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Enhanced sludge dewatering and drying comparison of two linear polyelectrolytes co-conditioning with polyaluminum chloride

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ABSTRACT

This paper investigated the influence of polyaluminum chloride (PAX-14) co-conditioning with two linear polyelectrolytes on the dewatering and drying performances of urban residual sludge. Experiments were carried out on activated sludge samples collected after thickening from the Grosses Battes wastewater treatment plant. Dual conditioning implying PAX-14 coagulant and two cationic polymers, only differing by their molecular weight, were tested. The first part of the study was an experimental study of sludge dewatering improvement in terms of dry solids content of the dewatered cake and the evaluation of specific resistance to filtration (SRF) determined using a filtration–compression cell. The results showed that dual conditioning including PAX-14 addition has a positive impact on the dewatering process, based on the increase of cake dryness limit after PAX-14 addition. It was also found that the use of filtration theory based on Carman's equation to determine the SRF parameter presents some limitations to describe accurately the filtration step. The second part of the work consisted in drying the sludge cake obtained after the dewatering stage. The results indicated that, for the same water content, the use of both substances: PAX-14 and flocculant helped to achieve higher drying rates in comparison with the use of a single conditioning to flocculate the bio-material, allowing a reduction of the drying time. Based on the statistical analysis results, the efficiency of the two conditioning types were shown to be the same. The shrinkage response exhibited a linear decrease with two zones. For both sludge conditioned, the final volume reduction was found to be closed to 70% after drying and was directly dependent on the nature of the sludge.

Keywords: Wastewater sludge treatment; Sludge flocculation; Dewatering; Convective drying; Linear polymers; PAX-14

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1. Introduction

According to the directive of the Council of European Communities concerning urban wastewater treatment [1], municipalities have to face with growing amounts of wastewater sludge. The annual sludge production in EU-15 grew from 6.5 million tons dry solids (DS) in 1992 to 8.25 million tons DS in 2010. At the same time, the production within the new member states reached 1.38 million tons DS in 2010. Taking into account the gap still to be filled in newest country members, an annual production exceeding 13 million tons DS is expected by 2020 [2]. Furthermore, the directive on waste landfill [3] has planned the progressive reduction of sludge disposal in dump sites until 2016 [4,5]. At present, two major issues are used for sludge disposal: energy valorization through incineration and agriculture valorization through landspreading [5].

Excess sludge which is produced by the biological treatment of wastewater still contains more than 99% of water at the bottom of thickeners. A further mechanical dewatering step is essential prior to drying. However, sludge is a colloidal system in which small sludge particles form a stable suspension in water, making them very difficult to be separated from the water phase. To overcome this problem, the addition of chemical conditioners such as flocculants and/or coagulants is often necessary to help the sludge particles to agglomerate into settleable flocs prior to solid–water separation, usually by mechanical dewatering. More precisely, coagulant chemical is used in sludge conditioning to destabilize colloidal suspension, during which small suspended particles can be stuck together. Concerning flocculation, it refers to the process by which destabilized particles actually conglomerate into larger aggregates which can be separated from treated water. A polyelectrolyte conditioner (flocculant) can alone be used to enhance sludge dewatering such as in the investigation by Jing et al. [6]. Vaxelaire and Olivier [7] showed that better dewatering efficiency in terms of DS content and shorter filtration time can be achieved in both a filtration compression cell and a laboratory scale belt press, by using different cationic polymers. These past decades, the application of prehydrolized polyaluminum chlorides (PACls or PAX) as coagulant has increased, particularly in China, Japan, Russia, and Western Europe [8]. As a consequence, PACls are extensively investigated for their coagulation performance, characterization, and speciation [8,9]. Compared with conventional Al salts such as $AlCl_3$ and $Al_2(SO4)_3$, PAX-14 can achieve higher coagulation efficiencies as a result of the formation of superior quality species once added to wastewater, with the highly charged tridecameric polymer (or polycation) $[AlO_4Al_{12}(OH)_{24}(H_2O)_{12}]^{7+}$, being recognized as the most important polymeric Al species [10,11].

Depending on the dewatering technique, the so-called sludge cake reaches around 15–35% of DS content, which represents the total solids captured after water removal. Thermal drying can then be used to remove totally or partially the remaining water, depending on sludge final use. This obviously reduces the mass and volume of waste and, consequently, the cost for storage, handling, and transport. The removal of water to such a low level increases drastically the lower calorific value, transforming the sludge into an acceptable combustible [12].

Conditioning, dewatering, and drying cannot be seen as independent steps. Indeed, some wastewater treatment plant managers have observed that, in some cases, the shear stresses underwent by the sludge in centrifuges will alter its drying behavior.

As thermal drying is highly energy consuming, this process still needs to be optimized [12] considering the whole chain effect including conditioning and dewatering. As just stated before, this effect is known to exist but there is not sufficient scientific papers concerning this issue [13,14].

Very little is known about the impact of dual conditioning involving PAX-14 coagulant on the dewatering and drying behaviors of urban residual sludge. Recently [15], it was shown that the sludge drying was improved thanks to the PAX-14 addition when it was used in combination with a polymer for sludge conditioning. In their research, the authors mentioned that the effect of the couple PAX-14/polymer conditioning on the efficiency of sludge treatment results in a more open sludge structure when this complex interacts with sludge particles, hence facilitating the dewatering and drying steps. Nevertheless, the effect of the PAX-14/polymer dosing on the sludge drying process needs further research to get a deeper understanding regarding the involved mechanisms. In this context, the aim of this work was to examine the impact of polyaluminum chloride coagulant co-conditioning with two types of linear polymers, on dewatering performances and subsequent convective drying behavior. The effect of wastewater sludge conditioning with PAX-14 was proposed to become a technically feasible and very effective method to enhance sludge dewaterability and drying [15].

2. Materials and methods

2.1. Sludge samples characteristics and conditioners

The study was performed on activated sludge samples collected after thickening from the wastewater treatment plant of the Grosses Battes, located close to the University of Liège (Belgium). This plant is designed for treatment of domestic wastewater from a part of the city of Liège in an amount of 59,041 PE (population equivalent). Operating on the principle of activated sludge, the plant has removal of organic carbon, nitrogen as well as phosphorous by biological process. After transportation to the laboratory, the sludge samples were stored at room temperature of 25 ± 2°C in open vessels under continuous gentle stirring. At this temperature, the industrial purpose reality can be well-simulated [16].

Before sludge was used in the flocculation step, its characteristics in terms of DS and volatile solids (VS) content were determined at the beginning of each experiment, according to standard methods [17]. Precisely, DS and VS content of raw sludge were, respectively, determined by drying repetitively the wet material at 105°C until the mass stabilization (usually 24 h), then by calcinating the dried residue at 550°C for 2 h, and weighing. Three replicated tests were carried out to evaluate the reliability of the experiments. Finally, DS and VS content of raw sludge as a percent (%) were estimated according to, respectively, (Eqs. (1) and (2)):

$$\mathrm{DS} = \frac{W_\mathrm{d}}{W_\mathrm{s}} \times 100 \tag{1}$$

where DS is the total dry solids content of the control sample (%); W_d is the total weight of the control sample, after drying at 105°C (g); W_s is the weight of the control sample, before drying (g):

$$\mathrm{VS} = \left(1 - \frac{W_\mathrm{q}}{W_\mathrm{d}}\right) \times 100 \tag{2}$$

where VS is the volatile solids content of the sample (g); W_q is the total weight of the dried sample, after calcination at 550°C (g).

The moisture content X (expressed in $\mathrm{kg_{water}/kg_{DS}}$) on a dry basis, largely used in drying studies, can also be obtained following Eq. (3):

$$X = \frac{W_\mathrm{s} - W_\mathrm{d}}{W_\mathrm{d}} \tag{3}$$

Table 1 presents DS and VS characteristics obtained for sludge collected during two successive weeks. The DS values are slightly different, which can be explained by a possible variation of sludge quality from one week to another. The repeatability of the measurements can be considered as satisfactory with regard to standard errors below 0.05%. Concerning the VS content, the values can be considered as constant and stable within the considered time span.

Table 1
Sludge characteristics

	Week 1	Week 2
Dry solids content (%)	0.9 ± 0.01	0.8 ± 0.02
Volatile solids content (%)	60.5 ± 0.5	60.7 ± 0.2

The polyaluminum chloride coagulant was commercially available PAX-14 from Kemira Rotterdam (basicity 26 ± 6%; density of 1.3 kg/L; Al concentration of 7.2 ± 0.3 wt%). PAX-14 solution was characterized by the presence of the highly charged tridecameric polymer or polycation $[\mathrm{AlO_4Al_{12}(OH)_{24}(H_2O)_{12}}]^{7+}$, in short referred to as the $\mathrm{Al_{13}}$-polymer, as explained in Section 1.

About the two cationic polymers used in this study, they were obtained as 40 wt% active substance from the "French National Society" supplied in emulsion form. The one, referenced as 640 LH was a linear polymer with a low molecular weight, whereas the other (640 CT) was a linear polyelectrolyte with a high molecular weight. Both polymers were obtained with a high charge density. These charged organic polymers gained a large market share over the last decades in sludge treatment since they can be dosed in much lower quantities than inorganic flocculants, such as lime and iron chloride [18]. Furthermore, these organic polyelectrolytes are easily biodegradable and can be obtained at economic costs. The characteristics of the two polymers are summarized in Table 2.

2.2. Sludge conditioning

Before the sludge was used for dewatering tests, it was conditioned at the laboratory, aiming at mimicking similar operating conditions. The chemical conditioning implies the addition of undiluted amount of PAX-14 in combination with cationic polymer [19].

A classical Jar test device (Floctest, Bioblock scientific 82993) was used to mix the couple PAX-14/polymer with the sludge. More specifically, 600 mL of sludge were mixed in a beaker of 800 mL, PAX-14 was firstly added (typically 0; 4 and 8 g of PAX-14/$\mathrm{kg_{DS}}$ depending on the experiment) while intensive stirring was applied for 1 min at 120 rpm. Then a defined quantity of the diluted polymer solution (prepared the day before its use) was added rapidly and further stirring was applied at the same rotation speed and time (120 rpm, during 1 min) to promote PAX-14/polymer dispersion. After this period, the

Table 2
Characteristics of cationic polymers, used for sludge conditioning[a]

Polymer	Molecular weight 10^6 (Da)	Charge density (mol%)	Structure (–)
640 LH	2–4	60	Linear
640 CT	6–9	60	Linear

[a]Data obtained from the supplier (FNS).

rotation speed was reduced and the sludge was gently stirred at 40 rpm during 3 min, to promote flocs growth. Once the supernatant removed, the sludge can be used for the dewatering stage. The required polymer dosage was obtained using capillary suction time (CST) method, described in detail in the following part.

2.3. CST measurements

The time that the filtrate requires to travel a fixed distance in the filter paper is referred to as CST. The whole purpose of CST is to determine dewatering characteristics of a given sludge rapidly and easily. A large CST is usually indicator of poor sludge dewaterability.

The apparatus consists of a timing device, an upper plate containing probes that activate the timing device, and a lower plate that holds the filter paper, and a metal sample container [20]. A sample of conditioned sludge was placed in the sample container. As water migrates through the filter paper (Whatman filter #17) and reaches the first probe, it activates the timer. When water reaches the second probe the timer stops. CST is generally plotted vs. chemical dosage. The dosage that gives the fastest time is considered the optimum chemical dosage [21,22]. Even though the use of this method is controversial, it remains largely employed in the literature [19,23]. CST measurements were performed three times in order to evaluate the reproducibility of the experiment, using a Triton Electronics 304 M CST meter.

2.4. Sludge dewatering

After conditioning, the dewatering process was realized using a normalized filtration–expression cell (AFNOR 1979). The cell was a 270mm-deep cylindrical stainless steel chamber with an internal diameter of 70 mm (Fig. 1). A perforated disk was located at the bottom of the cylinder in order to support the filter medium. Filter medium was polypropylene material with permeability of 8 L/dm^2/min and a thickness of 0.77 mm. The flocculated sludge was poured with the

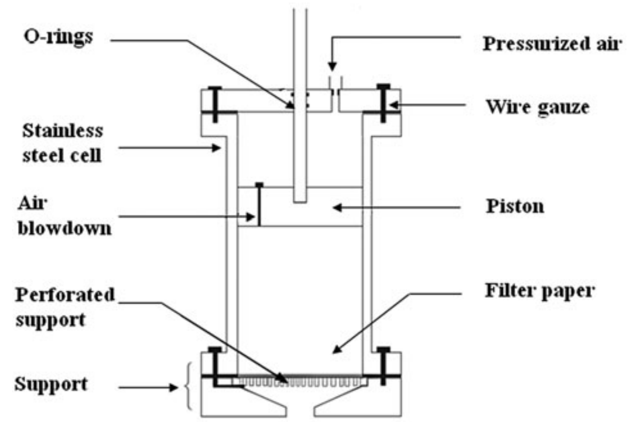

Fig. 1. Filtration–expression cell.

supernatant into a filtration cell. Then, the pressure on the piston was applied and controlled by pressurized air; it was fixed at 5 bars.

When filtration cell device is filled by the flocculated sludge, a certain amount of the supernatant flows by gravity: this volume of water is called the gravity drainage volume. This amount of water is, in principle, not taken into account to estimate the total volume of the filtrate, because at this stage, no pressure is still applied to the sludge sample (the gravity drainage volume will be subtracted from the total volume of the filtrate at the end of the experiment). The mass of the collected filtrate was recorded every 10 s on personal computer linked to a precision balance device. The filtration was stopped after a time fixed at 1.5 h for all experiments. Thus, the filtration time can be the same for all tests in order to provide a significant comparison between them. Time needed to complete filtration varies significantly between each test, and 1.5 h was supposed to be sufficient for all trials to be fully filtrated.

The end of the filtration phase can be obtained by linear fitting adjustment. To do so, the mean square error (MSE) (Eq. (4)) and the correlation coefficient R^2 (Eq. (5)) were calculated; then, fitted curve was determined using a defined program in MATLAB software. A straight line was adjusted initially on the first five data points, and then the following points were added one by one. The end of the linear part corresponds to the experimental point from which MSE increases and R^2 coefficient drops [14]. Fig. 2 shows the evolution of the two parameters (MSE and R^2) as a function of the experimental points and the transition between the two area parts, indicated by the black line in that figure.

$$\mathrm{MSE} = \sqrt{\frac{\sum_i^n (x_{\mathrm{cal}_i} - x_{\exp_i})^2}{n-q}} \quad (4)$$

$$R^2 = \frac{\sum_{i=1}^n (x_{\mathrm{cal}_i} - \overline{x_{\exp}})^2}{\sum_{i=1}^n (x_{\exp_i} - \overline{x_{\exp}})^2} \quad (5)$$

where $x_{\exp}$ is the experimental values; $\overline{x_{\exp}}$ is the mean of experimental values; x_{cal} is the fitted values; n is the number of observations; q is the modeling parameters number.

Before drying, sludge cakes obtained after mechanical dewatering were extruded through a circular die of 14 mm of diameter and cut at a height of 14 mm, yielding cylindrical samples with mass of approximately 2.5 g, as used in several industrial belt dryers.

2.5. Convective drying rig

Convective drying experiments (Fig. 3) were carried out in a so-called "micro-dryer" specially designed for handling small extruded samples with a mass between 0.5 and 5 g. The micro-dryer is a classical convective rig controlled in relative humidity,

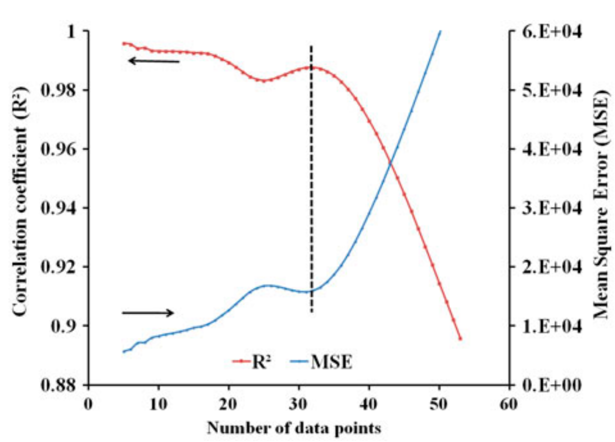

Fig. 2. Evolution of the two parameters (R^2, MSE) as a function of the considered experimental points for the fitting of Carman's equation.

temperature, and air velocity, which has already been described in detail in a previous study [24].

Drying curves representing the drying rate (kg_{water}/s) vs. the water content on a dry basis X (kg_{water}/kg_{DS}) are obtained from these mass curves vs. time data. Dividing the drying rate by the external exchange area yields the so-called Krischer's curves commonly used to study drying, i.e. the drying flux ($kg_{water}/(m^2\,s)$) vs. water content on a dry basis X (kg_{water}/kg_{DS}). The experiment ended when the sludge sample reached a constant mass. Then, the dried sample was removed from the micro-dryer and weighed on the precision balance. The time required to fully complete an experimental drying test was also evaluated, using the following method: a second-degree polynomial model was fitted on the whole drying curve and the fitted value at 95% of water removal (95% DS) was considered. This procedure allows evaluating the real drying time because beyond this value, the drying curve usually admits an asymptotic behavior rather than a constant value.

Results reported in this study refer to the following operating conditions: temperature of 130°C, superficial velocity of 1 m/s, and the absolute humidity of the air fixed at 0.005 $kg_{water}/kg_{dry\ air}$.

2.6. X-ray microtomography

To determine Krischer's curves, it is necessary to know the exchange surface developed by the sludge sample, assumed to be the external sample surface. Following a method developed inside the laboratory [25,26], it was evaluated by using X-ray microtomography, acting as a medical scanner. This method allows the determination of shrinkage curves from series of 2D crosssection images of the sample. The X-ray microtomographic device used in this study was a "Skyscan-1074 X-ray scanner". The X-ray source operated at 40 kV and 1 mA. The detector was a 2D, 768 × 576 pixels, and 8-bit X-ray camera giving images with a pixel size of 41 μm. The sample can be either rotated in a horizontal plane or moved vertically in order to get scans at different vertical positions. The minimum vertical distance between two scans equals 41 μm. The sludge sample was periodically (approximately every 5 min) removed from the micro-dryer and placed in the microtomograph. Once the sample was put in the microtomograph, a zone covering approximately a height of 10 mm was selected for tomographic investigation. The rotation step was fixed at 3.6° in order to reduce acquisition time down to 3 min. The following sequence was repeated several times during one drying run experiment: drying interruption-tomographic analysis-drying resumption.

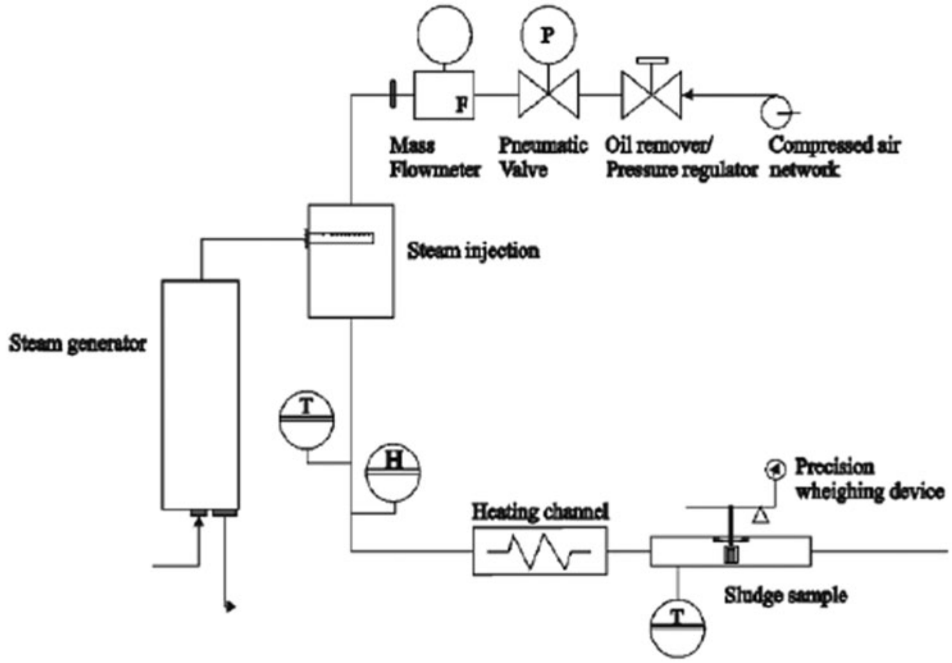

Fig. 3. Detailed scheme of the convective micro-dryer.

This exercise sequence aims to determine the height and the equivalent diameter of the sample. The sample was weighed before and after each scan, allowing to control the mass lost during each measurement. For each experimental trial, the continuous drying provides the information to access to the mass loss curve while drying with interruption was necessary to calculate the sample exchange surface. These linked data were needed to access to the evolution of the drying flux. A previous work has shown that repeated interruptions of the drying experiment have been proved to not have impact on the drying kinetics [24].

2.7. Statistical analysis

In order to determine the effect of the conditioning type on the cake DS content, drying time and drying rate to achieve 95% of water removal, analysis of variances (ANOVA) was used to test the differences between the two setups. Differences were considered to be statistically significant when p-value < 0.05. The Excel 2007 software was used to compute the data.

2.8. Experimental design

An experimental design was used to investigate the effect of input factors on a response variable. To have a better understanding of the dosing effect, five points of experiments (Fig. 4) were carried out in order to study the effect of polyaluminum chloride coagulant combined to polyelectrolyte chemical on both the sludge dewatering process and drying behavior. The polyelectrolyte interval dose, which covers the underdosing to overdosing area for the two polyelectrolytes ranges from the half to the double gram polyelectrolyte per kilogram of sludge dry matter from the optimum dosage, determined by using CST method. Concerning the polyaluminum chloride coagulant, preliminary tests [15] showed that a dose ranging above 8 g of PAX-14/kg_{DS} was observed to be ineffective, no flocs growth were observed. The method

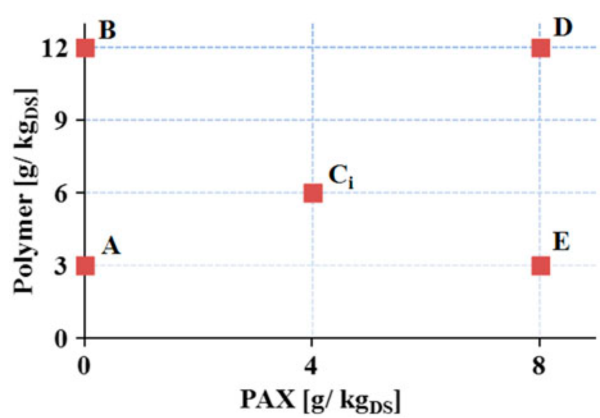

Fig. 4. Design of experiments: graphical matrix.

consisted in investigating the range below this value (0; 4 and 8 g of PAX-14/kg_{DS}). Day 1 served to determine the optimum dosage prior to the measurement campaign by CST. The trials were performed in two weeks in random sequence, except for the central point (*C*) which was repeated 4 times respectively at the beginning and the end of each week, which secured almost the same sludge characteristics. The range investigated for each parameter and experimental plan are presented in Table 3 and Fig. 4.

3. Results and discussion

3.1. Optimum polymer dosage estimation by CST

CST test was applied to conditioned sludge samples for evaluation of their dewatering capacity. For the two cationic polyelectrolytes, the CST values were plotted in function of polymers dosage, depicted in Fig. 5. The CST value decreased after the addition of the polymer and dropped to the lowest value at the dose of 6 g/kg_{DS} for both polymers. This value was defined as the optimal dosage according to the occurrence of minimum CST. As shown in that figure, the CST curve corresponding to the 640 CT polymer exhibited a slight decreasing zone compared to that obtained with 640 LH flocculant. This difference can be explained by the fact that, the estimation of the optimal dose by this method is often not easy to obtain, as mentioned by many authors (see Section 2). The dosage used below the optimum dose is called underdosing and over this value is an overdosing. As reported by many researchers [27,28] an overdosing of the polymer increases the viscosity of the filtrate and then, the flow of the filtrate through the filter paper is reduced. This phenomenon can delay the release of water and cause a deterioration of sludge dewaterability.

Table 3
Experimental design route

Experimental days	Design procedure
Monday	CST (s)
Tuesday	C_1
Wednesday	*A*
Thursday	*B*
Friday	C_2
Monday	CST (s)
Tuesday	C_3
Wednesday	*D*
Thursday	*E*
Friday	C_4

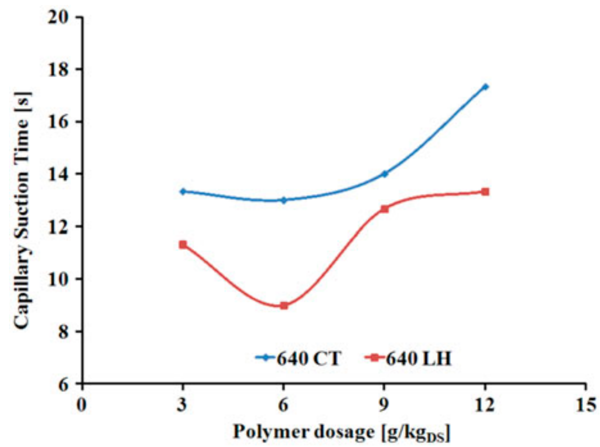

Fig. 5. Experimental results of the CST for the two polymers conditioned sludge.

3.2. Impact of sludge conditioning on the dewatering process

The dewatering process of sludge is usually described by plotting time divided by filtrate volume (t/V) as the ordinate and filtrate volume as the abscissa, as can be seen on Fig. 6. In theory, mechanical dewatering under a constant pressure drop can be divided into two successive steps: filtration and expression stages. The filtration phase is characterized by the linear part and it corresponds to cake formation due to the accumulation of the solid particles on the surface of a filter medium. The second part represents the expression phase. It describes the removal of water by cake squeezing [7]. During the filtration phase, the ability of forming the cake to let the water go through is commonly characterized by the specific resistance to

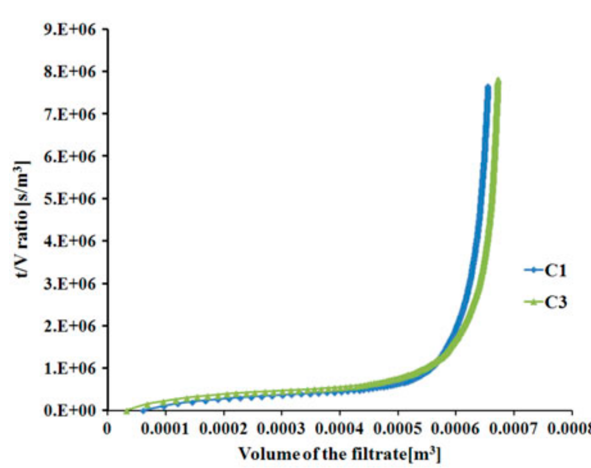

Fig. 6. Dewatering curves at the central point PAX-14/640 LH-repeatability test.

filtration (SRF) [7]. This parameter is classically calculated by the slope of the straight line portion of the graph according to the Carman's equation (Eq. (6)), based on Darcy's law [29]:

$$\frac{t}{V} = \mu\,\mathrm{SRF}\frac{C}{2\mathrm{PA}^2}V + \frac{\mu\,R_\mathrm{f}}{\mathrm{PA}} \tag{6}$$

Fig. 6 also presents two of the four dewatering repeatability curves at the central point of PAX-14/640 LH conditioners. The dewatering behavior seems to be repeatable. However, it is noticed that there is a little shift at the beginning of the filtration curves, which corresponds to the difference observed at the end of the expression phase. This difference can be explained by the fact that the initial volume of the filtrate after the correction of drainage gravity volume can slightly vary, depending on the start time of applied pressure and the time step of computer data acquisition system. This method finds its first limit, as the flocculated sludge should be thickened by gravity drainage before its introduction into the filtration-expression cell device.

In order to evaluate the sludge filterability of the two conditioning types, Table 4 presents some dewatering parameters including: the SRF values, the volume of the filtrate removed during the filtration stage (V_{carman}), the total volume collected at the end of the whole dewatering process (V_{total}). Then, the ratio of these two volumes was calculated ($V_{\mathrm{carman}}/V_{\mathrm{total}}$), the DS content of the dewatered sludge was also shown.

The SRF values for the two ways of conditioning showed a high dispersion of the data and then, stay quite difficult to analyze accurately. Finally, no relevant information can be obtained for this parameter. In fact, the importance of the use of SRF to express the ease of sludge dewatering performance should be used with caution, and remains controversial, and then difficult to achieve experimentally. Several reasons can be advanced: first, the so-called linear part of t/V vs. time (Carman's law) is really not linear; as we can see in Fig. 6. Consequently, the SRF value might be difficult to determine correctly. Similar limitations concerning SRF evaluation by using t/V vs. V dewatering curves were also observed by recent works [30,31]. Second, detection of the filtration phase mainly depends on the number of points used to calculate the MSE as we have explained in Section 2. These two reasons increase the difficulty to determine the exact numerical value of this parameter.

The ratio of the volume of the filtrate removed during the filtration stage under the total volume collected at the end of the whole dewatering process is depicted in the sixth column of Table 4. In our opinion, this ratio could provide additional information needed to access the comparative efficiency of the two conditioning types used. Regarding this parameter, the sludge conditioned with the couple PAX-14/640 CT exhibits a much higher ratio ($V_{\mathrm{carman}}/V_{\mathrm{total}}$) than

Table 4
Filtration characteristics after dewatering step

	Trials points X[a]	SRF (10^{13} m/kg)	V_{Carman} (mL)	V_{total} (mL)	$V_{\mathrm{Carman}}/V_{\mathrm{total}}$ (–)	Cake dryness (%)
PAX-14/640 LH conditioning	A (0; 3)	2.57	246.1	711.4	0.35	13.21 ± 0.12
	B (0; 6)	1.02	650.9	700.4	0.93	14.86 ± 0.03
	D (8; 12)	16.1	58	779.8	0.07	21.40 ± 0.40
	E (8; 3)	7.46	89.7	749.8	0.12	17.30 ± 0.20
	C_1 (4; 6)	4.71	157.5	658.9	0.24	17.30 ± 0.20
	C_2 (4; 6)	6.67	123	760.6	0.16	17.72 ± 0.01
	C_3 (4; 6)	4.60	150.6	654.6	0.23	17.30 ± 0.20
	C_4 (4; 6)	3.11	201.5	761.3	0.26	14.70 ± 0.30
PAX-14/640 CT conditioning	A (0; 3)	0.59	575	724.4	0.79	15.96 ± 0.01
	B (0; 6)	1.49	560.5	691.8	0.81	14.66 ± 0.33
	D (8; 12)	11.3	130.4	773.5	0.17	21.40 ± 0.30
	E (8; 3)	6.63	192.3	772.4	0.25	20.60 ± 0.10
	C_1 (4; 6)	1.19	496.8	654.5	0.76	17.00 ± 0.10
	C_2 (4; 6)	3.40	263.1	729.8	0.36	17.54 ± 0.29
	C_3 (4; 6)	1.53	474.1	671.4	0.71	17.80 ± 0.20
	C_4 (4; 6)	4.65	271.2	749.5	0.36	16.40 ± 0.20

[a]X (PAX-14 dosage in g/$\mathrm{kg_{DS}}$; polymer dosage in g/$\mathrm{kg_{DS}}$).

the sludge conditioned with PAX-14/640 LH chemical, excepted for the trial B. This statement means that sludge released some more water during the filtration step for PAX-14/640 CT conditioners than for the PAX-14/640 LH. Unfortunately at this stage, the ratio (V_{carman}/V_{total}) cannot give more information to differentiate the two ways of conditioning types in terms of dewatering performances.

The DS content of the filtrated cake obtained after a constant pressure is another important parameter that can be useful to describe the dewatering efficiency [7]. The DS content obtained for the two types of sludge conditioners are shown in the last column of Table 4. In PAX-14/640 LH series and without coagulant adding (i.e. polymer only), the DS of the dewatered cake increased from 13.2 to 14.9% when the polymer dosage increased from 3 to 6 g/kg_{DS}. Conversely, for the sludge treated by the dual chemical conditioning (PAX-14/640 CT), the DS value significantly increased from 17 to 21% for all trials involving PAX-14 addition. The best situation was shown when PAX-14 and polymer were at their maximum dosage. The increasing of DS value of the dewatered cake is the sign of enhanced dewaterability. It seems that PAX-14 contributed to increase DS content of the dewatered sludge when it was coupled with flocculant, improving the dewatering rate. Concerning the reproducibility at the central point, it was shown that the DS values were similar only for three replicates. The cake dryness of the C_4 experiment was low compared to the other replicates (around 15%), may be due to an experimental error or a possible deterioration beginning of the biological sludge material after a long period of storage. Nevertheless, the results can be considered repeatable if the point C_4 is excluded.

For the PAX-14/640 CT series and without PAX-14 addition, a decrease of the DS value from 16 to 14.7% was observed, for the same polymer dosage range used during the first conditioning. The difference observed can be probably explained by the fact that the two collected samples were produced at an interval around 2 months, with possible changes in sludge quality. This highlights the difficulty to work with such a complex and versatile material.

When PAX-14 was added in combination with 640 CT polyelectrolyte, the DS parameter significantly increased from 17 to 21%. For this conditioning, the best situation was also shown for the trial *D*, but in case of the point *E*, the cake dryness peaked at 20% while it was found close to 17% when the dual PAX-14/640 LH conditioners were used. It seems that PAX-14 does not affect sludge dewatering similarly according to both polymer types and at low dosage (3 g/kg_{DS}). Nevertheless, this second dual conditioning way confirms the positive impact of PAX-14 chemical on the sludge dewatering behavior, in terms of enhancement of cake drying when it was combined with polymer.

The statements mentioned above show that dual conditioning including PAX-14 solution change the structure of the sludge sample. In fact, the PAX-14 can achieve higher coagulation efficiencies as a result of the formation of superior reactive species once added to liquid sludge suspension, allowing to neutralize more negative sludge charges, and then an increase of the dewatering kinetics in terms of final DS content was observed. Similar (but preliminary) result was observed by Peeters et al. [15] by studying the activated sludge drying in relation with sticky phase phenomenon. Authors argued that the beneficial effect of PAX-14 conditioning of waste sludge was due to the bound hydration water associated with the super aluminum structures of PAX-14 solutions, attached on the exterior of the flocs upon dosing of PAX-14 to sludge. In addition to neutralizing the surface charge of colloidal particles, PAX-14 can bind small particles into the large flocs. This statement was demonstrated in previous works [32] by analyzing average floc size particles after sludge pre-conditioned by two chemical products (PAX-14/flocculant).

After showing that dual conditioning involving PAX-14 associated with polymer contributed to the improvement of the dewatering process, it is interesting to compare the efficiency of the two conditioning types. ANOVA was used to discriminate the two ways of sludge conditioning. Table 5 presents the data-set performed on the four replicates of the central point (C_1, C_2, C_3, and C_4) and Table 6 presents the results of the ANOVA test, in order to compare the efficiency of the conditioning type on dewatering and thermal drying behaviors. They include the sum of squares (SS), the number of degrees of freedom (DF), the mean sum of squares (MS), the *F* statistic of the model, and its associated probability (*p*-value). Statistical results on the dewatering comparison tests are illustrated in the second row of Table 6. They show that, the effect of the two conditioning types on the DS content of the dewatered cake was not significant (p-value = 0.591 > 0.05). Finally, it appears that sludge conditioned either by the complex PAX-14/640 LH or PAX-14/640 CT leads to similar dewatering performances.

3.3. Impact of sludge conditioning on the convective drying behavior

The measurements of the material moisture content as a function of time, under constant drying air conditions is called the drying curves (mass loss).

Table 5
Dewatering and drying parameters at the central point, used for statistical analysis

	Replicates at the central point (–)	Cake dryness (%)	Drying time 95% DS (s)	Drying rate 10^{-4} (g/s)
PAX-14/640 LH Conditioning	C_1	17.30	3,920	5.043
	C_2	17.72	3,720	5.282
	C_3	17.30	4,310	4.589
	C_4	14.70	3,880	5.237
PAX-14/640 CT Conditioning	C_1	17.00	3,885	5.097
	C_2	17.54	3,360	5.839
	C_3	17.8	3,490	5.619
	C_4	16.40	3,715	5.359

Table 6
Statistical parameters obtained from the ANOVA test performed on the two conditioning types PAX-14/640 LH vs. PAX-14/640 CT

Parameters tested	Source of variation	SS	DF	MS	*F*	*p*-value
DS (%)	Between groups	0.370	1	0.370	0.321	**0.591**
	Within groups	6.903	6	1.151	–	
	Total	7.273	7	–		
Drying time (s)	Between groups	238,050	1	238,050	4.062	**0.090**
	Within groups	351,600	6	58,600	–	
	Total	589,650	7	–		
Drying rate (g/s)	Between groups	0.389	1	0.389	3.820	**0.098**
	Within groups	0.610	6	0.102	–	
	Total	0.999	7	–		

Notes: SS: sum of squares; DF: degree of freedom; MS: mean sum of squares; *F*: Fischer's number; DS-p value = 0.591314461; drying time-p = 0.090461142; drying rate-p = 0.098454779.

To produce such curves, and to determine the effects of sludge conditioners on drying behavior, several drying experiments were realized. Fig. 7 shows the mass loss of the samples vs. time obtained for the different points of the experimental design. For the two series of experiments, classical drying curves were obtained showing the decrease of the mass of the samples.

For both conditioning types, a simple examination of the slope of the five curves at time approximately equal to 4,000 s shows that, the loss of water is more rapid in the case of the three PAX-14/flocculant conditioning sludge: they achieve faster stable weight whereas for the other two curves, the sample continues to lose water. As expected, the final mass of the three sample dual conditioning is higher than the single conditioning one. This is due to the fact that, these samples contain more dry solid materials at the end of drying. Finally, this result suggests that the addition of the PAX-14 on sludge conditioning has a positive impact on the drying kinetics, by reducing the drying time. Nevertheless, it can be noted that the initial water content differs from one sample to another. Further information will be provided, including the normalized drying rate calculation, which will take into account the difference between the samples initial water content.

Results can be well highlighted by analyzing the curves obtained by derivation of mass loss curves, which consists in representing the drying flux vs. water content on a dry basis. The so-called Krischer's curves are shown in Fig. 8, for both PAX-14/640 LH and PAX-14/640 CT set-up. The drying flux was calculated by dividing the drying rate by the external exchange area obtained by X-ray microtomography. This illustration of drying flux (Krischer's curve) is commonly used to understand drying phenomena [14].

The shape of the drying flux is typical of that described by Deng et al. [33] for convective drying of

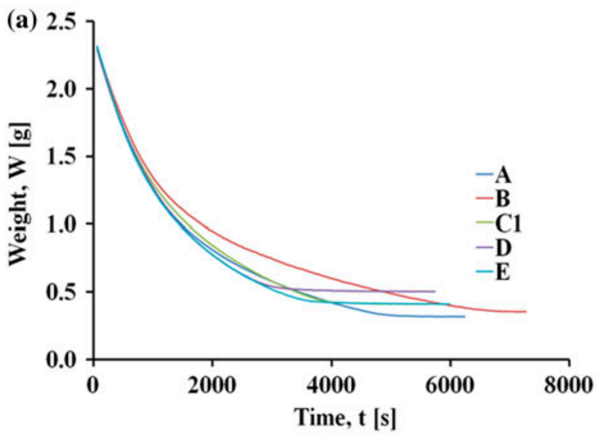

Fig. 7. Mass loss curves (decreasing mass vs. time) for the experimental design: (a) and (b) were the sludge samples, respectively, conditioned by PAX-14/640 LH and PAX-14/640 CT. *A* (0; 3); *B* (0; 6); C_1 (4; 6); *D* (8; 12); *E* (8; 3). The numbers in the brackets of each experimental point represent the required dose expressed in gram per kilogram of DS content (g/kg_{DS}), respectively, for PAX-14 coagulant and polymer dosages.

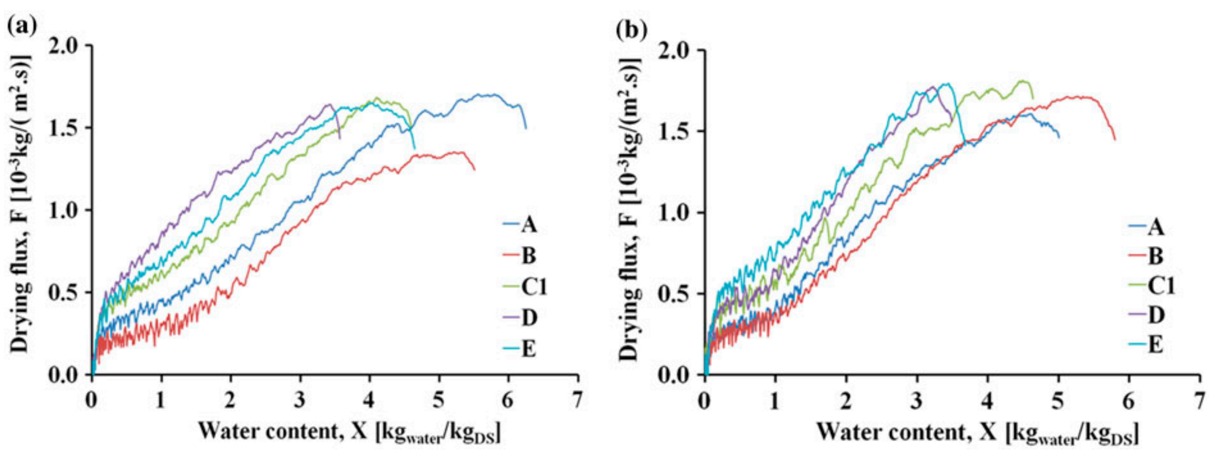

Fig. 8. Krischer's curves (drying flux vs. water content) for the experimental design: (a) and (b) were the sludge samples, respectively, conditioned by PAX-14/640 LH and PAX-14/640 CT. *A* (0; 3); *B* (0; 6); C_1 (4; 6); *D* (8; 12); *E* (8; 3). The numbers in the brackets of each experimental point represent the required dose expressed in gram per kilogram of DS content (g/kg_{DS}), respectively, for PAX-14 coagulant and polymer dosages.

sludge. In accordance with the convective drying theory, three periods can be identified [33,34]: the first period, or the preheating period, represents a period of adaptation of the sample to the drying conditions. During this period, the solid temperature and the drying rate increase considerably. The second period is called the constant drying flux rate. During this period, the supplied heat serves essentially to the evaporation of the product water. As explained by Deng et al. [33], the evaporated water in this period is free water. Finally, the last one is the long-falling drying rate period, ending with stabilization in moisture content at an equilibrium value corresponding to the end of drying. In this period, the energy serves to evaporate the product water and to increase its temperature.

It can be clearly observed that both conditioning types accelerate the drying process: for the same given water content, the drying flux of the sludge conditioned with polymer only was lower (*A* and *B* curves), while this parameter increased with simultaneous PAX-14 and polymer addition. Finally, the addition of PAX-14 coagulant allows accelerating the drying flux. This result can be correlated with that observed by Peeters [32]. The authors argued that, the sludge drying kinetic improves due to the direct PAX-14/ polyelectrolyte dosing, and can be explained by the

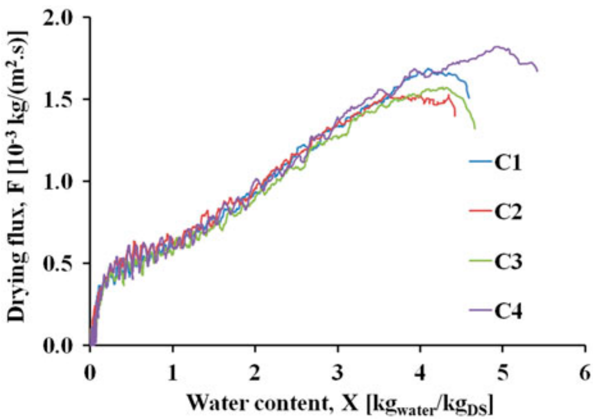

Fig. 9. Krischer's curves at the central point PAX-14/640 LH repeatability test.

absence of a crust formation at the outside of sludge sample which facilitates the water releasing. Nevertheless, more research is needed here to be more conclusive. Moreover, when the sludge was conditioned by the PAX-14 and the polymer 640 CT, the increased amplitude of the drying rate was the largest (1.8×10^{-3} against 1.6×10^{-3} kg/(m^2 s)), but probably not very significant.

The reliability of the experiment was evaluated on four replicated tests carried out on central points for the two experimental designs. A good repeatability was obtained. For the sake of clarity only one series of drying curves repeatability test, performed on sludge conditioned by the couple PAX-14/640 LH was presented (see Fig. 9). The results obtained from the PAX-14/640 CT conditioners lead to the same remarks.

In order to compare the effect of the dual PAX-14/polymer conditioners on drying kinetics of sludge samples, some drying characteristics are illustrated on Table 7. These drying parameters are defined as follows:

(1) The initial and final weight is the weight of the dewatered sample, respectively, before and after drying at 130°C.
(2) The initial water content corresponds to the initial moisture content (X_0) of the dewatered sample.
(3) The total amount of the evaporated water at 95% of dry matter content is obtained by the following formula:

$$W_{95\%\ \mathrm{DS}} = (X_0 - X_{95\%}) \times W_\mathrm{f};\ \text{with}\ X_{95\%} = (1/0.95) - 1 \quad (7)$$

where W_f is the weight of the dewatered sample after drying at 130°C (g).

(1) The drying time is the time necessary to achieve a dryness of 95% (on the mass loss curve, a plateau for which the mass of the dried sample was quite stable, is clearly observed).

Table 7
Influence of conditioning type on drying characteristics

	Trials points (gPAX-14/kg$_{DS}$; g$_{Polymer}$/kg$_{DS}$)	Initial weight (g)	Final weight (g)	Initial water content (g$_{water}$/kg$_{DS}$)	Total evaporated water at 95% DS (g)[b]	Drying time 95% DS (s)[c]	Average drying rate 10^{-4} (g/s)	Normalized drying rate (–)
PAX-14/640 LH conditioning	*A* (0; 3)	2.386	0.317	6.527	2.052	4,850	4.232	0.851
	B (0; 12)	2.386	0.355	5.721	2.012	6,100	3.299	0.664
	D (8; 12)	2.383	0.504	3.728	1.852	3,155	5.872	1.181
	E (8; 3)	2.388	0.410	4.824	1.956	3,640	5.375	1.081
	C_i (4; 6)[a]	2.387	0.399	4.982	1.967	3,957	4.971	1.000
PAX-14/640 CT conditioning	*A* (0; 3)	2.386	0.381	5.262	1.985	5,030	3.946	0.730
	B (0; 12)	2.381	0.338	6.044	2.025	5,265	3.847	0.712
	D (8; 12)	2.386	0.504	3.734	1.855	3,615	5.133	0.950
	E (8; 3)	2.385	0.493	3.838	1.866	3,450	5.409	1.001
	C_i (4; 6)[a]	2.384	0.411	4.800	1.951	3,612	5.403	1.000

[a]The C_i samples were the mean of the 4 replicates at the central point.
[b]Total evaporated water at 95% DS: the evaporated water required to achieve 95% of water samples removed.
[c]Drying time 95% DS: the drying time required to achieve 95% of water samples removed.

(2) Finally, the average drying rate during the drying process was calculated by dividing the total amount of evaporated water at 95% DS by the drying time. The normalized values were calculated using the value of the central point as a reference, for both series of experiments.

The total amount of evaporated water and the drying time were related to the $DS_{95\%}$, then, the normalized average drying flux of each sample can finally be compared with that obtained at the central point, taken as a reference.

In the case of PAX-14/640 LH conditioning and in the absence of coagulant, the results show that normalized drying rate from the sample A was higher than that obtained for sample B, by a factor of about 28%.

In contrast, when the raw sample was flocculated by dual conditioning, the normalized drying rate was shown to be faster than those obtained in case of single conditioning, with almost similar effects for the tests *E* and C_i, and a higher enhancement of drying rate for the *D* test. This result confirms that the PAX-14 allows a reduction of the drying time by increasing the rate of evaporation of water contained in the sludge, and could thereby contribute effectively to the reduction of the energy consumption necessary for drying the biomaterial.

About the sludge conditioned by the couple PAX-14/640 CT (in the case of single conditioning), as in the previous case, the sample A dried slightly faster than its counterpart B (see column 9 of Table 7). Nevertheless, the beneficial effect was shown to be weaker (2.5%). Furthermore, the result is partially in agreement with that we observed in Fig. 8(b), which clearly shows that the two curves were superimposed in the portion of moisture content between 5 and 3 kg_{water}/kg_{DS}. This difference can be explained by the fact that the drying rate does not take into account the exchange surface of the sludge sample.

When the sludge was flocculated by both PAX-14 and the polymer solution, the yield of drying process is always better when the moisture content drops. However, a difference of trend was observed, compared to the previous case: the most favorable situation in terms of drying rate enhancement was globally described by the trial *E*, whereas for the PAX-14/640 LH conditioning, the trial of the *D* sample was found to give better result. This result suggests that the two polymers flocculation mechanisms definitely depend on the chain length. In conclusion, results show that, the total evaporated water and drying time decrease are related to the increase of the average drying flux.

To compare the performance of the two conditioning types, the statistical ANOVA results on drying parameters are also shown in the last two rows of Table 6. On this table, we can see that the calculated *p*-value concerning thermal drying characteristics is more than 0.05 threshold (p-value = 0.090 and 0.098, respectively, for drying time and drying rate). According to this statistical result, it appears the two flocculation types are similar in terms of the drying performance.

3.4. Shrinkage behavior during the drying process

During drying, the texture of the material evolves, including shrinkage and cracks/voids development. In order to get the drying flux and the final dimensions of the sampling sludge at the end of the drying experiments, intermittent drying experiments were done. To do so, the sample was temporarily removed from the micro-dryer every five minutes, for X-ray microtomography scanning during three minutes. Fig. 10 shows some scanning images of sludge cake in case of the sludge conditioned by PAX-14/640 LH at the central point. The first image located on the left side was a radiography of the initial wet sample, and the last right one was the corresponding image at the end of drying. The wet cake sample is cylindrical in shape and uniform in interior density. When sample is completely dry, volume shrinkage occurred simultaneously with cracks development during drying.

These images illustrate the decrease in the sample volume when its water content is progressively falling down. At approximately $X = 1.930\ kg_{water}/kg_{DS}$, the initial cracks that survived continued to develop in both width and length. No preferable orientation was noted for the cracks to be developed on cake surface. For better performance prediction of bio-sludge drying, the analysis should incorporate both volume shrinkage and crack development. Disregarding these parameters would inevitably incorrectly estimate the drying rate.

Shrinkage phenomenon can be quantified as the ratio between the initial and final volumes, noted ε and defined as follows:

$$\varepsilon = \frac{V_1 - V_2}{V_2} \tag{8}$$

where ε is the shrinkage ratio (–); V_1 is the initial volume of the wet sample (mm^3); V_2 is the final volume of the dried sample (mm^3).

Fig. 11 shows the different shrinkage curves for sludge conditioned by the two ways flocculating tests and the corresponding fitting curves, using the X-ray

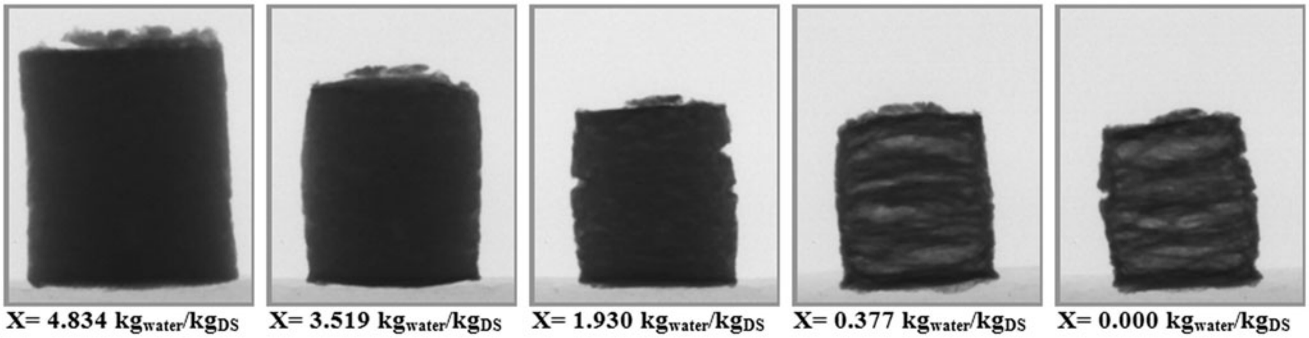

Fig. 10. Example of 2D cross section showing the volume shrinkage and crack development during the drying.

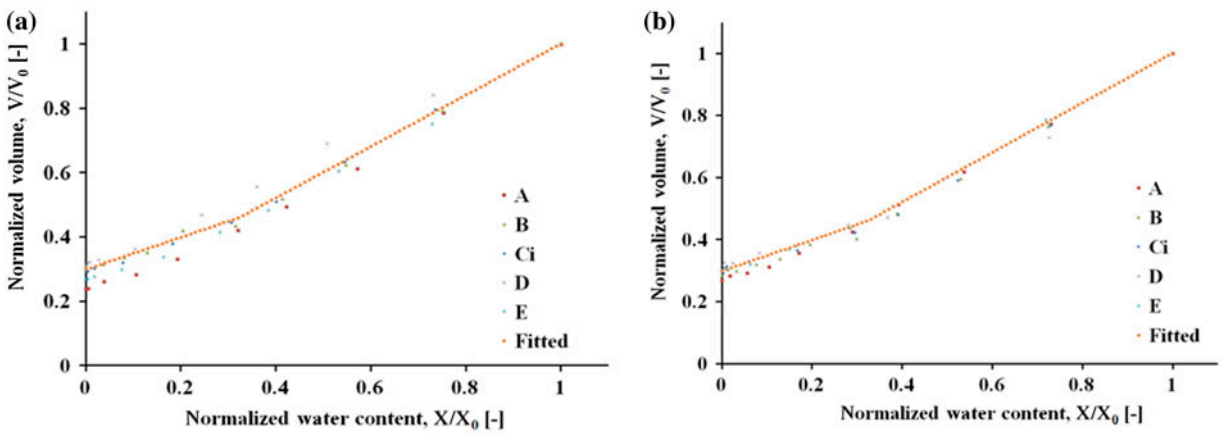

Fig. 11. Shrinkage volume vs. normalized moisture content for the experimental design: (a) and (b) were the sludge samples, respectively, conditioned by PAX-14/640 LH and PAX-14/640 CT. *A* (0; 3); *B* (0; 6); C_1 (4; 6); *D* (8; 12); *E* (8; 3). The numbers in the brackets of each experimental point represent the required dose expressed in gram per kilogram of DS content (g/kg_{DS}), respectively, for PAX-14 coagulant and polymer dosages.

microtomography method. These curves represent the evolution of the normalized sample volume V/V_0 vs. the normalized water content X/X_0.

For all trials, the sample's volume decreases linearly with decreasing moisture content until a X/X_0 threshold value around 0.3. Below this value, a break in slope materializing the beginning of the second period of shrinkage can be seen. During this second phase, the sludge volume also decreases linearly with the normalized water content until the sample reaches its final dimensions. For all sludge samples, the sludge cake shrank in volume around 70% of the initial value. The result is in agreement with that described by Léonard [14] in one of the chapters of her PhD thesis devoted to the study of the influence of the humidity of air on the shrinkage of Embourg's sludge.

According to this figure, the shrinkage reduction seems to be totally independent of the amount of PAX-14/polymer dosage, for given drying operating conditions: all curves are almost superimposed, except in case of the trial *D* of the experiment noted (a), which showed a small shift. It seems that, during drying, the structure of this sample tends to stiffen much more than the others. In this way, the shrinkage will stop before the end of the removal of water: the importance of the shrinkage properties depend on the rheological properties of the sludge.

On the first period, the volume shrinkage of the sample can be easily correlated to the quantity of evaporated water. The texture of the solid material does not hamper the shrinkage process. However, during the second period, the structure of solid stiffens and then influences the shrinkage phenomenon [35,36]: water is replaced by air and porosity is created. This period corresponds to a phase of decreasing deformation rate (ε) marking the gradual rigidifying of the matrix until no further deformation was observed, the solid was totally rigidified. Contrary to what was observed by Léonard et al. [35], during the second phase, it appears a slowdown of shrinkage rather than definitive constant value (plateau). Nevertheless, this type of shrinkage with two straight line periods can be found in the literature. It is usually shown for deformable solid materials; while for the first case (constant value at the end of second period of shrinkage) is shown in the case of non-malleable solid materials [37].

To describe the shrinkage phenomenon that occurs during the drying process, linear models were selected. Thus, a first linear model based on the set of data points was tested. It has been rejected according to the bad shape of the shrinkage curves obtained. Inspired by the studies of Léonard et al. [35], a second model with two straight lines fitting, corresponding to the two periods of the shrinkage curve was used. The mathematical modeling is given by the following forms:

$$V/V_0 = a\,X/X_0 + b;\ I < X/X_0 < 1$$

$$V/V_0 = c\,X/X_0 + d;\ X/X_0 < I \quad (9)$$

$$I = (d - b)/(a - c)$$

where a and b represent the slope and the ordinate parameters for the first part of the model (–); c and d: represent the slope and the ordinate parameters for the second part of the model (–); I is the intersection (threshold) between the two terms of the model.

The model was used to determine the constants a, b, c, and d in the case of the two sludge conditioning types, to check the reliability about shrinkage response conclusions (no difference between shrinkage curves). The results, performed on the central points are shown in Fig. 12. This figure clearly shows that the conditioning type has no significant influence on the shrinkage curves: the amplitude of the parameters a, b, c, and d is each time similar, regardless of the conditioning type used to flocculate the sludge.

This result confirms that the sample shrinkage that occurs during drying does not depend on the polyelectrolyte type or dosage, but could certainly be related to the sludge characteristics and composition. In fact, a study performed by Léonard et al. [35] on the dewatering and drying abilities of two sludge samples collected from two separate wastewater treatment plants showed that during the second period of shrinkage, the sample reduction volume after drying was different from a collected sampling site to another. The authors claimed that the difference was

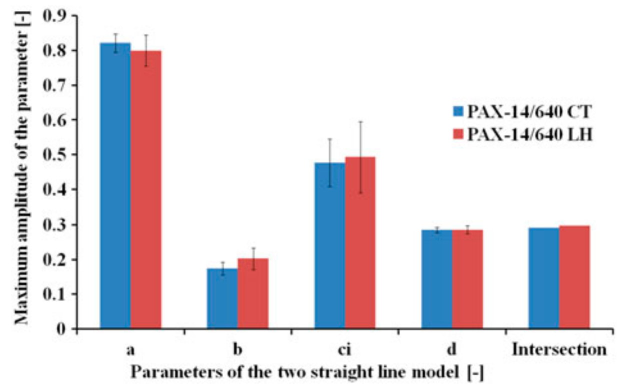

Fig. 12. Parameters comparison (a, b, c, and d) of the two straight line model at the central point (C_i).
*Intersection: is the break point between the two linear terms of the model. **C_i represents the average of the four replicates performed on the central point.

related to the sludge organic matter content. In another work, the same authors [25] have compared the shrinkage curves from the drying of two samples from the same wastewater treatment plant, conducted at the same temperature but at different airflows. They concluded that no detectable difference between shrinkage curves was observed despite the difference in airflow inlet (50 and 80 NL/min). This result suggests that the extrinsic sludge parameters (air flow, flocculation chemical products) do not influence the shrinkage phenomenon during drying activity. On the contrary, the temperature parameter was shown to have an effect on the shrinkage process. A high temperature (120–160°C) leads to a smaller sample volume reduction, while at the low values (80°C) the shrinkage is more pronounced. This observation is linked to hardening and crusting phenomena: beyond 120°C, increasing the temperature causes the formation of a dry outer layer which impedes the shrinkage of the sample [14]. According to Ruiz et al. [38], the shrinkage effect is directly dependent on the sludge properties associated with the mass percentage of the DS content, constituted by the VS content assumed to be equal to the organic solid compounds.

Table 8 shows the model coefficients values and the corresponding statistical parameters. The correlation coefficients (R^2) are all high and close to 1 and the MSE values are small. The model with two straight lines can be considered to be good to describe the shrinkage response in the experimental investigated region. Nevertheless, according to the results, the D trial was shown to be not closed to the other data, for this reason a model with only one straight line seems to be suitable.

Table 8
Results of the fitting shrinkage model for the two sludge conditioning types

	Trials points X^a	a (–)	b (–)	c (–)	d (–)	R^2 (–)	MSE (–)
PAX-14/640 LH conditioning	A (0; 3)	0.862	0.132	0.491	0.236	1.000	0.003
	B (0; 12)	0.817	0.182	0.449	0.305	0.998	0.005
	D (8; 12)	0.698	0.313	–	–	–	–
	E (8; 3)	0.828	0.164	0.483	0.273	0.998	0.004
	C_i (4; 6)	0.799	0.203	0.493	0.286	0.992	0.021
PAX-14/640 CT conditioning	A (0; 3)	0.808	0.189	0.505	0.264	0.999	0.002
	B (0; 12)	0.856	0.145	0.427	0.282	0.999	0.003
	D (8; 12)	0.801	0.190	0.426	0.326	0.999	0.003
	E (8; 3)	0.794	0.207	0.504	0.293	1.000	0.001
	C_i (4; 6)	0.822	0.174	0.477	0.285	0.997	0.013

Notes: –: refers to a linear model with only one straight line.
[a]X (PAX-14 dosage in g/kg_{DS}; polymer dosage in g/kg_{DS}).

4. Conclusions

Sludge conditioning process is a critical aspect to improve the sludge filterability prior to mechanical dewatering. To achieve this purpose, this study compared the effectiveness of two conditioning types including PAX-14 used like a coagulant, on both dewatering and drying performances. The dewatering characteristics were assessed by evaluating the DS content of the dewatered cake and SRF.

Results showed that samples dosed with coagulant and polymer exhibited higher DS content compared to the DS content achieved with single polymer conditioning, indicating a more sludge permeability after PAX-14 addition. Nevertheless, the use of Carman's law to evaluate the efficiency of dewatering step was shown to be inadequate to describe the filtration stage. In some cases, the filtration phase is not always linear, which leads to errors in the determination of SRF parameter. For this reason, the concept of final dryness of the filter cake seems to be the most useful index to assess at sludge filterability.

The drying experiments of sludge after a filtration step were also considered. The drying flux subsequent to single conditioning was lower than the sludge that conditioned with the dual PAX-14/polymer conditioners. The positive effect of PAX-14 addition on drying rate was effective, consequently a decrease of the required drying time was observed. According to the statistical analysis, it appears that the two conditioning types used to flocculate the raw material produced the same performances on the thermal drying process. The evolution of shrinkage ratio during drying was almost similar for both conditioned sludge. It showed a linear decrease with two straight line periods, with a final volume reduction close to 70% at the end of drying. This shrinkage effect was shown to be independent on the polyelectrolyte chemicals but seems to be attributed to the sludge properties.

Future work will be done by investigating the use of cross linked polymers and their relationship with textural rheological properties, including drying and shrinkage sludge modeling to simulate the experimental results.

Acknowledgments

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Nomenclature

A	—	filter sectional (m^2)
C	—	ratio of mass of solid deposited by volume of collected filtrate (kg/m^3)
CST	—	capillary suction time (s)
DS	—	dry solids content (%)
P	—	applied pressure (Pa)
R_f	—	resistance of the filter medium (m^{-1})
SRF	—	specific resistance of filtration (m/kg)
t	—	time (s)
V	—	volume of the filtrate (m^3)
V_0	—	initial volume of the filtrate (m^3)
V_1	—	initial volume of the wet dewatered sample, before drying at 130°C (mm^3)
V_2	—	final volume of the dried sample at 130°C (mm^3)
VS	—	volatile solids content (%)
W_d	—	weight of the control sample, after drying at 105°C (g)
W_f	—	weight of the dewatered sample, after drying at 130°C (g)

W_q — weight of the dried sample, after calcination at 550°C (g)
W_s — weight of the control sample, before drying at 105°C (g)
$W_{95\% DS}$ — weight of the total amount of the evaporated water at 95% DS (g)
X — dry basis water content (kg_{water}/kg_{DS})
X_0 — initial water content (kg_{water}/kg_{DS})
x_{exp} — experimental values (–)
$\overline{x_{exp}}$ — mean of experimental values (–)
x_{cal} — fitted values (–)

Roman and greek letters
a — slope of the first part of the model (–)
b — ordinate of the first part of the model (–)
c — slope of the second part of the model (–)
d — ordinate of the second part of the model (–)
I — threshold between the two terms of the model (–)
n — number of observations (–)
q — modeling parameters number (–)
μ — liquid viscosity (Pa s)
ε — shrinkage ratio (–)

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