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## Waste activated sludge dewaterability: comparative evaluation of sludge derived from CAS and MBR systems

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### ABSTRACT

Sludge dewatering represents, nowadays, one of the greatest operational cost to wastewater treatment cycle. Physical–chemical and biological parameters are recognized to influence the sludge dewaterability. However, many authors agree in identifying the sludge origin as one of the main aspect involved in sludge dewaterability. Indeed, the sludge origin such as the processes involved in liquid–solid separation, seriously affect the sludge features. In order to elucidate the key factors influencing the dewaterability process, the present work is aimed to investigate the influence of the treatment plant lay-out on sludge dewaterability. The analyzed sludge samples were derived from four conventional activated sludge and two membrane bioreactor wastewater treatment plants. Experimental investigation was focused to highlight difference in sludge dewaterability derived from the application of European Standards adopted for sludge characterization. The achieved results confirmed the complexity of the inter-relationships between many factors affecting the sludge dewaterability.

*Keywords:* Sludge dewaterability; Activated sludge; MBR; Capillary suction time

### 1. Introduction

Nowadays, waste activated sludge management represents one of the main aspects involved in the entire cycle of wastewater treatment. Indeed, after the solid–liquid separation by sedimentation or filtration operation, an additional separation is required to achieve a reduction in sludge volume to facilitate transport and handling operations [1]. Sludge dewatering, recognized as one of the most complex and

expensive operation involved in wastewater treatment cycle [1–5], requires significant technical as well as economical efforts [6]. As a matter of a fact, 1t of fresh sludge to be disposed is composed, on average, by 0.25–0.30t of suspended solids (SS), with a cost for treatment and disposal around €280–470/t [7]. A better understanding of sludge dewatering features, could lead to an improvement in pretreatment approaches focused to enhance the dewaterability efficiency [6]. In detail, Vesilind et al. [8] have defined four different types of water contained in sludge: free

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water, interstitial water, vicinal water, and water of hydration. More in detail, free water can be easily separated by gravitational settling; interstitial water separation can be achieved only by mechanical dewatering devices, such as centrifugation or vacuum filtration; vicinal water, physically bound to solid particles surface, cannot be separated by any mechanical device. Water of hydration, chemically bound to solid particles surface, can be separated only by heating at temperature above 105°C [6]. Thus, dewatering process is mainly focused to separate the bound water content, represented by the sum of interstitial, vicinal, and hydration water. Several investigations reported that while in high water content condition (over 80%) the water separation could be achieved with relatively low cost, when the water content decreases under 80%, the energy demand cost, drastically increases [9–11].

Despite several technologies, such as membrane bioreactor (MBR) systems, have been developed with the focus also to reduce the specific sludge production, still mechanical dewatering represents a crucial step to limit the amount of sludge to be disposed [12]. As a matter of fact, the efficiency of dewatering process is related to many physical–chemical parameters, such as floc structure, particle size, bound water content, surface charge as well as hydrophobicity. However, many authors agree in identifying the sludge origin as one of the main aspect involved in sludge dewaterability [1,11,13].

Sludge dewaterability is significantly affected by operational wastewater treatment plant settings. In detail, there are some key parameters which strongly influence the sludge dewaterability: sludge retention time (SRT), extracellular polymeric substances (EPS), soluble microbial products (SMP), sludge salt content and presence of filamentous bacteria [14–17]. More in detail, activated sludge flocs are mainly composed by water, biomass and EPS, that are highly charged polymers interacting as a gel with water molecules [18]. The EPS can play a significant role in binding organic and inorganic matter enhancing the attachment of bacteria to surfaces [4]. Together with bound water content, the EPSs are considered as the most important parameters affecting sludge dewaterability [6]. However, due to the complex dynamics of sludge matrix it is still challenging to assess the influence played by extracellular organic features on sludge dewaterability [19]. Indeed, some authors report that dewaterability of sludge improves after EPS reduction [20]; on the contrary, some authors [21,22] found that sludge dewaterability initially increases with EPS content but then decreases once EPS content rises over a threshold value, thus rising some controversial in such

aspects. Moreover, rheological features (e.g. viscosity), that provide information on sludge structure at macroscale play an important role in the discussed phenomena [6].

In the light of the above discussion, it comes up that several parameters could affect simultaneously the dewatering process. However, a lot of the discussed parameters are strongly related to plant layout. Indeed, the EPS production as well as particle size distribution (PSD) or floc structure is significantly related on wastewater treatment plant (WWTP): conventional activated sludge (CAS) or MBR.

Bearing in mind the above discussion, in order to elucidate the key factors which influence the dewaterability process, the present work aims to investigate the influence exerted by treatment plant lay-out on sludge dewaterability. Particularly, sludge samples drawn from four CASs and two MBRs have been investigated and compared in terms of dewaterability features. Samples were collected from both water line and sludge line (namely, digestion) in order to detect possible sludge differences. Different parameters have been investigated to better understand sludge dewatering: capillary suction time (CST) [20,23] and specific resistance to filtration (SRF) [24,25].

## 2. Materials and methods

### 2.1. The investigated case studies

The sludge samples drawn from four CASs and two MBR plants were investigated according to experimental procedures discussed in the following. In Table 1, the main features of the investigated plants are summarized.

All investigated WWTPs serve combined sewers which convey both domestic and stormwater flows. The investigated WWTPs ranged from 12,000 to 440,000 equivalent inhabitants, thus covering a representative fraction of the conventional treatment plant application. Moreover, two CASs were also equipped with primary sedimentation unit, thus providing a complete outlook of the possible CAS scheme application. The investigated MBR plants were, on the contrary, representative of small communities (up to 30,000 equivalent inhabitants). Further, the WWTPs were also located in places significantly affected by touristic fluctuation. However, sludge samples were drawn during the winter season, and thus not influenced by tourists. From each WWTP, samples (about 20 L) were collected from oxidation unit and also from stabilization unit. The collected samples were stored at 4°C until the laboratory was reached.

Table 1  
Main features of the investigated WWT plant

WWTP	EI	AF (m <sup>3</sup> d <sup>-1</sup> )	OLR (kg BOD <sub>5</sub> d <sup>-1</sup> )	OV (m <sup>3</sup> )	AV (m <sup>3</sup> )	DV (m <sup>3</sup> )	MLTSS (kg m <sup>-3</sup> )	DTTSS (kg m <sup>-3</sup> )
CAS1	440,000	152,000	30.800	17,872	–	–	4.89	13.50
CAS2	12,000	–	1,038	720	700	447	2.44	13.72
CAS3	32,000	6,400	2,080	2,800	355	1,094	4.58	13.66
CAS4	88,000	24,000	5,280	1,200	–	2,400	6.08	31.08
MBR1	15,000	3,540	810	660 + 110 <sup>(*)</sup>	220	–	4.03	–
MBR2	30,000	6,465	1,800	1,800 + 44 <sup>(*)</sup>	1,000	–	12.00	5.91

Notes: EI = equivalent inhabitants; AF = average flow; OLR = organic loading rate; OV = oxidation volume; AV = anoxic volume; DV = digestion volume; MLTSS = mixed liquor total suspended solids; DTTSS digestion tank total suspended solids; (\*) oxidation tank volume + MBR tank volume.

## 2.2. Experimental procedures

Sludge samples were analyzed for the determination of total suspended solids (TSS) and volatile suspended solids, in accordance with international standards [26]. The PSD for each sludge sample has been also carried out by means of Malvern Mastersizer 2000 particle size analyzer. Moreover, the diameter corresponding to 10, 60, and 90% (V/V) of each PSD was determined. Sludge volume index (SVI) and stirred sludge volume index (SSVI) test were performed in accordance with EN 14702-1 and EN 14702-2 standards [27–32]. In detail, SVI was assessed without dilute or concentrate sludge, and thus at the sludge concentration reported in Table 1; conversely, sludge samples used for the SSVI assessment were diluted with tap water until the sludge concentration reached the value of 3.5 g SST L<sup>-1</sup> as required by the 14702-2. Furthermore, sludge of CAS 2 was concentrated in order to reach the target concentration required to assess the thickenability. Moreover, tests for the determination of CST, SRF, compressibility, drainability, and thickenability were carried out in accordance with international standards (Table 2).

In detail, the CST was measured on fresh samples and it was used as indicator for deriving the proper dosage of poly-electrolytes needed for conditioning the sludge in accordance with scientific literature [1,33]. Indeed, a poly-electrolyte cationic (DRYFLOC 442H-SNF) was formerly dissolved in liquid solution with a concentration equal to 1 g L<sup>-1</sup> and thus dosed in a range from 2 to 30 mg of flocculants per g TSS. After one minute of mixing phase (200 rpm) and 20 min of flocculation phase (30 rpm), samples of conditioned sludge were collected and investigated for CST. The optimal flocculants dosage was the one corresponding to the minimum value of the achieved CST [34].

The SRF was evaluated in reduced pressure condition and under pressure condition. In detail, the vacuum condition was achieved by means of a vacuum pump (–50 kPa) connected to a Buchner funnel where Whatman 41 (20 µm pore size) filter paper was placed. The under pressure SRF measurements (50 kPa) were achieved connecting an air pressure system to a filtration device realized in accordance with standards [28]. The sludge compressibility was investigated with the same apparatus adopted for the SRF determination under pressure. Four different pressure ranges were applied: 50, 100, 150, and 300 kPa. The sludge compressibility coefficient (*S*) was evaluated in accordance with Eq. (1):

$$S_{P_1-P_2} = \frac{\log \frac{SRF_2}{SRF_1}}{\log \frac{P_2}{P_1}} \quad (1)$$

where  $S_{P_1-P_2}$  is the sludge compressibility;  $SRF_2$  and  $SRF_1$  represent the specific resistance to filtration achieved by applying positive pressure equal to  $P_2$  and  $P_1$ , respectively;  $P_2$  and  $P_1$  are, respectively, the superior and the minor pressure (measured in kPa) applied. Particularly, values of the sludge compressibility higher than one indicates an increase in the specific resistance to filtration more than proportional to the pressure, thus indicating a lack of convenience in operating at high pressure. Flocculated sludge drainability was investigated by adopting three filtering medium normally used in full-scale drainage device (filterpress). In detail, the adopted filtering medium, provided from Testori® Group, were P 4422, N 4462, and N 4423 with a pore size equal to 25, 38, and 49 µm, respectively. An electronic weighing balance (accuracy 0.001 g) was employed for recording the weigh variation each 0.25 s. The sludge thickenability was investigated by stirring (1 rpm) 3.5 L of sludge for 30 min in a 50 cm height cylinder.

Table 2  
Measured parameters and Standard methods applied

Parameter	Document	Reference
CST	Characterization of sludge-filtration properties—Part 1: Capillary suction time (CST)	EN 14701-1:2006
SRF	Characterization of sludge-filtration properties—Part 2: Determination of the specific resistance to filtration	EN 14701-2:2006
Compressibility	Characterization of sludge-filtration properties—Part 3: Determination of the compressibility	EN 14701-3:2006
Drainability	Characterization of sludge-filtration properties—Part 4: Determination of the drainability of flocculated sludge	EN 14701-4:2010
SVI	Characterization of sludge-settling properties—Part 1: Determination of settleability	EN 14702-1:2006
Thickenability	Characterization of sludge-settling properties—Part 2: Determination of thickenability	EN 14702-2:2006

### 3. Results and discussion

In Fig. 1, the mean values of CST, measured for mixed liquor (ML) and for digested sludge (DIG) are reported.

The data reported in Fig. 1 shows that the highest CST takes place for the CAS digested sludge. In general, the CST values for the digested sludge, withdrawn from CAS and MBR, were relatively high and thus indicate poor dewaterability properties. More in detail, the CST for the samples withdrawn from digested sludge is constantly higher, almost double, than the mixed liquor one. Mowla et al. [6] found that the energy required for sludge dewatering increase when sludge water content decrease; as the digested sludge water content is conventionally lower than mixed liquor, the dewaterability of digested sludge resulted more laborious than mixed liquor. Conversely, regarding the mixed liquor, the CST for CAS resulted always lower than the MBR one. The latter circumstance is probably ascribable to the deflocculation effect exerted by the MBR lay-out that significantly affects the dimension of activated sludge

flocs [35,36]. On the contrary, regarding the CST of the digested sludge, it was found that such value was higher for CAS than MBR. Such a difference is probably ascribable to process parameters involved in the two different treatment schemes. Indeed, it is well known that with the focus to minimize excess sludge production [37], MBR conventionally operate with SRT higher than CAS. Thus, in agreement with Al-Halbouni et al. [15], that found that higher SRT leads to sludge with significantly better dewaterability properties compared to sludge with lower SRT, it looks reasonable that the MBR digested sludge seems to be more easily dewaterable than the CAS digested sludge. In other words, it is characterized by lower CST values. With regards to the sludge floc dimension, in Fig. 2(a) the PSD of the mixed liquor of the investigated samples is plotted. In Fig. 2(b) the main features of each PSD curve are reported.

In detail, Fig. 2(a) and (b) show that MBR flocs are much more thinner than CAS. Particularly, in Fig. 2(b), it is possible to notice that 90% in volume of the sludge floc has a mean diameter lower than 44–66  $\mu\text{m}$  for MBR1 and MBR2, respectively. On the other hand, the minimum value of  $d_{90}$  of the investigated CAS was equal to 90  $\mu\text{m}$ . Such observation, which confirms the deflocculating effect exerted by MBR, is in accordance with the CST results. Indeed, the CST results showed a lower measured value for CAS mixed liquor rather than MBR. Shao et al. [19] found that the particle size of the sludge flocs has a significant effect on the CST. Particularly, it was reported that the CST increases when mean particle size of activated sludge decreases. Moreover, Higgins et al. [38] indicated the supracolloidal range size (1–100  $\mu\text{m}$ ) as the most influencing on sludge dewaterability. Thus, taking into account the PSD, the CAS mixed liquor should be more dewaterable than MBR, but as the dewaterability is also depending on biological aspects

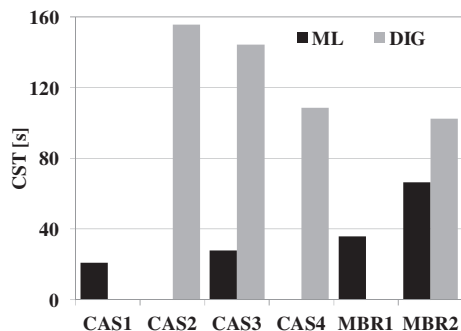


Fig. 1. CST mean values for mixed liquor and digested sludge samples of different WWTPs.

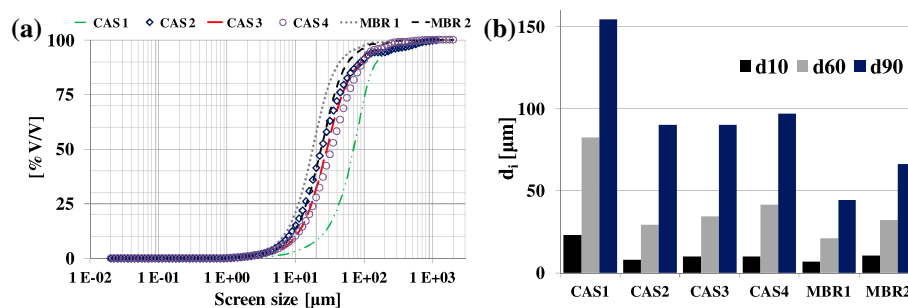


Fig. 2. PSD of mixed liquor samples (a) and main features of each PSD (b).

(e.g. SRT, EPS, and SMP content), the dimensional classification provided by PSD would not represent an exhaustive indicator of sludge dewaterability properties.

Sludge has been conditioned by dosing a poly-electrolyte cationic in accordance with results achieved with CST. In detail the optimal dose for CASs resulted equal to 12 mg of poly-electrolyte g SS<sup>-1</sup> except for CAS1 sample where the optimal dose resulted equal to 10 mg of poly-electrolyte g SS<sup>-1</sup>; furthermore the CST corresponding to the optimal dose were equal to 17, 32, 28, and 26 s for CAS 1, 2, 3, and 4, respectively. With reference to MBR, the optimal dose resulted equal to 8 mg of poly-electrolyte g SS<sup>-1</sup> for both MBR 1 and 2 and the corresponding CST resulted equal to 16–18 s for MBR 1 and 2, respectively.

Regarding the SRF in reduced pressure condition, measures were carried out both on unconditioned sludge and on conditioned sludge and results are reported in Fig. 3. Particularly, as sludge filtration is conventionally carried out on the digested sludge, the SRF assessment has been carried out mainly on digested sample. However, for the CAS1 the digested sludge volume available was not sufficient to carry out the SRF and so the mixed liquor was investigated. With reference to both MBR the investigated sludge was the mixed liquor; furthermore as in MBR2 a sludge digestion tank exists, the SRF was also evaluated and is identified as MBR2 d in the Fig. 3 legend.

It is worth noting that there is not a significant difference with raw samples. Particularly, all the investigated sludge samples are characterized by a SRT value above the threshold value (namely,  $5 \times 10^{12} \text{ m kg}^{-1}$ ). The threshold value (horizontal dotted red line Fig. 3) has been derived by a recommended value of EN 14701-2 [28]. According to the Standards, below such threshold value, sludge can be considered filterable on industrial scale and thus not well dewaterable by void filtration.

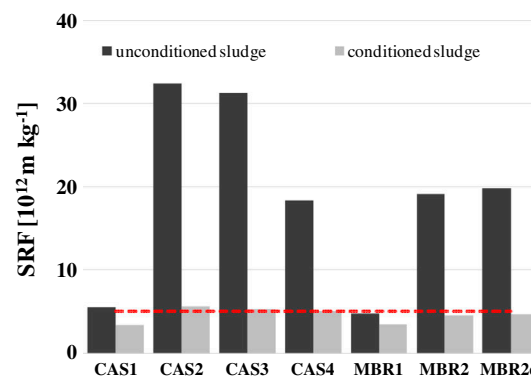


Fig. 3. Reduced pressure SRF for CAS1 mixed liquor, CAS2, CAS3, and CAS4 digested sludge, MBR1 and MBR 2 mixed liquor and MBR 2 digested sludge.

Moreover, the flocculants dosing resulted efficient only with the MBR sludge. Indeed, for the MBR sludge, the SFR reached values below the threshold after the chemical dosing. Conversely, for three sludge of the CASs, the SRF did not decrease below the threshold; thus showing some shortcomings in the sludge filterability. Particularly, the SFR values, measured after chemical conditioning, were equal to  $5.62 \times 10^{12} \text{ m kg}^{-1}$ ,  $5.32 \times 10^{12} \text{ m kg}^{-1}$ , and  $5.07 \times 10^{12} \text{ m kg}^{-1}$  for CAS2, CAS3, and CAS4, respectively. The SRF has been investigated also on pressure cell with a positive applied pressure equal to 50, 100, 150, and 300 kPa. The results are reported in Fig. 4(a) and (b). Such results were used to evaluate the sludge compressibility.

The derived results did not highlight significant differences between CAS and MBR. Moreover, even after the chemical conditioning, the SRF values remained almost constantly above the threshold (horizontal dotted red line of Fig. 4) thus demonstrating a scarce sludge filterability on an industrial scale. However, as soon as chemical flocculants was added, the filterability features were improved. Furthermore,

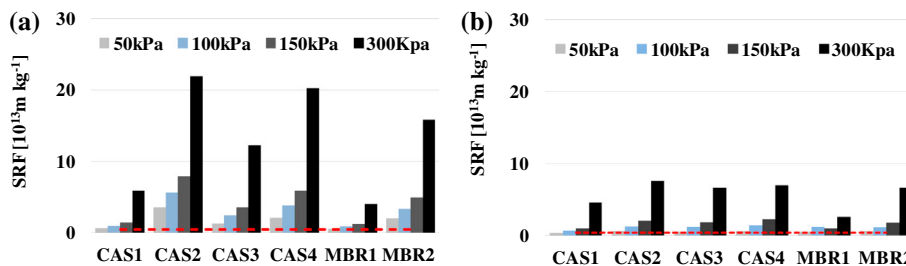


Fig. 4. SRF for unconditioned sludge (a) and conditioned sludge (b).

the achieved SRF results allowed to evaluate the compressibility coefficient  $S$  (Table 3).

The poor under pressure filterability, highlighted by the SRF results, was confirmed also by the compressibility coefficient evaluated for the investigated sludge. In detail, by increasing the applied pressure, the compressibility coefficient raised up to values above one. More in detail, with reference to  $S_{150-300}$ , none of the investigated sludge, raw as well as conditioned, resulted compressible under high pressure. However, the derived results highlighted that for low applied pressure ( $S_{50-100}$ ) all the raw samples, CAS and MBR, resulted with good compressibility features. Conversely, for the same applied pressure, all the conditioned sludge samples resulted with higher value of  $S$ , thus indicating that chemical flocculants dosing caused a worsening of the sludge compressibility features contrasting the results achieved for the SRF assessments.

The drainability of the sludge has been evaluated by means of three filtering devices and, as example, in Fig. 5 are reported the results regarding drainability carried out with  $38 \mu\text{m}$  filtering device for CAS3 and MBR1.

In detail, despite the chemical conditioning improved sludge drainability features, the results did not highlight significant differences between CAS and MBR sludge. On the contrary, regarding the effect of

chemical flocculants dosage, a major effect was observed for MBR sludge. As an example, in Fig. 5(a) the ratio  $M_t$  vs.  $M_0$ , where  $M_t$  is the liquid mass filtered after  $t$  seconds and  $M_0$  is the initial mass to be filtered, is plotted vs. time. In Fig. 5(b), the slope of each interpolating line is reported. The ratio  $M_t/M_0$  vs. time provides information about the velocity of the drainage. For the analyzed samples, drainage velocity improved more for MBR sludge than for CAS. Indeed, due to the flocculants effect, drainage velocity for CAS3 was 1.56 time higher than for raw sludge. Conversely, the drainage velocity of MBR1 increased up to 1.98 time higher after chemical conditioning. Such a result, reported as an example, is representative of all the investigated sludge. On average, the drainage velocity after chemical conditioning increased, respect to raw sludge, up to 1.72–1.91 time for CAS and MBR sludge, respectively. Thus, in apparent contrast with the results observed for the compressibility, the drainability of sludge was improved by chemical conditioning.

Regarding sludge settleability and thickenability features, the achieved values of SVI and SSVI index are summarized in Table 4.

The reported results, demonstrate the poor settleability features of the investigated sludge. In detail, the derived data indicates bulking phenomena for both MBRs and for CAS2 and CAS3. Such a result is

Table 3  
Compressibility for raw and conditioned sludge

WWTP	Sample	Raw sludge			Conditioned sludge		
		$S_{50-100}$	$S_{100-150}$	$S_{150-300}$	$S_{50-100}$	$S_{100-150}$	$S_{150-300}$
CAS1	ML	0.63	1.01	2.06	0.97	0.75	2.17
CAS2	DIG	0.66	0.83	1.94	0.85	1.22	1.84
CAS3	DIG	0.86	0.95	1.76	1.02	1.10	1.75
CAS4	DIG	0.85	1.10	1.78	1.12	1.04	1.62
MBR1	ML	0.78	0.84	1.69	0.80	1.08	1.83
MBR2	DIG	0.77	0.92	1.68	1.74	1.08	1.90

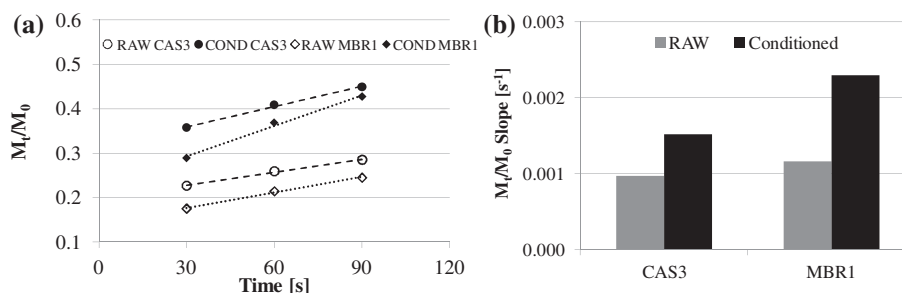


Fig. 5. Drainage with 38  $\mu\text{m}$  filtering device (a) and slope of the plotted results (b).

Table 4  
SVI and SSVI

WWTP	SSV ( $\text{ml g}^{-1}$ )	SSVI ( $\text{ml g}^{-1}$ )
CAS1	110	55
CAS2	270	120
CAS3	230	100
CAS4	150	60
MBR1	270	140
MBR2	270	40

probably due to WWTP operational conditions. Moreover, taking into account the obtained results for the SSVI, significant differences between CAS and MBR sludge were not underlined; indeed the investigated sludge were all characterized by low values of SSVI indicating a good sludge thickenability.

#### 4. Conclusions

The activated sludge dewatering certainly represents one of the most crucial and controversial aspect involved in the wastewater treatment managing. Several factors, such as WWTP lay-out, operational parameters, EPS and organic load influence sludge dewaterability. The interaction between the aforementioned factors remains still to be clarified. In the present study, a comparative evaluation of the dewaterability features of sludge samples derived from CASs and MBRs has been carried out. To carry out a comprehensive comparison, the international standards methods conventionally adopted for sludge characterization have been employed.

The obtained results showed a lower CST for MBR digested sludge. On the other hand, different results have been derived with respect to the mixed liquor where the thinner floc dimension, underlined also by the PSD evaluation, was likely the key factor of a worse dewaterability. Moreover, with reference to MBR conditioned sludge, it was found a better

suitability to be filtered under reduced pressure (void filtration) condition. The under pressure filtration, investigated with SRF measurements, showed a scarce sludge filterability at high pressure and a poor compressibility of raw sludge as well as conditioned sludge. Controversial results have been obtained regarding the sludge conditioning. As a matter of a fact, while the sludge compressibility was found worsened by chemical flocculants addition, on the contrary, the drainability of the sludge was improved by the conditioning.

To sum-up, this study confirmed the inter-relationships of the main factors which control/depend the sludge dewaterability (i.e. WWTP lay-out, physical-chemicals, and biological processes). The derived results, allowed to gain insights to better understand the complexity of the sludge dewatering and the necessity to make a comparative evaluation that take into account also the biological aspect and the operative condition as well as the rheological features of the sludge to be dewatered.

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