosages of polyelectrolyte (to achieve optimal polymer dosage) in order to produce drier cakes. This can also be an evidence of limitation of MD processes carried out in the laboratory.

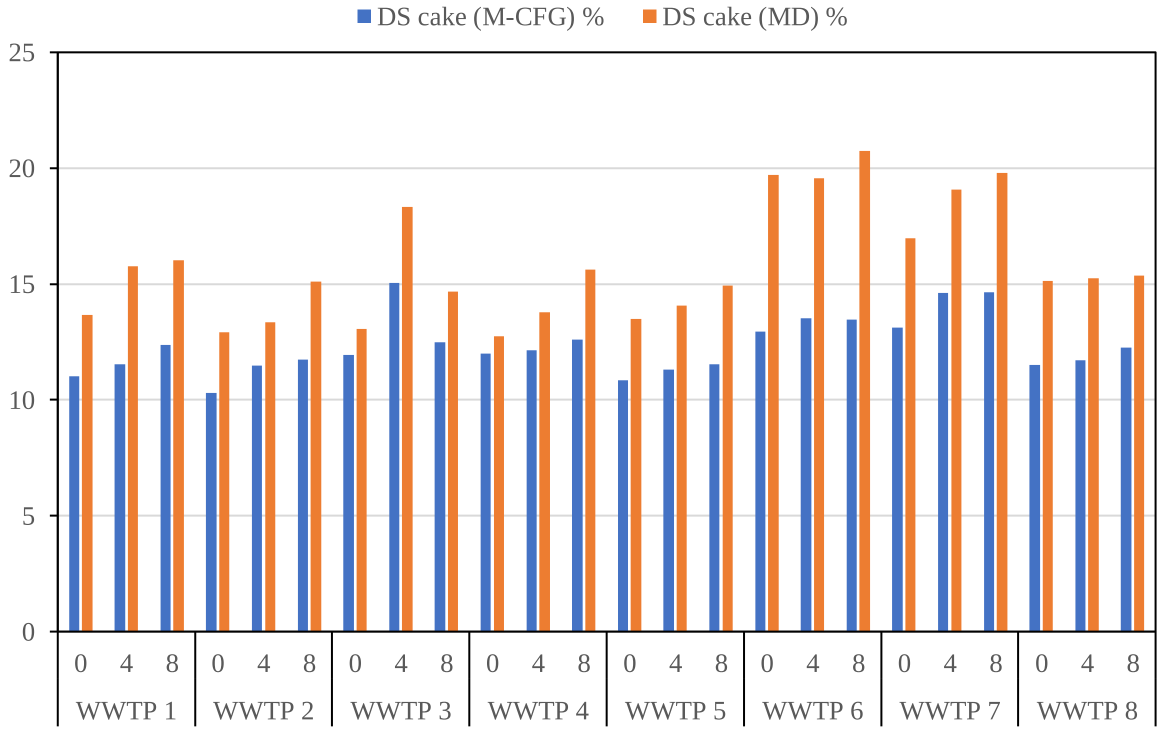

Figure 24 DS contents achieved in mCFG and MD tests carried out in the laboratory.

4.3 ELECTRO-DEWATERING

Initial DS, final DS of the cake, TSS of the filtrate, CE, and SEC after EDW of TU and TC sludges are reported in Table 7.

The range of DS content achieved after EDW is 29-45.3%. This confirmed that EDW can produce cakes with DS up to 45% as reported by many authors (Feng et al. 2014; Mahmoud et al., 2011; Tuan et al., 2012; Weng et al., 2013).

Table 7 Sludge characteristics after EDW tests.

WWTP	Polymer dosage	DS	DS cake (EDW)	TSS filtrate	Solid Capture	SEC
	g/kg$_{DS}$	(%)	%	g/L	%	Wh/kgH2O
WWTP 1	0	1.56	33.8	0.42	97.6	123.3
	4	1.51	43.2	0.75	96.1	121.3
	8	1.44	45.3	0.75	95.2	135.3
WWTP 2	0	2.94	29.0	0.35	98.9	113.4
	4	2.86	38.1	0.35	98.8	98.9
	8	2.77	38.9	0.43	98.6	106.0
WWTP 3	0	2.60	39.7	0.47	98.3	106.1
	4	2.50	42.1	0.40	98.5	109.7
	8	2.35	43.0	0.55	97.8	105.1
WWTP 4	0	3.50	30.3	0.67	98.2	101.2
	4	3.23	36.3	0.35	98.9	109.3
	8	2.80	38.2	0.60	97.6	122.7
WWTP 5	0	1.74	39.9	0.50	97.4	103.8
	4	1.88	40.2	0.50	97.3	95.3
	8	1.58	40.3	0.38	97.6	107.9
WWTP 6	0	3.93	37.9	0.85	97.9	96.8
	4	3.56	38.9	0.28	99.3	92.6
	8	3.37	40.6	0.57	98.5	106.7
WWTP 7	0	3.40	34.9	0.60	98.3	104.4
	4	3.20	38.8	0.55	98.3	114.6
	8	3.04	40.3	0.35	98.9	104.4
WWTP 8	0	3.76	29.6	0.42	98.9	173.4
	4	3.01	31.0	0.35	98.9	142.7
	8	3.02	36.3	0.28	99.2	122.5

Looking at WWTP 1, 2, 3, 4, 5, 6 and 7, the cake DS content of TC samples dosed at 4 g/kg$_{DS}$ and 8 g/kg$_{DS}$ were similar. This demonstrates that the addition of polyelectrolyte does not always confer a positive effect on the efficiency of the EDW process (Citeau et al., 2011). The polymer dosage did not directly contribute to the final cake DS achieved during the polarization phase. As already known, EDW process is performed with a preliminary compression at constant pressure and the increasing polyelectrolyte dosage mainly influences this phase. The added polyelectrolyte makes the sludge flocculate and facilitates the drainage of interparticle water during the compression phase. When the water removal by compression is reduced, the DS increases, and the permeability of the sludge decreases to the point that the polyelectrolyte is no longer able to exert observable effects. When the electric field is applied, the water removal rate suddenly surges up and is mainly due to the mechanisms of electrophoresis and electroosmosis, which depend strongly on factors such as the size and shape of the particles, the zeta potential, the viscosity of the liquid and the dielectric constant, rather than the permeability of the sludge (Mahmoud et al., 2010). It is believed that conditioning enhances the compression phase rather than the stage in which the power supply is switched on. Thus, this explains why dosing at 8 g/kg$_{DS}$ provided better results with m-CFG and MD, but proved to be not as efficient in EDW. However in both MD and EDW, the addition of polyelectrolyte was proved to be necessary to induce formation of a network of flocs, resulting in reduced water retention by the sludge as stated by Saveyn et al. (2005b).On the contrary, for the sample of WWTP 8, it seems that the dosage had a considerable effect on the increase of final dry matter, probably due to the high initial DS content of both TU conditioned at 4 g/kg$_{DS}$ as well as 8 g/kg$_{DS}$. Indeed, that sample might need higher dosage to achieve higher final DS contents. In conclusion, ZP, CST and SRF are good indicators for mechanical dewatering, but does not provide any information on the suitability for the application of EDW (Visigalli et al., 2018).

Comparing the results of MD and EDW achieved in the same laboratory scale device, it was observed that from a range of final cake DS of 12.8-20.8% obtained by MD, EDW was able to increase DS of more than 15-30%. Figure 25 shows that EDW produced drier cakes than MD tests. With respect to the final DS of the cake, EDW is the most favorable technique. The CE of both MD and EDW were in the short range of 95.2-99.7% because the dewatering process was carried out on the same laboratory scale device with same type of filter (same pore size). In order to understand the effect of electric field on the disruption of sludge particles, analysis on the filtrate to check the presence of organic matter and EPS should be carried out.

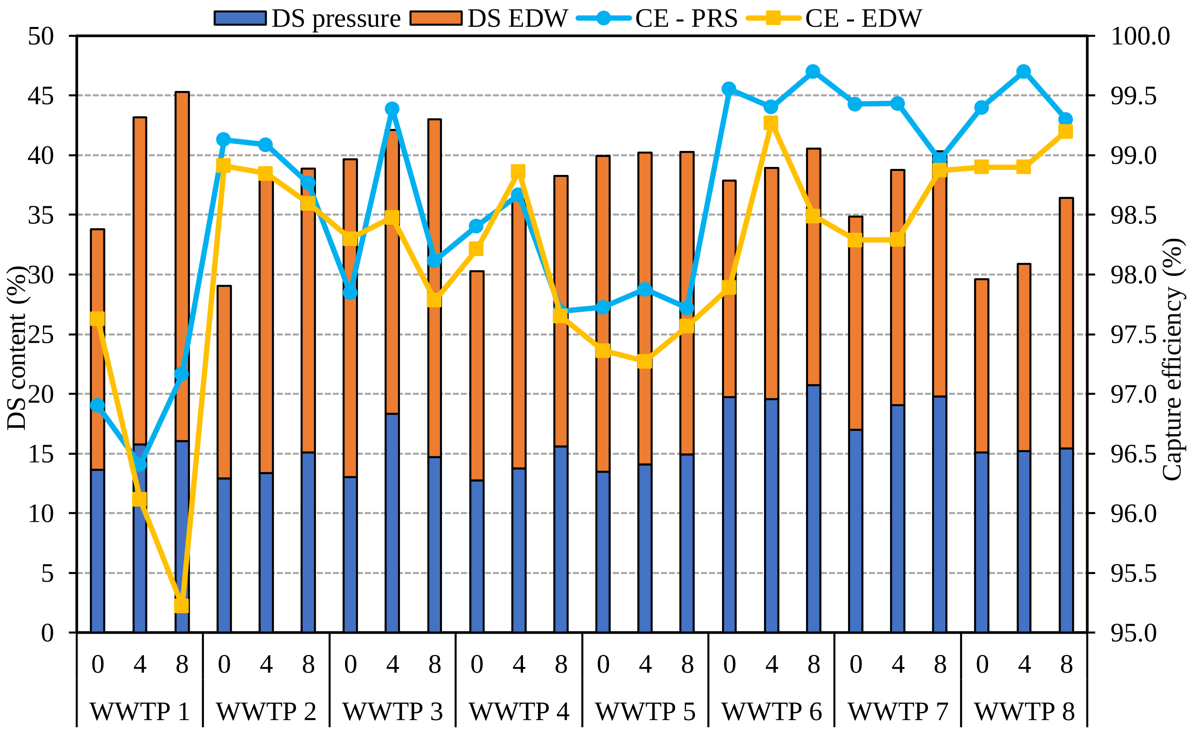

Figure 25 EDW and MD performance overview.

EDW is a suitable technique that can produce sludge cakes that are suitable for incineration without additional any preliminary thermal treatments (Visigalli et al., 2018). EDW is reported to remove the interstitial and vicinal water to some extent which is not possible by CMD (Tuan et al., 2012). Although the SEC of EDW process is in the range of 92.6-173.4 Wh/kg$_{H2O}$, which is less than the thermal drying (612-1200 Wh/kg $_{H2O}$) (Mahmoud et al., 2013, 2011), it is expected to be drastically higher than CMD although it depends on the electric field applied and the duration of application. The energy consumption is not uniform throughout the process and it is observed that it increases with the increase in DS of the sludge. Therefore, energy consumption of EDW process is different for different sludges. Therefore, the overall dewatering cost varies for each sludge and is significantly increasing if

CMD is replaced with EDW which is undesirable. However, with a DS range of 29-45.3% achieved by EDW (laboratory), the volume of sludge is drastically reduced which reduces complications in the choice of transport vehicle and the transportation cost. In order to be able to optimize the polymer dosage and maximize the dewatering efficiency, an economic analysis that takes into account all the aspects involved is required.

4.4 RELATIONSHIP OF INDICATORS WITH SLUDGE DEWATERABILITY

4.4.1 **CST vs. DS (TU/TC)**

Table 2 shows that CST decreased when the DS content of TU/TC samples decreased. This is true when considering a single WWTP, due to the influence of the conditioning process. Indeed, water content increases when polymer is added to the sludge suspension. Therefore, as already reported in literature (Vesilind, 1988), CST is strictly dependent on the initial DS content. However, considering sludge samples from different WWTPs, CST is not only affected by DS content. The dispersion diagram in Figure 26 shows that there is no correlation between CST and DS content. Therefore, CST values of different WWTPs plants cannot be compared.

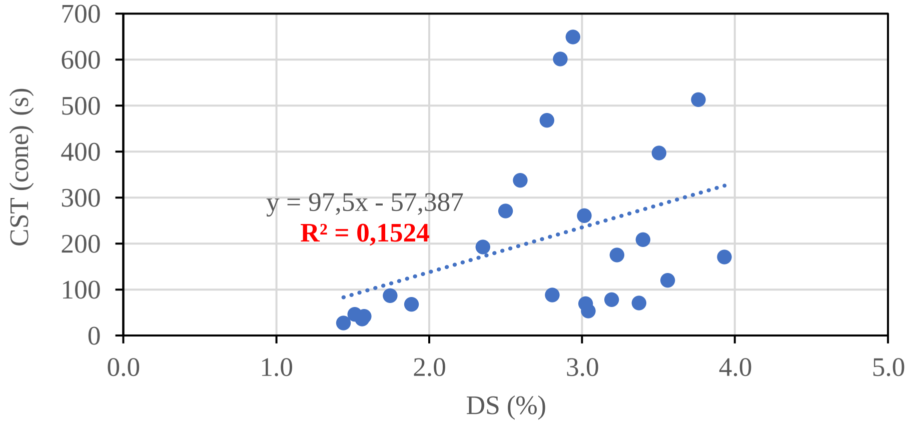

Figure 26 Dispersion diagram of CST vs. DS of TU and TC samples.

4.4.2 NORMALIZED CST vs. DS (MD)

Since CST values didn't help in comparison of characteristics of sludge from different WWTPs, normalized CST was calculated by dividing CST values by TSS (expressed as s·L/g_{TSS}) (Yu et al., 2008). Low normalized CST indicates a higher dewaterability. For each WWTP, higher the normalized CST value, lower was the DS content achieved after mechanical dewatering. This again emphasis the importance of conditioning in order to achieve higher DS contents.

Figure 27 shows the dispersion diagram of normalized CST and DS of the cake after mechanical dewatering. No correlation between normalized CST and final DS was observed. This indicates that normalized CST cannot be associated with the final DS achieved. Thus, normalized CST also do not allow to predict dewaterability of sludges.

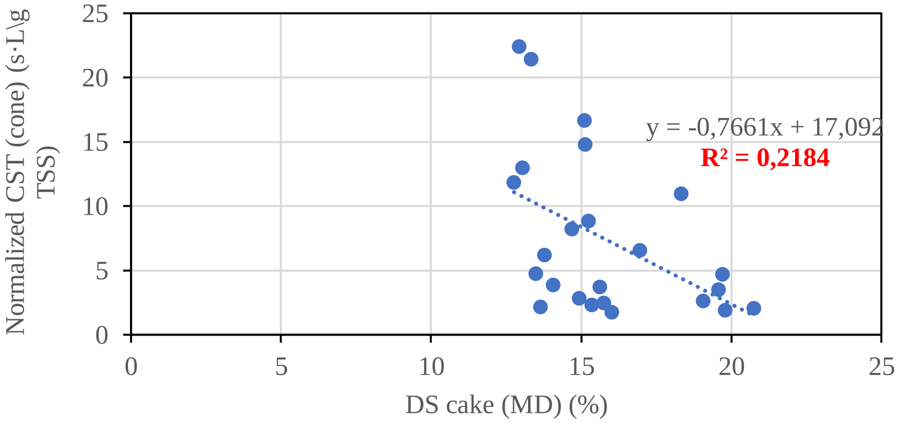

Figure 27 Dispersion diagram of normalized CST vs. DS after MD.

4.4.3 ZP vs. DS (MD\EDW)

When ZP values of TU and TC samples increased, higher was the final DS achieved after MD and EDW. ZP is an indicator for sludge conditioning. As discussed previously, addition of polymer dosage to the sludge enhances its ability to release water during the filtration process. However, ZP values of different WWTPs cannot be compared. Figure 28 shows dispersion charts of ZP and final DS content after MD and EDW. It is evident that there is no correlation between ZP and final cake solid content. Therefore, ZP cannot be directly associated with dewaterability.

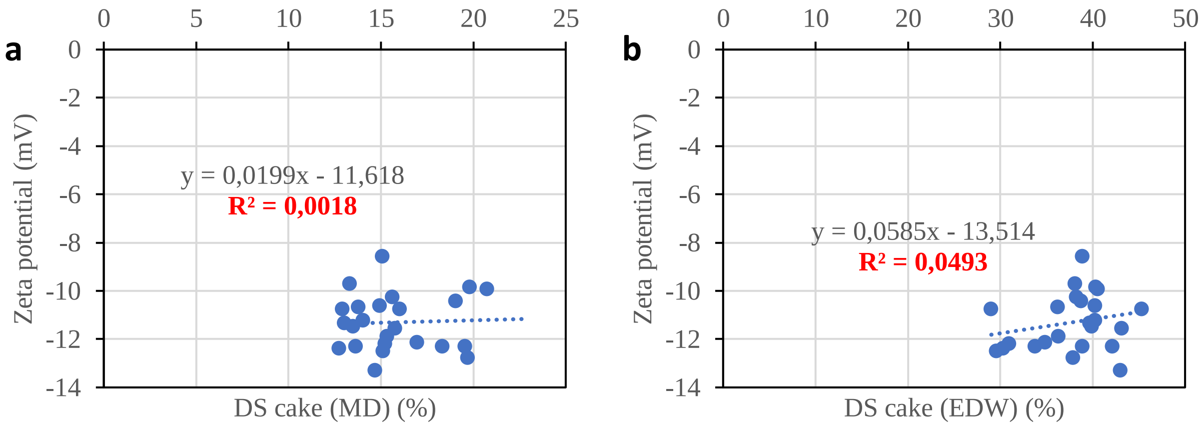

Figure 28 Dispersion diagram of ZP vs. DS after (a) MD and (b) EDW.

4.5 PRELIMINARY STATISTICAL EVALUATION

4.5.1 RELATIONSHIP BETWEEN SLUDGE CHARACTERISTICS AND CST

The ANOVA results reported in Table 8 show that polymer dosage is affecting CST, but only when considering also the origin of the sludge (namely the WWTP): CST is reduced by increasing the polymer dosage but there is not any general model that can describe the relationship between CST and polymer dosage (p-value > 0.05) since CST is strictly dependent on the origin. Moreover, the origin of the sludge and the initial DS of the sludge are strongly influencing the CST value, as already discussed in Section 4.4.1. This confirmed the fact that comparison of CST values of sludges from different WWTPs containing different DS amounts is not feasible. CST is useful to evaluate the effect of polymer dosage in a selected WWTP but cannot be used to assess sludge dewaterability.

As shown in the following section, zeta potential provides information about the polymer dosage in a selected WWTP. This means that, similarly to polymer dosage, it influences CST only when considering the sludge origin. Indeed, there is not any model that is able to describe the relationship of zeta potential with CST independently, without considering the source of WWTP or the DS content of the sludge.

Skinner et al. (2015) stated that higher the organic fraction, lower is the dewaterability due to a higher EPS fraction. As CST is not representing the whole dewatering, results cannot be compared with dewaterability. Here, VSS has been found to slightly affect sludge filterability measured by CST: higher the organic fraction, lower is the filterability. However, the generated model had a scarce reliability, with a low R^2 value.

Table 8 Results of ANOVA and GLM over CST.

Source	F-Value	P-Value	R^2
Polymer dosage	3.77	0.065	10.7%
WWTP	19.37	0.000	83.9%
Polymer dosage	12.08	0.001	
WWTP	26.46	0.000	91.8%
DS	28.45	0.000	
WWTP	8.45	0.000	74.4%
Zeta potential	7.42	0.017	
VSS	5.76	0.025	17.1%

As already reported in Figure 21, CST (cylinder) and CST (cone) well correlates (R^2=95.1%), meaning that only one of the two reservoirs can be used. Similarly, as shown in Figure 22, SRF and CST are well correlated (R^2=86.9%). In literature, it has been demonstrated that, differently from CST, SRF is independent of the DS values and may be used to compare filterability between different WWTPs. Here, correlation between CST and SRF values seems to contradict this observation. However, SRF experiments should be extended to all the eight WWTPs in order to confirm this behavior.

4.5.2 RELATIONSHIP BETWEEN SLUDGE CHARACTERISTICS AND ZP

Table 9 shows the results of the ANOVA and GLM for zeta potential. It has been found that zeta potential is effectively influenced by the polymer dosage, but only when considering a single WWTP. Indeed, as stated in previous sections, if the dosage increases, ZP increases too.

Table 9 Results of ANOVA and GLM over ZP.

Source	F-Value	P-Value	R^2
WWTP	22.48	0.000	73.2%
Polymer dosage	5.98	0.002	

ZP is also influenced by DS and TSS, when considering the origin of the sludge. This is because DS and TSS of the samples change according to the dosage during conditioning. Therefore, it is again proving the influence of polymer dosage on ZP values, hence evidencing the fact that ZP can be used to assess the conditioning step.

4.5.3 RELATIONSHIP BETWEEN SLUDGE CHARACTERISTICS AND MD

The results of ANOVA describing the DS content after MD (Table 10), show that, focusing on each WWTP, the final DS content increases with the polymer dosage. Therefore, statistical analysis supports the results discussed in Section 4.2.

It was confirmed that ZP influences the final DS content after MD when considering a specific WWTP. This again illustrates that addition of polyelectrolyte is directly proportional to the performance of MD. As discussed earlier, ZP assesses the effectiveness of conditioning and this process has been proven to be an essential step during dewatering.

For each WWTP, a model was developed with ZP and DS of centrifuged sludge. The models showed that increasing both ZP and DS after centrifugation, led to an increase of DS after MD. In other words, higher DS cakes can be achieved with an increase in the polymer dosage and improving thickening. Hence, conditioning and thickening process contributes in a good way to MD.

From the statistical analysis, it was found that both CST and SRF influences the MD process: lower the filterability time, higher the DS contents achieved after MD. This behaviour comes from the relationship of CST and polymer dosage. However, the models generated by GLM had low R^2 values for both SRF and CST, meaning that they can hardly be used as indicators to predict sludge dewaterability. This supports the results discussed in Section 2.4.

Finally, ANOVA showed that VS/DS and the DS content after CFG influence MD efficiency. From the model, it is inferred that VS negatively affects the dewaterability of the sludge while the DS content after CFG has a positive effect. Though, the fit of the data to the generated model is poor, the inferences from the model are valid since it supported by the previous results.

Table 10 Results of ANOVA and GLM over DS content after MD.

Source	**F-Value**	**P-Value**	**R^2**
WWTP	11.48	0.000	82.1%
Polymer dosage	8.14	0.014	
WWTP	29.07	0.000	91.6%
Zeta potential	32.20	0.000	
WWTP	36.60	0.000	95.2%
Zeta potential	22.90	0.000	
DS cake (CFG)	10.66	0.007	
CST (cone)	4.59	0.044	13.5%
SRF	7.19	0.023	36.0%
VS/DS	7.92	0.010	42.7%
DS cake (CFG)	9.82	0.005	

4.5.4 RELATIONSHIP BETWEEN SLUDGE CHARACTERISTICS AND EDW

Table 11 shows the ANOVA results of DS content after EDW. It has been demonstrated that polymer dosage slightly influences the final DS of the cake after EDW, probably due to its strong effect on the preliminary compression carried out during the tests.

Focusing on specific WWTPs, ZP influences the EDW process: increase in ZP results in higher final cake solids. Again, the significance of conditioning to enhance initial compression phase is displayed.

CST and SRF seems to have an effect on final cake solids after EDW. It is inferred that CST and SRF does not replicate the actual EDW process and it can only provide information about of water removal during initial constant compression phase. Therefore, using CST and SRF to assess EDW process is inappropriate. Statistical analysis (low R^2 values) also supports the fact that CST and SRF can be used as indicators as discussed in Section 2.4. However, CST and SRF can be applied for the evaluation of the conditioning step or the dewatering performance by mechanical means in a specific WWTP.

Table 11 Results of ANOVA and GLM over DS content after EDW.

Source	**F-Value**	**P-Value**	**R^2**
Polymer dosage	10.46	0.004	29.2%
WWTP	4.87	0.005	72.6%
Polymer dosage	26.94	0.000	
WWTP	5.15	0.004	63.1%
Zeta potential	16.74	0.001	
CST (cone)	9.87	0.005	27.8%
SRF	7.45	0.021	37.0%
Conductivity	11.00	0.003	30.3%
Polymer dosage	16.85	0.001	59.5%
Conductivity	17.47	0.000	
Zeta potential	5.45	0.030	42.0%
Conductivity	16.72	0.001	

From the analysis, it was found that conductivity hinders achieving higher final cake DS. In other words, DS after EDW is inversely proportional to the conductivity of the sludge: higher the conductivity of the sludge, lower is the final cake DS. However, this result is in contrast to what is generally reported in literature (Olivier et al., 2015). Indeed, a higher sludge conductivity should correspond to higher developed current densities, which in turn make the dewatering rate to increase. The results reported in this work confirmed the higher current densities at higher conductivity values, but DS content after EDW was negatively affected. This fact may be attributed to a dissipation of the energy through Joule effect, which caused an increase of the temperature that may have allowed water evaporation during the process. Similar results have been found when considering also the polymer dosage or the zeta potential in the ANOVA: addition of polyelectrolyte has a positive impact on overall performance of EDW while conductivity reduces the efficiency of the process.

From ANOVA results (Table 12), a relationship between SEC and conductivity was found with respect to each WWTP. From the model, it is defined that an increase in conductivity corresponded an increase in the SEC. Increase in SEC is undesirable since the operational cost of EDW increases. Therefore, the model supports the previous inferences stating conductivity has a negative impact on the overall performance of the EDW.

Table 12 Results of ANOVA and GLM over SEC.

Source	F-Value	P-Value	R^2
WWTP	5.35	0.003	66.4%
Conductivity	6.31	0.026	

ΔDS is the difference of DS content after EDW and DS content after MD. It is a representation of the increase in DS due to the application of electric field. Therefore, it can be used as a tool to assess the performance of EDW during the polarization phase. A model was generated that established a relationship between DS content after centrifugation, polymer dosage, conductivity and ΔDS. The results of ANOVA are shown in Table 13. According to the model, DS cake (CFG) and conductivity show a negative effect (confirming the hypothesis of the increase of the temperature), and the polymer dosage has a positive effect when electric field is applied.

Table 13 Results of ANOVA and GLM over ΔDS.

Source	F-Value	P-Value	R^2
Polymer dosage	9.97	0.005	51.4%
Conductivity	9.09	0.007	
DS cake (CFG)	8.08	0.010	

It is interesting that the results of ANOVA for EDW are different from those achieved with MD data. Therefore, it is proven that sludge characteristics does not influence MD and EDW in a similar way.

4.6 ECONOMIC ASSESSMENT

Economic assessment was carried out to evaluate the possibility to replace conventional dewatering devices with an EDW device. The high consumption of electricity (more than 92.6 Wh/kg_{H2O}) induced by the EDW process seems to suggest that the use of an electric field in a commercial-scale prototype, as a substitute for conventional mechanical dewatering (CMD), is not economically viable. However, any reduction in the polymer dosage and a decrease in the volume of dewatered sludge due to increased DS contents can produce significant savings in the cost of conditioning and disposal. The results of the economic assessment are reported in Table 14.

Different polyelectrolyte such as Tillmanns Tillflock 6480 (powder), Tillmanns Tillflock CL 1480 (emulsion), Tillmanns Tillflock CL 1853/1953 (emulsion) are used in different WWTPs (Table 2). In WWTPs, if the polyelectrolyte used is in emulsion form, twice the quantity of defined dosage is added to ensure proper conditioning which means the cost of conditioning is also doubled. Therefore, conditioning performed in WWTPs cannot be compared with one another. As said earlier, to make a uniform comparison of performance of EDW within the WWTPs, all sludge samples are dosed at 4 g/kg_{DS} and 8 g/kg_{DS} with the same electrolyte Praestol 645 BC (powder).

Table 14 Results of the economic assessment.

WWTP	**Method**	**Polymer dosage**	**Costs**				
			Conditioning	**Dewatering**	**Disposal**	**Total cost**	**SAVING**
		g/kg$_{DS}$	**(€/m^3)/year**	**(€/m^3)/year**	**(€/m^3)/year**	**(€/m^3)/year**	**%**
1	CMD	4.4	0.20	0.23	12.87	13.29	
	EDW	0	0.00	2.07	7.33	9.39	**29.34**
	EDW	4	0.18	2.35	5.82	8.35	**37.17**
	EDW	8	0.36	2.67	5.60	8.63	**35.11**
2	CMD	18.2	1.29	0.37	0.75	2.41	
	EDW	0	0.00	2.33	0.68	3.01	-24.81
	EDW	4	0.21	2.42	0.53	3.16	-31.14
	EDW	8	0.43	2.62	0.52	3.57	-47.94
3	CMD	13.3	0.83	0.40	6.42	7.65	
	EDW	0	0.00	2.38	3.77	6.15	**19.58**
	EDW	4	0.19	2.53	3.60	6.31	**17.47**
	EDW	8	0.38	2.45	3.50	6.33	**17.21**
4	CMD	23.4	1.96	0.58	9.31	11.86	
	EDW	0	0.00	3.06	7.25	10.31	**13.04**
	EDW	4	0.25	3.65	6.27	10.18	**14.13**
	EDW	8	0.51	4.23	5.92	10.66	**10.06**
5	MD	10.4	0.33	0.19	11.29	11.81	
	EDW	0	0.00	1.47	5.52	6.99	**40.85**
	EDW	4	0.13	1.37	5.41	6.91	**41.53**
	EDW	8	0.25	1.54	5.43	7.23	**38.79**
6	CMD	8.6	0.61	0.18	2.44	3.24	
	EDW	0	0.00	1.70	1.36	3.06	**5.38**
	EDW	4	0.29	1.65	1.35	3.29	-1.58
	EDW	8	0.57	1.99	1.29	3.85	-19.06
7	CMD	27.4	2.24	0.40	6.56	9.21	
	EDW	0	0.00	1.91	5.18	7.09	**22.97**
	EDW	4	0.25	2.28	4.73	7.26	**21.11**
	EDW	8	0.50	2.13	4.61	7.24	**21.38**
8	CMD	19.7	1.78	0.45	1.59	3.82	
	EDW	0	0.00	4.13	1.77	5.91	-54.70
	EDW	4	0.27	3.56	1.70	5.54	-44.99
	EDW	8	0.55	3.47	1.49	5.50	-44.07

Considering the conditioning step, EDW tests were carried out on sludge samples with lower dosages than the dosage used in all the WWTPs, except for WWTP 1.

It is observed that the cost of CMD is lower than EDW, due to the lower energy consumption. But it is noted that the disposal of sludge represents the greatest share in the cost of the treatment of the sludge in conventional WWTPs. A higher DS content in the final cake considerably reduced the disposal costs in comparison with the site-specific disposal cost. In WWTPs 1, 4 and 5, the cost saving was the highest with the TC dosed at 4 g/kg_{DS} confirming the fact that an increase in dosage did not directly contribute to the efficiency of the process. Even though the TC dosed at 8 g/kg_{DS} produced lesser volumes of dewatered sludge and contributed to lower disposal costs, the TC dosed at 4 g/kg_{DS} significantly saved the cost in conditioning. For WWTPs 3, 6 and 7, the maximum savings for the EDW process were achieved with the TU sample because of the absence of conditioning. Overall, the higher disposal cost of TU of WWTP 3, 6 and 7 was offset by the cost saved on conditioning and dewatering.

For WWTPs 2 and 8, due to massively high cost of EDW, it is observed that the CMD is economically the better option. But it is to be noted that the DS achieved after EDW is above 25%.

Therefore, the economic analysis has highlighted the fact that the dosages used and the conditions adopted while testing in laboratory allowed to reach a higher final DS content resulting in significant reduction in the sludge volume, but at the expense of a slightly higher total costs in the cases of WWTP 2, 6 and 8. EDW can result in a saving of minimum 10% up to 41% saving in the best case. We should also remember that a pre-thickening was performed in the laboratory by centrifugation, in order to increase the DS content up to 8-10% and reduce energy consumption in the first phase of EDW. As per the economic assessment, conditioning cannot be eliminated in dewatering process of WWTP 3,6 and 7 to save cost.

Remarkably, EDW can be performed on liquid as well as mechanically dewatered sludge. Even if the cost of dewatering is high, it is proven that higher final DS can be achieved by EDW in comparison with CMD. Moreover, using EDW process as an additional treatment method for CMD is easy and economically feasible and may be used to replace thermal treatments methods before sludge incineration (Visigalli et al., 2018).

Despite of the identified disadvantages, EDW is a processing technology. Further research will unquestionably redefine the possibilities of commercial use of EDW. The economic assessment performed is simple and does not provide the information of replacing MD with EDW. Therefore, economic assessment including the investment cost, operating cost (high consumption of electricity), maintenance cost of commercial EDW machines and return of investment should be included in the future study.

5 CONCLUSIONS

In this thesis, the influence of polymer dosage in mechanical dewatering and electro-dewatering was investigated. Thickened unconditioned (TU) sludge samples were collected from eight different WWTPs located in Milan, Italy. Thickened conditioned (TC) sludge samples at selected dosages of 4 and 8 g/kg$_{DS}$ were prepared in the laboratory by means of jar test. The characterisation of sludge proved the variability of the samples under study.

ZP values were found to be increasing with the increase in polymer dosage due to charge neutralisation. From a preliminary statistical evaluation, it was found that, within a selected WWTP, ZP can be used to assess the effectiveness of conditioning. On the other hand, CST was observed to decrease with the dosage due to the increase in free water during floc formation. It was verified that CST is strictly dependent on the DS of sludge and its origin, which evidences that CST values of samples from different WWTPs cannot be compared. However, CST can be used as a tool to assess filterability and effectiveness of conditioning of samples within a specific WWTP. A good correlation between CST values measured with cylinder and cone was established, which confirmed the reliability of both the reservoirs. Similarly to CST, SRF values decreased with the increase of polymer dosage. Interestingly, a good correlation was found between SRF and CST values. However, using CST and SRF as an indicator to assess EDW is inappropriate since it fails to replicate the actual process of dewatering and it can only provide partial information about the preliminary compression phase.

Further research is needed to understand the influence of free water and bound water in dewatering. Nonetheless, TGA and DSC results show that the addition of polyelectrolyte has different effect on free water and bound water of sludges from different WWTPs.

mCFG and MD produced cakes with higher DS when the polymer dosage was 8 g/kg$_{DS}$. Between mCFG and MD, MD was found to be more efficient. EDW produced final cakes with higher DS when compared to MD. Similarly to MD, final DS content increased with the polymer dosage, but the addition of polyelectrolyte significantly contribute to dewatering efficiency only when dosed at 4 g/kg$_{DS}$. Therefore, it was inferred that polyelectrolyte influenced the compression phase of EDW rather than the dewatering kinetics during the polarisation phase. Yet, the study proves that conditioning and thickening improves the performance of both MD and EDW.

From a preliminary statistical evaluation, it was verified that VS has a negative influence over dewatering efficiency. Moreover, it was observed that an increase in sludge conductivity increases SEC values and negatively influences EDW performance. It was also observed that energy consumption of EDW increases with the increase in DS of the sludge.

Finally, in some cases, the preliminary economic assessment suggested that EDW allows to achieve savings when compared to CMD. It was found that maximum savings is achieved by EDW when the sample was dosed at 4 g/kg_{DS}. In spite of high operating costs due to the high energy consumptions, it is proven that EDW produces sludge cakes with high DS when compared to CMD, which will lead to a drastic reduction in the volume of sludge and reduces sludge handling and disposal costs.

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